

PLATINUM-GROUP ELEMENTS IN TULAMEEN COAL, BRITISH COLUMBIA, CANADA—A DISCUSSION

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Sir: In her article concerning the origin of platinum-group elements (PGE) in Tulameen coals (Van der Flier-Keller, 1991) and in a companion paper treating the same data (Van der Flier-Keller, 1990), Van der Flier-Keller concluded that the distribution of PGE in coal was primarily controlled by dissolution and precipitation processes occurring in circulating PGE-rich ground waters. Specifically, she concluded that the concentration of PGE in coal measures at the Blakeburn opencast pit was due to selective fixation by organic complexing of Au and PGE carried as solute or colloidal suspensions. Anomalous high concentrations of PGE in fault zones were explained by enhanced ground-water flow along more permeable channelways which promoted greater fluid-rock (coal) interactions. Two sources for the PGE were identified: an external Pt-rich source, the nearby Tulameen Ultramafic Complex; and an internal source comprising volcanic units interbedded with the coal, including tonsteins, bentonites, and basalt. On the basis of the relative abundances of Pt, Pd and Au in stream sediments, coals, and ultramafic rocks of the Tulameen Complex, Van der Flier-Keller (1991, p. 394) further proposed that the precipitation of PGE from ground waters could also account for the origin of these metals in alluvial placers of the region.

It was the latter conclusion, requiring wholesale mobility and precipitation of PGE in the surficial environment, that prompted a close examination of the data that led Van der Flier-Keller to favor a low-temperature origin for PGE in coals and alluvial sediments of the Tulameen district. Previously, Raicevic and Cabri (1976) and Nixon et al. (1990) had documented a magmatic origin for platinum-group minerals in Tulameen placers and demonstrated a genetic link with chromitites in the core of the Tulameen Ultramafic Complex. Of course, there are many well-documented examples of the mobility and hydromorphic dispersion of noble metals (to varying degrees) during surface weathering of rocks and ores (e.g., Taufen and Marchetto, 1990; Wood and Vlassopoulos, 1990). In addition, experimental and theoretical work has demonstrated the ability of organic acids to complex with PGE in aqueous solutions (e.g., Wood, 1990; Plimer and Williams, 1987). However, given our present state of knowledge of the distribution of PGE in coal (Swaine, 1990), it seems unwise to invoke some poorly understood process such as regional hydromorphic dispersion of PGE in order to account for subeconomic concentrations of these

metals in coal when other more conventional mechanisms have not been fully explored.

It is the purpose of this note to reexamine the evidence for the ground-water precipitation hypothesis as proposed by Van der Flier-Keller and to analyze other data bearing on the origin of the PGE in coals and interbedded sediments of the Tulameen basin. Several fundamental issues need to be addressed: (1) Do the geochemical data for PGE and Au in coals and associated sediments or alluvial placers unequivocally demonstrate that the distribution of PGE is primarily controlled by chemical reactions occurring in ground waters? (2) What specific local source(s) of PGE may be recognized and is there evidence for localized mobility of noble metals?, and (3) Were the PGE derived from the Tulameen Ultramafic Complex? The latter question is particularly important because it involves ground-water transport and concentration of PGE over distances of up to 10 km from areas of known mineralization in the Tulameen complex. In addition, there are errors in table 5 (Van der Flier-Keller, 1991) where sample numbers for deformed Blakeburn coals have been misplaced (L. J. Cabri, written commun., 1991; Van der Flier-Keller, pers. commun., 1991). It should also be pointed out that hydrothermal PGE deposits were certainly well known prior to 1982 (e.g., Cameron and Desborough, 1964; McCallum et al., 1976) and not "first recognized in 1982" as erroneously stated by Van der Flier-Keller (1991, p. 387).

As detailed below, it is my contention that the data presented by Van der Flier-Keller cannot be used to substantiate the ground-water precipitation hypothesis as a mechanism for concentrating the PGE in Blakeburn coals. Furthermore, this hypothesis is inconsistent with the available data for alluvial placers in the region and there is no conclusive evidence that the Tulameen Ultramafic Complex supplied PGE to the coals, although it does remain a likely candidate. A reinterpretation of the data presented by Van der Flier-Keller suggests that there is no evidence for mobility of noble metals at any scale after deposition of the rocks which host them and that a detrital origin for the PGE and Au must be considered. However, this origin cannot be tested adequately using geochemical data alone. In the discussion below, important facets of the geology, geochemistry, and mineralogy necessitate reproduction of some figures in the original article; however, references cited are minimal and largely supplement those given already (cf. Van der Flier-Keller, 1991).

The location of the Tulameen coal basin and Tulameen Ultramafic Complex are shown in Figure 1. The Tulameen basin represents a synclinal outlier of Tertiary volcanics and basin fill (Princeton Group), one of many such isolated remnants in the southernmost part of the Intermontane belt of the Canadian Cordillera (Read, in press). Basaltic to rhyolitic volcanic rocks (Cedar Formation) at the base of the Princeton Group rest with angular unconformity on Late Triassic metavolcanic and metasedimentary

rocks of the Nicola Group. The Cedar Formation is overlain by sedimentary rocks of the Allenby Formation which hosts the coal deposits studied by Van der Flier-Keller (Fig. 1; and see Van der Flier-Keller, 1991, fig. 1 for more detailed geology).

