Canadian Mineralogist
Vol. 26, pp. 161-175 (1988)

GEOLOGY AND PLATINUM-GROUP-ELEMENT GEOCHEMISTRY OF THE SERPENTINE HILL COMPLEX, DUNDAS TROUGH, WESTERN TASMANIA

ANTHONY V. BROWN
Geological Survey of Tasmania, P.O. Box 56, Rosny Park, Tasmania 7018

NORMAN J PAGE
U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025, U.S.A.

ALONZO H. LOVE
U.S. Geological Survey, P.O. Box 25046, DFC, Lakewood Colorado 80225, U.S.A.

ABSTRACT

Field relations, petrology, and the platinum-group-element (PGE) geochemistry of ultramafic and mafic rocks in the Middle Cambrian Serpentine Hill Complex indicate that it is an orthopyroxene-rich one with similarities to Alaskan-type complexes and is not a dismembered ophiolite, as previously described. The complex consists of multiple intrusions which formed an orthopyroxene-rich layered sequence, an olivine-rich layered sequence, and a gabbroic unit. The orthopyroxene-rich layered sequence is composed of thin repetitive units of serpentinized olivine cumulate and orthopyroxene cumulate, with minor olivine-orthopyroxene cumulate. Locally these units are plagioclase-bearing. Primary structural features include unconformities, troughs, modal layering, slump structures, and syndepositional faults. The layered sequence is intruded by plagioclase-bearing dunite which locally contains chromite-rich zones. The chromite ranges from 0.64 to 0.69 in Cr/(Cr+Al) and 0.37 to 0.46 in $Mg/(Mg+Fe^{2+})$. In places, the plagioclase-bearing dunite sequence is layered and contains cognate xenoliths of the orthopyroxene-rich layered sequence. The two ultramafic sequences are cut by gabbroic rocks of variable grain-size. The Pt content in rocks of the complex ranges from 17 to 60 ppb and is highest in the gabbroic rocks, which also have the highest Pd content (max. 18 ppb). The ultramafic rocks of the layered and olivine-rich sequence contain no detectable Ir (<20 ppb) or Ru (<100 ppb) and less than 2 ppb Pd, in contrast to chromitites which contain up to 90 ppb Ir and 420 ppb Ru. Laurite and Os–Ir alloy occur in the chromitites. Comparison of chondrite normalized PGE ratios of chromitites with those of ophiolite, stratiform, and komatiitic complexes shows distinctive differences. Although the overall chondrite normalized pattern shows relative enrichment in Ru and Ir relative to Pt and Pd, similar to patterns for ophiolitic chromitite, Pt is more enriched than in ophiolites.

Keywords: platinum-group elements, ultramafic and mafic rocks, chromitites, Serpentine Hill Complex, Tasmania.

SOMMAIRE

De par les relations de terrain, les aspects pétrologiques, et les concentrations en éléments du groupe du platine, les roches mafiques et ultramafiques du complexe Serpentine Hill (d'âge cambrien moyen), en Tasmanie, définissent plutôt un complexe stratiforme riche en orthopyroxène de type Alaska qu'un cortège ophiolitique déchiqueté, comme on le pensait auparavant. Le complexe est le résultat d'intrusions multiples qui ont produit une séquence litée riche en orthopyroxène, une autre riche en olivine, et une unité gabbroïque. La séquence riche en orthopyroxène contient de minces unités répétées de cumulats à olivine, maintenant serpentinisée, et à orthopyroxène, avec une proportion moins importante de cumulats à olivine + orthopyroxène. Par ci, par là, ces cumulats contiennent du plagioclase. Parmi les structures primaires, on trouve nonconformités, chenaux, stratifications modales, affaissements, et failles syndépositionnelles. Cette séquence stratifiée est recoupée par une dunite à plagioclase qui contient, par endroits, des zones riches en chromite. Celle-ci varie de 0.64 à 0.69 et de 0.37 à 0.46 dans ses rapports Cr/(Cr + Al) et $Mg/(Mg + Fe^{2+})$, respectivement. La dunite peut aussi montrer une stratification; elle contient des enclaves cogénétiques de la séquence de cumulats à orthopyroxène. Les deux unités ultramafiques sont recoupées par des roches gabbroïques à granulométrie variable. La teneur en Pt des roches du complexe varie de 17 à 60 ppb; les roches gabbroïques en sont les plus enrichies. Elles contiennent aussi les plus hautes teneurs en Pd (jusqu'à 18 ppb). Les roches ultramafiques litées et riches en olivine ne contiennent pas d'Ir et de Ru décelables (< 20 et <100 ppb, respectivement), et moins de 2 ppb Pd, en comparaison des chromitites, qui peuvent contenir jusqu'à 90 ppb d'Ir et 420 ppb de Ru. On peut trouver laurite et un alliage Os–Ir dans les chromitites. Suite à une comparaison des teneurs en éléments du groupe du platine, normalisées par rapport aux teneurs chondritiques, les chromitites sont distinctes de celles des ophiolites, massifs stratiformes et komatiites. Quoique ces chromitites sont relativement enrichies en Ru et Ir comparé à Pt et Pd, points en commun avec les chromitites ophiolitiques, le Pt est plus concentré que dans celles-ci.

(Traduit par la Rédaction)

Mots-clés: éléments du groupe du platine, roches ultramafiques et mafiques, chromitites, complex de Serpentine Hill, Tasmanie.

Introduction

Tasmania was a major supplier of osmiridium, produced from placer deposits during 1912 to 1925, at which point the production from the Witwatersrand surpassed that of Tasmania (Quiring 1962). The osmiridium was mined from placer deposits associated with some of the ultramafic–mafic complexes in Western Tasmania. In this study we selected and sampled a number of ultramafic complexes in Western Tasmania for an investigation of their platinum-group-element (PGE) geochemistry. The focus of the study was the Serpentine Hill Complex. The ultramafic–mafic complexes of Western Tasmania have been described previously both as disrupted ophiolites (Rubenach 1973, 1974) and ophiolitic (Varne 1978, Varne & Brown 1978, Brown *et al.* 1980). Recent field studies (Brown 1986) suggest that no ultramafic complex within Tasmania can be described as an ophiolite, nor does it appear plausible that these complexes formed in a deep ocean-floor setting.

Three different suites of ultramafic rocks have been recognized within the Eocambrian–Cambrian sequence of volcanic and sedimentary rocks of the Dundas Trough of western Tasmania. One of these three suites, a multiple intrusive ultramafic–gabbro succession, forms the Serpentine Hill Complex, which has anomalously high PGE contents with respect to the other two ultramafic suites. The Serpentine Hill Complex is a relatively small (2 km^2) body, and contains two different phases of ultramafic rocks, both with evidence of multiple pulses of magma. The ultramafic assemblages were followed by multiple intrusion of two-pyroxene gabbro. The other two ultramafic rock suites are a high-magnesium layered dunite–harzburgite suite (LDH) that contains a tectonic fabric, and a layered pyroxenite–dunite suite (LPD). The LDH suite consists of interlayered dunite, orthopyroxene-bearing dunite and harzburgite, depending on the percentage of orthopyroxene present in any specific layer. Olivine (Fo_{93-94}), orthopyroxene (En_{93-94} with less than 0.5 wt.% CaO) and chromite (Cr/Cr+Al = 0.87–0.93) make up the LDH rocks. The LPD suite consists of uniform layers of orthopyroxenite, olivine orthopyroxenite and dunite, with harzburgite absent. The rocks consists of orthopyroxene (En_{85-89}, CaO = 0.6 to 2.0 wt.%), olivine (Fo_{87-90}), chromite (Cr/Cr+Al = 0.64) and diopside (Ca:Mg:Fe = 0.47:0.49:4). Both of these suites are devoid of feldspar and are described in detail elsewhere (Brown 1986).

The purposes of this paper are: (1) to describe the geology and petrology of the Serpentine Hill Complex within a regional framework and to compare its characteristics with Alaskan-type complexes, (2) to present PGE data for the three different ultramafic suites, (3) to compare and contrast the PGE geochemistry of the three suites, and (4) to compare the PGE geochemistry of Tasmanian ultramafic complexes with those elsewhere.

