

# Os-isotope study of platinum-group minerals in chromitites in Alpine-type ultramafic intrusions and the associated placers in Borneo

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## Abstract

$^{187}\text{Os}/^{186}\text{Os}$  ratios were determined for *in-situ* laurite grains in Alpine-type chromitites and platinum-group minerals (PGM) in the associated alluvial placers in Borneo, Indonesia/Malaysia. The Os-isotope ratios of laurite grains in chromite define an  $^{187}\text{Os}/^{186}\text{Os}$  ratio for the 100 Ma mantle source of c. 1.04. The low  $^{187}\text{Os}/^{186}\text{Os}$  ratios in all grains confirm the essential derivation of these platinum-group elements (PGE) from the mantle. A minor variation in  $^{187}\text{Os}/^{186}\text{Os}$  ratios was detected among PGM from placers, but no variation was found within individual grains, including a grain with chemical inhomogeneity. The values are similar to those for PGM in the associated chromitites. The data are consistent with a detrital origin of PGM in placers: the placer PGM originated in the ultramafic section of ophiolites and the release of these grains from igneous rocks and their deposition in placers was almost entirely by mechanical processes.

**KEYWORDS:** osmium isotopes, platinum-group minerals, laurite, chromitites, Borneo, Indonesia, Malaysia.

## Introduction

THE  $^{187}\text{Os}/^{186}\text{Os}$  ratios of crustal rocks are much greater than 10, and more variable than the ratios of the mantle (c. 1.0) due to the high and varied Re/Os ratios of the crustal rocks (e.g. Allègre and Luck, 1980; Morgan *et al.*, 1981; Chou *et al.* 1983; Luck and Turekian, 1983). The large difference in  $^{187}\text{Os}/^{186}\text{Os}$  ratios between crustal and mantle-derived rocks may be useful in evaluating the origin and history of the rocks and minerals. Os-isotopes may be particularly interesting for the study of the genesis of PGM and for distinguishing between crustal and mantle sources for the PGE. This paper presents  $^{187}\text{Os}/^{186}\text{Os}$  ratios of *in-situ* laurite in chromitites of an Alpine-type ultramafic-mafic complex and of PGM from the associated placers on Borneo Island, Indonesia/Malaysia.

## Geology of the area

Most of the samples were collected from the Meratus-Bobaris region in Southeast Kalimantan, southern Borneo (Fig. 1A). The placers in Southeast Kalimantan occur along river systems which pass through a series of Middle to Late Cretaceous deep-sea sediments and basic volcanic rocks (Alino Formation), Alpine-type ultramafic complexes, clastic sedimentary rocks (Paniungan Beds), and a series of probably Cretaceous crystalline schists. The rocks in the area are highly deformed and segments of different lithologies are juxtaposed during regional tectonic activity. The ophiolite rocks are believed to be a mixture of an obducted oceanic crust and trench sediments formed in the Middle to Upper Lower Cretaceous at around 114 Ma (Burgath, 1988). The area was later intruded by numerous calc-

alkaline rocks of Upper Cretaceous age and the tectonic activity continued into the Pliocene.

The ultramafic rocks are dismembered into two northeast-trending parallel belts: the main mass

to the east is the Meratus Range and the other to the west is the Bobaris range (Fig. 1A). Both consist of mainly lherzolite and clinopyroxene harzburgite with numerous small intercalated