The Tulameen ultramafic complex is a Late Triassic Alaskan-type intrusion characterized by rock types ranging from dunite through clinopyroxenite to gabbroic-syenitic rocks. Chromitites in the dunite core of the complex at Grasshopper Mountain (Fig. 1) con-

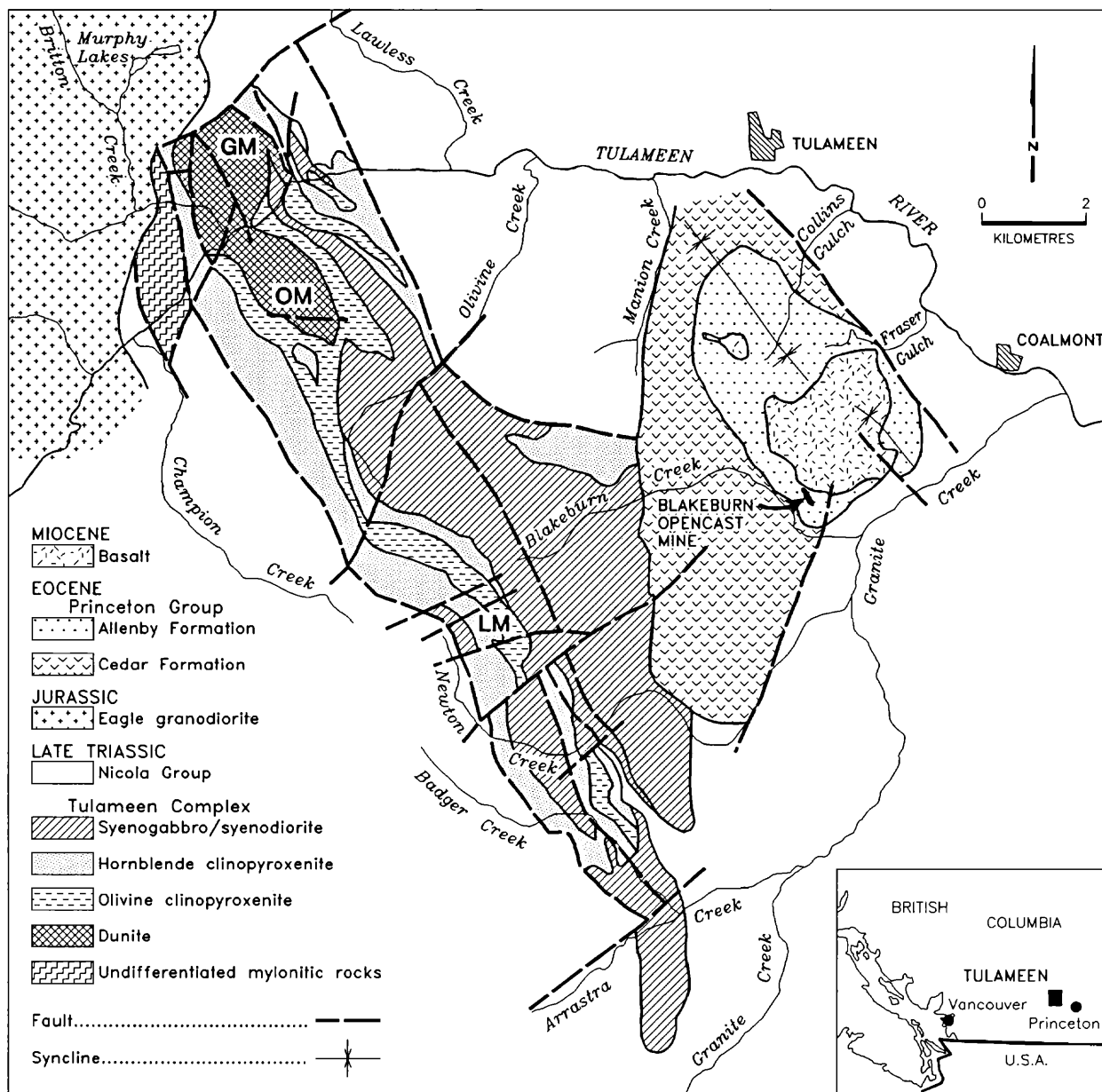


FIG. 1. Location of Tulameen coal basin and Alaskan-type Tulameen Ultramafic Complex showing major lithologic units (modified after Findlay, 1963, and Van der Flier-Keller, 1991). GM = Grasshopper Mountain, LM = Lodestone Mountain, OM = Olivine Mountain.

tain anomalous abundances of PGE and are an important source of alluvial platinum in the Tulameen-Similkameen Rivers, as well as streams that drain the eastern margin of the complex (Ruble, 1986; St. Louis et al., 1986; Nixon et al., 1990). These PGE-rich placers have developed since the last glacial maximum (i.e., late Wisconsinan or Fraser glaciation ca. 15,000 yr B. P.) when ice moved across the Tulameen region in a south-southwesterly direction (Rice, 1947; Blaise et al., 1990).

