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Ore mineral associations and industrial minerals in the ultramafic rocks of Jamaica and Tobago

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ABSTRACT. The ultramafic rocks in Jamaica are dunites with minor lherzolite, most of which are at least partly serpentinised. They are part of a dismembered ophiolite complex. In Tobago, dunites, wehrlites, pyroxenites and hornblendites constitute the lower part of a Cretaceous plutonic complex of island arc affinity. The chromite in Jamaica is high in Al and Mg, whereas that in Tobago is rich in Fe, as in Alaskan-type intrusives. Ni-Cu-PGE assemblages in Jamaica consist of pentlandite, with paragenetically later low temperature heazlewoodite, awaruite and native copper, the latter sometimes Pt and Pd enriched. The low temperature assemblage is probably associated with the serpentinisation event. In Tobago there is a sulphide assemblage of pentlandite, pyrrhotite, pyrite, chalcopyrite, much less affected by later alteration, and Pt, and RhPtIr phases. The dunites in Jamaica have sufficient MgO to be considered a potential source of industrial olivine. The higher Fe in the olivine from Tobago indicates that olivine cumulates in plutonics from island arc settings are a less suitable source of the mineral. Although oxide minerals develop during tropical weathering in the Blue Mountains of Jamaica, the formation of Ni-laterites is unlikely because of the high topographic relief. In Tobago the prospect for Ni-laterites is low as there is much less Ni in the olivines. Chrysotile asbestos, talc and magnesite are absent in both ultramafic complexes. This is likely to be a consequence of the lack of secondary serpentine recrystallisation to form fibrous chrysotile veins, the deep tectonic level and lack of hydrothermal circulation for magnesite formation, and the absence of metamorphic/metasomatic events and/or late stage extension tectonics which might have yielded talc.

INTRODUCTION

Ultramafic rocks are the host for several different metal ores and industrial minerals. Magmatic minerals include chromite, and Fe, Ni, and Cu sulphides, sometimes with Co. Ultramafic complexes are also the major economic source of platinum group element (PGE) minerals. Olivine is an essential constituent of many ultramafic rocks, and where serpentinisation is not pervasive and olivine is the dominant mineral, as in dunites, a deposit of commercial value may be present. Chrysotile asbestos is an important product of the serpentinisation of ultramafic rocks. It occurs commonly as veins, but where it is a rock-forming mineral with the fibres in an interlocking texture it can constitute an exploitable resource.

Sulphide and PGE ore mineral assemblages are usually changed significantly as a consequence of serpentinisation (Ramdohr, 1967; O'Hanley, 1996). The primary magmatic sulphides, dominated by pyrrhotite and pentlandite, are replaced at lower temperature by Ni sulphides and native metals. Post-serpentinisation processes, including metamorphism, metasomatism, and alteration, referred to as epigenetic mineralisation by O'Hanley (1996), can result in further hydration and carbonatisation of the serpentine and other minerals. This can lead to the formation of other industrial minerals, including talc, magnesite, sepiolite and sometimes very uncommon minerals such as huntite and hydromagnesite (Scott, 1987; Ebrahimi-Nasrabadi, 1990; Kostakis, 1990). Deep tropical weathering of ultramafic rocks creates an important source of lateritic Ni and Co. In sulphide poor ultramafic rocks, the bulk of the Ni and Co is held within the olivine structure and the weathering process can concentrate these elements in secondary hydrous silicates, such as garnierite and Ni-saponite.

In Jamaica, ultramafic rocks, mostly serpentinite and dunite, are found in one small area in the Blue Mountains (Fig. 1). They are probably part of a dismembered ophiolite suite (Wadge et al., 1982, 1984; Jackson et al., 1998). Ultramafic rocks in Tobago (Fig. 2) are a minor part of a single fractionated plutonic body made up largely of gabbro and diorite with minor amounts of tonalite (Frost and Snoke, 1989). It has primitive island arc affinities.

