Geochemistry of some lateritic nickel-ores with particular reference to the distribution of noble metals

S. AHMAD AND D. F. C. MORRIS

Nuclear Science Centre, School of Chemistry, Brunel University, Uxbridge UB8 3PH

PLATINUM, palladium, gold, and iridium have been determined by radiochemical neutron-activation analysis in three lateritic profiles developed on serpentinized peridotite. In addition, a number of major, minor, and other trace elements have been estimated by conventional chemical, instrumental neutron-activation, and radiochemical methods. The fractionation of the elements as a result of the tropical weathering has been investigated as a function of depth. Each of the profiles L—Guatemala, BNC—New Caledonia, and BIP—Indonesia —has a lower decomposed serpentinite zone and upper zones enriched in iron[III] oxides and hydroxides. There is marked depletion of silicon and magnesium, and sodium is also largely leached out as a result of the weathering. The deposits are of economic importance primarily in that they are enriched in nickel; this element is concentrated in the ferruginous parts but also it is relatively plentiful in the intermediate saprolitic zones. Noble metals are concentrated in each of the profiles, particularly in the A and B horizons; it appears in the case of platinum and palladium that there has been some mobility as a result of the weathering and probably these elements have been brought into solution prior to subsequent redeposition.

The three profiles have many features in common, although the analytical and other information indicates that BNC is more mature than L. It appears that there is a fairly general sequence of differentiation in the development of laterites from ultrabasic rocks.

The full text appears in the Miniprint section, pp. M4–8.

it. It is unlikely that the titanomagnetite was actually pressed into contact since the remainder of the pyrite periphery retains its spheroidal form and granular integument. Adhesion of the sulphide melt to a titanomagnetite grain is even more convincingly shown in Fig. 2E where the grain only maintains contact with a pear-shaped pyrite by virtue of the latter's departure from a spherical form. Its present shape no doubt results from a recessive movement of the titanomagnetite relative to the sulphide globule while the host mesostasis was still fluid. Fig. 2F, on the other hand, appears to represent a sulphide globule confined and distorted, while still fluid, by adjacent plagioclases displaced by movement in the host mesostasis.

Summary and conclusions

The Imachar composite dyke is important as affording evidence of the emplacement and crystallization of two tholeiite members which, despite their chemical similarity, show petrographic individuality which can only be a consequence of differing circumstances of emplacement and the divergence of their subsequent cooling histories.

The outer and earlier member shows textural evidence of rapid intrusion followed by the immediate onset of crystallization, the latter being initiated under temporary conditions of undercooling which, in addition to marginal chilling, resulted in the development of poikilitic overgrowths on earlier-formed, probably intratelluric, plagioclase phenocrysts and glomeroporphyritic xenocrystal groups. Continued crystallization produced further, entire, mantling overgrowths of less calcic composition on the plagioclase phenocrysts, while new individuals of a seriate succession of smaller plagioclases were developed in the matrix. The ferromagnesian silicates joined plagioclase rather early in the crystallization sequence, while iron ores (titanomagnetite) are virtually confined to the ultimate mesostasis. These characters indicate crystallization under essentially closed-system conditions, and are compatible with the failure of this member to reach the contemporary earth-surface. Its thermal effects on its country-rocks are small, as is appropriate to a minor intrusive which served as a conduit to a limited volume of magma.

The inner tholeiite shows, in contrast, no evidence of chilling against its country-rocks which, where initially schistose-grits, have suffered transformation to cordierite-buchite over a distance in excess of 20 cm from contact. This implies a major accession of heat, supplied over a comparatively protracted period. Petrographically the rock offers evidence of rather slow cooling from an unusually high initial temperature, since its not infrequent bytownite, and the majority of its labradorite-cored phenocrysts lack poikilitic overgrowths such as are characteristic of the outer member. It is likely that the few plagioclase phenocrysts present in the inner tholeiite which do show poikilitic mantles have been derived from mobilized outer tholeiite, while the occasional plagioclases showing mechanical distortion are labradorites of intermediate structure acquired by the rising magma from a crystalline basic mass at greater depths. The early separation of titanomagnetite and delayed appearance of augite indicate crystallization under virtually open-system conditions, all being in keeping with the view that the inner tholeiite reached the contemporary earth-surface and there served as feeder to fissure-eruption of lava. Since under such conditions the rapidly rising magma is likely to have acquired significant superheat of gravitational origin, the conversion of immediately contiguous schistose-grits to buchite is readily understood.

The original connotations of the terms "variole" and "variolite" have been lost sight of by a majority of petrologists active during the past century. The term variolite and the adjectival "variolitic" have been widely used in connection with rocks which have little or no textural or structural similarity to the true variolites. Rocks having the characters implicit in the early usage do indeed exist, and for this reason a return to this usage is

long overdue. In the inner, variolitic, tholeiite at Imachar varioles have resulted when droplets of buchitic melt became dispersed in the tholeiitic magma, and it is concluded that it is only in this manner that they have been developed in the present association. The survival of the structure until the consolidation of the host is a consequence of the immiscibility of acidic in basic melts at liquidus temperatures, a relation which fails only when advancing crystallization of the host yields a mesostasis convergent on the composition of the intra-variolitic liquid.

Reflected-light examination shows that the titanomagnetites of both dyke-members have homogeneous structure despite their quite high content of ulvöspinel molecule as revealed by chemical analysis. Their individual compositions and deduced temperatures of crystallization accord well with their textural relations to the respective host rocks. The textural evidence of sulphide immiscibility in both tholeiites is of general interest, while in the present context the relations of the pyrite bodies to their host rocks is strikingly analogous to those of the varioles in the inner tholeiite.

The recognition of the inner tholeiite as a former feeder for lava extrusion is important in that it suggests the directly volcanic function of one more of the many dykes of the Hebridean Tertiary swarms (Holgate 1969, pp.133-134).

Specimens referred to in the present paper are identified by their accession numbers in the Geological Collections of the Hunterian Museum, The University of Glasgow.

References

Bailey (E.B.) et al., 1924. The Tertiary and post-Tertiary geology of Mull, Loch Aline and Oban. Mem. geol. Surv. U.K.
Buddington (A.F.), Fahey (J.) and Vlisidis (A.), 1955. Am. J. Sci. 253, 497-532.
------------------ and Lindsley (D.H.), 1964. J. Petrology 5, 310-357.
Daly (R.A.), 1933. Igneous rocks and the depths of the Earth. New York and London.
De (A.), 1974. Bull. geol. Soc. Am. 85, 471-474.
Deer (W.A.), Howie (R.A.) and Zussman (J.), 1962. Rock-forming minerals. Vol. 5. London.
------------, ------------ and ------------, 1963. Rock-forming minerals. Vol. 4. London.
Fraser (D.), 1968. Heat transfer in automotive alternators. Unpubl. Ph.D. Thesis, University of Glasgow.
Gélinas (L.), Brooks (C.) and Trzcienski (W.E., Jr.), 1976. Can. J. Earth Sci. 13, 210-230.
Gunn (W.), 1903. The geology of North Arran, South Bute and the Cumbraes. Mem. geol. Surv. U.K.
Harker (A.), 1932. Metamorphism. London.
Harris (P.G.), 1962. Am. J. Sci. 260, 763-766.
Haughton (D.R.), Roeder (P.L.) and Skinner (B.J.), 1974. Econ. Geol. 69, 451-467.
Holgate (N.), 1954. J. Geol. 62, 439-480.
------------, 1969. Scott. J. Geol. 5, 97-139.
Holmes (A.) and Harwood (H.F.), 1929. Mineral. Mag. 22, 1-52.
Levinson-Lessing (F.), 1935. Trav. Inst. Petr. Akad. Sci. USSR. 5, 21-27.
McBirney (A.R.), 1975. Nature, Lond. 253, 691-694.
------------ and Nakamura (Y.), 1974. Yb. Carnegie Instn Wash. 73, 348-352.
Mercer (R.A.) and Miller (R.P.), 1963. J. scient. Instrum. 40, 352-354.
Osborn (E.F.), 1959. Am. J. Sci. 257, 609-647.
Skinner (B.J.) and Peck (D.L.), 1969. Econ. Geol. Monogr. 4, 310-322.
------------, 1928. The Geology of Arran. Mem. geol. Surv. U.K.
Tyrrell (G.W.), 1917. Geol. Mag. 54, 305-315 and 350-356.
Yoder (H.S., Jr.), 1954. Yb. Carnegie Instn Wash. 53, 106-107.
------------, 1971. Ibid. 70, 105-108.
------------, 1976. Ibid. 75, 491-508.