Samples collected from the Blakeburn opencast pit at the southwestern margin of the Tulameen coal basin (Fig. 1) were treated as two groups: channel samples from a measured section; and deformed coal taken along faults affecting the same stratigraphy (Van der Flier-Keller, 1991, figs. 3 and 2, respectively). The PGE and Au were analyzed by two different methods, nickel sulfide fire assay followed by neutron activation analysis (NAA) and lead sulfide fire assay with a direct current plasma spectroscopic finish (DCP). Channel samples were analyzed by NAA whereas deformed coal samples were analyzed by both NAA and DCP. Analytical precision, as estimated from duplicate samples, was "generally less than 25% (relative); however, significantly higher values were determined for samples with anomalous Pt and Pd values" (Van der Flier-Keller, 1991, p. 389).

With regard to the distribution of noble metals in the various lithologies, Van der Flier-Keller states that the "concentrations of all PGE except Ru are more enriched in coal than in sediment" (1991, p. 389, abstract and conclusions). This observation is supported by arithmetic means for PGE abundances in each lithology (Van der Flier-Keller, 1991, table 3). However, these means are highly misleading since they incorporate very few samples (seven or less for each lithology) above analytical detection limits, and values for samples below detection limits have been assumed (admittedly, not an uncommon practice in the statistical analysis of geochemical data). In channel samples, the means for Os, Pd, and Re include only one value above detection limits; and Rh concentrations (2 ppb or less) have too narrow a range and are too close to the detection limit (1 ppb) to be meaningful. Thus, for the channel sample data, only Pt provides any clear indication that higher abundances (total range 8-170 ppb Pt for 7 coal out of 12 samples above detection limit) are preferentially associated with coal. Even these data may not be representative when it is considered that 26 of 27 coal horizons were sampled in the section compared to 13 of 41 sedimentary units of which only three were volcanoclastic (tonstein-bentonite). Discussions below assume that these data are representative and examine evidence for precipitation versus a detrital origin for the PGE and Au.

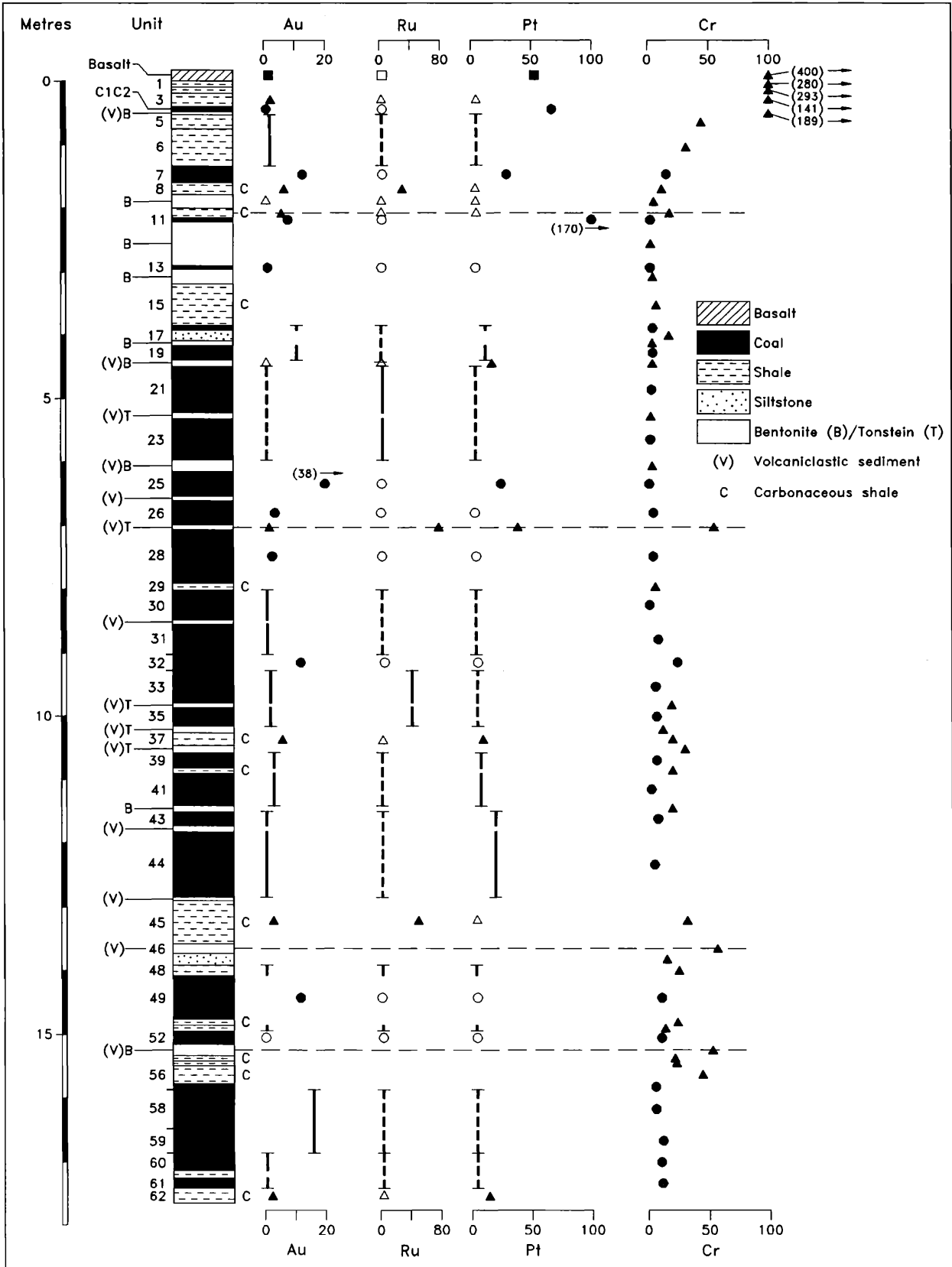
The stratigraphy and vertical distribution of se-