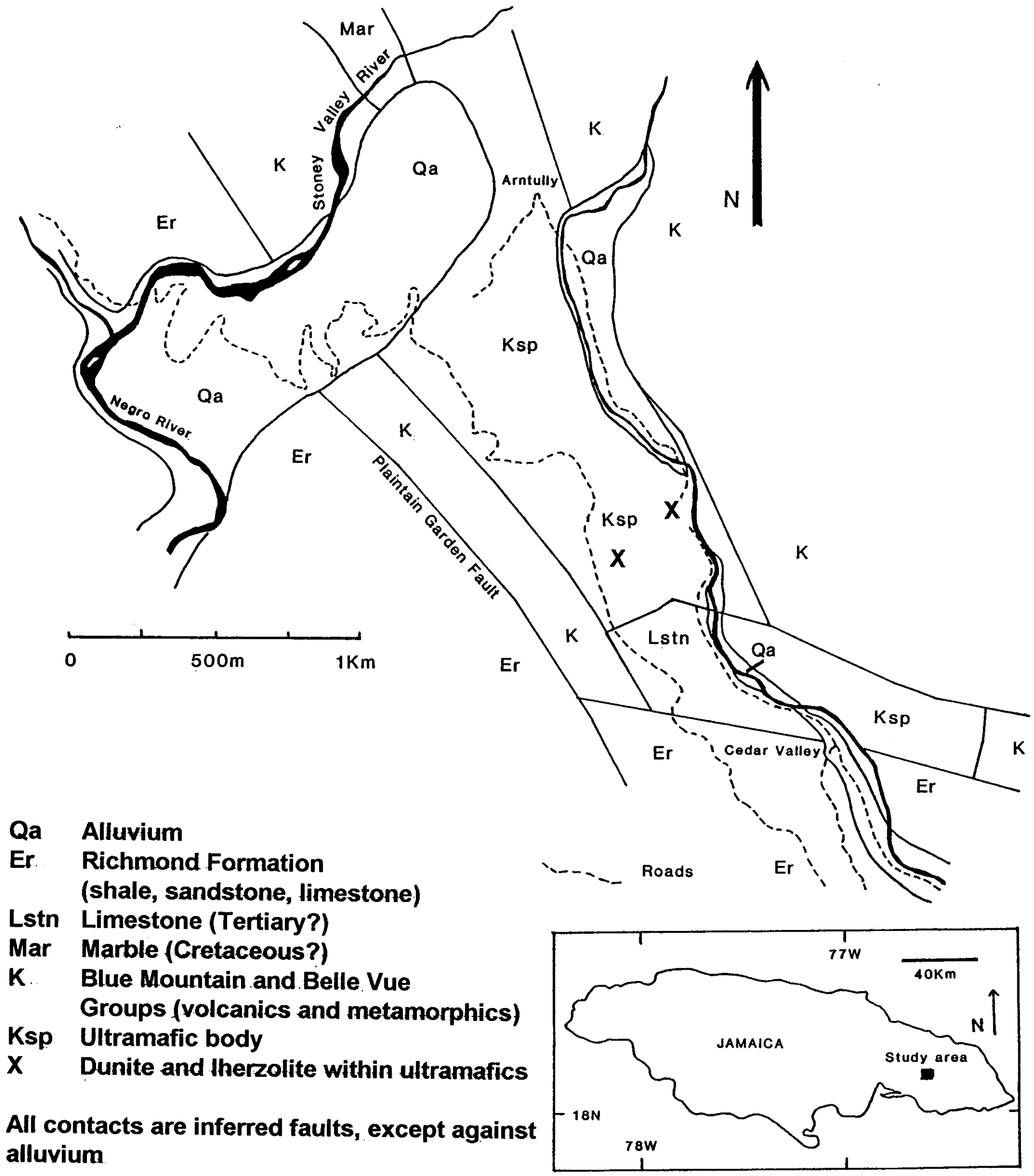

Figure 1. Geological map of the ultramafic rocks and adjacent strata in Jamaica. Inset map shows location (based on Scott et al. 1992).

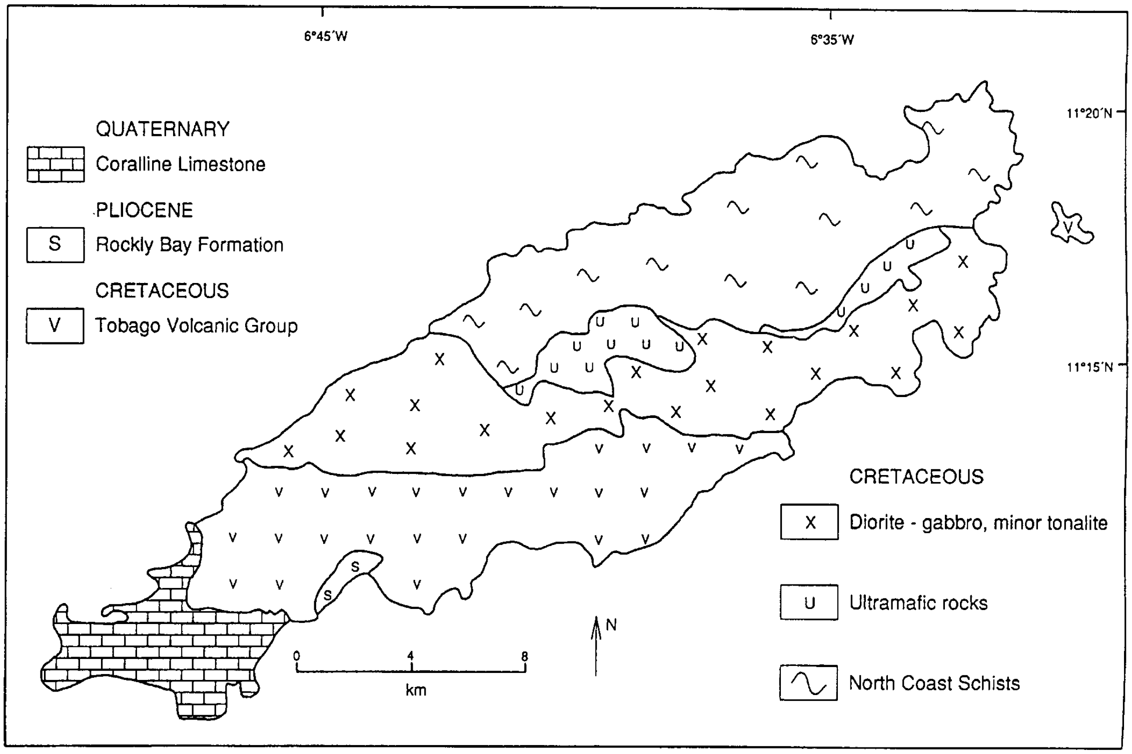

Figure 2. Geological map of Tobago showing location of the ultramafic rocks. Simplified from Frost and Snoke, 1989.

The objectives of this work are to describe the similarities and differences in the ore mineral associations and industrial minerals in the ultramafic rocks of Jamaica and Tobago; to show the evidence that can be used to confirm the tectonic setting and alteration history of the two complexes; and to attempt to explain why some industrial minerals commonly found in ultramafic rocks are absent.

EXPERIMENTAL WORK

The study was carried out on more than 100 samples, representing as far as possible all the types of ultramafic rocks in the two countries. They were collected by the authors during several field visits to each area. The ultramafic rocks in Jamaica were remapped (Scott et al., 1992). In Tobago, where dense tropical vegetation abounds, sampling was largely from river sections and forestry tracks and roads. A combination of optical microscopy, scanning electron microscopy, and X-ray diffraction was used for identifying mineral phases. This was supported by whole rock chemical analysis made by X-ray fluorescence spectrometry, using a Philips PW1400 spectrometer at Camborne School of Mines. A thorough search through polished thin sections was made to establish the range of sulphide and related ore minerals, including PGE minerals. Mineral chemistry was determined by electron microprobe analysis using a JEOL Superprobe and wavelength dispersive analysis at the University of Leicester for chromite, olivine, sulphides and associated ore minerals from Jamaica and a JEOL 840 Scanning electron microscope and energy dispersive analysis at Camborne School of Mines for the sulphides and PGE from Tobago. Detection limits are as follows: JEOL Superprobe: SiO_2, 0.04%; TiO_2, 0.05%; Al_2O_3, 0.02%; Cr_2O_3, 0.05%; FeO, 0.05%; MnO, 0.05%; MgO, 0.02%; NiO, 0.07%; CaO, 0.03%; Fe, 0.04%; Co, 0.06%; Ni, 0.06%; Cu, 0.08%; S, 0.03%; Pt, 0.44%. JEOL SEM: Fe, 0.26%; Co, 0.34%; Ni, 0.24%; Cu, 0.28%; S, 0.20%; Pt, 0.46%. The differences between the detection limits does not affect comparison between the data from the two instruments.

GEOLOGY OF THE ULTRAMAFIC ROCKS AT ARNTULLY, JAMAICA

A small area of serpentinised ultramafic rocks (approx. 2 km^2) thought to be of Upper Cretaceous age

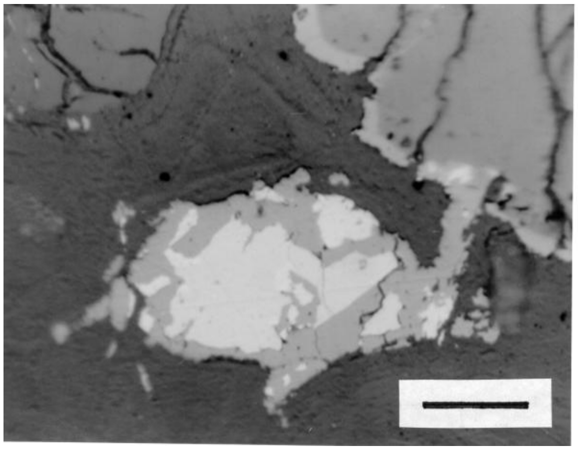

Figure 3. Reflected light photomicrograph of part of a large crystal of chromite (upper right), rimmed with magnetite (lighter grey), the latter having inclusions of pentlandite and awaruite (both lightest grey), in a matrix of serpentine. Arntully, Jamaica. Scale bar = 25 µm.