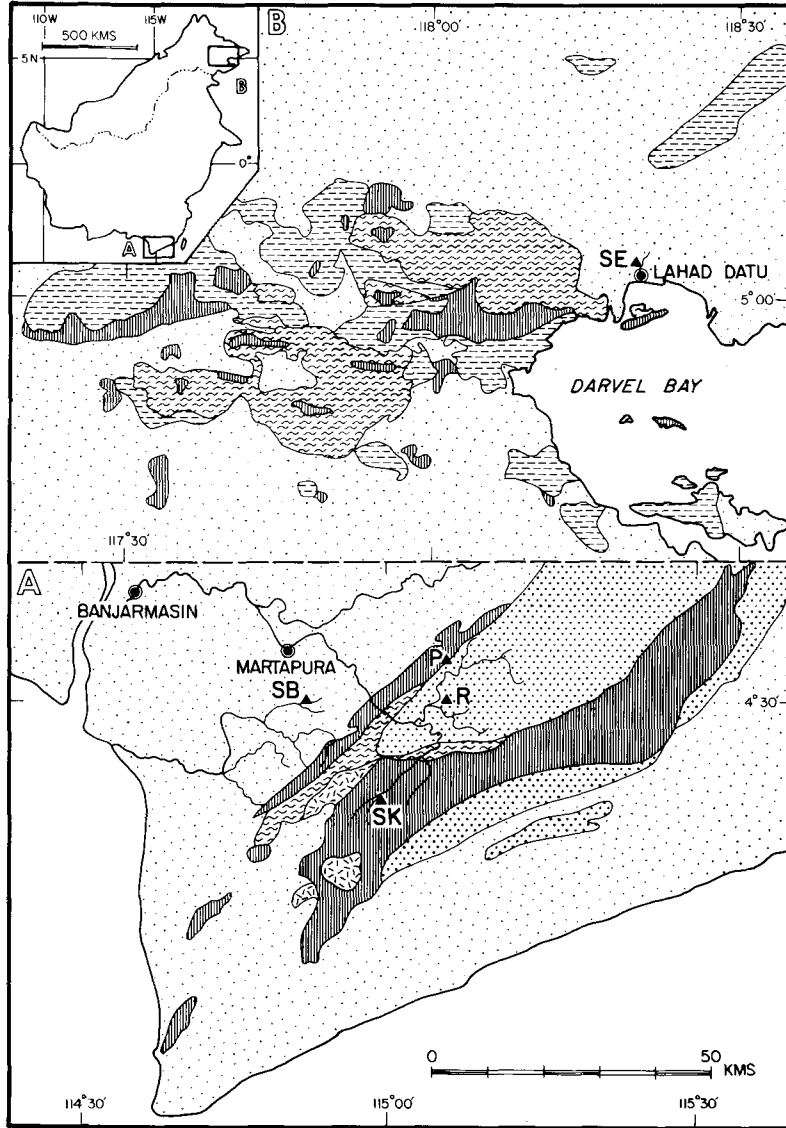


FIG. 1. (A) Geology of Southern Kalimantan and sample locations. Vertically striped area: ultramafic-mafic complex. Northeastern vertically striped area: Bobaris Range. Southwestern vertically striped area: Meratus Range. Close stippled area: Cretaceous sedimentary rocks. Wavy patterned area: crystalline schists. Random dashed area: Late Cretaceous to early Tertiary granitoid. Open stippled area: younger volcanic and sedimentary rocks. Town of Banjarmasin and village of Martapura are also shown. Solid triangles: (sample locations): P, Pamali; R, Riam Kanan; SB, Sungai Besar; SK, Sungai Kalaan. (B) Geology of eastern Sabah and sample location. Vertically striped area: ultramafic-mafic complex. Horizontal dashed area: Tertiary chert and altered mafic volcanic rocks. Wavy patterned area: gneiss. Open stippled area: Pleistocene to Holocene sedimentary rocks. LD, Lahad Datu; SE, Sungai Edam River.

serpentinized dunite bodies. Some of these dunite bodies contain PGE-rich chromitite seams (Burgath, 1988).

Two samples from the chromitite seams were selected for this study. The chromite in the chromitites from Sungai Kalaan in the Meratus Range (SK in Fig. 1A) has high Cr/Fe (*c.* 2.8) and Cr/Al ratios (*c.* 5). This chromitite seam probably represents the uppermost mantle section of the ophiolite sequence. The sample from Pamali (P in Fig. 1A) most likely represents a chromitite in the mantle-crust zone, reflected by low Cr/Fe and Cr/Al ratios (1.8 and 1.5 respectively) and high TiO<sub>2</sub> contents (>0.3 wt.%) in the chromites.

Placer samples came from Riam Kanan and from Sungai Besar. The former is downstream from the Meratus Range on the Cretaceous sedimentary rocks (R in Fig. 1A). The latter downstream from the Bobaris Range on the Tertiary sedimentary and volcanic rocks (SB in Fig. 1A).