Ahmad & Morris: Noble metals in laterites

GEOCHEMISTRY OF SOME LATERITIC NICKEL-ORES WITH PARTICULAR REFERENCE TO THE DISTRIBUTION OF NOBLE METALS

S. Ahmad and D.F.C. Morris

Nuclear Science Centre,
School of Chemistry,
Brunel University,
Uxbridge UB8 3PH

The definition of the term "laterite" and its origin is discussed in detail by Maignien (1966). Ferruginous deposits of this type occur in India, Malaysia, Indonesia, Australia, Cuba, the Hawaiian Islands, and the tropical regions of Africa and Central and South America. For laterization the following conditions appear to be pretty essential:

(1) a warm humid tropical or subtropical climate conducive to extensive chemical weathering;

(2) a flat, or nearly level topography (peneplain) where water has relatively little power to wash away products of chemical weathering;

(3) sufficient time of exposure to the weathering process.

Nickel is enriched in various profiles which have originated from such weathering of ultrabasic rocks and, whilst sulphide minerals, particularly pentlandite, currently provide the major source of the element, lateritic ores are worked on a large scale (Boldt and Queneau, 1967; Skinner, 1976) and are considered to contain about 75 per cent of the known reserves of nickel (Canterford, 1975). Platinum and palladium may exhibit similar apparent radii in crystals of analogous type [single-bond metallic r: Pt, 1.295 Å; Pd, 1.283 : octahedral covalent r: Pt(IV), 1.31; Pd(IV) 1.31 : ionic r: Pt^{2+}, 0.80; Pd^{2+} 0.86; Pauling, 1960; Ahrens, 1952] and these magnitudes correspond quite closely to those for nickel [single-bond metallic r: Ni, 1.154 Å : octahedral covalent r: Ni(II) 1.39 : ionic r: Ni^{2+}, 0.72]. Moreover, the second ionization potentials of platinum (18.56eV), palladium (19.42), and nickel (18.15) are of like order. Such similitude in properties led one of us to suggest that there might be a notable concentration of platinum and palladium in lateritic nickel-ores.

The mineralogy and geochemistry of lateritic weathering of ultra-basic rocks has been studied by several workers (Santos-Ynigo and Esquerra, 1961; Hotz, 1964; Schellman, 1964; Zeissink, 1969, 1971). Using the colorimetric method of analysis developed by Grimaldi and Schnepfe (1968), Zeissink (1971) determined platinum and palladium in two Australian profiles; the distribution of the two elements in the overlying weathering zones appears to be somewhat erratic, but there seems to be some possibility of concentration in the nickeliferous deposits. In general, relatively little is known about the geochemical behaviour of noble metals during weathering (Crocket, 1969, 1974).

The present paper reports on three lateritic profiles of different degrees of development and from widely separated localities. Each of the occurrences represents a useful source of nickel. The distribution of platinum, palladium, gold, and iridium as a function of depth has been determined. For the analysis of these trace elements neutron-activation has been the preferred method. In addition, the fractionation of several major, minor, and other trace constituents has been examined.

The localities are as follows:

Guatemala. - Samples coded L were obtained from a profile in eastern Guatemala, some 50 miles inland from Puerto Barrios on the Caribbean coast. Lateritic material occurs over a large area in association with hills of partly serpentⁱized peridotite on the sides of Lake Izabal. The pattern of distribution at various elevations on gentle to fairly steep slopes and on ill-defined terraces is probably partly due to block faulting. The climate is tropical and the vegetation developed over the ultramafic rock area is sparse in comparison with the dense growth covering surrounding regions.

BNC - New Caledonia. - This deposit occurs at Lat. $22°17'$S and Long. $166°58'$E. The peridotite consists of peridotite and its alteration products. The peridotite is believed to have been introduced during the tertiary period. Lateritic type weathering evidently took place on a peneplain or mature land form that was being subjected to uplift and block faulting.

BIP - Indonesia. - This profile is located in the Pomalaa district, Lat. $4°10'$S, Long. $121°37'$E. In this region large areas of ultra-basic rocks are in part overlain by nickel-bearing laterites. Topography is rugged, although there are plateaux. The climate is tropical, with heavy rainfall and dry intervals.

A description of the samples investigated is given in Appendix 1.

The nomenclature used in our study to describe the various horizons in the profiles is as follows:

A - horizon: the eluviated (leached) top layers.

B - horizon: the illuviated (enriched) intermediate layers.

C - horizon: weathered parent material.

D - horizon: largely unaltered parent material.

An idealized section through the kind of ore-body that we have studied is illustrated by de Chételat (1967) and by Roorda and Queneau (1973).

Mineralogical information obtained from microscopic examination was inadequate because the samples were supplied in a very finely powdered form. A further complication was the presence of an iron oxide coating on most of the grains. Such coating was removed by chemical treatment with 0.03M acetic acid prior to electron-microscopic examination.

The mineral assemblages of the profiles comprised: serpentine minerals, limonite, goethite, chlorite, montmorillonite, and talc. Minor amounts of other minerals, such as magnetite and chromite, were identified. Goethite is microscopically recognisable as anisotropic flakes, and diffraction patterns corresponding to a mixture of amorphous to poorly crystalline material (limonite, goethite, and hematite) were characteristic of all the profiles. Quartz was identified in very small amounts and was of chalcedonic type.

Although nickel was a significant constituent of the samples analysed, no specific mineral of the element was identified. In each profile the deepest or "least weathered zone" is mainly serpentinized peridotite.

Analytical Methods

The radiochemical neutron-activation method (RNAA) for determination of platinum, palladium, gold, and iridium has been described elsewhere (Ahmad, Ahmad, and Morris, 1977).

Conventional chemical methods were used for quantitative analyses of silica, magnesium, chromium, iron, manganese (Maxwell, 1968), copper, cobalt, (Sandell, 1959), and nickel (Vogel, 1962). In addition, chromium, cobalt, copper, iron, manganese, nickel, scandium, sodium and zinc were estimated by instrumental neutron-activation analysis (INAA) (Ahmad and Morris, 1977a). Determinations of total chlorine content and water-leachable chlorine were made by a nondestructive neutron-activation procedure (Ahmad and Morris, 1977b). Uranium was determined by an adaptation of the radiochemical procedure of Baltakmens (1975), and involved beta-counting at a suitable time interval (~ 1 day) after separation.