lected metals at Blakeburn are shown in Figure 2. These data were compiled from sources cited in the figure caption. As detailed by Van der Flier-Keller (1991), the succession has been correlated with the upper part of the (middle) Eocene Allenby Formation which comprises thin coal seams and interbedded fine-grained clastics and tuffaceous sediments including bentonites and tonsteins (McMechan, 1983; Read, in press). An olivine-augite-phyric basalt flow at the top of the section has been dated by K-Ar whole-rock methods at 9.0 ± 0.9 Ma (Church and Brasnett, 1983) and belongs to a regionally extensive outpouring of basalt that comprises the Chilcotin Group (Mathews, 1989).

Chromium has an important bearing on potential sources of PGE in the section and the sampling density is twice that for the noble metals (Fig. 2). At the top of the section, Cr decreases systematically downward from the basalt flow (400 ppm) to unit 10. Co (not shown) also shows a similar distribution with a maximum of 74 ppm in the basalt (N. B. Church, unpub. data) and less than 5 ppm in most coals and sediments (cf. Goodarzi and Van der Flier-Keller, 1989, table 2). Anomalously high Cr abundances (141-290 ppm) in fine-grained clastics below the basalt are most readily explained by incorporation of relatively large amounts of basaltic tephra produced immediately prior to the flow. Using simple mixing calculations, the amount of basaltic material in these units, assuming Cr is immobile (Shaw et al., 1990) and basalt-free sediment contains 15 ppm Cr, is between 33 and 73 wt percent. This distribution of Cr raises the possibility that the unconformity separating the Miocene and Eocene successions would be better placed lower in the section, at the base of unit 4 or perhaps lower. Cr abundances throughout the remainder of the section are generally lower in coals (avg 7.4 ppm, $n = 27$) than in shales (avg = 18.4 ppm excluding units 1-6, $n = 13$) and highest in certain tuffaceous sediments, bentonites, and tonsteins in the Eocene succession (>50 ppm in units 27, 46, and 53). Most of the latter lithologies represent altered pyroclastic air-fall deposits of rhyolitic to basaltic composition (Church and Brasnett, 1983). Cr abundances in these lithologies may thus be used to distinguish between silicic and more mafic (andesitic-basaltic) protoliths which would be expected to contain higher abundances of PGE (Crocket, 1981).

As discussed by Van der Flier-Keller, the highest abundances of Pt (and Ir) and Au in the channel samples occur in coals; Ru is associated with interbedded clastics (Fig. 2).

With respect to Pt, Van der Flier-Keller (1991) states that "The distribution of Pt is thought to be primarily controlled by Pt availability in ground water" (p. 390) and that "The highest Pt concentrations occur in coal benches in the upper zone of the



coal-bearing section, and concentrations generally decrease with depth in the section" (p. 389–390). By analogy with previous work (Van der Flier-Keller, 1990), an upward increase in Pt was considered to reflect leaching of the platiniferous basalt cap by downward movement of ground waters and selective fixation of Pt in the coals due to organic complexing. From Figure 2, it would seem more appropriate to describe the distribution of Pt with depth (or for that matter any of the other PGE or Au) as erratic, with an incidence of higher Pt abundances in coal units in the uppermost 2 m of the section. There is certainly no clear indication of a systematic decrease in Pt down section that might be used to support such a leaching mechanism, considering either the coal layers alone or the section as a whole.

In order for the ground-water precipitation hypothesis to explain successfully the distribution of Pt (and Ir) at Blakeburn, Van der Flier-Keller invoked wholesale mobility of Pt throughout the section. If this hypothesis is correct, it is curious that there is no direct evidence for more localized mobility of PGE. For example, chromiferous volcanoclastic horizons (bentonites-tonsteins) such as unit 27 are potential sources of PGE throughout the section. Since the majority of such horizons have not been analyzed, localized leaching and organic fixation could perhaps explain the relatively minor amounts of Pt (<23 ppb) in coals below unit 11 where volcanoclastic layers are most numerous. Yet in tonstein 27 which has the highest amounts of Pt (39 ppb) and Ru (80 ppb), adjacent coals do not exhibit any significant enrichment in PGE. Conversely, coals at the top of the section that contain the highest abundances of Pt (29–170 ppb) are surrounded by chromiferous sediments that are apparently devoid of Pt. Only coal C1C2 has a potentially Pt-rich chromiferous bentonite (unit 4) in contact below. Extremely efficient leaching of PGE in sedimentary and volcanoclastic source rocks could be used to explain the latter occurrences, but not the former. Clearly, localized mobility of PGE does not appear to be a factor in the vertical distribution patterns, although more data are needed to test this observation thoroughly.