Regional Geological Setting

The following brief regional geological summary is based on Williams (1978) with specific details on the Dundas Trough sequences from Brown (1986). The Eocambrian–Cambrian volcanic and sedimentary rock sequences of the Dundas Trough formed in elongate rift troughs within and between regions of polydeformed Precambrian siltstone, orthoquartzite, and minor volcanic rocks (Fig. 1). The earliest Eocambrian deposits (the Success Creek Group) consist of 1000 m of shallow-water to fluviatile sedimentary rocks which unconformably overlie the Precambrian basement. This siliceous shallow-water sequence is conformably overlain by the Crimson Creek Formation, consisting of basic volcaniclastic sedimentary rocks with *ol*- and *qtz*-normative tholeiitic lavas.

Following the accumulation of the above terrigenous and tholeiitic sequences a phase of high-magnesium andesitic volcanism extruded. This high-magnesium lava has the chemical characteristics of a second-stage melt (Duncan & Green 1980, Jenner 1981) and one of the ultramafic suites, the layered dunite–harzburgite suite, is consistent with having been formed as a cumulate from this magmatic phase at high temperatures and low pressures in a crustal magma chamber.

In early Middle Cambrian times the tectonic regime in western Tasmania changed from tensional to compressive, causing disruption of the ultramafic cumulates and their re-emplacement along steep faults into the basinal Eocambrian sequences. This was followed by a third phase of volcanic activity that produced low-titanium tholeiitic lavas which interdigitate with basal conglomerates (Dundas Group and correlates). In the late Middle Cambrian a widespread, but probably short-duration, subaerial acid to intermediate volcanic phase, the Mt. Read volcanics, formed contemporaneously with the sedimentary rock sequences of the Dundas Group. During Late Cambrian to Early Devonian times, the southeastern part of the Dundas Trough and most of the Mt. Read volcanic belt were covered in sequence by (1) terrestrial to shallow-marine siliceous conglomerate and sandstone (Owen Conglomerate), (2) shallow-water limestone (Gordon Limestone) and, (3) shallow-marine alternating siliceous sandstone and siltstone–mudstone sequences (Eldon Group).

During late Early to early Middle Devonian times at least two main phases of folding extensively deformed the rocks of western Tasmania, produc-

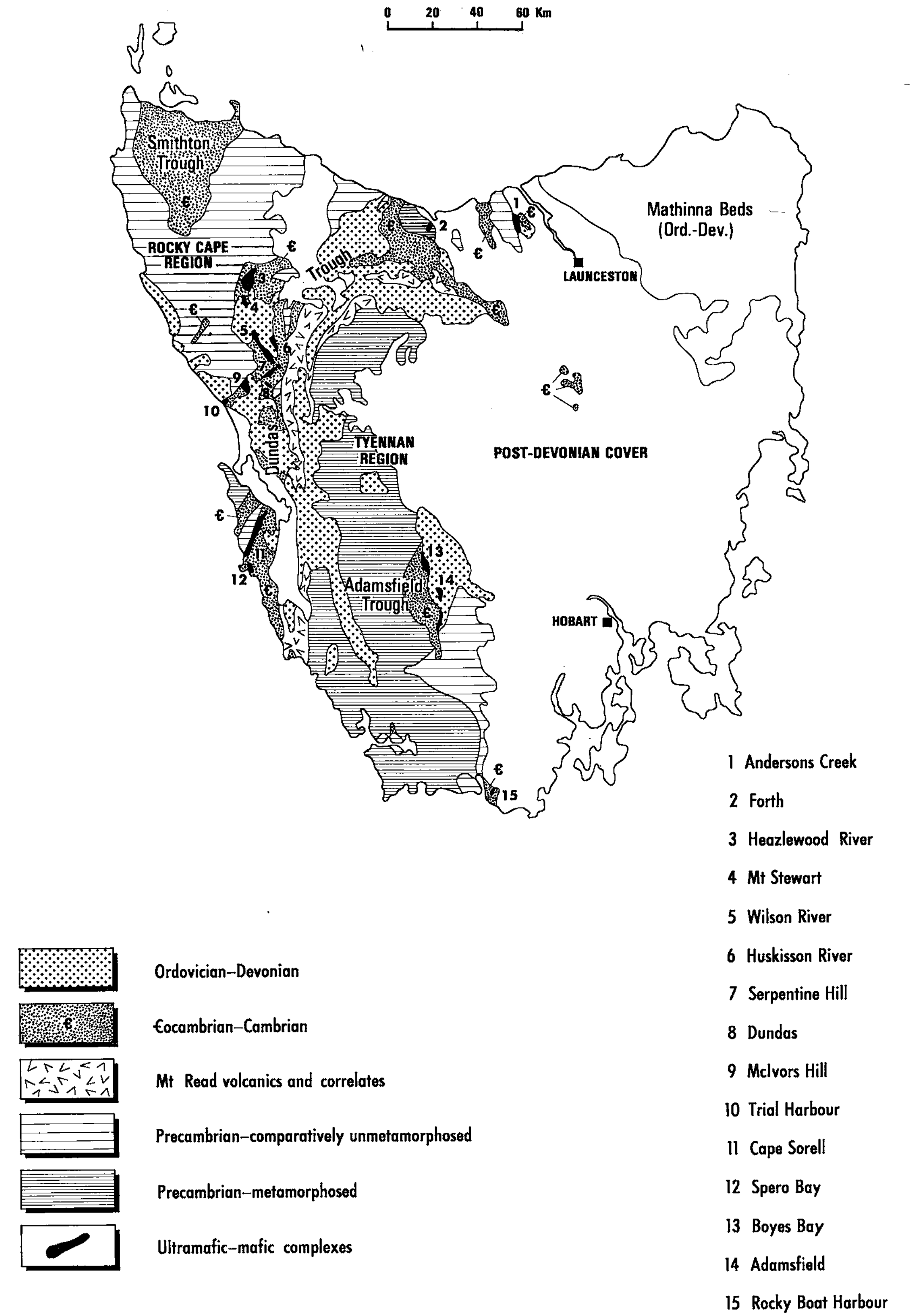

FIG. 1. Schematic geologic map of Tasmania showing location of ultramafic–mafic complexes. Rock distribution after Williams (1976).