One placer sample was collected along the Edam river near the town of Lahad Datu, Sabah, northeast Borneo, Malaysia (Fig. 1B). The area is covered by alluvium sediments of Pleistocene to Holocene age which are underlain by the eastern extension of the Darvel Bay–Labuk–Banggi ophiolite Complex Belt (Fig. 1B). The studied sample probably originated from the ultramafic complex. The ultramafic section of the complex extends north to the Palawan Island, in the Philippines (e.g. Hutchison, 1975). The amphiboles and micas in the metamorphosed host rocks of the ultramafic complex on Palawan Island gave K–Ar ages of *c.* 40 Ma (Raschka *et al.*, 1985). This age agrees in general with the geologically estimated age of the ophiolite (Leong, 1974).

Sample locations are shown in Figs. 1A and B. Further description of the geology and the occurrences of PGM in Borneo may be found in Stumpfl and Clark (1966), Stumpfl and Tarkian (1973), Burgath and Mohr (1986), and Burgath (1988).

#### Description of studied samples

The chromitites in the Meratus–Bobaris ophiolite in the Southeast Kalimantan are high in Ru, As, and Ir, and they contain grains of Ir- and Os-bearing laurite and rarely of osmium iridium (Burgath, 1988). These laurite grains were subjected to Os-isotope analyses.

The laurite grain from Sungai Kalaan has an euhedral shape of *c.* 10 µm and is enclosed by an octahedral sulphide inclusion in chromite (Fig. 2). The sulphide inclusion is a mixture of pentlandite, chalcopyrite, and bornite, which are

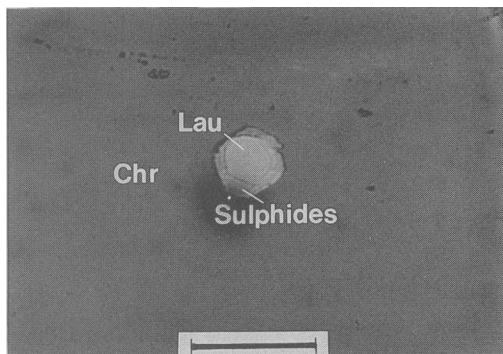


FIG. 2. Photomicrograph of laurite (sample, 2636). It is enclosed by a mixture of chalcopyrite, pentlandite, and bornite within chromite. The sample came from Sungai Kalaan in the Meratus Range (SK in Fig. 1A). Sulphides, a mixture of chalcopyrite, pentlandite and bornite; Chr, chromite; Lau, laurite. Scale bar 25 µm.

believed to be decomposition products of high-temperature chalcopentlandite (Burgath, 1988). These sulphide minerals, however, may have crystallized from a trapped sulphide melt enclosed in a negative octahedral void of the chromite. In either case, the <sup>187</sup>Os/<sup>186</sup>Os ratio of the laurite should represent that of magma from which chromite was formed.

The studied laurite grains from Pamali occur in a partially serpentinized chromitite in the Bobaris Range (P in Fig. 1A). The chromite grains display extensive cataclastic deformation. One grain of laurite is completely enclosed in chromite. The second grain (Lau A in Fig. 3) is enriched in Os, and attached to a porous ferrite-chromite rim, an alteration product of the chromite. The third

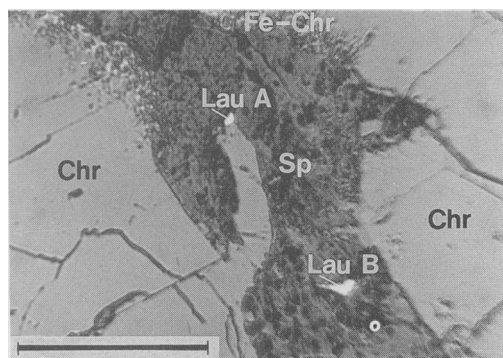


FIG. 3. Photomicrograph of laurite grains (sample 2616). The sample is partially serpentinized olivine chromitite from Pamali in the Bobaris Range (P in Fig. 1A). Two laurites (Lau A and Lau B) occur. Spongy ferrite-chromite (Fe-Chr) is developed on the margins of chromite (Chr). Sp: serpentine. Scale bar 100 µm.

grain (Lau B in Fig. 3) displays a delicate angular outline and is completely enclosed in serpentine.