Considering geologic factors relevant to the origin of gold, Van der Flier-Keller (1991, p. 393) states that "Au is preferentially associated with coal in thin layers interbedded with abundant sedimentary units,

suggesting a source for the Au from adjacent sedimentary partings." If this observation applies to gold, it is certainly true for the distribution of Pt at the top of the section. Unfortunately, from the geochemical data available, shales and siltstones do not appear to be lucrative hosts for noble metals, with the possible exception of Ru. Nonetheless, Van der Flier-Keller favored local remobilization of gold in ground waters circulating through such host rocks and precipitation or adsorption in association with organic matter.

PGE distributions in samples of deformed coal collected along faults were considered by Van der Flier-Keller to reflect enhanced concentration by ground waters moving along more permeable channelways. This hypothesis drew support from spectacular abundances of Pt (>10,000–1,200 ppb) and Pd (6,100–750 ppb) reported in three samples of low-ash (<7 wt %) coal. However, these samples also highlight a sampling problem, viz., the lack of reproducibility of splits of the same sample analyzed by INAA and DCP methods. The analytical data for deformed coal samples are plotted in Figure 3. In the high concentration range, there appears to be a systematic bias toward higher Pt, Pd, and Ir abundances in splits of the same sample analyzed by DCP, whereas the NAA method appears to yield higher gold values. The discrepancies among subsamples appear much too great to be attributed to the combined errors associated with differences in the recovery efficiency of fire-assay collection materials (Potts, 1989), analytical techniques, and sample preparation (e.g., Finkleman and Aruscavage, 1981). Rather, these results point to sample heterogeneity or a "nugget" effect, despite the relatively large sample size submitted for analysis (100 g; Van der Flier-Keller, pers. commun., 1991). Until such sampling problems are addressed, the association of higher concentrations of Pt and Pd with coals in fault zones versus those in the channel section may be more apparent than real. Thus, there is no clear case for large-scale mobility of PGE-rich ground waters along fault zones. Furthermore, if the noble metals were indeed precipitated from aqueous solutions, it is difficult to understand why such severe nugget effects would exist; a more dispersed, homogeneous distribution would seem more reasonable, especially in the vicinity of permeable channelways such as faults. The lack of any correlation between PGE and Au, noted by Van der Flier-Keller, is even

FIG. 2. Stratigraphic distribution of noble metals and Cr in Blakeburn opencast pit, Tulameen coal basin. Abundances reported to whole coal; Au, Ru, and Pt in ppb; Cr in ppm. Data sources: Van der Flier-Keller (1991, table 2 and fig. 3); Goodarzi and Van der Flier-Keller (1989, tables 1 and 2); E. Van der Flier-Keller (1991, pers. commun.) and B. N. Church (unpub. data for Cr in basalt at top of section). Symbols: square = basalt, circles = coal, triangles = clastic rocks, bars = composite samples taken from more than one unit (gaps left where units omitted). Open symbols and dashed bars are values below detection limits (1 ppb Au, 5 ppb Ru and Pt, and approx. 2 ppm Cr).

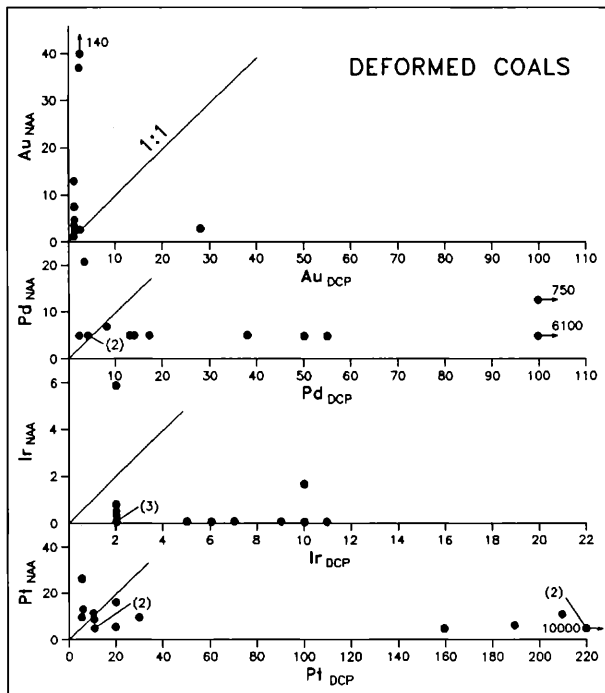


FIG. 3. Comparison of noble metal abundances in splits of deformed coal samples determined by neutron activation analysis (NAA) and direct current plasma spectroscopy (DCP). Results in perfect agreement lie on the solid line. Numbers in brackets refer to multiple points (omitting Au where most analyses lie near the origin).

more curious since this rules out the formation of amalgams of PGE and Au, or their combination as trace components in mineral solid solutions, even though these metals were traveling in the same fluids and similar factors are believed to control their precipitation. The magnitude of the nugget effect, however, is readily explained if PGE and Au occur as rare, highly concentrated, discrete grains (native metals or alloys) in the coals, as indeed inferred by Van der Flier-Keller (1991) from the lack of interelement correlations.