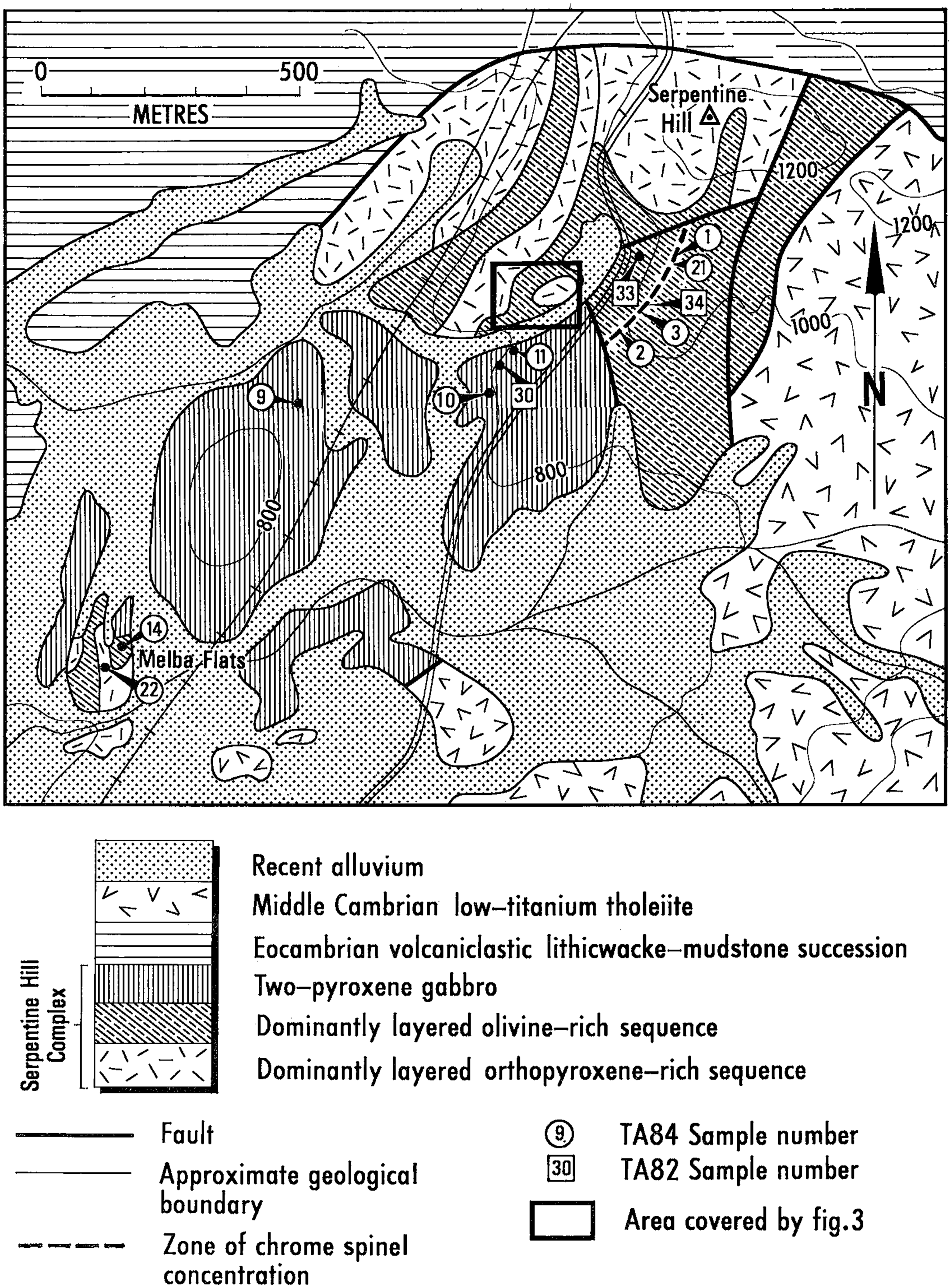

FIG. 2. Geologic map of the Serpentine Hill Complex, western Tasmania. Geology modified from Brown (1986).

ing open fold structures with steep axial surfaces and associated cleavages. The folding was accompanied by faulting and re-emplacement of the ultramafic suites into their present spatial configuration, and was followed by the emplacement of granitic batholiths into the basement and trough sequences.

The Serpentine Hill Complex

The Serpentine Hill Complex (Fig. 2) consists of fault-disrupted blocks of multi-phase ultramafic-gabbroic sequences that are exposed through a fault window between an area of Eocambrian basic volcaniclastic rocks, to the north and west, and fossiliferous Middle to Late Cambrian strata to the south and east.

The first ultramafic unit to form was an orthopyroxene-rich layered sequence, which was later intruded and dismembered by a magma that produced an olivine-rich layered sequence. Both sequences were in turn intruded by a two-pyroxene gabbro (see Fig. 3).

Orthopyroxene-rich sequence

The layering in the orthopyroxene-rich sequence consists of a variety of alternating rock-types. Owing to the fault-disrupted nature of this sequence, it was

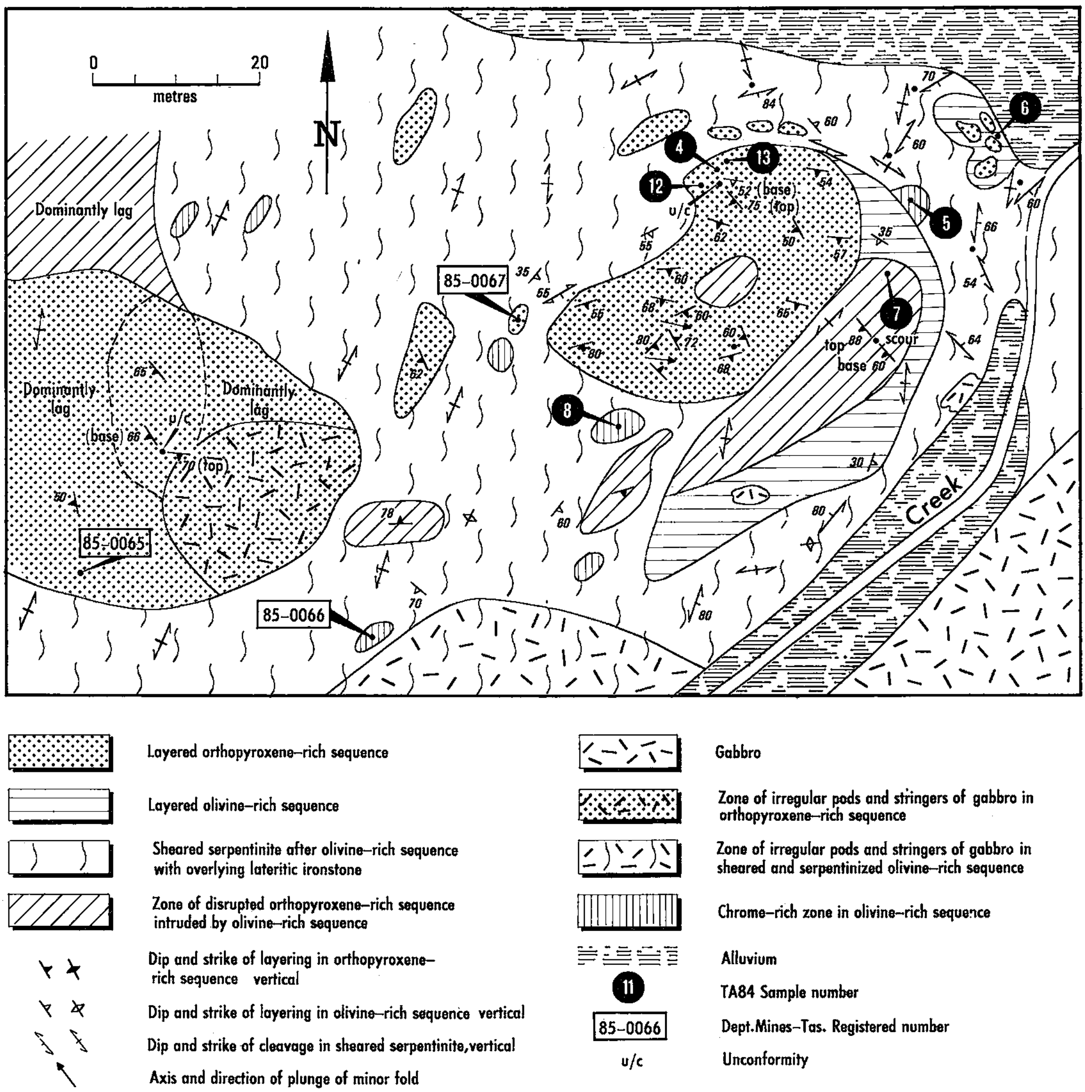

FIG. 3. Detailed geologic map of part of the Serpentine Hill Complex. Location of the map shown in Figure 2.

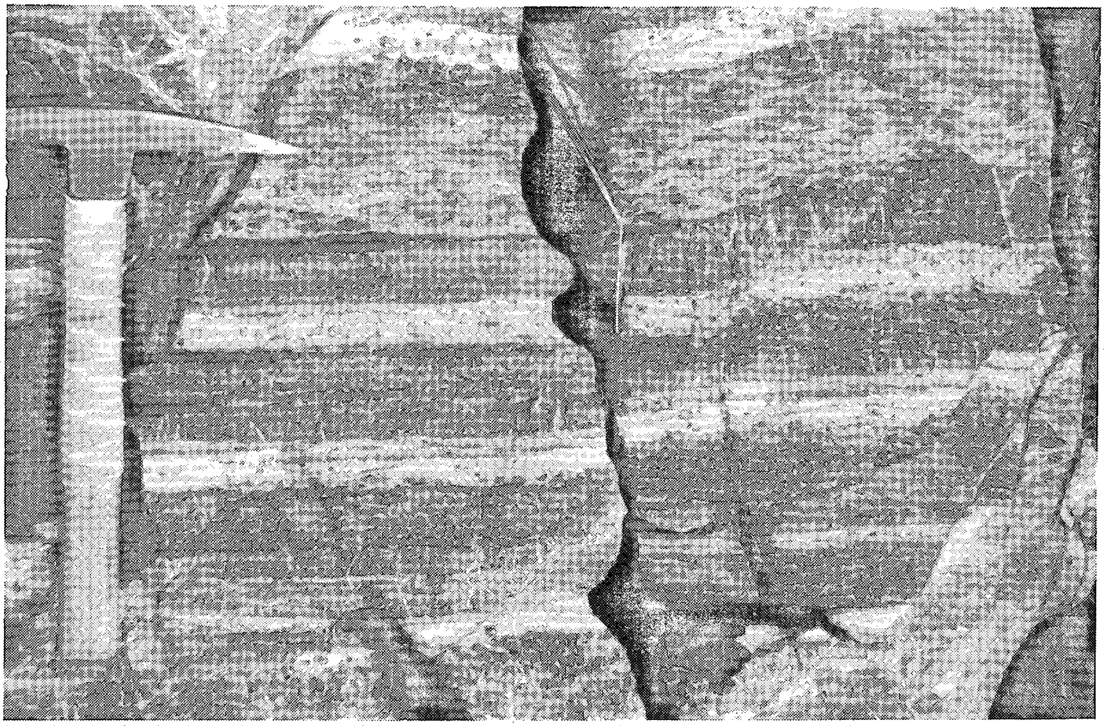

FIG. 4. Layering in the orthopyroxene-rich sequence composed of olivine cumulate (white), olivine-orthopyroxene cumulate (white and grey), and orthopyroxene cumulate (grey).