(Robinson, 1994), occurs in the Cedar Valley - Arntully area of St. Thomas Parish, within the Blue Mountains. The field relations have been briefly described by Kemp (1971), Draper (1979) and Scott et al. (1992) (Figure 1), and the petrology has been briefly discussed by Jackson et al. (1998). The ultramafic rocks are in tectonic contact mostly with volcanics and metamorphics of the Blue Mountain Inlier.

The primary ultramafic rocks, which occur in the centre of the outcrop area, mid-way between Cedar Valley and Arntully, are mainly dunite containing unaltered olivine, with some orthopyroxene, clinopyroxene and chromite. Occasionally there is enough pyroxene for them to classify as lherzolite. They are partly serpentinised. Completely serpentinised ultramafic rocks crop out in some river sections; but, much of the serpentinite in cliffs and in roadside sections is very broken up scree-like material, partly re-cemented. It is likely that this is exhumed debris from major palaeo-landslides. It has similarities to the serpentinites believed to have been emplaced by gravity sliding and described by Lockwood (1971), who refers to several examples of detrital serpentinites in the Caribbean. Where developed, the soils on the ultramafic rocks are reddish brown to brown. The steep topography prevents the development of a thick weathering mantle. Small pockets of pale green to pale grey and white rodingite up to 1-2 m across, made up of a suite of calc-silicate minerals, including wollastonite, zoisite, grossular, and vesuvianite, occur randomly in the serpentinite. Bodies of felsite, which have the appearance of dykes and sometimes form prominent outcrops, may be albitites.

GEOLOGY OF THE ULTRAMAFIC ROCKS IN TOBAGO

The mid-Cretaceous Tobago plutonic complex forms an east-west belt crossing the island (Fig. 2). It is in contact with the metamorphic North Coast Schists to the north, being deformed in the contact zone (Frost and Snoke, 1989; Jackson and Donovan, 1994). To the south it is overlain by the Tobago Volcanic Group of basalts, andesites and related calc-alkali volcanics. The ultramafic part of the plutonic complex is nearest to the North Coast Schists and occurs in the Central Forest Reserve area of the island. Exposure is poor and largely restricted to the forestry tracks and river sections. Thus, the relationship between individual rock types is usually obscured.

The ultramafic rocks include dunite, wehrlite, pyroxenite, and hornblendite, defined essentially on the dominance of olivine, olivine plus clinopyroxene, clinopyroxene, and amphibole, respectively. However, the relative proportions of olivine, clinopyroxene and amphibole vary widely. Sometimes complex intergrowth relationships exist between olivine and clinopyroxene, and there are replacement textures between clinopyroxene and amphibole. Crystal size reduction, giving a mosaic texture, possibly in response to deformation, is common in some olivine and clinopyroxene rich rocks. The dunites are often partly, or occasionally, completely serpentinised. Pale greenish white rodingites, containing prehnite, clinozoisite and chlorite, occur rarely. The petrographic characteristics of the rock suite, the evidence of local mesoscopic layered structures, referred to by Frost and Snoke (1989), and the major element geochemical data, also by Frost and Snoke (1989), suggest crystal accumulation during the cooling history of the igneous complex.

CHROMITE

The dunite and lherzolite from Jamaica contain disseminated chromite (<2% by modal analysis) as anhedral crystals up to 2.5 mm in size. Although deposits of massive chromite are found elsewhere in Caribbean ophiolites, such as in the large belt on the north side of Cuba (Kesler et al., 1990), local high concentrations and cumulate textures of chromite have not been found here. The mineral is brown in thin section, which is typical of low iron chromite. Crystals sometimes contain a rim of magnetite (Fig. 3). Chromite is also found occasionally as a relict primary mineral in the serpentinites, although magnetite

Table 1. Mean composition of chromites from Arntully, Jamaica and Tobago (nd = below detection limit)

	Arntully (21 analyses)		*Tobago (13 analyses)*	
	mean	std. dev.	mean	std.dev.
TiO_2	0.03	0.03	0.99	0.56
Al_2O_3	30.29	3.40	5.42	3.63
Cr_2O_3	36.64	4.34	22.15	7.74
FeO	17.10	1.17	63.17	10.22
MnO	0.21	0.08	0.54	0.10
MgO	13.82	0.72	2.95	1.58
NiO	nd	-	0.16	0.04
Total	98.09		95.38	

Formula on the basis of 9 cations and 12 oxygens (Fe^{3+} by calculation)

Ti	0.0020	0.0813
Al	3.2204	0.6972
Cr	2.6133	1.9115
Fe^{2+}	1.1278	2.5374
Fe^{3+}	0.1623	3.2288
Mn	0.0160	0.0499
Mg	1.8582	0.4799
Ni	-	0.0140

in aggregates and in disseminations is the major oxide mineral in these rocks. In Tobago, up to about 15% chromite is present in some partly serpentinised dunites. Crystals are generally euhedral to subhedral, typically 0.5 mm across and opaque in thin section. Aggregates of two to four crystals are reminiscent of cumulative textures in mafic and ultramafic layered plutonic rocks. In the wehrlites and pyroxenites from Tobago chromite is a rare accessory mineral. It is not found in the hornblendites.

The mineral chemistry of chromites from Jamaica and Tobago is given in Table 1, along with the mineral formulae. The two compositions are very different. The Jamaican chromite is characterised by high Cr, Al and Mg. This is typical of podiform chromite ore bodies of 'Alpine type' intrusions (Craig and Vaughan, 1994). There is much more Fe, particularly Fe^{3+}, and less Cr in the Tobago chromite, which has a composition similar to that found in many layered basic intrusions. More variation in composition, as illustrated by a larger standard deviation for Fe and Cr, is present in the Tobago chromite, which also contains a minor amount of Ni and more Ti. Plots of Cr/(Cr+Al) and $Fe^{3+}/(Cr+Al+Fe^{3+})$ against $Mg/(Mg+Fe^{2+})$ for the chromites are given in Figure 4, along with the fields for the various types of complexes in which chromite occurs, taken from Dick and Bullen (1984) and Jan and Windley (1990). The Jamaican chromites plot within the field of 'Alpine'-type peridotites, supporting the ophiolitic origin for the ultramafic rocks. The Tobago data have high $Fe^{3+}/(Cr+Al+Fe^{3+})$ ratios and a TiO_2 content similar to chromites from South East Alaskan Complexes (Irvine, 1967; Jan and Windley, 1990) and plot in a similar position for this type in Figure 4b. This is particularly significant as the Alaskan intrusives are similar to those from Tobago in being clinopyroxene-rich cumulate ultramafic rocks believed to have formed in magma chambers beneath volcanoes, overlying subduction zones in an island arc setting (Irvine, 1967; Dick and Bullen, 1984).