PGM from placers in the Southeastern Kalimantan are mostly alloys of Os, Ir and Ru of varied proportions, and Pt-Fe alloys (Burgath, 1988). The PGM nuggets are variably abraded, sub-angular to semi-rounded in shape. Some grains show irregular surface with embayments and some contain silicate inclusions (Burgath, 1988). Four PGM nuggets were selected for Os-isotope analysis: sub-rounded platinumian osmium iridium, sub-angular ruthenian iridian osmium, sub-angular platinumian osmium iridium, and semi-rounded osmium iridium. The names of alloys follow the nomenclature recommended by Harris and Cabri (1991). One grain (3135-2) displays a variation in Pd contents (Burgath, 1988).

One nugget from eastern Sabah, semi-rounded ruthenian osmium, was subjected to Os-isotope analyses.

#### Analytical procedures

Most of the chemical compositions of PGM and the analytical procedures were described in Burgath (1988). Laurite samples were analysed by a Siemens ELMISONDE electron microprobe, using the standards of pure Ru, Os, Ir, and (Fe, Ir)<sub>9</sub>S<sub>10</sub>. Alloy samples were analysed with a CAMEBAX electron microprobe using the standards of pure metals of Rh, Ru, Ir, Os, Au, Ag, Cu, and Ni.

Regular polished sections of chromitites were used for Os-isotopic analyses of laurites. Individual grains of PGM from placers were mounted in a resin for polishing. Isotopic ratios were determined on polished grains using the MIT-Harvard-Brown Cameca 3f ion microprobe. Operating conditions were essentially the same as those described by Hart and Kinloch (1989). Detailed operating conditions and reproducibilities of the analyses were described by Hattori *et al.* (1991). The primary O<sup>-</sup> beam current was 4 to 20 nA, and it was focused to 10 µm. The ions at masses of 185, 186, 187, 188, and 189 were determined for each analysis in order to correct the ratio of <sup>187</sup>Os/<sup>186</sup>Os for the contribution of <sup>187</sup>Re, hydrides, and mass fractionation. Correction for <sup>186</sup>W was not necessary in this study because <sup>183</sup>W was not detected before and after each analysis. For the studied samples, the Re correction ranged from 0 to 1.4% and the hydride fraction was less than 0.5%. The mass fractionation factor ranged from 0.5 to 1% per atomic mass unit. The hydride fraction and mass fractionation factor were calculated by normalizing the ratios of <sup>186</sup>Os/<sup>188</sup>Os to 0.12035 (Luck and

Allègre, 1983). The 2σ of the measurement of <sup>187</sup>/<sup>186</sup> peak ratios was normally below ±0.2%.

Replicate analysis of the same grains made over a 10 month period shows a precision (2σ) of ±0.6%. The precision of each result, therefore, was given as ±0.6% or the in-run measurement of the peak ratios, whichever was larger.

#### Results

One iridian osmium grain, which showed more than 20 times higher Re peaks than any of the samples of this study, contains Re below the detection limit of an electron probe, <0.06 wt.% (Hattori *et al.*, 1991). Rhenium concentrations of the studied PGM are, therefore, very low (<<0.06 wt.%). Low concentration of Re in the studied PGM and the young age of the samples compared with the long half-life <sup>187</sup>Re, 4.56 × 10<sup>10</sup> yr (Luck and Allègre, 1983), indicate that the radiogenic <sup>187</sup>Os due to *in-situ* Re decay is insignificant within the PGM. The observed <sup>187</sup>Os/<sup>186</sup>Os values, therefore, are the same as the initial values at the time of their formation.