Using scanning-electron microscopy, Van der Flier-Keller (1991, p. 394) also identified "discrete, irregular, subrounded Au particles" in a single sample of deformed coal. A detrital origin was rejected due to the lack of a general correlation between Au concentration and ash contents of the coals, and a similar argument was advanced for the PGE (Fig. 4). The lack of such correlations, however, need not be a valid argument against a detrital origin. For example, detrital grains of noble metals and silicate mineral matter in the coal ash could quite reasonably be derived from more than one source region with different metal/silicate ratios, and the rate of supply of these variably metal-enriched sediments to the basin would be subject to variations in hydraulic factors

which are likely to vary in time and space (e.g., Fletcher and Day, 1989). In the case of coals in the Blakeburn accumulates in which heavy mineral grains are concentrated in proportions that correlate directly with their specific gravities (Gravel et al., 1990).

With respect to platinum, recent studies of fine-grained sediments ($<212 \mu\text{m}$) in streams draining the dunite core of the Tulameen Complex (Grasshopper and Olivine Mountains, Fig. 1) show a very clean separation of platinum into the heavy mineral fraction (Fletcher, 1989; Cook, 1991). Platinum in the soils and tills commonly occurs as Pt-Fe or Pt-Fe-Cu alloys enclosed in chromite or as free grains (Cook, 1991) due to mechanical disintegration of platiniferous chromitites in the bedrock (Nixon et al., 1990). Preliminary data for Pt in five moss mat samples at Grasshopper Mountain indicate concentrations (8-47 ppb) comparable to those in stream-sediment fines (8-78), whereas ground waters draining mineralized areas contain orders of magnitude less (<4 ppt Pt; Cook and Fletcher, 1990). Pt concentrations in ashed plants growing on mineralized areas are near or below the limits of detection (C. Dunn, pers. commun., 1990).

In the relatively low energy environment of coal swamps, it seems unlikely that mosses habitually behave as filters of fine-grained sediment traveling in the suspended load. It is more probable that preferential trapping of heavy minerals occurred during a radical change to a higher energy environment that terminates the life of the coal swamp. The minute grains of

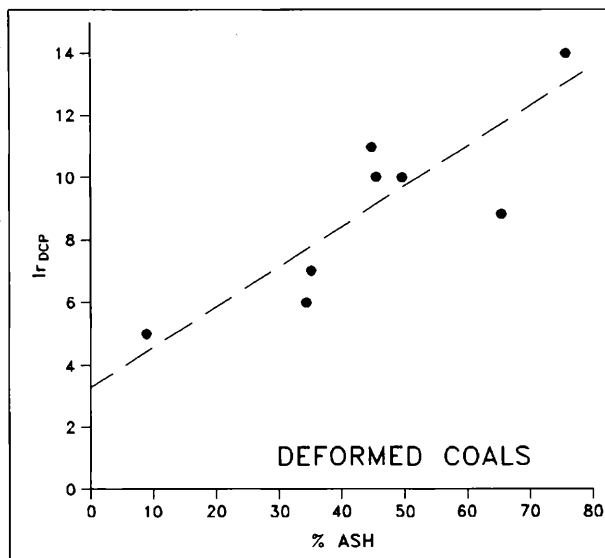


FIG. 4. Plot of Ir (ppb) vs. ash contents (wt %) of deformed coal samples (DCP analyses only). The least squares regression line (dashed) has a coefficient of correlation (r^2) of 0.72. Data from Van der Flier-Keller (1991, table 4).

gold and platinum-group minerals observed or inferred to be present in Blakeburn coals, along with other heavy minerals, may have selectively penetrated to significant depth within the mossy layer during overbank floods when a layer of silt or mud terminated the coal swamp environment. This explanation is consistent with the occurrence of highest Pt abundances with thin coals (units C1C2 and 11) at the top of the Blakeburn section. Thus, the moss matt analogy is an attractive alternative hypothesis because it can potentially produce mechanically enhanced concentrations of noble metals in coals and requires no mobility of PGE and Au after deposition.

On the basis of noble metal ratios in coals, stream sediments, and ultramafic rocks, Van der Flier-Keller (1991) inferred that the Tulameen Ultramafic Complex is the source of PGE in the coals and that the distribution of PGE in stream placers is also due to ground-water precipitation. She states (Van der Flier-Keller, 1991, p. 394): "Pt/Pd ratios in the deformed coals are most similar to ratios in -200-mesh-size Blakeburn Creek sediments. This suggests that enrichment of the deformed coal may be associated with circulating Pt-rich fluids, where Pt and Pd are similarly fractionated (during weathering and transportation) from the source, compared with stream sediments. Similar modes of transport of the Pt and Pd accumulating in stream sediments and coal are inferred. Derivation of the PGE from the Tulameen Ultramafic Complex is also suggested, since the stream placers are known to be derived from the Tulameen Ultramafic Complex (Ruble, 1986). Pt/Au ratios (combining the DCP and INAA data) for the deformed coal samples are within the ranges for chromite-rich ultramafics and the average for all ultramafic lithologies in the Tulameen Complex, supporting the contention that the PGE in the coals are derived from the Tulameen Ultramafic Complex."