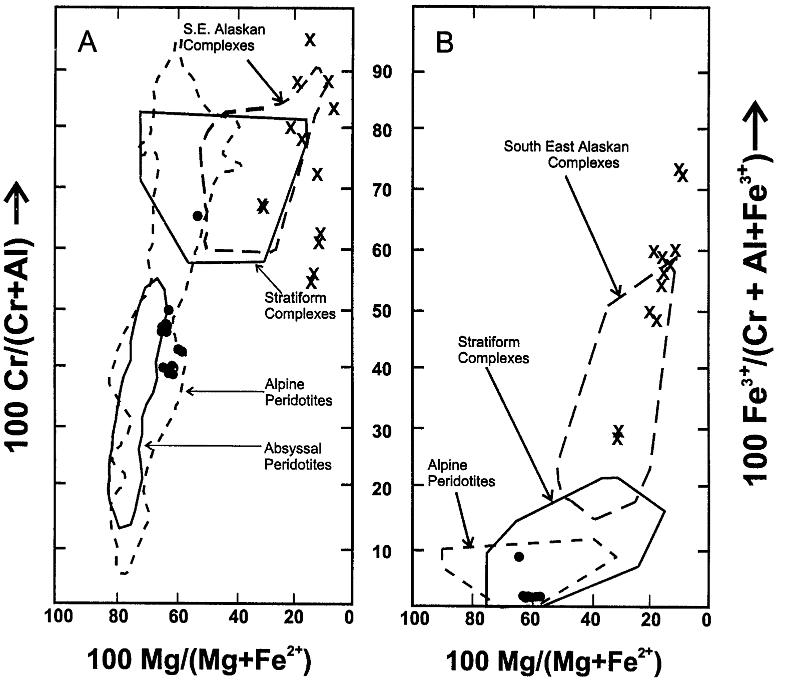

Figure 4. Plots of chromite mineral chemistry from Jamaica and Tobago showing (a) $Mg/(Mg+Fe^{2+})$ against Cr/(Cr+Al) and (b) $Mg/(Mg+Fe^{2+})$ against $Fe^{3+}/(Cr+Al+Fe^{3+})$. Data are electron microprobe analyses, with Fe^{2+} and Fe^{3+} calculated by assuming perfect stoichiometry in the mineral formulae. Symbols: •, Jamaica; ×, Tobago

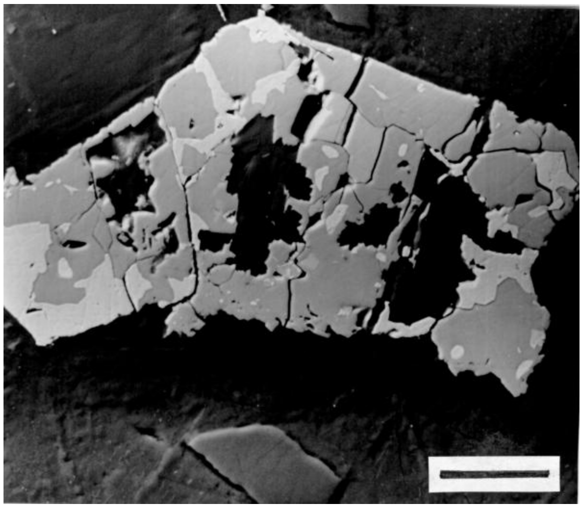

Figure 5. Backscattered scanning electron micrographs of a magnetite crystal (grey) with inclusions of pentlandite in centre part (mid-grey) to right of centre dark area, awaruite (light grey) towards and at the margins and native copper (lightest grey) at the top right and bottom right margin. Surrounding and included mineral is serpentine. Arntully, Jamaica. Scale bar = 25 µm.

Fe, Ni AND Cu SULPHIDE AND RELATED ORE MINERALS

A wide range of sulphide, native element and metal alloy ore minerals, typical of those found in ultramafic rocks, occur in both Jamaica and Tobago. Amounts are much less than 1%, and they occur as disseminated crystals and disseminated composite aggregates. In economic terms the mineralisation would appear to have minor significance, although some prospecting has previously taken place in the Arntully area of Jamaica, and recent interest by mining companies has been shown in Tobago. Data on ultramafic-hosted magmatic sulphides elsewhere in the Caribbean appear to be lacking. The only significant sulphide mineralisation reported is Cyprus-type volcanogenic deposits, for example in western Cuba (Kesler et al., 1990).

The mineral assemblage in Jamaica includes pentlandite (sometimes cobaltiferous), awaruite (a nickel-iron alloy), heazlewoodite (nickel sulphide) and native copper. These generally occur as very small (typically 0.01-0.1 mm) crystals associated with magnetite, either within the magnetite which surrounds chromite or within other magnetite crystals (Fig. 5). More than one phase is usually present in any one magnetite crystal. A fixed assemblage is present in any one sample (Table 2), but there appears to be no systematic variation between dunite, lherzolite and serpentinite. Representative electron microprobe analyses of each phase are given in Table 3. The Ni/Fe ratio in awaruite is somewhat variable. Minor, but variable amounts of Co are present in pentlandite. The paragenesis indicates that pentlandite is the earliest phase, followed by awaruite and heazlewoodite. Pentlandite and heazlewoodite are almost entirely mutually exclusive. The native copper is paragenetically very late. Sphalerite and chalcopyrite occur very rarely. Using the experimental data for the phase equilibria in the Fe-Ni-S system (Vaughan and Craig, 1978), the assemblage of awaruite and heazlewoodite indicates a low temperature (<400ºC) typical of low-modal sulphides (O'Hanley, 1996).

In Tobago, pyrrhotite, pentlandite, pyrite and chalcopyrite are the main sulphide phases. Two distinctly different assemblages are found: one in the dunites, wehrlites and their serpentinised equivalents, which is dominated by pyrrhotite and pentlandite; and the other in the pyroxenites and hornblendites where pyrite and chalcopyrite are most common (Table 2). Pentlandite and pyrrhotite occur as small (approx. 0.1 mm) crystals, sometimes within or associated with magnetite (Figs. 6 and 7). Representative analyses are

Table 2. Sulphide and related ore mineral assemblages in ultramafic rocks from Jamaica and Tobago.