Leaching experiments were made by adding 50cm³ of distilled water (pH 6.5) to 10g of powdered lateritic sample in a polythene tube. The sealed tube was agitated for 1 hour, and, 24 hours later, measurements were made with an EIL direct reading pH meter, model 23A.

Results

The analytical results for the elements platinum, palladium, gold, and iridium in the three profiles are summarized in Table I. Contents of other elements are listed in Table II.

General Interpretative Procedures

Various procedures have been used as general aids to interpretation of the distribution of the elements in the profiles.

(i) Plots have been made of molar concentration of element, expressed as mole per kg of sample, as a function of depth - cf. Reiche (1950).

(ii) An indication of relative concentration in the profiles was gained by taking the ratio of the concentration of an element in a sample relative to its concentration in the U.S. Geological Survey Reference - Peridotite PCC-1 (Flanagan, 1973; Ahmad, Ahmad and Morris, 1977). This is not so satisfactory as the use of concentration factors related to fresh unaltered rock underlying the laterites, cf. Zeissink (1971), but regrettably we did not possess samples of such material].

(iii) Correlation coefficients have been computed for the distribution of pairs of constituents in order to identify geochemical coherences.

(iv) Reaction pH measurements were made to gain some indication of the effects of weathering on the composition of natural waters. Of course,

---

the data obtained, and listed in Table III, should be considered as giving only a rough guide to field conditions.

Discussion

General - An examination of the analytical results as a function of depth reveals many characteristics in the geochemical behaviour of major and trace elements which recur in each of the profiles investigated. The weathering of the ultramafic rocks has resulted in relative depletion of silicon and magnesium and enrichment of iron, cobalt, nickel, copper, zinc, and scandium. Moreover, the concentration of noble metals is enhanced in the laterites.

Reaction pH through the profiles increases with overall depth, although the variations from monatonic behaviour shown in Table III may be of some consequence. Top surficial horizons are acidic in BNC and BIP, and in the relatively well developed New Caledonia profile magnesium and silicon have been pretty thoroughly leached out. On the other hand, in the case of the L-profile the reaction pH for the A-horizon is slightly basic, and the higher magnesium concentration is compatible with the fact that some weathered serpentine remains in this part of the laterite.

The basicity of a metal ion is a relevant factor affecting its distribution in a lateritic profile. Britton (1942) suggested that the basicities of metal ions be measured by the precipitation pH values of their hydroxides or oxides. In many cases of weathering, however, deposition arising from coprecipitation processes, involving either isomorphous replacement or surface adsorption, or both, rather than separation of pure hydroxides, is important. Norton (1973) has described the conditions favouring the formation of laterite and bauxite as indicated by Eh-pH diagrams.

The distribution of the individual elements in the nickeliferous lateritic profiles is discussed below.

Platinum and palladium. - In the three profiles there is a notable enrichment of both platinum and palladium relative to the parent rock. Results for the Guatemalan L-deposit demonstrate a striking correlation between the occurrence of platinum and nickel and also some correspondence between the distribution of palladium and nickel (Fig. 1). On the other hand, there does not appear to be geochemical coherence between either of the two noble metals and nickel in the New Caledonian weathering site - BNC. In all three profiles the contents of platinum metals are enhanced in horizons where the concentration of hydrous iron[III] oxide is high. Razin et al. (1965) suggested that platinum metals released from decomposed minerals are sorbed by freshly formed hydrated iron[III] hydroxides and demonstrated such an effect with laboratory experiments.

Stability constants for the formation of anionic platinum and palladium chloro-complexes are large (Sillén and Martell, 1964, 1971) and such complexes in aqueous solution may be of consequence in the transport of the elements (Otteman and Augustithis, 1967; Cousins, 1973a,b). Fuchs and Rose (1974) have suggested that in an area containing aqueous media the higher the chloride content the greater the mobility of the precious metals, and although chloride may not necessarily be essential for their migration it can certainly promote it.

Formation of organopalladium complexes could have an influence on the distribution of palladium. The Pd-content of a tree-sample has been reported by Fuchs and Rose (1974), who have suggested a possible palladium mobility in an organic cycle - see also Cousins and Vermaak (1976).

Iridium. - This element has a very low abundance in the lithosphere and there is relatively little reliable information on its geochemical distribution (Crocket, 1969). Iridium is not readily attacked by acids, and the metal appears to be rather resistive towards chemical reaction in nature. In each of the three lateritic profiles there is a concentration of iridium relative to fresh rock, particularly in the A and B horizons.

Gold - From an assessment of 149 analyses of ultramafic rocks Crocket (1974) has derived a weighted average value of 6.6 ppb for gold content; this figure is compatible with results for the bottom specimens in each of the lateritic profiles - Table I. Our analyses show that the element becomes concentrated as a result of the tropical weathering, particularly in the more mature New Caledonian profile.

Gold, like the platinum metals, is noble, and its compounds are readily reduced to metal. Hence, it is largely found in the native state, and because of its high density it often tends to become concentrated in placer deposits - again showing resemblance to platinum metals. Nevertheless, gold may be dissolved and transported in aqueous medium, either as a complex ion, such as AuCl₄, or in colloidal solution (Crocket, 1974). Tenyakov, Rakovskiy and Fillipova (1970) have noted that if gold is dissolved as an ionic species in the weathering process, adsorption on hydrous iron or aluminium oxide or clay minerals may effectively limit its prolonged leaching by ground water. Also it is appropriate to point out that the ion AuCl₄ and complex chloro-anions of platinum metals are strongly sorbed at low acidities and chloride concentrations by synthetic anion-exchangers (Diamond and Whitney, 1966).

Silicon. - The geochemical distribution of silicon in the three profiles conforms to tendencies reported previously for laterites developed on ultramafic rocks. Silicon is depleted in all the weathered samples. There may be some discontinuities in this overall trend; thus near the surface of the BNC-deposit there is a residual concentration of difficulty soluble silicates, and this is borne out by mineralogical examination which revealed minute particles of the resistant group of silicates, typified by quartz.

The transport of silicaceous material takes place both in the colloidal state and in true solution (Krauskopf, 1959). A hydrous silica sol can undergo extensive migration, because it is very insensitive to the flocculation caused by electrolytes in solution. Moreover, additional stabilization may be brought about by protective colloids of organic origin.

Magnesium. - Depletion of magnesium accompanying the transformation of rock to laterite is a pronounced feature of each of the profiles investigated. This trend appears to be a usual one, e.g., see Harriss and Adams (1966), Zeissink (1969). It is generally accepted that rainwater, containing carbonic acid, attacks olivine, which may contain 25% Mg (Goldschmidt, 1954), and leaches out the magnesium as bicarbonate.

Our correlation coefficients show a marked coherence between the distribution of magnesium and silicon [Mg-Si: for L, +0.88; BNC, +0.93; BIP + 0.99]. The effect of rock-weathering on the composition of natural waters begins when rain-water comes in contact with mineral surfaces. It is apparent that alkaline conditions are produced, as indicated by the reaction pH of fresh rock, even when the rock is "acidic" in character - Harriss and Adams (1966). The higher the pH the more silica goes into solution, and magnesium, once brought into aqueous solution, will only commence to be reprecipitated independently as the hydroxide at a pH of more than 10.