FIG. 5. Layering in the orthopyroxene-rich sequence composed of orthopyroxenite with layers of variable grain size (coin is 28 mm in diameter).

not possible to recognize the cyclicity of the layers. The layers are composed of variable proportions of cumulus olivine and orthopyroxene, which in places have feldspar as a postcumulus phase. There are four main types of layering, each defined by mineralogy and grain size. The first type consists of a lower layer, 5–10 mm thick, composed of olivine and minor chromite. A sharp but discontinuous contact separates the lower layer from an overlying 25–50-mm-thick layer where orthopyroxene (up to 1–2 mm across) joins olivine as the cumulus phase. A sharp contact separates this layer from the succeeding layer where orthopyroxene is the only cumulus phase. The layers of orthopyroxene cumulate range from 50 to 100 mm in thickness.

The second type consists of very thin layers, typically less than 5 mm, but up to 20 mm, with an occasional 50–60 mm layer. These are bounded by sharp contacts and are composed of olivine, olivine and orthopyroxene in different proportions, and orthopyroxene cumulates (Fig. 4). In any section a layer of orthopyroxene cumulate separates two, three, or four combinations of other types of cumulus layers.

A third type consists of 100–200-mm-thick layers of olivine–orthopyroxene cumulate containing stubby crystals of orthopyroxene with a uniform 8–10 mm cross-section and minor feldspar as a postcumulus phase. This is followed by a 20- to 50-mm-thick layer of feldspathic orthopyroxenite. The orthopyroxene grains are usually 4 – 5 mm across, and the feldspar makes up between 30 and 50% of the layer. Within this layer type, unconformities and scour features are common.

The fourth type consists of orthopyroxenite in which layers are defined by differences in grain size. Contacts are sharp; within any specific layer the grain size is consistent (Fig. 5). All the above layers contain 1 – 2% disseminated chromite.

Numerous primary features are found within the orthopyroxene-rich sequence and include unconformities (Fig. 6), troughs, modal layering, slump structures, and syndepositional faults. Some angular discordance between layers appears to have been formed by scouring, as the infilling layers contain cross-bedding and reverse grading. The cross-bedding is defined by thin layers of flow-aligned crystals. Olivine-rich layers that cross-cut underlying layers usually contain a thin basal zone (1 – 2 mm thick) with a higher concentration of chromite.

Syndepositional soft-sediment faults are marked by sharp basal steps in the overlying layer; the intraformational disruption of some zones within an otherwise well-layered suite indicates slumping. Channels up to 200 mm deep occur in some layers of orthopyroxene cumulate. These channels were

FIG. 6. Unconformity in the orthopyroxene-rich sequence.

infilled by alternating layers of olivine cumulate and orthopyroxene cumulate that range from 10 to 25 mm in thickness.

Very little of the primary mineralogy remains owing to the degree of serpentinization of the sequence. In thin section, olivine cumulate layers now contain serpentine minerals, dominantly lizardite, magnetite and chromite. Only olivine–orthopyroxene layers have minor remnant orthopyroxene grains within a serpentine matrix. The majority of orthopyroxenite samples displays some cataclastic deformation and has undergone partial recrystallization. This results in large orthopyroxene grains (7–8 mm in length) surrounded by small recrystallized grains 0.5 mm across. Other samples have an adcumulus texture with a range in size of orthopyroxene grains from 1 to 10 mm. Minor intergranular anhedral clinopyroxene, as well as exsolution lamellae and blebs of clinopyroxene within larger orthopyroxene, occur in these samples.

Locally, some layers contain 7 - 8-mm-long grains of orthopyroxene that enclose euhedral chromite (0.01 - 0.15 mm) and clinopyroxene (3–5 mm across). Some clinopyroxene grains show simple twinning and other grains have exsolution lamellae of orthopyroxene. The texture varies between adcumulus and slightly recrystallized. In feldspar-bearing orthopyroxenite samples, most pyroxene grains are stubby and 3 to 5 mm across. The feldspar has been altered to hydrogarnet.

Orthopyroxene from the layered sequence has an average composition of Ca:Mg:Fe = 2.1:87.0:10.9, with coexisting clinopyroxene of Ca:Mg:Fe = 47.6:48.4:4.0 (Fig. 4). Associated chromite has an average Cr/(Cr+Al) ratio of 0.62 and Mg/(Mg+Fe^{2+}) of 0.47 (Fig. 5) and is enclosed by tremolite or tremolitic hornblende.

FIG. 7. Blocks of the orthopyroxene-rich sequence (grey) enclosed in the olivine-rich sequence (white).

Olivine-rich sequence

The olivine-rich sequence is dominated by chromite-rich olivine cumulates with zones that contain either orthopyroxene or feldspar as postcumulus phases. The magma from which the olivine-rich sequence formed appears to have intruded, as sills, in the earlier layered orthopyroxene-rich sequence, and to have broken this earlier sequence into irregularly shaped rafts, blocks and xenoliths. Layers of olivine with chromite, locally with postcumulus feldspar or orthopyroxene, formed within these sills. Where the sills were only a few meters thick the resultant layering was plastically deformed by sinking rafts and blocks of the layered orthopyroxene-rich sequence, forming zones in which the olivine-rich crystal mush has been squeezed between the accumulating blocks. Layers in undisturbed parts of this sequence are thin (less than 5 to 6 mm), in places discontinuous and lens-like over the scale of a few meters.

Isolated blocks of the orthopyroxene-rich sequence enclosed by the olivine-rich sequence have smooth scalloped edges (Fig. 7), a feature which may indicate either that the orthopyroxene-rich rocks were not perfectly consolidated prior to intrusion of the olivine-rich sequence, or that a reaction zone occurs between the intruding sequence and the earlier formed sequence. Sharp, regular or irregular contacts between the two sequences have been observed only in the disrupted zones.

Layers (50–100 mm thick) of cumulus orthopyroxene (10–15 mm in length) occur in some parts of the olivine-rich sequence. The cumulus orthopyroxene defines a mineral foliation parallel to layering.

The olivine-rich sequence also contains zones with a high chromite content, either as concentrations of disseminated grains or as irregular pods and lenses of massive chromitite. In the area south of Serpentine Hill (Fig. 2, areas of 1 to 3TA84), a 5-m-thick zone in this sequence contains irregular pods and lenses (50–70 mm thick) of chromite, the pods being separated by several meters from each other along the zone. Within this area numerous gabbro dykes intrude the sequence at a constant altitude, nearly parallel to layering. The host rock of the chromitite pods and lenses ranges from an olivine cumulate with postcumulus plagioclase, to olivine cumulate with poikilitic orthopyroxene. This area does not contain blocks of the orthopyroxene-rich sequence, but thin (20–100 mm) orthopyroxenite dykes intrude the area at a high angle to layering. Similar, thin (20–100 mm) orthopyroxenite dykes also cut both of the ultramafic sequences in other parts of the complex.

Despite complete serpentinization, the majority of samples show a remnant cumulus texture. Abundant euhedra of chromite (0.5 to 2.0 mm) are enclosed by olivine grains, and some chromite grains contain silicate inclusions (0.05 to 0.15 mm). In samples with postcumulus plagioclase, olivine ranges from 1 to 5 mm, chromite grains are 0.25 to 0.35 mm, and plagioclase has been replaced by hydrogarnet.