Arntully, Jamaica	**Tobago**
Rocktypes: dunite, lherzolite and serpentinite.	***Rocktypes:*** dunite, wehrlite and serpentinite
Assemblages: pentlandite + awaruite + copper	***Assemblages:*** pyrrhotite
pentlandite + sphalerite + awaruite + copper	pyrrhotite + pentlandite
pentlandite + awaruite	pyrrhotite + pentlandite + chalcopyrite
pentlandite + awaruite + copper + Cu sulphide	pyrrhotite + pentlandite + pyrite
pentlandite + awaruite (Pt) + copper (Fe, Pt, Pd) + heazlewoodite	pentlandite + awaruite
awaruite + copper	***Rocktypes:*** pyroxenite and hornblendite
awaruite + chalcopyrite	***Assemblages:*** pyrite
awaruite + heazlewoodite + copper (Fe, Pt, Pd)	pyrite + chalcopyrite
awaruite + heazlewoodite	pyrite + chalcopyrite + sphalerite
	pyrite + chalcopyrite + digenite
	pyrite + copper + Pt sulphides

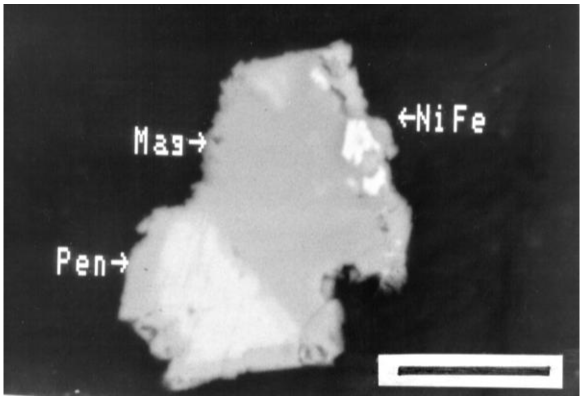

Figure 6. Backscattered scanning electron micrograph of magnetite (Mag) with inclusions of pentlandite (Pen) and awaruite (NiFe). Scale bar = 10 µm. Host rock is dunite, Tobago.

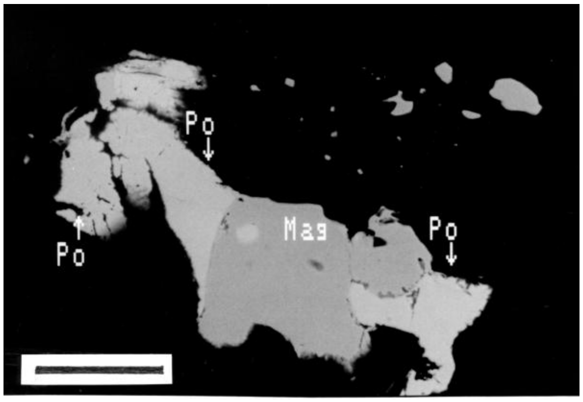

Figure 7. Backscattered scanning electron micrograph of composite grain of magnetite (Mag) and pyrrhotite (Po). Scale bar = 10 µm. Host rock is serpentinised dunite, Tobago.

given in Table 3. The Ni/Fe ratio in the pentlandite is higher compared with Jamaica. The phase diagrams of Barton and Skinner (1979) would indicate crystallisation of the pentlandite/pyrrhotite assemblage in the absence of pyrite at no more than 500ºC. Where pyrite joins these other two phases in the dunites, wehrlites and serpentinites, equilibrium crystallisation at no more than 250ºC is likely. Chalcopyrite and pyrite within the hornblendites and pyroxenites are usually much larger (approx. 1 mm) and are usually subhedral to euhedral. Partial alteration of the sulphides to Fe oxide minerals is common in some samples. Sphalerite, digenite and awaruite are found very rarely.

PLATINUM GROUP ELEMENTS

A very large number of different platinum and other PGE minerals are recognised in ultramafic rocks (Cabri, 1981; Prichard, 1988), and they often have complex paragenetic relationships. In Jamaica, Simpson et al. (1990) detected a PGE anomaly in the stream sediments from rivers that drain the ultramafic body. Scott et al. (1992) identified rare, small irregular shaped grains (0.25-0.5 mm) of Pt and Pd enriched native copper occurring within magnetite (Table 2). They are likely to have formed as a result of the remobilisation of platinum and palladium during serpentinisation. Awaruite has also been found rarely to contain a minor amount of Pt.

Table 3. Representative electron microprobe analyses of sulphide and associated minerals in ultramafic rocks from Jamaica and Tobago.

	a (1 – 8). Jamaica								b (9 – 12). Tobago			
%	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Fe	2.3	4.23	23.94	37.19	35.92	36.37	1.82	6.72	59.91	60.38	30.92	29.92
Co	0.52	0.40	1.12	0.87	3.59	1.98	-	-	0.88	0.10	4.25	5.35
Ni	70.83	69.75	73.01	61.21	26.98	28.54	2.83	6.36	0.15	0.23	31.88	32.76
Cu	-	-	1.45	0.34	-	-	96.06	87.27	-	-	-	-
S	26.53	25.42	-	-	32.74	33.04	-	-	38.76	38.74	32.70	32.76
Total	100.21	99.80	99.52	99.61	99.23	99.93	100.71	100.34	99.70	99.42	99.85	100.17
Formula												
Fe	0.1001	0.1835	2.5008	3.8522	5.0046	5.0292	0.2046	0.7508	0.8875	0.8946	4.3001	4.1565
Co	0.0212	0.016	0.1109	0.0854	0.4740	0.2592	-	-	0.0124	0.0014	0.5604	0.7044
Ni	2.8940	2.8789	7.2552	6.0314	3.5759	3.7536	0.3027	0.6759	0.0021	0.0032	4.2173	4.2856
Cu	-	-	0.1331	0.0310	-	-	9.4927	8.5733	-	-	-	-
S	1.9848	1.9210	-	-	7.9455	7.9580	-	-	1.0000	1.0000	7.9223	7.8535
Σcations	5.0000	5.0000	10.0000	10.0000	17.0000	17.0000	10.0000	10.0000	1.9019	1.8992	17.0000	17.0000

1-2, heazlewoodite. 3-4, awaruite. 5-6, pentlandite. 7-8, native copper, 9-10, pyrrhotite (formula calculated on basis of 1.0000 atoms S). 11-12, pentlandite. - , below detection limit.

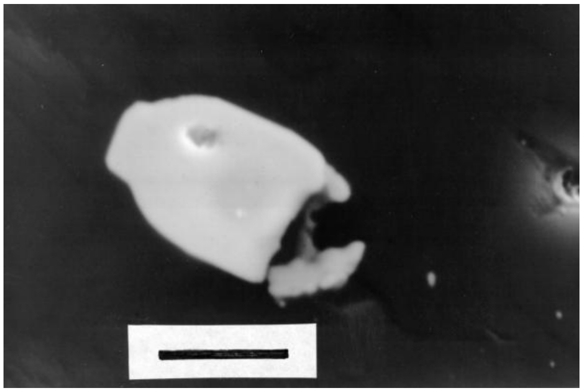

Figure 8. Backscattered scanning electron micrograph of a PtS phase (left) and a smaller RhPtIrCuAsS composite grain (right) within a hornblende crystal. Rock is a hornblende-bearing clinopyroxenite, Tobago. Scale bar = 25 μm.