This does not appear to be a reasonable assessment of the data at hand. First of all, the Pt/Pd ratios in the stream sediments (0.3–20.9) and deformed coal (0.4–16.1) cover a similarly extensive range, and major (unexplained) discrepancies exist in the data for the -200-mesh-fraction in different creeks (Pt/Pd = 0.8 in Newton Creek vs. 20.9 in Blakeburn Creek). Likewise, Pt/Au ratios show a huge range in coal (5–10,000) relative to sediment where discrepancies are again large between the -200-mesh fines from the same creeks (Pt/Au = 0.4 vs. 38, respectively). From these data it is difficult to justify any statement concerning the behavior or "fractionation" of noble metals.

Secondly, the inference that placer platinum is somehow related to colloidal precipitation or "accretion" of small particles released by leaching of mineralized bedrock (Cousins and Kinloch, 1976; cf. Van der Flier-Keller, 1991, p. 391) contradicts earlier ob-

servations by Raicevic and Cabri (1976) and Nixon et al. (1990). The latter authors were able to demonstrate that the textures and compositions of PGM and gangue minerals included in platinum nuggets were the result of primary magmatic processes with some modification by later high-temperature hydrothermal fluids. There is simply no textural or mineralogical evidence in Tulameen placers for accretion or precipitation of PGE in ground waters as proposed by Van der Flier-Keller and earlier authors (see also discussions in Cabri and Harris, 1975). Furthermore, recent measurements of Os isotope systematics in a worldwide sampling of platinum-group minerals from placers associated with Alpine- and Alaskan-type ultramafic complexes, including the Tulameen Complex, provide evidence that the PGE were derived from a mantle source without significant contribution of crustal Os (Hattori and Cabri, in press). These authors concluded that the platinum-group mineral grains formed in a high-temperature magmatic environment and were subsequently weathered, eroded, and concentrated in placers by mechanical processes, in concert with their mineralogy and textures.

Finally, the "similarity" of Pt/Au ratios is hardly a valid argument for concluding that the PGE in Blakeburn coals were derived from the Tulameen Ultramafic Complex. Alluvial gold in modern placers, at least, has been derived from more than one source, and the origin of much of the gold in the region has been related to a younger (Jurassic?) period of vein-type mineralization (Rice, 1947). In addition, these placers have been developed on a regional blanket of glacial till and undoubtedly incorporate detritus from a variety of sources (Cook and Fletcher, 1990). Furthermore, since Au and PGE in coals form separate mineral phases, it would seem extremely fortuitous if Pt/Au ratios did in fact reflect relative abundances of these metals in source rocks, regardless of which transport and deposition mechanism was at work. Moreover, these considerations may all be outweighed by the extreme sample heterogeneity noted earlier.

If the PGE are indeed present as detrital platinum-group minerals in the coals, a more rigorous test for an Alaskan-type heritage might be contained in the relative abundances of PGE in a given sample. The shape of PGE abundance patterns for various rock types of the Tulameen Complex, a potential source for PGE in Blakeburn coals, is given in Figure 5. The highest concentrations of PGE occur in chromitites which are characterized by M-shaped patterns with peaks at Ir and Pt separated by a trough at Ru. This pattern appears unique to Alaskan-type chromitites and is related to the accumulation of discrete platinum-group minerals, notably Pt-Fe alloys with minor Ir (Rh and Pd) in solid solution (Nixon et al., 1990;