The depletion of magnesium in the BNC-profile is more complete than

in the L-profile, and this agrees with the conclusion that the former has undergone more thorough weathering.

Iron. - Upper parts of the three profiles are rich in iron[III] oxide and hydroxide minerals, such as goethite, hematite, and limonite. This very marked concentration may be regarded to some extent from the point of view that depletion of iron[III] occurs at a slow rate in comparison with other constituents. However, in the New Caledonian profile there is some indication that iron has been dissolved in the uppermost layer and been redeposited at greater depth. Hydrous iron[III] hydroxide has the low precipitation pH value of 2, but humic or fulvic acids could play a part in bringing about such solubility through complexing and reduction (Maignien, 1966). The several factors affecting the solubility of iron in nature are discussed by Garrels and Christ (1965) and Berner (1970).

Nickel - Each of the three lateritic deposits that we have studied is a commercially important source of nickel (Boldt and Queneau, 1967). In the Guatemalan profile nickel is most concentrated in the B-horizons, and there appears to be correlation between the distribution of nickel and iron. A relationship between goethite and nickel in laterite was pointed out by Combes (1963). Turner (1968) showed that high nickel values are associated with zoned goethite concretions which contain high amounts of manganese; this corresponds with the correlation coefficient for Ni-Mn of +0.84 noted for the profile - L. In the profiles BNC and BIP nickel is more concentrated at deeper horizons. Probably the nickel is initially sorbed on the iron[III] hydroxide, but in the maturer profiles leaching has been more thorough, so that the relatively loosely held nickel has migrated downward until it is fixed, e.g., in serpentine. Redeposition may occur in small cracks and interstices in serpentine (Goldschmidt, 1954). The nickel magnesium hydrosilicate, garnierite, has been frequently reported at various localities in New Caledonia, but it was not identified in the BNC-profile from our mineralogical examinations.

Cobalt. - Undoubtedly cobalt[II] and nickel[II] may undergo some substitution for iron[II] in lattice positions of constituent silicate minerals in serpentinized peridotite, and such isomorphous replacement is compatible with the similarity in ionic radii - Fe^{2+} $\underline{r}$ = 0.76Å, Co^{2+} $\underline{r}$ ≈ 0.74, Ni^{2+} $\underline{r}$ = 0.72 (Pauling, 1960). Cobalt is strongly enriched as a result of lateritic weathering, and a parallelism in behaviour between cobalt and nickel is quite apparent in the case of the profile - L. On the other hand there is negligible similarity between the distribution of cobalt and nickel in the part of the laterite - BIP studied; in this case a very close association between cobalt and manganese and cobalt and iron occurs (correlation coefficients: Co-Fe +0.99, Co-Mn +0.94, Co-Ni -0.80). In both the BNC and BIP profiles the cobalt appears most enriched in asbolite (cobaltion wad).

Chromium. - The usual amount of chromium in fresh serpentine is 0.31 per cent - De Wall (1971). In primary rock the element occurs as accessory chromite, and it is also incorporated in minor quantities in olivine and chlorite. The lateritic samples contain only relatively small amounts of chromite and olivine, and some of the chromium in the profiles may well be affiliated with chlorite. Roorda and Queneau (1973) have demonstrated association of chromium with limonite. Our concentration factors for Cr as a function of depth indicate a loss of chromium from the shallow horizon and strong concentration at intermediate depths. Chromium[III] forms an insoluble hydroxide, but under strong oxidizing conditions soluble chromate[VI] may be formed which may migrate downward until fixed as iron chromate (Santos-Ynigo and Esquerra, 1961; Wolfenden, 1965). Santos-Ynigo uses this argument to explain the tendency for chromium to be concentrated near the base of the iron-rich zone in Phillipino - and Cuban laterites.

Manganese. - In the fresh ultramafic rocks manganese probably occurs predominantly as Mn^{2+} ($\underline{r}$ = 0.80Å), substituting for Fe^{2+} ($\underline{r}$ = 0.76). Enrichment of the element is noted in the laterites, particularly in fractions high in poorly crystalline iron[III] hydroxide. During weathering manganese[II] is probably initially leached from the rock mainly as bicarbonate, and in this respect it behaves like iron[II]. The manganese[II] is oxidized to the quadrivalent state quite readily and such oxidation may take place in the weathering solution. Manganese[IV] may remain first in solution as colloidal hydroxide and later may precipitate as wad or finely divided MnO_2; manganomelane has been identified also by Zeissink (1971) in material from Australian nickeliferous lateritic profiles - (incidentally, he also recognized lithiophorite).

Manganese[IV] hydroxide has a weakly acidic character, whilst $Fe(OH)_3$ is weakly basic. Therefore, $Mn(OH)_4$ hydrosol is negatively charged and $Fe(OH)_3$ hydrosol is positively charged. If the two sols are brought into contact with each other, their charges are neutralized, and they flocculate together. Hence a mixture of hydroxides is formed. When there is an excess of one of the sols, the least abundant one will be recharged (Rankama and Sahama, 1950) and may migrate in ground water and surface water under suitable conditions. This may account, at least in part, for the decrease in enrichment of manganese in comparison to iron observed in the surficial layer of profiles L and BNC.

Copper. - Faust and Fahey (1963) reported copper contents of fresh serpentines ranging from 4 to 52 ppm, while the parent rocks under two Australian nickeliferous lateritic profiles studied by Zeissink (1971) were found to contain 23 and 7 ppm, respectively. Wedepohl (1974) in his review has stated that olivine from abundant peridotitic rocks is expected to have an average copper content between 40 to 50 ppm and that other common constituent minerals will not contribute much Cu. It follows from this information and our analyses that copper is considerably enriched in the laterites in the A,B, and C horizons.

Sorption of copper[II] from aqueous solutions has been studied experimentally by Correns (1924) and by Krauskopf (1956), and it has been proposed that copper may be fixed near the surface as an insoluble basic carbonate or be sorbed by iron[III] hydroxide. Moreover, the high copper values in the top parts of profiles may be connected in part to association with organic material. Krauskopf's experiments demonstrated that at pH 7.7 to 8.2 the following extents of removal of copper[II] may be achieved by different adsorbents: montmorillonite, 99.4%; freshly precipitated hydrous ferric oxide, 98%; freshly percipitated hydrous manganese dioxide, 96%; dead plankton, 42%; peat, 98%; lignite, 66%.

Scandium. - Frycklund and Fleischer (1963) estimate the abundance of scandium in the lithosphere as 30 ppm and Faust and Fahey (1962) report values in the range of 1-19 ppm Sc in serpentinites. It follows, therefore, that the element is quite enriched in the surficial and shallow horizons of the laterites. There is a striking correlation between the distribution of scandium and iron in the weathering profiles. [correlation coefficient Sc-Fe: for L-profile +0.96; for BNC +0.90; for BIP +0.94] - Fig. 2. The ionic radii Sc^{3+} $\underline{r}$ = 0.81Å and Fe^{3+} $\underline{r}$ = 0.64, according to Pauling (1960), are not similar, but it has been reported by Frondel (1968, 1970) that a more representative value for the radius of 6 - coordinated Sc^{3+}, suitable for most generalized geochemical purposes, is ca. 0.73Å or possibly less. A diadochic relation between Sc^{3+} and Fe^{3+} is thus understandable. Following

extensive tropical weathering, scandium probably becomes largely associated with goethite. The ion Sc^{3+} is quite generally believed to be adsorbed by hydrous iron[III] and aluminium oxides and by colloidally divided clays (Lange, 1957; Turekian and Wedepohl, 1961; Vlasov, 1968). It has been found experimentally to be strongly sorbed from artifical seawater by hydrous iron[III] oxide and clay, reaching 90-100 per cent at pH 7-8 (Yoshimura and Tatega, 1962). The carrying by ferric hydroxide starts at a pH rather above 4 and reaches a maximum in the range where complete hydrolysis of Sc^{3+} commences, pH ~ 6.5 (Grebenschchikova and Prokudina, 1963).