The measured <sup>187</sup>Os/<sup>186</sup>Os values are all low, ranging from 1.04 to 1.09 (Table 1). The values of laurite grains hosted in chromite from the Meratus and Bobaris Ranges are similar within analytical uncertainty. The values for laurite grains from chromitite at Pamali in the Bobaris Range, however, show a spread in <sup>187</sup>Os/<sup>186</sup>Os ratios within a polished section. The lowest value is observed in a laurite grain enclosed in chromite, while laurites in serpentine in the same section show slightly higher values.

The ratios of <sup>187</sup>Os/<sup>186</sup>Os for the PGM from placers from Kalimantan are similar to those for the laurites in chromitites. A small difference in Os-isotope ratios between grains of placer PGM from Kalimantan and those from Sabah is also noted.

No variation of <sup>187</sup>Os/<sup>186</sup>Os was detected within individual grains. The sample displaying chemical inhomogeneity (sample # 3135-2) did not show any significant variation in <sup>187</sup>Os/<sup>186</sup>Os ratios. The ratios of three different areas in the grain are identical (Table 1).

#### Discussion

The range of observed <sup>187</sup>Os/<sup>186</sup>Os ratios is typical for young mantle-derived rocks (Allègre and Luck, 1980; Martin, 1991). These values are quite different from higher 'crustal' ratios observed in large layered intrusive complexes such as the Bushveld (Hart and Kinloch, 1989), Stillwater (Lambert *et al.*, 1989; Martin, 1989),

Table 1. Isotope compositions of laurites and metal alloys

Sample no <sup>(1)</sup>	Phase <sup>(2)</sup>	Composition in weight percent <sup>(3)</sup>								<sup>187</sup> Os/ <sup>186</sup> Os <sup>(4)</sup>
		Pt	Pd	Rh	Ir	Os	Ru	Fe		
Chromitite seam, Pamali, in the Bobaris Range, SE Kalimantan ("P" in Fig. 1A)										
2616-2	laurite in chromite									1.039 ± .010
2616-3	laurite in serpentine (Lau B in Fig. 3)	n.d. <sup>(5)</sup>	n.d.	n.d.	10.28 (13.70)	15.42 (20.61)	35.62 (58.04)	2.11 (4.53)		1.088 ± .010
2616-4	laurite in serpentine attached to chromite (Lau A in Fig. 3)	n.d.	n.d.	n.d.	16.83 (22.43)	25.17 (33.64)	21.97 (35.80)	2.07 (4.44)		1.049 ± .006
Chromitite seam, Sungai Kalaan, Meratus Range, SE Kalimantan ("SK" in Fig. 1A)										
2636	laurite in Cu-Ni-Fe-S hosted in chromite (Lau in Fig. 2)	n.d.	n.d.	n.d.	6.16 (8.21)	20.91 (27.95)	35.17 (57.30)	0.92 (1.97)		1.044 ± .010
Placer sample from Riam Kanan, SE Kalimantan ("R" in Fig. 1A)										
2698	platinian osmium iridium (angular, 1.1 x 1.0 mm) different area in the grain different area in the grain different area in the grain	6.46	0.08	0.94	69.15	23.98	0.27			1.057 ± .006 1.061 ± .006 1.061 ± .006 1.058 ± .006
Placer sample from Sungai Besar, SE Kalimantan ("SB" in Fig. 1A)										
3135-1	platinian osmium iridium (semi-rounded, 300 μm x 200 μm) different area in the grain different area in the grain different area in the grain different area in the grain	9.79	0.04	1.57	54.62	33.34	1.69			1.053 ± .006 1.050 ± .006 1.055 ± .006 1.049 ± .006 1.053 ± .006
3135-2	ruthenian iridian osmium (rectangular, 200 μm x 400 μm) different area in the grain different area in the grain	0.40	0.23	0.29	43.77	47.53	7.93			1.052 ± .006 1.052 ± .006 1.052 ± .006
3135-3	osmium iridium (semi-rounded, 500 μm x 300 μm) different area in the grain	1.40	n.d.	0.57	61.60	35.22	2.04			1.041 ± .006 1.041 ± .006
Placer sample from Sungai Edam, SE Sabah ("SE" in Fig. 1B)										
3092	ruthenian osmium (angular, 40 x 60 μm) different area in the grain different area in the grain	n.d.	0.04	0.28	9.67	71.32	16.75			1.065 ± .006 1.069 ± .006 1.063 ± .006

(1): First 4 digits indicate section number and the last one for grain number.  
Sample 2616 and 2636 are chromitite sections and the rest are grain mounts of placer nuggets.