Pods and lenses of chromite concentrations consist of euhedral to subhedral grains ranging in size from 0.1 to 1 mm, locally with a mosaic texture. Some of the grains contain silicate inclusions. In samples with less chromite, the chromite grains occur (1) as strings around cumulus olivine and are enclosed by postcumulus orthopyroxene; (2) as euhedral to subhedral grains, between 0.7 and 1.15 mm, that are clustered around stubby orthopyroxene grains in dominantly olivine cumulate layers.

Chromite from the olivine-rich sequence has a slightly lower average Cr/(Cr + Al) ratio than that from the orthopyroxene-rich sequence (0.59 compared to 0.62), whereas samples from the 5-m-thick zone of chromite pods and lenses have a much higher average ratio (0.69). All chromite compositions from the Serpentine Hill Complex plot within the field defined by samples from the layered pyroxenite-dunite succession from elsewhere within the Dundas Trough, but the presence of plagioclase, the evidence of multiple magma phases, and the presence of associated gabbro all suggest that the Serpentine Hill Complex is derived from a different parental magma. The chromite compositions obtained from the Serpentine Hill sequences overlap the lower part of the field from Alaskan-type ultramafic bodies (Fig. 8).

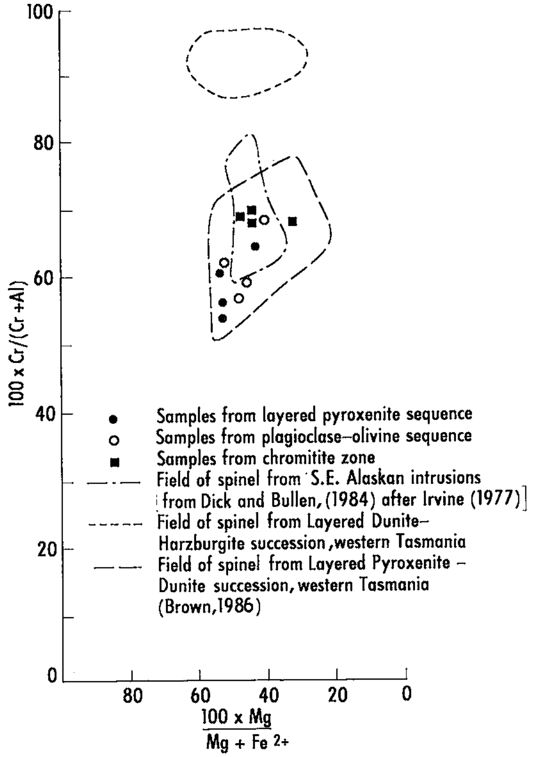

FIG. 8. Plot of chromite compositions from the Serpentine Hill Complex in terms of 100 Cr/(Cr + Al) and 100 $Mg/(Mg + Fe^{2+})$ and comparison with those from southeastern Alaskan intrusions. See Figure 9 for analytical conditions.

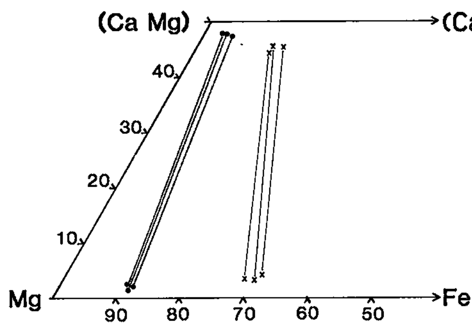

FIG. 9. Plot of coexisting high- and low-calcium pyroxene compositions from the orthopyroxene-rich sequence (•) and the gabbro sequence (×) on part of the pyroxene quadrilateral. Silicate and oxide mineral grains were analyzed by simultaneous quantitative analysis for 14 elements (Na, Mg, Al, Si, P, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Ni) using a JEOL JX50A electron-microprobe scanning-electron microscope fitted with an energy-dispersive system, at the Central Science Laboratory, University of Tasmania. Operating conditions used an accelerating voltage of 15kv, a beam current of 0.7 nA, a beam diameter of less than 0.5 μm and 60-s (machine time) counting time. Standard ZAF corrections were made with a CSIRO Min. 3P program.

Two-pyroxene gabbro

In the area covered by Figure 3, gabbro intrudes both the orthopyroxene- and olivine-rich sequences as irregular dykes, stringers and pegmatitic patches. To the south (Fig. 2, near 9 and 10TA84), evidence of the multiple intrusive nature of the gabbroic phase is found in the form of sharp contacts between areas of varying grain size, that is, fine-grained dyke margins against coarse-grained gabbro. Gabbroic and ultramafic sequences have been intruded by late-stage, thin and uniform diopside–plagioclase dykes (20 - 50 mm thick), and by irregular pegmatitic patches from which clinopyroxene crystals up to 100 mm in length have been recorded.

Gabbros range in texture from a fine-grained granular mosaic through medium-grained and coarse-grained granular to pegmatitic. Coarse-grained rocks contain stubby plagioclase grains, 3 to 4 mm long, in a matrix of anhedral clinopyroxene and hypersthene.

The electron-microprobe analysis of component mineral phases shows that the two varieties of pyroxene are hypersthene with an average Ca:Mg:Fe = 3.9:66.6:29.5, and diopside with an average Ca:Mg:Fe = 45.4:42.4:12.3 (Fig. 9). The plagioclase has an average composition of $An_{88.5}Ab_{10.9}Or_{0.7}$.

Comparison with Other Types of Ultramafic Complexes

In characteristics such as tectonic setting, petrology, internal structures, and size, the Serpentine Hill Complex is distinct from large, layered stratiform complexes and ophiolites. Alaskan-type complexes, as described by Ruckmick & Noble (1959), Noble & Taylor (1960), Irvine (1963, 1974), Taylor & Noble (1960), Taylor (1967) and Findlay (1969), are generally small, elliptical to circular (in plan) multiple intrusive bodies that have distinctive internal structures (unconformities, troughs, modal layering, slump structures, syndepositional faults, cross-bedding, *etc.*) and compositional characteristics. Ideally, the cumulus rock series include dunite, wehrlitic peridotite, olivine clinopyroxenite, magnetite hornblende clinopyroxenite, and hornblende gabbro. Dominant minerals are clinopyroxene and magnetite; orthopyroxene is sparse. The Serpentine Hill Complex shares many features of Alaskan-type complexes. The outstanding difference, however, is the absence of orthopyroxene in Alaska-type complexes and its abundance in the Serpentine Hill Complex. Synorogenic intrusive complexes, such as Rana, Norway, possess features in common with the Serpentine Hill Complex, but generally contain a larger proportion of mafic rocks such as norites and troctolites, and usually have suffered by deformation of nearly the same age as the intrusion. Although compositionally different, the Serpentine Hill Complex appears to be more similar to an Alaskan-type complex than to any other type of ultramafic complex.

PGE Geochemistry of Ultramafic Suites of Northwestern Tasmania

Concentrations of palladium, platinum, rhodium, ruthenium and iridium from samples of the ultramafic–mafic sequences of northern and western Tasmania are listed in Table 1. Grab samples from surface outcrops were analyzed by a fire-assay – atomic absorption technique (Haffty *et al.* 1977, Simon *et al.* 1978, and Page *et al.* 1980) for platinum, palladium and rhodium, and by a fire-assay – spectrographic technique for iridium and ruthenium Haffty *et al.* 1980). The precision of each technique is given in the cited publications. Detection limits are in part defined by sample size; the limits under optimum conditions are 1, 10, 1, 20, and 100 parts per billion for palladium, platinum, rhodium, iridium, and ruthenium, respectively. The locations of samples from the Serpentine Hill area are shown in Figures 2 and 3; those from other areas listed in Table 1 are shown in Figure 1. Samples from Serpentine Ridge and from the Heazlewood River area are from the layered dunite–harzburgite suite, whereas those from the Riley Knob, Lynch Hill and the '14 km Quarry' are from the layered pyroxenite–dunite suite. Mean, standard deviation, and the number of values (values below detection limits not included) for each of the different areas and suites are presented in Table 2.