Sodium. - Stueber and Goles (1967) determined sodium in a total of 113 ultramafic rocks by neutron-activation analysis. The arithmetic mean of the results was 0.104 per cent Na, and the highest concentrations of the element were in the more pyroxene-rich rocks.

Sodium content of the laterites generally decreases as a result of the transformation of rock and significant leaching occurs. Fluctuations in the general trend of depletion may be largely because of the occurrence of the element in detrital phases, such as clay minerals, but inevitably at least some sodium is present adsorbed on mineral phases and ion-exchange sites and as dissolved Na^+ in interstitial fluids.

Uranium. - The concentration of uranium in ultramafic rocks (dunites, serpentinites, etc.) is extremely low, 10-80 ppb (Rogers and Adams, 1969). Heier and Carter (1964) give the average figure as 14 ppb. In the lateritic profiles there is some increase in concentration in B and C-horizons, relative to that in fresh rock. During weathering, the uranium most probably has been brought into solution as uranium[VI] (uranyl ion, UO_2^{2+})* and been somewhat leached out of the shallow horizon. The soluble uranyl species are readily sorbed on hydroxide gels of iron, aluminium, and manganese, and on silica gel (Rankama and Sahama, 1950).

---

* It is of interest to note that the main hydrolyzed species of UO_2^{2+} in water at 25°C are UO_2OH^+, $(UO_2)_2OH^{3+}$, $(UO_2)_3(OH)_5$, although the formation of polymerized hydroxo-bridged species may not be very relevant at the ultramicro-concentrations of uranium that pertain in ground waters in the lateritic profiles.

Zinc. - In peridotites the average abundance of zinc is 56 ppm and serpentinites contain about the same amount, indicating no general loss or gain on serpentinization (Wedepohl, 1972). The redistribution of zinc during weathering follows a pattern similar to that of manganese [correlation coefficients Zn-Mn: L +0.81; BNC + 0.98; BIP +0.98]. In the Guatemalan and Indonesian profiles there is correlation between zinc and iron [corr. coef. Zn-Fe: L +0.96; BIP +0.94] and the zinc is probably largely sorbed by goethite. On the other hand, in the profile-BNC the element is most concentrated in C horizons. This difference in distribution from that in profile-L, where the zinc is richest in the ferruginous A and B1 horizons, again illustrates a greater extent of weathering in the New Caledonian occurrence.

Chlorine. - Several workers have noted the high chlorine content of serpentinized ultramafic rocks (Fuge, 1974). Earley (1958) has suggested that this has arisen during serpentinization by chloride-rich solutions. Rucklidge (1972) has shown that the chlorine may occur in solid solution in serpentine, being absent from olivine. However, there is evidence to suggest that chlorine may play a significant role in the alteration of olivine.

Goldschmidt (1954) assumed that during the process of weathering all of the chlorine in magmatic rocks would be released. According to Hem (1970), chlorine released during weathering is readily soluble in water, is not adsorbed to any marked degree on mineral surfaces, and is concentrated considerably by only a few groups of organisms. Hence, the enrichment of chlorine in intermediate and deeper zones of the laterites is perhaps rather surprising. Garrels (1967) has suggested that much of the chloride in ground waters has been derived from rain water, small amounts possibly being added from chloride-rich fluid inclusions. The greatest source of chlorine in rainfall is the sea, and the chloride-content of rain water is greater near the coast than inland (Eriksson, 1952; Junge and Werby, 1958).

It is possible that chlorine may be lost from aqueous solution because of its incorporation in such minerals as chlorite (Johns, 1963). A conversion of montmorillonite to chlorite may arise because of assimilation of Cl⁻ ions together with OH⁻ ions in intermediary layers of the chlorite, as magnesium hydroxychloride.

As mentioned earlier, the possibility of complexing platinum and palladium by chloride under oxidizing conditions may well affect the distribution of the two precious metals in lateritic profiles. Moreover, Krauskopf (1967) has shown by calculation that gold may be dissolved as $AuCl_4^-$ in the presence of oxygen or MnO_2 under natural conditions.

Concluding Remarks

The mechanism of formation of laterites is still incompletely understood (Alexander and Cady, 1962; Maignien, 1966). Thorough aqueous leaching is involved, because laterites are best developed where drainage is good and where rainfall is heavy for at least part of the year. Moreover, the higher temperatures that pertain in the humid tropical (equatorial) belt are clearly relevant to the intense weathering - Pickering 1962).

It has been emphasized by Krauskopf (1967) that clay minerals are not true end-products of weathering but they are metastable substances formed as intermediates in the slow breakdown of rocks into constituent oxides. Hence in tropical regions, where conditions of rainfall and topography are particularly favourable for thorough leaching, reactions may go beyond the clay-mineral stage. Evidence for this hypothesis is provided by the fact that normal clay soils are found in the tropics where leaching is less complete.

A comparison of our geochemical results with those for different major lateritic deposits studied by others (e.g., Hotz, 1964; Santos-Ynigo and Esquerra, 1961; Zeissink, 1969, 1971; Schellman, 1972; Reynolds, et al., 1973) indicates many common trends in development, although the extent of weathering may be different in the various localities.

Note

Pauling's (and Ahrens's) crystal ionic radii have been cited in this article, and we consider that they provide a generally convenient numerical description for geochemical purposes, e.g., for appreciation of diadochic relationships. However, it must be pointed out that they are not compatible with electron density distributions in "ionic crystals" as determined by X-ray diffraction methods (Morris, 1968). On the other hand, radii derived from electron density minima are probably only realistically applicable to alkali halides and similar crystals, and even among these salts the interionic distances show small deviations from strict additivity. The savant Kasimir Fajans (1969) once exclaimed: "ionic radii - simple - they do not exist!"