(2): Nomenclature of the PGM is followed by recommendation by Harris and Cabri (1991)

(3): Numbers in brackets are compositions calculated as metal-bisulphides.

(4): Precision is taken to be the ratio measurement counting statistics or 0.7 %, whichever is larger; see text.

(5): not detected by the electron microprobe.

and Freetown, Sierra Leone (Hattori *et al.*, 1991). This is not surprising because Alpine-type peridotite-gabbro-basalt complexes (ophiolites) would not have any opportunity to assimilate old crustal rocks with high <sup>187</sup>Os/<sup>186</sup>Os ratios during their crystallization in an oceanic environment and their final tectonic emplacement in island arcs or continental margins. Any assimilation of host gabbros and basalts of similar ages would not have modified <sup>187</sup>Os/<sup>186</sup>Os ratios of the ultramafic rocks, which have an Os content an order of magnitude higher than basalts and gabbros.

Laurite enclosed in chromite records the <sup>187</sup>Os/<sup>186</sup>Os ratios of the mantle source for the magma because chromite is an early crystallizing phase in the undifferentiated magma, which was derived from partial melting of lherzolite in an oceanic environment. The observed <sup>187</sup>Os/<sup>186</sup>Os ratios of laurite grains enclosed in chromites, *c.* 1.04, therefore represents the value of the mantle source at 100 Ma. The value of the <sup>187</sup>Os/<sup>186</sup>Os ratios coincides with that of the bulk mantle value in the late Cretaceous time predicted by Allègre and Luck (1980).

The absence of a difference in the  $^{187}\text{Os}/^{186}\text{Os}$  ratios of laurites from the Meratus and Bobaris Ranges confirms the tectonically dismembered nature of the two ultramafic intrusions.

*Os-isotope ratios of laurite.* The  $^{187}\text{Os}/^{186}\text{Os}$  ratios observed in laurite grains in serpentine which are slightly higher than the value for laurite in chromite may be attributed to the formation of laurite during serpentinization or to the variation in  $^{187}\text{Os}/^{186}\text{Os}$  of the magmas. The former interpretation implies that PGE including Os were mobile during serpentinization and that crustal  $^{187}\text{Os}$  was incorporated in the laurite grains during this process. The latter interpretation implies that laurite grains formed in the interstitial space of cumulates were formed from magma different from that for cumulates. It is possible that the  $^{187}\text{Os}/^{186}\text{Os}$  ratio of the magma changed during its solidification processes. Petrographic evidence and mineral chemistry data are consistent with either interpretation. The xenomorphic angular shape of the laurite grains outside chromite grains (Fig. 3) may support either model. Compositional differences between laurite grains in and outside chromite (Table 1) may also be attributed to either model. In the former model, the variation reflects the changes in fluid chemistry or modification of compositions of laurites by serpentinizing fluids. In the latter model, the variation is attributed to the change in temperature and  $f_{\text{S}_2}$  of the magma. Higher Os contents in the laurites outside the chromites are consistent with lower temperatures of the formation (Burgath, 1988).

The two possibilities are equally valid from petrological points of view, but the Os-isotopic data and contents of PGE in variably serpentinized ultramafic rocks are unfavourable to the formation of laurite during serpentinization. Many analyses of contents of PGE in ultramafic rocks indicate that there is essentially no change in the contents between non-serpentinized and serpentinized ultramafic rocks (e.g. Ross and Keays, 1979; Oshin and Crocket, 1982). The data suggest no significant mobility in PGE during the serpentinization.

Re/Os ratios in the ultramafic rocks are low compared with many crustal rocks because of high Os contents in ultramafic rocks, but Os is concentrated in chromitites and the rest of the rocks in the ultramafic unit should be relatively high in Re/Os. Serpentinization involves the breakdown of the silicate minerals, which could release Re and radiogenic Os if fluids can dissolve Os. If laurite can be formed from fluids during serpentinization, then  $^{187}\text{Os}/^{186}\text{Os}$  ratios of laurite should be significantly high by incorporating the radiogenic  $^{187}\text{Os}$  released from silicates.