Within the Serpentine Hill Complex, chromitite samples differ from samples from the other suites. The chromitites have higher ruthenium and iridium contents (Tables 1, 2) and a higher mean rhodium content (99.5% confidence level) than other rock types. There is no significant difference (99.5% confidence level) between other rock types in their palladium, platinum and rhodium contents, based on pooled standard deviations and Student's *t*-tests. The only exception is that the mean palladium content of the gabbro samples is higher than those of other rock types. Within the Serpentine Hill Complex, gabbros have a much higher average Pd/(Pd + Pt + Rh) ratio (0.22) than the orthopyroxene-rich sequence (0.04), the olivine-rich sequence (0.06), or the chromitites (0.06).

The mean platinum content of samples from the Serpentine Hill complex is greater than for samples from other areas in Tasmania (except for Riley Knob and Melba Flat samples), and the mean values for the different areas are significantly different at a 99.5% confidence level. Similarly the mean platinum content for lithologies from Serpentine Hill are higher than, and significantly different from, the other two suites.

Chondrite-normalized PGE values in chromitite samples with greater than 7 wt. % Cr (Fig. 10A) demonstrate the following: (1) all samples have higher platinum than palladium; (2) five of seven samples have higher platinum than rhodium; (3) six of seven samples have higher ruthenium than iridium. Chondrite-normalized ratios for the averages (Table 2) of other rock groups show progressively greater depletion of rhodium, platinum, and palladium. Lynch Hill, 14 km Quarry areas, and the orthopyroxene-rich sequence at Serpentine Hill are exceptions.

TABLE 1. CONCENTRATION OF PLATINUM-GROUP ELEMENTS IN SAMPLES FROM ULTRAMAFIC-MAFIC SUITES IN WESTERN TASMANIA

Sample Number	Pd	Pt	Rh	Ru	Ir	Description
		(parts per billion)				
Location 1: Andersons Creek (LDH?)						
1 TA82	<1	44	<1	<100	<20	Pyroxenite
2 TA82	<1	27	<1	<100	<20	Serpentinized harzburgite
3 TA82	<1	21	<1	<100	<20	Dunite
4 TA82	<1	24	<1	<100	<20	Rodingitized gabbro
Location 3: Heazlewood River - northern part (LDH)						
9 TA82	<1	11	<1	<100	<20	Olivine cumulate
12 TA82	1	21	<1	<100	<20	Troctolite
10 TA82	<1	15	<1	<100	<20	Serpentinized dunite
11 TA82	<1	17	<1	<100	<20	Serpentinized peridotite
Location 3: Heazlewood River - southern part (LDH)						
13 TA82	<1	15	<1	<100	<20	Serpentinized peridotite
14 TA82	<1	20	<1	<100	<20	Serpentinized peridotite
15 TA82	<1	21	<1	<100	<20	Serpentinized peridotite
16 TA82	<1	16	<1	<100	<20	Serpentinized peridotite
17 TA82	<1	19	<1	<100	<20	Serpentinized peridotite
18 TA82	<1	19	<1	<100	<20	Orthopyroxenite with olivine and plagioclase interstitial
Location 5: Wilson River - Middle Part - Serpentine Ridge (LDH)						
16 TA84	1	13	1	<100	<20	Chromite stringers in
25 TA82	<1	10	<1	<100	<20	Serpentinized dunite
26 TA82	<1	15	<1	<100	<20	Disseminated chromite in serpentinized dunite
19 TA84	<1	12	<1	<100	<20	Harzburgite
17 TA84	<1	<10	<1	<100	<20	Chromite clots in dunite
18 TA84	2	<10	<1	<100	<20	Chromite clots and layers in dunite
20 TA84	1	31	12	150	40	Chromitite nodule in serpentinized dunite
Location 5: Wilson River - Southern Part - Riley Knob (LPD)						
23 TA84	<1	<10	<1	<100	<20	Pyroxenite
24 TA84	2	40	<1	<100	<20	Pyroxenite
25 TA84	1	43	<1	<100	<20	Pyroxenite
Location 6: Huskisson River - Middle Part - Lynch Hill (LPD)						
26 TA84	1	17	1	<100	<20	Pyroxenite
27 TA84	1	17	1	<100	<20	Pyroxenite
28 TA84	1	15	<1	<100	<20	Pyroxenite
Location 6: Huskisson River - Southern Part - 14 km Quarry (LPD)						
24 TA82	1	31	<1	<100	<20	Serpentinized harzburgite-dunite
15 TA84	1	16	2	<100	<20	Pyroxenite
Location 7: Serpentine Hill						
Orthopyroxene-rich layered sequence						
28 TA82	1	50	3	<100	<20	Dunite-pyroxenite layers
4 TA84	2	14	<1	<100	<20	Olivine cumulate
12 TA84	<1	22	2	<100	<20	Pyroxenite
13 TA84	2	58	1	<100	<20	Pyroxenite
Olivine-rich layered sequence						
29 TA82	<1	27	<1	<100	<20	Dunite
31 TA82	<1	17	<1	<100	<20	Disseminated chromite in dunite
32 TA82	<1	44	<1	<100	<20	Magnetite with serpentine
33 TA82	<1	43	9	310	80	Chromitite
34 TA82	2	38	4	350	90	Chromitite
1 TA84	5	47	4	250	40	Chromite pods in serpentinized dunite
2 TA84	4	42	5	130	50	Chromitite
3 TA84	4	66	7	160	80	Chromitite
5 TA84	1	15	<1	<100	<20	Chromite stringers in dunite
6 TA84	1	17	1	<100	<20	Chromite stringers
7 TA84	1	14	<1	<100	<20	Layered chromitite-dunite
8 TA84	1	<10	<1	<100	<20	Disseminated chromite in olivine cumulate
21 TA84	2	31	8	420	70	Chromitite
Gabbroic sequence						
30 TA82	18	64	<1	<100	<20	Gabbro
9 TA84	3	21	<1	<100	<20	Medium-grained gabbro
10 TA84	10	35	1	<100	<20	Fine-grained gabbro
11 TA84	10	24	<1	<100	<20	Medium-grained gabbro

Table 1: (Cont.)

Sample Number	Pd	Pt	Rh	Ru	Ir	Description
			(parts per billion)			
Location 7: Southern Part - Melba Flats						
14 TA84	5	<10	<1	<100	<20	Disseminated chromite in dunite
22 TA84	4	1240	54	180	70	Chromitite
Andesites and Basalts						
29 TA84	25	37	<1	<100	<20	Low-Ti tholeiitic lava near Location 7
30 TA84	3	25	<1	<100	<20	High-Mg andesitic lava near Location 9
31 TA84	<1	<10	<1	<100	<20	Olivine-quartz normative tholeiitic lava near Location 5

Location names and place numbers refer to Figures 1, 2 and 3. LDH: layered dunite-harzburgite suite; LPD: layered pyroxenite-dunite suite.

A comparison of chondrite-normalized PGE values for chromitites from Alaskan-type and ophiolite complexes is shown in Figure 10B. PGE data for rocks from Alaskan or zoned complexes are sparse. Chromitite schlieren in dunite and serpentinized dunite from five Uralian complexes (Fominykh & Khvostova 1970) are reported to range from tenths of parts per billion for ruthenium to several parts per million for palladium and platinum. PGE patterns of chromitite schlieren are highly variable, with negative and positive slopes as well as 'M'-shaped patterns. The patterns obtained from the dunite samples have a certain sympathetic regularity, usually with a characteristic chondrite-normalized ruthenium depletion. A similar M-shaped pattern with ruthenium depletion was found for a chromitite sample from the Tulameen complex by Talkington & Watkinson (1986). An average pattern for chromitite schlieren (labelled "Average Ural Chromite Ratio" ÷ 10) is shown in Figure 10B. PGE data from ophiolite complexes are far more abundant and chondrite-normalized patterns show progressively greater depletion in the order ruthenium, rhodium, palladium, and platinum. Figure 10B shows a field of chondrite-normalized patterns for chromitites from Paleozoic and Mesozoic ophiolites (after Page *et al.* 1982) with a single average pattern for the Polar Urals.

Except for the chromitite sample from Melba Flats, the other chromitites from Serpentine Hill have chondrite-normalized patterns similar to those obtained from chromitite of ophiolite sequences (compare Figs. 10A and 10B). The pattern for average rocks from Serpentine Ridge is also similar. The chromite sample from Melba Flats has a platinum-enriched pattern similar to those from the Urals and the Tulameen complex, although the palladium value is strongly depleted.