TABLE I. Distribution of noble metals as a function of depth through lateritic profiles. Values in ppb ($\mu g\ kg^{-1}$)

Profile	Sample No.	Depth m	Au	Pt	Pd	Ir
Guatemala L	1	1.5 – 2	11.8±0.8	140±4	84±3	8.2±0.1
	2	2.5 – 3	13.8±0.7	145±1	79±4	13.9±0.4
	3	3.5 – 4	8.9±0.1	173±9	57±1	15.2±0.5
	4	5.25-5.75	5.9±0.4	135±1	93±3	13.2±2.2
	6	8 –8.5	5.6±0.4	101±1	50±1	7.4±0.1
	5	8 –8.5	8.8±0.1	97±1	46±2	6.7±0.4
	7	10.25-10.75	3.2±0.2	68±2	37±1	5.0±0.6
New Caledonia BNC	1	0 –2	30.4±3.7	108±9	80.0±2.1	8.0±0.7
	2	2 –7	31.7±2.2	164±3	52.5±3.1	5.4±0.4
	3	7 –11	40.5±0.6	151±5	80.2±1.2	5.2±0.5
	4	11 –13	11.3±0.3	131±2	27.5±1.3	5.7±0.7
	5	13 –14	8.0±1.3	132±2	24.6±1.0	6.5±0.3
	6	14 –17	9.5±0.5	110±3	21.5±0.5	5.1±0.6
	7	17 –20	6.3±0.3	83±2	21.0±0.5	4.8±0.7
Indonesia BIP	1	11 –13	14 ±1.9	67±3	52 ±2	16 ±1.3
	2	13 –17	8.5±1.5	43±5	45 ±3	7 ±1.2
	3	18 –19	6.2±1.9	18±3	30 ±3	5.3±1.2

Results are based on quadruplicate analyses of samples and the standard
deviation for a single determination is quoted.
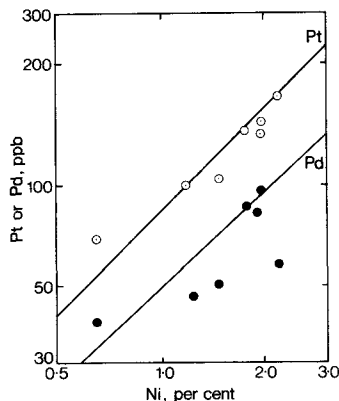
Fig. 1. Relationship between platinum and palladium and nickel
in samples from the Guatemalan profile - L.

TABLE II. Distribution of elements in lateritic profiles. Contents in per cent unless indicated elsewhere. Singly underlined figures refer to INAA and doubly underlined figures are from radiochemical analysis.

Guatemalan

Sample No.	L1	L2	L3	L4	L6	L5	L7
Depth, m	1.5 – 2	2.5 – 3	3.5 – 4	5.25-5.75	8 – 8.5	8 – 8.5	10.25-10.75
Cl*	0.053(0.0013)	0.044(0.0012)	0.060(0.0057)	0.022(0.0051)	0.058(0.0054)	0.019(0.0031)	0.022(0.0012)
Co	0.13 0.12	0.15 0.14	0.29 0.26	0.15 0.15	0.21 0.20	0.13 0.12	0.081 0.073
Cr	0.087 0.083	0.086 0.081	1.34 1.25	1.29 1.21	1.30 1.01	0.78 0.68	0.66 0.65
Cu	0.13 0.13	0.14 0.14	0.13 0.12	0.13 0.13	0.12 0.12	0.11 0.11	0.016 0.016
Fe	43.82 42.4	32.2 31.5	25.2 24.9	9.15 9.10	22.6 22.2	10.5 10.1	7.95 7.88
Mg	4.28	8.95	12.84	10.35	5.23	8.34	16.55
Mn	0.28 0.26	0.31 0.31	0.26 0.25	0.22 0.22	0.20 0.20	0.12 0.12	0.098 0.098
Ni	1.71 1.71	1.92 1.91	2.13 1.98	1.91 1.85	1.68 1.45	1.18 1.15	0.65 0.62
Sc(ppm)	128	81	61	22	95	24	21
SiO2	3.25	7.25	20.35	32.75	10.25	21.50	34.25
Na	0.0075	0.0231	0.0245	0.0240	0.0175	0.0233	0.0262
U(ppb)	6.3	8.5	17	13	13	11	75
Zn	0.014	0.012	0.0065	0.0026	0.0057	0.0037	0.0024

New Caledonian

Sample No.	BNC1	BNC2	BNC3	BNC4	BNC5	BNC6	BNC7
Depth, m	0 – 2	2 – 7	7 – 11	11 – 13	13 – 14	14 – 17	17 – 20
Cl*	0.027 (0.007)	0.017 (0.0067)	0.038 (0.019)	0.043 (0.020)	0.271 (0.19)	0.315 (0.096)	0.26 (0.12)
Co	0.062 0.057	0.081 0.079	0.106 0.093	0.15 0.15	0.26 0.25	0.15 0.14	0.089 0.080
Cr	0.31 0.35	0.34 0.34	0.83 0.69	1.50 1.47	1.75 1.65	2.15 2.04	1.05 1.01
Cu	0.13 0.12	0.15 0.13	0.17 0.16	0.25 0.24	0.27 0.23	0.22 0.21	0.16 0.13
Fe	47.0 46.7	49.5 48.5	51.0 49.1	49.5 49.3	52.3 52.0	38.1 38.8	12.5 11.3
Mg	< 0.2	< 0.2	< 0.2	0.2	0.8	1.4	11.2
Mn	0.13 0.14	0.21 0.21	0.20 0.20	0.25 0.25	1.80 1.80	1.72 1.69	0.67 0.72
Ni	0.73 0.71	1.52 1.47	1.65 1.59	1.41 1.35	1.75 1.71	3.21 3.10	1.61 1.56
Sc(ppm)	98	108	110	84	122	96	55
SiO2	3.85	2.65	4.15	4.75	4.25	14.08	26.32
Na			0.026	0.012	0.043	0.066	0.127
U(ppb)	4.0	4.2	6.4	13	11	34	17
Zn	0.68	0.63	0.65	0.64	0.94	0.51	0.07

Indonesian

Sample No.	BIP1	BIP2	BIP3
Depth, m	11 – 13	13 – 17	18 – 19
Cl*	0.074 (0.059)	0.033 (0.022)	0.020 (0.014)
Co	0.12 0.12	0.064 0.059	0.031 0.022
Cr	1.35 1.21	1.05 0.98	0.37 0.35
Cu	0.075 0.070	0.12 0.11	0.051 0.048
Fe	49.1 49.1	20.8 19.1	10.1 9.1
Mg	0.26	8.28	10.4
Mn	0.82 0.81	0.64 0.68	0.27 0.26
Ni	1.46 1.46	2.83 2.71	2.41 2.35
Sc(ppm)	90	56	18
SiO2	4.34	22.04	27.60
Na	0.0021	0.0027	0.0011
U(ppb)	17	42	13
Zn	0.011	0.0060	0.0019

ppb is to be read as parts per 10^9, not per 10^{12}.
All analytical results are the arithmetic mean of at least
two determinations.
*Figures in parentheses for Cl represent water-soluble
chlorine content (Ahmad and Morris, 1977b) determined
from leaching at room temperature.

TABLE III. Reaction pH measurements of weathered profiles

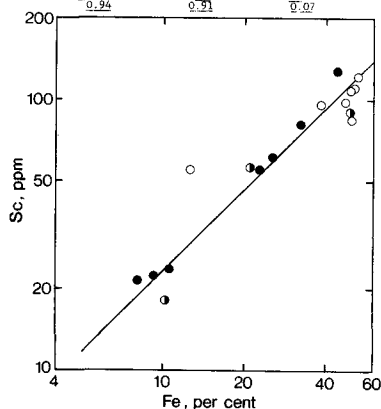| Profile	Guatemala Sample No.	pH	New Caledonia Sample No.	pH	Indonesia Sample No.	pH
	L1	7.05	BNC1	6.5	BIP1	6.8-7.0
	2	7.2	2	6.2	2	7.0-7.3
	3	7.5	3	5.9	3	7.8-8.3
	4	8.3	4	5.8		
	6	7.5	5	6.3		
	5	8.2	6	7.3-7.8		
	7	9.2	7	7.25-9.00		

Fig. 2. Geochemical coherence between scandium and iron in the lateritic deposits.