Table 4. Electron microprobe analysis of Pt sulphide mineral from Tobago, illustrated in Figure 8. mean of 12 analyses, formula based on 10 atoms

	%	Formula
Pt	88.10	5.570
Fe	0.92	0.203
S	10.99	4.227
Total	100.01	10.000

In Tobago, one small grain of a PtS mineral has been found in a hornblendite (Fig. 8 and Table 4). An associated composite PGE grain containing Rh, Ir, Pt, Cu, As and S is also present. The latter is too small for accurate quantitative analysis using the available electron microprobe, but the overall composition is close to the hollingworthite-irarsite series. As with the Fe, Ni and Cu sulphides in Tobago, the PGE phases are likely to be the product of a primary stage of metallisation, rather than a lower temperature re-mobilised assemblage. This is the first record of PGE minerals from the Republic of Trinidad and Tobago.

OLIVINE

Most commercial deposits of olivine in the world are in dunites from ‘Alpine’-type intrusions (Harben and Bates, 1990). The olivine mineral itself sometimes is metamorphic, having been produced by the upper amphibolite facies metamorphism of serpentinites, as for example in the Appalachians, USA (O’Hanley, 1996). For industrial applications, olivine is required to be low in iron (typically no more than 7-8%, expressed as FeO) with 45-51% MgO and 40-43% SiO_2 (Harben, 1992). The loss on ignition needs to be low (<2%) and in deposits where there is a significant degree of serpentinisation, the raw material has to be calcined. This is especially necessary before use in the foundry and refractory industries. As olivine is a low value commodity, only a minimal amount of processing of the dunite can be afforded in commercially profitable operations.

The mean, standard deviation, and ranges of values of electron microprobe analyses of olivines from Jamaica, and from Tobago are given in Table 5. The chemistry of the host dunites and partly serpentinised dunites from both locations are also presented. The Jamaican olivines have a high MgO content. They fall within the requirements for use by industry, but with a slightly high FeO content. There is little variation in the olivine composition. However, the dunites and partly serpentinised dunites have much lower MgO, and even in the least serpentinised dunite, which is represented by the minimum value for the loss on ignition and the maximum value for MgO in Table 4, the loss on ignition is >8%. Thus a significant degree of processing of the dunite to concentrate the olivine at the expense of serpentine would be necessary to produce a suitable olivine product from this rock. The total iron oxide content (expressed as FeO) of the dunites and serpentinites (mean 6.70% as FeO) is significantly less than that of the olivine (mean 8.57%). This is surprising and indicates that, although iron oxides as magnetite are a product of serpentinisation, some of the original Fe in the olivine is lost from the rock during the alteration. The iron oxide content, therefore, of an olivine industrial mineral product, which would contain olivine along with a small amount of other minerals, is likely to contain less iron oxide than would be indicated by the electron microprobe analyses of the olivine itself.

The Tobago olivines are much more fayalitic (mean 14.77% FeO) compared with those from Jamaica. They also show a greater variation in their chemistry. There is also a higher iron oxide content in the dunites and serpentinised dunites, along with a correspondingly lower amounts of MgO. These data suggest that dunite cumulates in plutonic rocks from island arc settings are less suitable as a source of industrial olivine compared with those from ophiolite complexes.

Ni-LATERITES

Nickel-rich laterites overlying ultramafic rocks are a significant source of nickel. There are large Ni-Co deposits and prospects in the Caribbean, where they occur over the ultramafic parts of the ophiolite

Table 5. Electron microprobe analyses of olivine from Jamaica and Tobago, and chemical analyses of host dunites and serpentinised dunites.

a. Olivine.

%	Arntully, Jamaica (n = 49)				Tobago (n = 34)			
	mean	std.dev.	max.	min.	mean	std.dev.	max.	min.
SiO_2	41.10	0.20	41.47	40.43	40.29	0.33	40.79	39.70
FeO	8.57	0.20	9.06	8.21	14.77	1.70	7.28	11.23
MnO	0.13	0.03	0.19	0.05	0.26	0.04	0.34	0.18
MgO	50.53	0.36	51.63	49.88	46.17	1.62	48.94	43.62
NiO	0.39	0.04	0.48	0.33	0.11	0.05	0.19	0.09
CaO	0.01	-	0.05	nd	0.04	-	0.05	nd

b. Host dunite and serpentinised dunite.

%	Arntully, Jamaica (n = 18)				Tobago (n = 4)			
	mean	**std.dev.**	**max.**	**min.**	**mean**	**std.dev.**	**max.**	**min.**
SiO_2	39.13	0.46	40.51	38.58	36.42	0.82	37.35	35.43
TiO_2	<0.01	-	0.03	nd	0.07	0.03	0.10	0.04
Al_2O_3	1.04	0.32	1.85	0.62	0.81	0.11	0.93	0.68
Cr_2O_3	0.41	0.13	0.84	0.28	0.56	0.55	1.38	0.19
FeO	6.70	1.02	7.72	3.24	11.09	0.25	11.37	10.81
MnO	0.11	0.02	0.15	0.09	0.20	0.03	0.24	0.17
MgO	37.93	1.72	41.43	34.72	35.63	0.43	36.17	35.18
NiO	0.31	0.03	0.37	0.23	0.15	0.03	0.18	0.11
CaO	0.70	0.43	1.66	nd	0.63	1.11	2.29	0.07
Na_2O	0.06	0.02	0.10	0.03	0.03	0.01	0.04	0.02
K_2O	nd	-	0.02	nd	nd	-	0.01	nd
LOI	12.25	1.88	15.71	8.42	11.87	1.19	12.90	10.20

nd = below detection limit. LOI = loss on ignition. n = number of analyses.

complexes in Cuba and Hispaniola (Kesler et al., 1990). In these countries the topography is often gently undulating and a thick tropical weathering mantle can develop. In Jamaica, chemical weathering of silicates does yield oxide minerals such as gibbsite in the thicker soils of the Blue Mountain area (Scott, 1992). Thus, there is a potential for Ni enrichment in the soils by weathering over the ultramafic complex. However, the topography of the Blue Mountains area is far too steep, and the rate of physical erosion far too great for any significant thickness of Ni laterites to accumulate, whether *in situ*, or allochthonous. In Tobago, the topography is less dramatic, and a thick weathered horizon is probably developed in some areas beneath the forest. The authors have observed almost complete kaolinisation of the feldspars in the gabbro/diorite part of the plutonic complex in some areas. The dominant ultramafic rocks in Tobago, however, are clinopyroxenites, wehrlites and hornblendites. Dunites and their serpentinised equivalents form a relatively minor part of the ultramafic complex. Also, the Ni content in olivine and in the host dunites and serpentinites is much lower compared with that in Jamaica (Table 4). Thus, the prospect for significant Ni enrichment in the weathering mantle is reduced.