TABLE 2. SUMMARY OF PLATINUM-GROUP-ELEMENT CONCENTRATIONS IN ULTRAMAFIC-MAFIC SUITES OF WESTERN TASMANIA

Area or Lithology	Pd	Pt	Rh	Ru	Ir
		parts per billion			
Layered dunite-harzburgite suite					
Anderson Creek	<1	29.0 ± 10.3(4)	<1	<100	<20
Heazlewood River (northern part)	1(1)	16.0 ± 4.2(4)	<1	<100	<20
Heazlewood River (southern part)	<1	18.3 ± 2.3(6)	<1	<100	<20
Wilson River - Serpentine Ridge	1.3 ± .6(3)	16.2 ± 8.5(5)	6.5(2)	150(1)	40(1)
Layered pyroxenite-dunite suite					
Wilson River - Riley Knob	1.5(2)	41.5 ± 2.1(2)	<1	<100	<20
Huskisson River - Lynch Hill	1(3)	16.3 ± 1.2(3)	1(2)	<100	<20
Huskisson River - 14 km Quarry	1(2)	22.5 ± 10.6(2)	2(1)	<100	<20
Serpentine Hill					
Orthopyroxene-rich sequence	1.7 ± .6(3)	36 ± 21.3(4)	2.0 ± 1.0(3)	<100	<20
Olivine-rich sequence	2.3 ± 1.6(9)	33.4 ± 16.1(12)	5.0 ± 2.8(6)	<100	<20
Gabbroic sequence	10.3 ± 6.1(4)	36 ± 19.6(4)	1(1)	<100	<20
Chromitites	3.4 ± 1.3(5)	44.5 ± 11.8(6)	6.2 ± 2.1(6)	270 ± 112(6)	68.3 ± 19.4(6)
Dunites	1.8 ± 1.8(5)	22.3 ± 11.6(6)	<1	<100	<20
Melba Flats	4.5 ± .7(2)	1240(1)	54(1)	180(1)	70(1)
Layered dunite-harzburgite	1.3 ± 0.5(4)	19.5 ± 8.0(19)	6.5(2)	<100	<20
Layered pyroxenite-dunite	1.1 ± .4(7)	23.6 ± 12.2(7)	1.3 ± .6(3)	<100	<20

Means and standard deviation calculated from Table 1 for individual areas and rock types. Number of values above detection limits in parentheses.

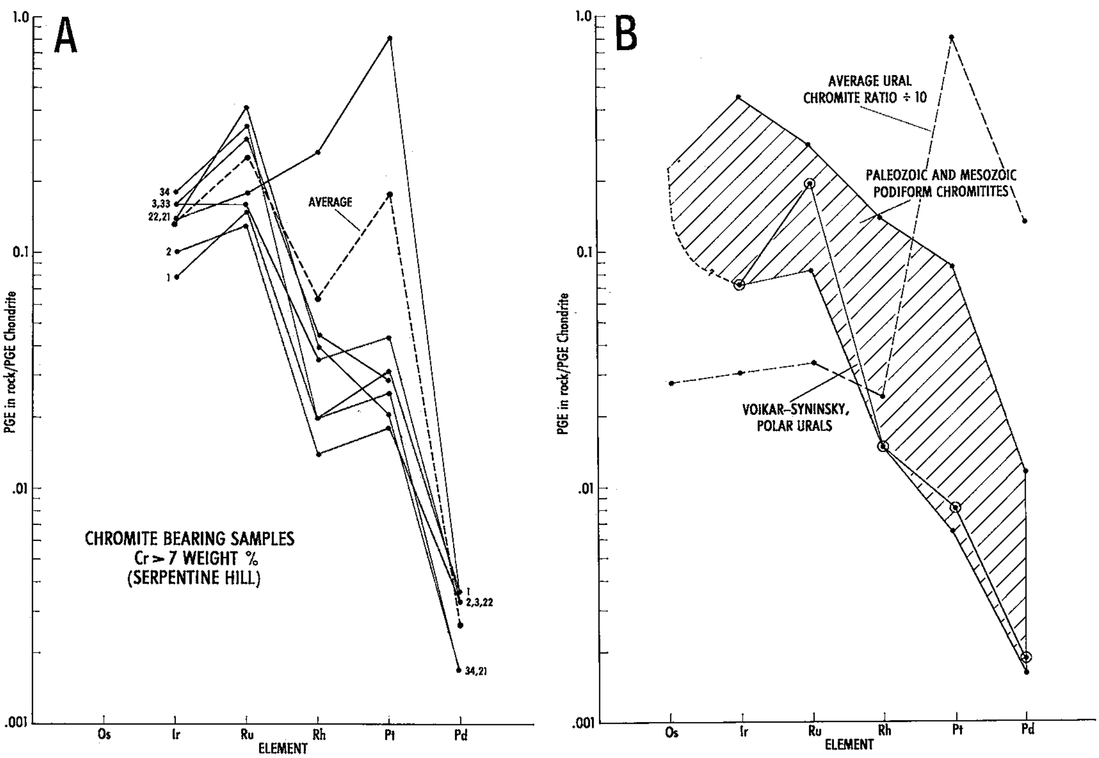

FIG. 10. Chondrite-normalized plots of PGE in chromite-rich rocks. (A) Chromite-bearing samples from the Serpentine Hill Complex, Tasmania. (B) Comparison of chromitite samples from ophiolites and Uralian complexes. Paleozoic and Mesozoic ophiolite boundaries from Page *et al.* (1983).

Although the geological information suggests that ultramafic rocks from Western Tasmania are not of ophiolitic affinity, the PGE geochemistry by comparison with other ophiolites suggests strong similarities. However, it is probable that the different patterns result from the degree of sulfur saturation of the magma from which the platinum-group minerals precipitated (Page & Talkington 1984, Talkington & Watkinson 1986). The negative patterns reflect the concentration of Ru, Os, and Ir, and the depletion of Pt, Pd, and Rh due to the occurrence of laurite, Os–Ir alloy as inclusions in chromite (see below), and the well-established occurrence of laurite in chromitites from ophiolites. The depletions of Pt, Pd and Rh reflect the lack of sulfides, except perhaps for the sample from Melba Flats. On the other hand, there is an uncertainty in the behavior and distribution of PGE in undepleted mantle rocks during partial melting and in different environments of magma crystallization. Owing to this uncertainty, it is possible that the patterns observed may result from these processes and the original heterogenous distribution of PGE in the mantle material, and not simply from the degree of sulfur saturation of the magma.

MINERALS OF THE PLATINUM-GROUP ELEMENTS

Although numerous polished thin-sections of chromitite samples were examined, only two primary PGE mineral grains were located, both enclosed by chromite. The first grain is a mixed Os–Ir–Ru alloy that also contains minor amounts of Cr, Fe, As and S. The PGE constitute 80.81 wt. % of this grain in proportions of $Os_{0.554}$:$Ir_{0.322}$:$Ru_{0.124}$. In section the grain is diamond-shaped, 10 μm long and 9 μm wide. The second grain has a rectangular shape (15 μm by 7 μm), and has a laurite-like composition. This grain consists of Ru, Os, Ir, and S (total wt. % 100.81) and has a formula of $(Ru_{1.003}Os_{0.055}Ir_{0.032})_{1.09}S_2$. The chromite that encloses both of these grains has a Cr/(Cr + Al) ratio of 0.69 and Mg/(Mg+Fe^{2+}) of 0.46 for the grain enclosing the Os–Ir mineral, and 0.41 for the grain that encloses laurite. Minute grains of native platinum and sperrylite have been reported with Cu–Ni sulfide ore associated with a gabbro dyke 1.5 km southwest of the study area (Fig. 2) at Cuni (Elliston 1965).

Elsewhere in Tasmania the only other PGE minerals found have been in alluvial and eluvial deposits (Twelvetrees 1914, Reid 1921, Nye 1929) associated with areas of the layered dunite-harzburgite (LDH) suite. All four main areas of LDH rocks produced Os–Ru-Ir alloys with variable Ru and Os contents. The minerals found are mainly iridosmine to rutheniridosmine with minor osmiridium and ruthenosmiridium (Cabri & Harris 1975, Ford 1981).