● = L-profile, ○ = BNC-profile, ◐ = BIP-profile

M8

REFERENCES

Ahmad (I), Ahmad (S), and Morris (D.F.C.), 1977. Analyst, 102, 17 - 24.
Ahmad (S) and Morris (D.F.C.), 1977a. Analyst, 102, 395-399.
——— and ——— 1977b. Radiochem. Radioanal. Letters, 28, 165 - 70.
Ahrens (L.H), 1952. Geochimica Acta, 2, 155 - 69.
Alexander (L.T) and Cady (J.G), 1962. Genesis and Hardening of Laterite in Soils. 90p. (U.S. Dept. Agric. Soil Conserv. Service Tech. Bull. 1282).
Baltakmens (D.A.), 1975. Analyt. Chem. 47, 1147 - 49.
Berner (R.) (Ed. K.H. Wedepohl), 1970. Handbook of Geochemistry II/2 26-Fe (Heidelberg, New York: Springer-Verlag) [M.A. 22 71 - 835].
Boldt (J.R.) and Queneau (P.), 1967. The Winning of Nickel (London, Methuen).
Britton (H.T.S.), 1942. Hydrogen Ions, 3rd. ed. II (London, Chapman and Hall).
Canterford (J.H.), 1975. Minerals Sci. Engng. 7 (1), 3 - 17 [M.A. 26 75 - 1962].
Châtelat de (E), 1963. Bull. Soc. Geol. France. Ser. 6, 17, 105 - 60.
Combes (P.J.), 1963. C.R. Acad. Sci., Paris, 256, 211 - 12 [M.A. 16 - 361].
Correns (C.W.), 1924. Kolloid Zeit. 34, 341 - 49.
Cousins (C.A.), 1973a J. Sth. African Inst. Mining Met. 7, 1 - 16.
——— 1973b Geol. Soc. Sth. Africa Trans. 76, 77 - 81.
——— and Vermaak (C.F.), 1976. Econ. Geol. 71, 287 - 305.
Crocket (J.H.) (Ed. K.H Wedepohl), 1969. Handbook of Geochemistry, II/1, 78-Pt and platinoids. (Berlin, Heidelberg, New York: Springer-Verlag) [M.A. 21 70-90].
——— 1974. Handbook of Geochemistry, II/4, 79-Au. (Berlin, Heidelberg, New York: Springer-Verlag) [M.A. 26 75 - 1813].
De Wall (S.A.), 1971. Min. Sci. & Eng. 3(2), 32 - 45 [M.A. 22 71 - 2727].
Diamond (R.M.) and Whitney (D.C.) (Ed. J.A. Marinsky), 1966. Ion Exchange, 1, 277 - 351.
Earley (J.W), 1958. Amer. Min. 43, 148 - 55 [M.A. 14 - 219].
Eriksson (E.), 1952. Tellus, 4, 280 - 303.
Fajans (K), 1969. Discussion with D.F.C.M.
Faust (G.T.) and Fahey (J.J.), 1963. The Serpentine-Group Minerals, 92 p. (U.S. Geol. Surv. Prof. Paper 348A) [M.A. 19 - 307].
Flanagan (F.J.), 1973. Geochimica Acta, 37, 1189 - 1200 [M.A. 25 74 - 1281].
Frondel (C), 1968. Zeits. Krist 127, 121 - 38 [M.A. 20 69 - 1254].
——— (Ed. K.H. Wedepohl), 1970. Handbook of Geochemistry, II/2, 21-Sc (Berlin, Heidelberg, New York: Springer-Verlag) [M.A. 22 71 - 835].
Fryklund (V.C.) and Fleischer (M.), 1963. Geochimica Acta, 27, 643 - 64 [M.A. 16 - 361].
Fuchs (W.A.) and Rose (A.W.), 1974. Econ. Geol. 69, 332 - 46 [M.A. 27 76 - 574].
Fuge (R.) (Ed. K.H. Wedepohl), 1974. Handbook of Geochemistry II/4, 17-Cl Berlin, Heidelberg, New York: Springer-Verlag) [M.A. 26 75 - 1813].
Garrels (R.M.) (Ed. P.H. Abelson), 1967. Researches in Geochemistry, vol.2. p. 405 (New York, London, Sydney: Wiley) [M.A. 12 - 87].
——— and Christ (C.L.), 1965. Solutions, Minerals and Equilibria (New York, Harper and Row) [M.A. 17 - 452].
Goldschmidt (V.M.) (Ed. A. Muir), 1954. Geochemistry (Oxford, Clarendon Press) [M.A. 12 - 295].
Grebenshchikova (V.I) and Prokudina (A.F.), 1963.
[Redkozem. Elementy Akad Nauk SSSR, Inst. Geokhim., Analit. Khim. 187 - 190].
Grimaldi (F.S.) and Schnepfe (M.M), 1968. Determinacion of Palladium and Platinum in Rocks. (U.S. Geol. Surv. Prof. Paper 600-B, 99 - 103) [M.A. 20 69-2785].
Harriss (R.C.) and Adams (J.A.S.), 1966. Amer. J. Sci. 264, 146 - 73 [M.A. 18-11].
Hem (J.D.), 1970. Study and Interpretation of the Chemical Characteristics of Natural Water. (U.S. Geol. Surv. Water-Supply Paper 1473, 363 pp) [M.A. 22 71 - 412].
Heier (K.S.) and Carter (J.L.) (Eds. J.A.S. Adams and W.M. Lowder), 1964. The Natural Radiation Environment, p 75 (Chicago: Chicago University Press).
Hotz (P.E.), 1964. Econ. Geol. 59, 355 -96.
Johns (W.D.), 1963. Fortschr. Geol. Reinland Westfalen, 10, 215.
Junge (C.E.) and Werby (R.T.), 1958. J. Meterol. 15, 417 - 25.
Krauskopf (K.B.), 1956. Geochimica Acta, 9, 1 - 32B [M.A. 14 - 492].
——— 1959. The Geochemistry of Silica in Sedimentary Environments, p. 4 - 19 (Soc. Econ. Pal. Min. Spec. publ. No.7).
——— 1967. Introduction to Geochemistry (New York, St. Louis, San Francisco, Toronto, London, Sydney: McGraw-Hill).
Lange (H.), 1957. Geologie, No's 6, 7, 610 - 39.
Maignien (R.), 1966. Review of Research on Laterites 148p. (Paris, UNESCO Publication).
Maxwell (J.A.), 1968. Rock and Mineral Analysis 584pp (New York, London, Sydney, Toronto: Interscience Publishers) [M.A. 20 69 - 1897].
Morris (D.F.C), 1968. Struct. Bonding 4, 63 - 82.
Norton (S.A.), 1973. Econ. Geol. 68, 353 - 61 [M.A. 26 75 - 1179].
Otteman (J.) and Augustithis (S.S.), 1967. Min. Depos. 1, 269 - 77 [M.A. 20 69 - 1527].
Pauling (L.), 1960. The Nature of the Chemical Bond, 3rd ed. (Ithaca, N.Y., Cornell University Press).
Pickering (R.J), 1962. Econ. Geol. 57, 1185 - 1206.
Rankama (K) and Sahama (T.G.), 1950. Geochemistry (Chicago: Chicago University Press) [M.A. 11 - 409].
Razin (L.V.), Khvostova (V.P.) and Novikov (V.A.), 1965. Geochemistry Int. 2, 118 - 131 [M.A. 18 -18].
Reiche (P.), 1950. A Survey of Weathering Processes and Products. 95p. (Albuquerque, N.M.: New Mexico University Pubs. Geology) [M.A. 11 - 208].
Reynolds (C.D.), Havryluk (I), Bastaman (S.), and Atmowidjojo (S.), 1973. Bull. Geol. Soc. Malaysia 6, 309 - 23 [M.A. 25 74 - 2003].
Rogers (J.J.W.) and Adams (J.A.S.) (Ed. K.H. Wedepohl), 1969 Handbook of Geochemistry II/1, 92-U (Berlin, Heidelberg, New York: Springer-Verlag) [M.A. 21 70 - 90].
Roorda (H.J.) and Queneau (P.E.), 1973, Trans. Inst. Min. Metal. C 82, 79 - 87.
Rucklidge (J.), 1972. Econ. Geol. 67, 38 - 40 [M.A. 24 73 - 2688].
Sandell (E.B.), 1959. Colorimetric Determination of Traces of Metals 3rd ed. (New York, Interscience Publishers) [M.A. 14 - 241].
Santos-Ynigo (L.) and Esguerra (F.B.), 1961. Geology and Geochemistry of the Nickeliferous Laterites of Nonoc and adjacent Islands, Surigao Province, Philippines 90p (Bur. Mines Spec. Proj. Ser. 18).
Schellman (W.), 1964. Geol. Jahrb. 8, 645 - 67.
——— 1971. Min. Depos. 6, 275 - 91 [M.A. 23 72 - 3105].
Sillén (L.G.) and Martell (A.E.) (compilers), 1964. Stability Constants of Metal-Ion Complexes (London, Chem. Soc. Spec. Pub. No. 17).
——— 1971. Supplement No. 1 to above (London, Chem. Soc. Spec. Pub. No. 25).
Skinner (B.J.), 1976. Earth Resources 2nd ed. (Englewood Cliffs, N.J., Prentice-Hall).