ASBESTOS, MAGNESITE AND TALC

Asbestiform chrysotile, magnesite, talc and other industrial minerals appear to be lacking in both Jamaica and Tobago. The reasons for this probably relate to the tectonic position and alteration history of the two complexes.

The principal deposits of chrysotile asbestos in ultramafic rocks are found in Archean serpentinised dunite cumulates within greenstone belts (O'Hanley, 1996). A few commercial deposits are found in serpentinised harzburgites and dunites of ophiolitic affinity. X-ray diffraction data show that the serpentinised ultramafics from Jamaica contain chrysotile and lizardite with only minor variation in relative proportions. Petrographically they have a massive, intergrown texture. The prograde serpentine mineral, antigorite, is not found. In Tobago, in the few places where complete serpentinisation of the ultramafics has occurred, the mineral assemblage is likewise chrysotile and lizardite. In both islands, fibrous veins of chrysotile, necessary for an asbestos deposit, have not been found. Substantial recrystallisation of serpentine minerals associated with stress and fluid movement through a serpentinite, producing for example slip-fibre type chrysotile, appears to be responsible for the formation of many commercial asbestos deposits. There is evidence of fluid movement from the recrystallised assemblage of the Cu and Ni minerals in the Jamaican ultramafics. However, this is more likely to have been at the same time as serpentisation, rather than a more extended or further, later fluid movement at an elevated temperature (approx 250ºC, O'Hanley, 1996), which would result in the formation of fibrous chrysotile. There is no evidence for fluid movement associated with stress at elevated temperature through the Tobago ultramafic complex.

Magnesite and talc commonly occur either as an intergrown mass, or as veins, pods and irregular masses of either mineral in hydrated and/or carbonated, serpentinised ultramafic bodies. They are sometimes present in commercial quantities, for example in ophiolitic ultramafic complexes of the Alpine belt of the Mediterranean region. In Jamaica and Tobago these minerals have not been found even in accessory amounts. However, ultramafic-hosted magnesite is found further west from Tobago in Margarita Island, Venezuala (Abu-Jaber and Kimberley, 1992a), which is likewise within the boundary zone of the Caribbean and South American plates (Robertson and Burke, 1989). Magnesite is probably absent because of the deep tectonic level of the ultramafic bodies in Jamaica and Tobago, it generally being accepted that vein type magnesite deposits form in near surface environments at low temperatures and pressures (Pohl, 1990; Abu-Jaber and Kimberley, 1992b), sometimes even within overlying alluvium (Ebrahimi Nasrabadi, 1990). The absence of sepiolite, huntite and hydromagnesite in the Jamaica and Tobago ultramafic rocks are similarly a consequence of the tectonic level of both bodies. Huntite and hydromagnesite can form as a precipitate from hydrothermal springs. Commercial sepiolite of the meerschaum type found in Eskisehir, Turkey is also unlikely in Jamaica and Tobago as it forms as a product of silicification of magnesite (O'Hanley, 1996).

Talc-rich rocks form in many cases by regional metamorphism or regional metasomatism of serpentinites (O'Hanley, 1996; El-Sharkawy, 1996), or where there is much evidence of fluid movement through the ultramafic bodies associated with late stage extensional tectonics, for example in the Lizard Complex, Cornwall, UK (Power et al., 1996, 1997). Talc does not form in the localised metasomatism which produces the Ca-silicate mineral assemblages of the rodingites. In Jamaica, the rocks of the Blue Mountain Inlier adjacent to the ultramafic complex on one side are partly metamorphic, and include the Westphalia and Mt. Hibernia Schists. The metamorphism of these schists is convergent, arc-trench in setting (Abbott et al., 1996) giving retrogressed blueschist and amphibolite facies mineral assemblages. If subjected to this metamorphism the ultramafic complex would have shown at least some shearing and most likely further evidence in its mineralogy. Talc might have formed, even though the metamorphic style is convergent rather than extensional. The current juxtaposition of the ultramafic body and the metamorphics is a consequence most likely of much later, dominantly strike-slip faulting. Steatisation of serpentinites is common at their margins in regionally metamorphosed rocks and also adjacent to metamorphosed pelites (O'Hanley, 1996). In Tobago, therefore, talc replacement of serpentinites might be expected in the ultramafic rocks immediately adjacent to the faulted contact with the North Coast Schists. There is much shearing associated with this contact and such an environment can produce talc/magnesite bodies, as for example in Unst, Shetland, UK (Grout and Smith, 1989).

CONCLUSIONS

The rocks at Arntully in Jamaica and those in Tobago are examples of ultramafic rocks of different geological settings in the Caribbean. The former is part of a dismembered ophiolite. The latter is part of an arc-related or Alaskan type intrusion. Ore minerals of the same metals and similar industrial minerals occur in both complexes. The detailed mineralogy and petrology of the chromite, Ni-Cu-PGE ores and olivine reflect differences in their origin or subsequent geological histories. In Jamaica, the assemblage of the Ni-Cu-PGE sulphides and associated minerals is a consequence of the serpentinisation. In Tobago, a low temperature magmatic assemblage of sulphides is dominant. Compared with Cuba and ophiolites elsewhere in the Greater Antilles (Hispaniola and Puerto Rico), there is little possibility in Jamaica or Tobago for Ni laterite deposits over the ultramafic rocks. In both Jamaica and Tobago the absence of asbestiform chrysotile, magnesite and talc can be explained in terms of the different tectonic levels and alteration history compared to ultramafic rocks elsewhere which contain commercial deposits of these minerals.

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REFERENCES

ABU-JABER, N.S. & KIMBERLEY, M.M. 1992a. Origin of ultramafic-hosted magnesite on Margarita Island, Venezuela. *Mineralium Deposita*, **27**, 234-241.

ABU-JABER, N.S. & KIMBERLEY, M.M. 1992b. Origin of ultramafic-hosted vein magnesite deposits. *Ore Geology Reviews*, **7**, 155-191.

ABBOTT, R.N., JACKSON, T.A. & MCSWEEN, H.Y. 1996. Metamorphic conditions in the Westphalia Schists of the Blue Mountain Inlier, Jamaica: tectonic implications. *International Geology Review*, **38**, 1143-1154.

BARTON, P.B. & SKINNER, B.J. 1979. Sulphide mineral stabilities. Pp. 278-403 in BARNES, H.L. (ED.) *Geochemistry of hydrothermal ore deposits*. J. Wiley, New York.

CABRI, L.J. (ED.) 1981. Platinum-group elements: mineralogy, geology and recovery. *Canadian Institute of Mining and metallurgy*, Special Volume **23**, 267 pp.