Conclusion

The Serpentine Hill ultramafic–mafic complex is a multiple intrusion consisting of a layered orthopyroxene-rich ultramafic, an olivine-rich ultramafic, and a two-pyroxene gabbro sequence. The olivine-rich sequence contains zones with a high chromite content; these occur either as areas of high concentration of disseminated grains, or as irregular pods and lenses of chromitite. The tectonic setting, internal structural features (unconformities, troughs modal layering, cross-bedding, slump structures, *etc.*) and size of the Serpentine Hill Complex are similar to features of Alaskan-type complexes; however, the orthopyroxene-dominated mineralogy is not.

The Serpentine Hill Complex has anomalously high PGE contents with respect to most other ultramafic rock suites in Tasmania. The Pd/(Pt + Pd) ratio of the gabbro sequence at Serpentine Hill is higher than either the earlier formed orthopyroxene-rich or olivine-rich sequences. Chromitite from this complex has detectable levels of Rh, Ir and Ru contents, but other rock types do not. The chondrite-normalized PGE patterns for the chromitite samples resemble those of chromitites from ophiolites.

Acknowledgements

A.V. Brown publishes with permission of the Director of Mines, Tasmania. The manuscript has been improved by the constructive comments of O.R. Eckstrand and an anonymous reviewer.

References

Brown, A.V. (1986): The geology of the Dundas - Mt. Lindsay - Mt. Youngbuck area. *Bull. Geol. Surv. Tas.* **62.**

______, Rubenach, M.J. & Varne, R. (1980): Geological environment, petrology and tectonic significance of the Tasmanian Cambrian ophiolitic and ultramafic complexes. *In* Ophiolites. Proc. Int. Ophiolite Symposium (A. Panayiotou, ed.), Cyprus, 1979. Ministry Agriculture Nat. Res., Cyprus.

Cabri, L.J. & Harris, D.C. (1975): Zoning in Os–Ir alloys and the relation of the geological and tectonic environment of the source rocks to the bulk Pt:Pt + Ir + Co ratio for placers. *Can. Mineral.* **13,** 266-274.

Dick, H.J.B. & Bullen, T. (1984): Chromian spinel as a petrogenetic indicator in abyssal and alpine-type periodotites and spatially associated lavas. *Contr. Mineral. Petrology* **86,** 54-76.

Duncan, R.A. & Green, D.H. (1980): Role of multistage melting in the formation of oceanic crust. *Geology* **8,** 22-26.

Elliston, J. (1965): Platinoid deposits of Tasmania. *In* Geology of Australian Ore Deposits (J. McAndrew, ed.). *Publ. 8th Commonw. Mining Metall. Congr.* 1,522.

Findlay, D.C. (1969): Origin of the Tulameen ultramafic–gabbro complex, southern British Columbia. *Can. J. Earth Sci.* **6,** 399-425.

Fominykh, V.G. & Khvostova, V.P. (1970): Platinum content of Ural dunite. *Dokl. Acad. Sci. SSR, Earth Sci. Sect.* **191,** 184-186.

Ford, R.J. (1981): Platinum-group minerals in Tasmania. *Econ. Geol.* **76,** 408-405.

Haffty, J., Haubert, A.W. & Page, N.J (1980): Determination of iridium and ruthenium in geological samples by fire assay and emission spectrograph. *U.S. Geol. Surv. Prof. Paper* **1129-C,** G1-G4.

______, Riley, L.B. & Gross, W.D. (1977): A manual on fire assay and determination of the noble metals in geological materials. *U.S. Geol. Surv. Bull.* **1445.**

Irvine, T.N. (1963): Origin of the ultramafic complex at Duke Island, southeastern Alaska. *Mineral. Soc. Amer. Spec. Pap.* **1,** 36-45.

______ (1974): Petrology of the Duke Island ultramafic complex, southeastern Alaska. *Geol. Soc. Amer. Mem.* **138.**

______ (1977): Origin of chromitite layers in the Muskox intrusion and other stratiform intrusions; a new interpretation. *Geology* **5,** 273-277.

Jenner, G.A. (1981): Geochemistry of high-Mg andesite from Cape Vogel, Papua New Guinea. *Chem. Geol.* **33,** 307-332.

Noble, J.A. & Taylor, H.P., Jr. (1960): Correlation of ultramafic complexes of southeastern Alaska with those of other parts of North America and the world. *Int. Geol. Congress* **21,** 13, 188-197.

Nye, P.B. (1929): The osmiridium deposits of the Adamsfield district. *Bull. Geol. Surv. Tas.* **39.**

Page, N. J, Aruscavage, P.J. & Haffty, J. (1983): Platinum-group elements in rocks from the

Voykar–Syninsky ophiolite complex, Polar Urals, USSR. *Mineral. Deposita* **18**, 443-455.

______, Cassard, D. & Haffty, J. (1982): Palladium, platinum, rhodium, ruthenium, and iridium in chromitites from the Massif du Sud and Tiebaghi Massif, New Caledonia. *Econ. Geol.* **77**, 1571-1577.

______, Myers, J., Haffty, J., Simon, F. & Aruscavage, P. (1980): Platinum, palladium, and rhodium in the Fiskenaesset complex, southwestern Greenland. *Econ. Geol.* **75**, 907-915.

______ & Talkington, R.W. (1984): Platinum-group elements in peridotites and chromitites from ophiolite complexes in Newfoundland. *Can. Mineral.* **22**, 137-149.

Quiring, H. (1962): Die Metallischen Rohstoffe, ihre Lagerungsvehaltnisse und ihre wirtschaftliche Bedeutung, Platinumetalle; Platin, Palladium, Iridium, Osmium, Rhodium, Ruthenium. *Stuttgart, Ferdinand Enke* **16**.

Reid, A.M. (1921): Osmiridium in Tasmania. *Bull. Geol. Surv. Tas.* **32**.

Rubenach, M.J. (1973): *The Tasmanian Ultramafic-Gabbro and Ophiolite Complexes.* Ph.D. thesis, Univ. Tasmania, Hobart, Tasmania.

______ (1974): The origin and emplacement of the Serpentine Hill Complex, western Tasmania. *J. Geol. Soc. Aust.* **21**, 91-106.

Ruckmick, J.C. & Noble, J.A. (1959): Origin of the ultramafic complex at Union Bay, southeastern Alaska. *Geol. Soc. Amer. Bull.* **70**, 981-1018.

Simon, F.O., Aruscavage, P. & Moore, R. (1978): Determination of platinum, palladium, and rhodium in geologic spectroscopy using electrothermal atomization. *176th Amer. Chem. Soc. Nat. Meet., (Miami Beach)* (abstr.).

Talkington, R.W. & Watkinson, D.H. (1986): Whole rock platinum-group element trend in chromite-rich rocks in ophiolitic and stratiform igneous complexes. *In* Metallogeny of Basic and Ultrabasic Rocks (M.J. Gallagher, R.A. Ixer, C.R. Neary & H.M. Prichard, eds.). Inst. Mining Metall., London, 427-440.

Taylor, H.P., Jr. (1967): The zoned ultramafic complexes of southeastern Alaska. *In* Ultramafic and Related Rocks (P.J. Wyllie, ed.). John Wiley & Sons, New York.

______ & Noble, J.A. (1960): Origin of the ultramafic complexes in southeastern Alaska. *Proc. 21st Int. Geol. Congr., Copenhagen* **13**, 175-187.

Twelvetrees, W.H. (1914): The Bald Hill osmiridium field. *Bull. Geol. Surv. Tas.* **17**.

Varne, R. (1978): The Cambrian volcanic association of Tasmania and their tectonic setting. *In* Geology and Mineralization of N.W. Tasmania. (D.C. Green & P.R. Williams, eds.). *Geol. Soc. Australia (Tasmanian Div.),* Hobart (abstr. of symposium).

______ & Brown, A.V. (1978): The geology and petrology of the Adams field ultramafic complex, Tasmania. *Contr. Mineral. Petrology* **67**, 195-207.

Williams, E. (1976): Tasmanian Fold Belt in Tasmania, 1:500,000 Structural Map of Pre-Carboniferous Rocks of Tasmania. *Dep. Mines, Tasmania.*

Williams, E. (1978): Tasmanian fold belt system in Tasmania. *Tectonophysics* **48**, 159-206.

Received June 18, 1986; revised manuscript accepted April 16, 1987.