Stueber (A.M.) and Goles (G.G), 1967. Geochimica Acta, 31, 75 - 93 [M.A. 18 - 179].
Tenyakov (V.A.), Rakovskiy (E.Ye), and Filippova (T.P.),1970. Dokly. Akad. Sci. U.S.S.R. Earth Sci. Sect. 195, 194 - 97 [M.A. 26 75 - 3337].
Turekian (K.K.) and Wedepohl (K.H.), 1961. Bull. Geol. Soc. Amer. 72, 175 - 92 [M.A. 15 - 279].
Turner (A.R.), 1968. AMDEL (Austral. Min. Devel. Labs) Bull. 5, 76 - 93 [M.A. 20 69 - 2964].
Vlasov (K.A.), 1968. Geochemistry and Mineralogy of Rare Elements and Genetic Types of Occurence, Vol. 3. Genetic Types of Rare Element Deposits. Engl. Transl. (Jerusalem: Israel Program for Sci. Transl.) [M.A. 19 - 9].
Vogel (A.I.), 1962. A Textbook Book of Quantitative Inorganic Analysis 3rd ed. (London, Longmans).
Wedepohl (K.H.), 1972. Handbook of Geochemistry II/3, 30-Zn (Berlin, Heidelberg, New York: Springer-Verlag) [M.A. 24 73 - 1212].
——— 1974. Handbook of Geochemistry II/4, 29-Cu (Berlin, Heidelberg, New York: Springer-Verlag) [M.A. 26 75 - 1813].
Wolfenden (E.B.), 1965. Geochimica Acta, 29, 1051 - 62 [M.A. 17 - 484].
Yoshimura (J.) and Tateda (A.), 1962 Nippon Kagaku Zasshi 83, 1018 - 22.
Zeissink (H.E.), 1969. Min. Depos. 4, 132 - 52 [M.A. 21 70 - 3258].
——— 1971. Chem. Geol. 7, 25 - 36.

APPENDIX 1

Description of weathering profile L located near Lake Izabal, Guatemala

Location and sample no.	Depth m	Weathering horizon	Description	Moisture content %
L-1	1.5-2	A	Red-brown soil with organic matter and ironIIIoxide pellets. Slight amount of weathered serpentine.	4.9
L-2	2.5-3	B₁	Highly weathered red-brown soil of plastic ironIIIoxides with some organic material. Fine earthy appearance.	5.6
L-3	3.5-4	B₀	Yellow-orange soil with less iron oxide than L-2 and with saprolitic texture and some fragments of soft peridotite.	5.7
L-4	5.25-5.75	C₁	Yellow-brown soil. Saprolitic texture with boulders of peridotite-serpentine.	5.7
L-5 Coarse	8-8.5	C₀	Gray-yellow colour.	8.0
L-6 Fines	"	"₀	Slightly weathered serpentine fragments and fine grained soil containing ironIIIoxide.	8.1
L-7	10.25-10.75	D	Slightly weathered peridotite-serpentine.	3.4

Description of weathering profile BNC located in southern New Caledonia, Lat. 22° 17'S and Long. 166° 58' E.

Location and sample no.	Depth m	Weathering horizon	Description	Moisture content %
BNC-1	0 - 2	A	Ferricrete surficial soil, consisting mainly of ironIIIoxide (limonite). Red-brown colour. Slight amount of organic matter and some fragments of serpentine are present.	4.5
BNC-2	2 - 7	A	Yellow-brown soils with	6.3
BNC-3	7 -11		texture analogous to	4.6
BNC-4	11 -13		BNC-1 but containing less organic matter. Textural resemblance begins to disappear in BNC-3 and BNC-4.	2.5
BNC-5	13-14	B	Highly weathered, dark red soil· rock completely disaggregated. Mostly limonite with asbolite.	2.7
BNC-6	14-17	C	Yellow-brown colour; mainly consists of saprolite and asbolite with less limonite. Some partly weathered serpentine rock fragments are also present in this horizon.	2.6
BNC-7	17-20	C	Grey-yellow colour; slightly weathered rock with saprolitic texture.	1.2

Description of weathering profile BIP located in the Pomalaa-Kolaka district of Sulawesi, Indonesia, Lat. 4° 10' S and Long. 121° 37' E.

Location and sample no.	Depth m	Weathering horizon	Description	Moisture content %
BIP-1	11 - 13	A	Red-brown colour with saprolite limonite, asbolite enstatite, and some grains of quartz.	1.7
BIP-2	13 - 14 16 - 17	B	Dark red saprolite, with ironIIIoxides enriched in base elements; asbolite.	2.0
BIP-3	18 -19	C	Grey-yellow saprolite; serpentinized peridotite with quartz boxwork.	2.5

Moisture content was estimated by the following procedure. - About 1g of sample was accurately weighed and transferred to a tared 30 cm³ - platinum crucible. This was placed in an oven, covered with a filter paper of 7cm.-diam., and heated at 105-110°C for 1 hour. The crucible was placed in a desiccator and allowed to cool for 30 min. before reweighing. The loss in weight was taken as representing the moisture content of the sample.