CRAIG, J.R. & VAUGHAN, D.J. 1994. *Ore Microscopy and ore petrography*; 2nd Edition. John Wiley and Sons Inc., 434 pp.

DICK, H.J.B. & BULLEN, T. 1984. Chromian spinel as a petrogenetic indicator in abyssal and alpine-type peridotites and spacially associated lavas. *Contributions to Mineralogy and Petrology*, **86**, 54-76.

DRAPER, G. 1979. *The tectonics of the regionally metamorphosed rocks of eastern Jamaica*. Unpublished PhD thesis, University of the West Indies, 277 pp.

EBRAHIMI-NASRABADI, K. 1990. *The industrial mineralogy of magnesite and Huntite from eastern Iran*. Unpublished PhD thesis, University of Hull, 495 pp.

EL-SHARKAWY, M. 1996. *Genetic and economic evaluation of some talc occurrences in the Eastern Desert of Egypt*. Unpublished PhD thesis, University of Tanta, Egypt, 357 pp.

FROST, C.D. & SNOKE, A.W. 1989. Tobago, West Indies, a fragment of Mesozoic oceanic island arc: petrochemical evidence. *Journal of the Geological Society of London*, **146**, 953 964.

GROUT, A. & SMITH, C.G. 1989. Scottish Highlands and Southern Uplands Mineral Portfolio: Talc resources. *British Geological Survey Technical Report* **WF/89/7**, 17 pp.

HARBEN, P.W. 1992. *The industrial minerals handybook*. Metal Bulletin plc, 148 pp.

HARBEN, P.W. & BATES, R.L. 1990. *Industrial minerals: geology and world deposits*. Metal Bulletin plc, 312 pp.

IRVINE, T.N. 1967. Chromian spinel as a petrogenetic indicator. Part 2. Petrologic applications. *Canadian Journal of Earth Sciences*, **4**, 71-103.

JACKSON, T.A. & DONOVAN, S.K. 1994. Tobago. Pp. 111-127 in DONOVAN, S.K. & JACKSON, T.A.(EDS.), *Caribbean Geology, an introduction*. University of the West Indies Publishers' Association, Kingston, 289 pp.

JACKSON, T.A., SCOTT, P.W. & SMITH, T.E. 1998. The petrology of ultramafic and maficigneous rocks from the Blue Mountain Inlier, Jamaica. In ALI. W., PAUL, A & YOUNG ON, V, (EDS.) *Transactions of the 14th Caribbean Geological Conference, Trinidad, July 16-21 1995*, 188-197.

JAN, M.Q. & WINDLEY, B.F. 1990. Chromian spinel - silicate chemistry in ultramafic rocks of the Jijal Complex, Northwest Pakistan. *Journal of Petrology*, **31**, 667-715.

KEMP, A.W. 1971. *The geology of the southwestern flank of the Blue Mountains, Jamaica*. Unpublished PhD thesis, University of the West Indies, 306 pp.

KESLER, S.E., LEVY, E. & CECILIA MARTIN, F. 1990. Metallogenic evolution of the Caribbean region. Pp. 459-482 in DENGO, G. & CASE, J.E. (EDS.) *The Geology of North America*, Vol. **H**, *The Caribbean Region*. 528 pp.

KOSTAKIS, M.G. 1995. Occurrence and genesis of huntite - hydromagnesite assemblages, Kozani, Greece - important new white fillers and extenders. *Transactions of the Institution of Mining and Metallurgy*, **104**, B179-186.

LOCKWOOD, J.P. 1971. Detrital serpentinite from the Guajira Peninsula, Columbia. *Geological Society of America, Memoir* **130**, 55-75.

O'HANLEY, D.S. 1996. *Serpentinites, records of tectonic and petrological history*. Oxford University Press, 277 pp.

POWER, M. R. ALEXANDER, A.C., SHAIL, R.K. & SCOTT, P.W. 1996. A re-interpretation of the internal structure of the Lizard Complex ophiolite, South Cornwall. *Proceedings of the Ussher Society*, **9**, 63-67.

POWER, M.R., SHAIL, R.K., ALEXANDER, A.C. & SCOTT, P.W. 1997. Alteration and vein mineralisation within the Lizard Complex, south Cornwall: constraints on the timing of serpentinisation. *Proceedings of the Ussher Society*, **9**, 188-194.

POHL, W. 1990. Genesis of magnesite deposits - models and trends. *Geologische Rundschau*, **79**, 291-299

PRICHARD, H.M. 1988. Development of techniques for the determination of the platinum-group elements in ultramafic rock complexes of potential economic significance: mineralogical studies. *Commission of the European Communities Report EUR* **11631**, 163 pp.

RAMDOHR, P. 1967. A widespread mineral association connected with serpentinization. *Neues Jahrbuch für Mineralogie Abhandlungen*, **107**, 241-265.

ROBERTSON, P. & BURKE, K. 1989. Evolution of southern Caribbean plate boundary, vicinity of Trinidad and Tobago. *Bulletin of the American Association of Petroleum Geologists*, **73**, 490-509.

ROBINSON, E. 1994. Jamaica. Pp. 111-127 in DONOVAN, S.K. & JACKSON, T.A. (EDS.), *Caribbean Geology, an introduction*. University of the West Indies Publishers' Association, Kingston, 289 pp.

SCOTT, P.W. 1987. The exploration and evaluation of industrial rocks and minerals. *Annual Review 1987, Irish Association for Economic Geology*, 19-28.

SCOTT, P.W., DRAKAPOULOS, Y.D. & DUNHAM, A.C. 1992. Platinum and palladium-bearing minerals in serpentinites from southwestern Blue Mountain area, Jamaica. *Transactions of the Institution of Mining and Metallurgy*, **101**, B121-124.

SCOTT, V.J.R. 1992. *A study of soils from the Cinchona area of the Blue Mountains, Jamaica.* Unpublished BSc thesis, University of Newcastle upon Tyne, 93 pp.

SIMPSON, P.R., ROBOTHAM, H & HALL, G.E.M. 1990. Regional geochemical orientation studies for platimium in Jamaica. *Transactions of the Institution of Mining and Metallurgy*, **99**, B183-187.

VAUGHAN, D.J. & CRAIG, J.R. 1978. *Mineral chemistry of metal sulphides*. Cambridge University Press, Cambridge, 493 pp.

WADGE, G., JACKSON, T.A., ISAACS, M.C. & SMITH, T.E. 1982. The ophiolitic Bath - Dunrobin Formation, Jamaica: significance for Cretaceous plate margin evolution in the north-western Caribbean. *Journal of the Geological Society of London*, **139**, 321-333.

WADGE, G. , DRAPER, G. & LEWIS, J.F. 1984. Ophiolites of the northern Caribbean: a reappraisal of their roles in the evolution of the Caribbean plate boundary. *Geological Society of London, Special Publication* **13**, 367-380.