Most crustal rocks including oceanic-island and ocean-ridge basalts have much higher Re/Os than the mantle Re/Os ratios (e.g. Morgan and Lovering, 1967; Chou *et al.*, 1983).  $^{187}\text{Os}/^{186}\text{Os}$  ratios of mafic volcanic rocks sharply increase after their formation. While it may be difficult to envisage a shift in the  $^{187}\text{Os}/^{186}\text{Os}$  ratios in geologically young terrains such as Borneo, simple calculations show that the change in these ratios does not take a very long time. For example, ocean ridge basalts (average  $^{187}\text{Re}/^{186}\text{Os}$  ratio of c. 160; Chou *et al.*, 1983), would change from 1.0 to 1.25 in 100 Ma. The  $^{187}\text{Os}/^{186}\text{Os}$  ratios of sedimentary rocks, which have an average ratio of  $^{187}\text{Re}/^{186}\text{Os}$  over 300, would increase from 1.0 to 1.50 within 100 Ma. Granitic rocks have even higher  $^{187}\text{Re}/^{186}\text{Os}$  ratios (Morgan and Lovering, 1967; Luck and Allègre, 1982), resulting in an even faster increase in the  $^{187}\text{Os}/^{186}\text{Os}$  ratios through geological time.

The ultramafic rocks in southeastern Kalimantan are highly deformed and imbricated, which resulted in the tectonic incorporation of slices of mafic volcanic and gabbroic rocks into the ultramafic section. The adjacent metamorphic rocks are blueschist and amphibolite grade and probably originated from deep-sea sedimentary and mafic volcanic rocks. The metamorphism is dated to the Cretaceous period (Eckhardt *et al.*, 1987). The sedimentary rocks adjacent to the ultramafic unit are also of Cretaceous age and consist of deep-sea shales, cherts, polymictic sandstones and conglomerates. All these rocks were intruded by Upper Cretaceous to Tertiary calc-alkaline igneous rocks (Fig. 1A).

Hydrothermal fluids would dissolve crustal Os from the non-ultramafic rocks if fluids were capable of transporting Os. The incorporation of a small amount of crustal  $^{187}\text{Os}$  through hydrothermal activity would have a profound effect on the  $^{187}\text{Os}/^{186}\text{Os}$  ratios of PGM in the ultramafic rocks. In addition, fluid flow may be controlled by fractures in the rocks and the  $^{187}\text{Os}/^{186}\text{Os}$  ratios of fluids and precipitating PGM would be highly varied.

The measured  $^{187}\text{Os}/^{186}\text{Os}$  ratios of laurites are low overall, <1.1, and the values are consistent. The present data suggest that the laurite grains were probably not formed during serpentinization after the obduction. The variation in  $^{187}\text{Os}/^{186}\text{Os}$  ratios among laurites is, therefore, attributed to the variation in the parent magma.

*Os-isotopes of PGM from placers.* Because of the rare occurrences of large PGM within ultramafic rocks, formation of PGM during tropical weathering and their *in-situ* growth in placers have been proposed (e.g. Bowles, 1986, 1988).

Borneo has a tropical climate and it would be a suitable location to find PGM formed by chemical sedimentary processes. If the studied PGM were indeed formed by such low-temperature chemical processes, they would show higher and varied  $^{187}\text{Os}/^{186}\text{Os}$  ratios due to the influence of crustal  $^{187}\text{Os}$ . The studied placer samples occurred along streams which dissect metamorphic rocks and Cretaceous to Tertiary sedimentary rocks. If the studied PGM precipitated from solution in the stream sediments, then the incorporation of  $^{187}\text{Os}$  from the adjacent and underlying rocks would be inevitable. The low  $^{187}\text{Os}/^{186}\text{Os}$  ratios of the studied alloys in the placers,  $<1.1$ , are within the range of the present-day mantle (Allègre and Luck, 1980; Martin, 1991). The data, therefore, are not consistent with the model of precipitation of nuggets of PGM from low-temperature solutions in sediments.

Another possible mechanism of large grains of PGM in placers is the physical coagulation of PGM during sedimentary processes, as proposed by Cousins (1973). Laurite is a sulphide and does not coagulate to form a large grain. On the other hand, metal alloys may have been able to coagulate at low temperatures. Detectable concentrations of Cu and Pt in nuggets compared with Cu- and Pt-free alloys in chromitites (Burgath, 1988) may support the hypothesis. The studied nuggets are semi-rounded, but they show optic continuity in individual grains. It is difficult to accept that mechanical coagulation of metals at low temperatures produces optically consistent crystals of the alloys. In addition, inclusions of sulphides and igneous silicate minerals are not uncommon in placer PGM (e.g. Ford, 1981). Sulphides and olivine are not stable in sedimentary environments. If the PGM in placers are aggregates of once different grains, variations in  $^{187}\text{Os}/^{186}\text{Os}$  ratios should be observed in individual grains. Consistent  $^{187}\text{Os}/^{186}\text{Os}$  ratios in grains within analytical uncertainty appear to reject the possibility.

The present data of  $^{187}\text{Os}/^{186}\text{Os}$  ratios are indicative of the derivation of most of the PGE from the mantle without a significant contribution of the crustal component. PGM in placers were most likely to have formed in ultramafic rocks, eroded and concentrated in placers. Absence of laurite in placers may simply manifest the instability of sulphide minerals in sedimentary processes.

Minor differences in the  $^{187}\text{Os}/^{186}\text{Os}$  ratios between PGM from Kalimantan and from Sabah may be attributed to the slightly younger age of the latter ophiolite (Leong, 1974). The values of the PGM from Sabah may also represent those of

the contemporaneous mantle considering the similar  $^{187}\text{Os}/^{186}\text{Os}$  ratios observed between PGM in chromites and PGM in placers in Kalimantan. Then, the mantle source region for the ultramafic rocks had an  $^{187}\text{Os}/^{186}\text{Os}$  ratio of *c.* 1.06 at *c.* 40 Ma.

The detrital origin of PGM in placers still leaves some unanswered questions concerning their genesis. These include the difference in grain size and mineralogy between PGM in chromitites and in placers. PGM in chromitites in the ultramafic rocks are all very small,  $<10\ \mu\text{m}$ , compared with large sized nuggets in placers,  $>200\ \mu\text{m}$ . PGM grains in chromitites are mostly laurite and those in placers are all alloys. It is interesting to note recent findings of coarse grained Pt-Fe alloys,  $<13\ \text{mm}$ , with lamellae of osmium in the Alto Condoto Alaskan-type complex in Colombia (Burgath and Tistl, unpublished data). They are not associated with chromitites. Instead, they are randomly distributed in the dunite core of the igneous complex. Large grains of the studied PGM from placers in Borneo may have been derived from grains dispersed in the ultramafic section outside the chromitite seams. Large euhedral grains of alloys of PGE in placers (Hagen *et al.*, 1990) and the essential lack of laurite in placers may be attributed to the very hard, durable and chemically stable nature of alloys of PGE during the sedimentary processes.

### Conclusions

Laurite grains enclosed in chromite provide an  $^{187}\text{Os}/^{186}\text{Os}$  ratio of the mantle source for *c.* 110 Ma ultramafic intrusions as *c.* 1.04. The values of a nugget from eastern Sabah suggest that the mantle source region had an  $^{187}\text{Os}/^{186}\text{Os}$  ratio of *c.* 1.06 at *c.* 40 Ma.

The  $^{187}\text{Os}/^{186}\text{Os}$  ratios of placer PGM are low and the values are similar to the ratios of laurites in the chromitites. No isotopic variation was detected within individual grains. The low values indicate that the PGE in the placer PGM were essentially derived from the mantle with no significant contribution of crustal  $^{187}\text{Os}$ . The data are consistent with the formation of PGM grains in ultramafic rocks and their mechanical derivation from the ultramafic rocks.

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