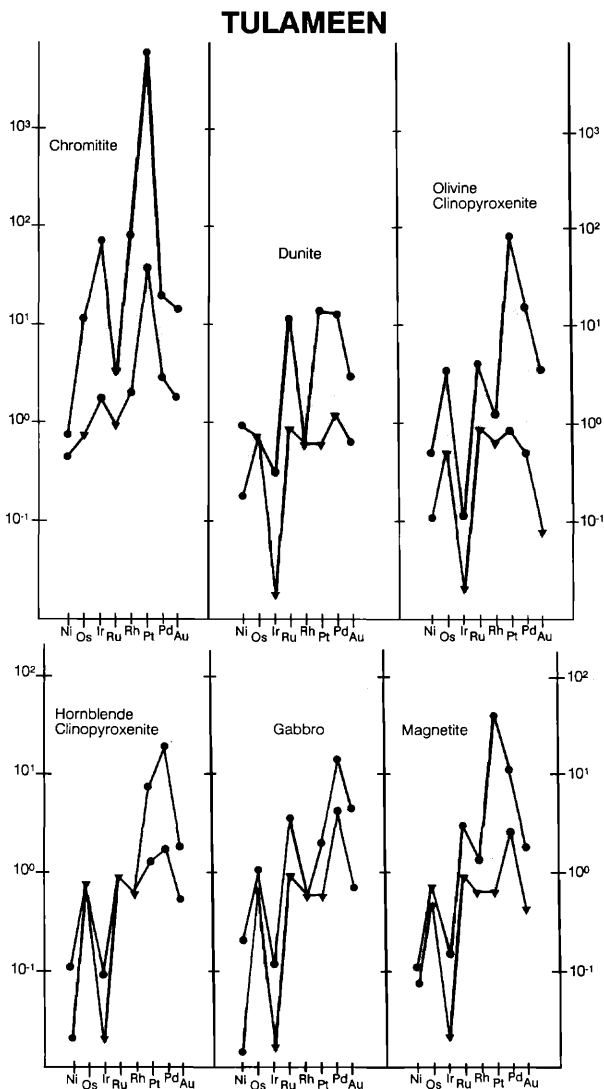


FIG. 5. Range of mantle-normalized PGE abundance patterns for common rock types of the Tulameen Ultramafic Complex (G. T. Nixon, unpub. data). Inverted triangles are values below detection limits. Normalizing values ($0.00815 \times C1$ chondrite for noble metals) are taken from Barnes et al. (1988).

Nixon and Hammack, 1991). Complementary depletions in Pt, Rh, and Ir are conspicuous in the dunite which hosts these chromitites. Also, the Pt/Pd ratio of the latter rocks is generally much higher than the ratio of these metals in pyroxenitic and feldspathic cumulates where Pt/Pd falls below unity. These patterns provide a basis for assessing the role of detrital mineral grains and rock fragments in the PGE abundances of Blakeburn coals.

There is some evidence to suggest that the platinum-group minerals that characterize Alaskan-type intrusions, in particular alloys, are fairly inert during weathering and transportation (e.g., Mertie, 1976; Raicevic and Cabri, 1976; Cabri et al., 1981). The

Goodnews Bay mining district in Alaska provides an excellent case in point (Mertie, 1976). High-grade platinum placers have been worked since 1927 in the valley and tributaries of the Salmon River. The source of the platinum-group minerals, predominantly Pt-Fe alloys and osmiridium intergrown with chromite and magnetite (Mertie, 1976; Rosenblum et al., 1986), has been traced directly to the dunite core of a nearby Alaskan-type intrusion. PGE abundances in 21 dredge concentrates collected from placers along the Salmon River valley are plotted in Figure 6. Without exception, the PGE abundances exhibit the same distinctive M-shaped pattern exhibited by Tulameen chromitites and reflect the composition of the principal alloys. A systematic increase in the abundance of Os and Ir relative to Pt downstream is primarily attributed to a decrease in grain size coupled with an influx of fine-grained Ir-Os alloy-rich material from streams entering the lower reaches of the Salmon River (Mertie, 1976). The integrity of the PGE pattern is maintained over the course of at least 10 km of placer claims, which is equivalent to the distance between Grasshopper Mountain, where most of the platiniferous chromitites are located, and coals at Blakeburn (Fig. 1). These data, therefore, suggest that transport and concentration of PGE in the surficial environment may be accomplished largely by physical processes, which has important ramifications for geochemical prospecting in Alaskan-type settings.

The abundance patterns for noble metals in selected Blakeburn coals are shown in Figure 7. The

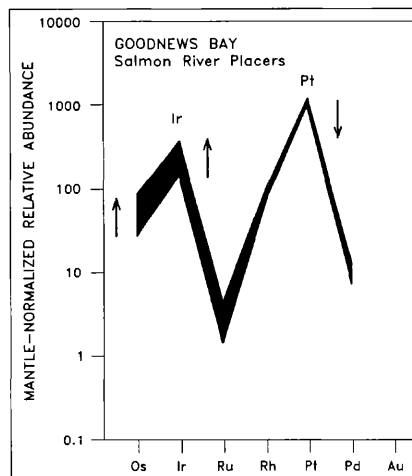


FIG. 6. Range of mantle-normalized relative abundance patterns of PGE in concentrates from dredge cleanups along the floor of the Salmon River valley, Goodnews Bay district, Alaska. Absolute concentrations are completely arbitrary. Arrows indicate systematic changes in the abundances of Os, Ir, and Pt with distance downstream. Normalizing values as in Figure 5. Data taken from Mertie (1976, table 22).

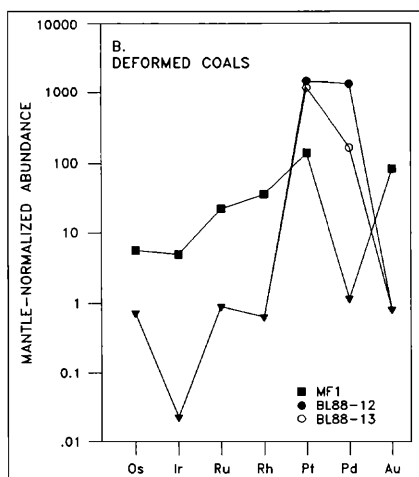


FIG. 7. Mantle-normalized PGE abundance patterns for selected coal samples in the Blakeburn section, Tulameen basin. A. Channel coals. B. Deformed coals (Van der Flier-Keller, 1991, tables 2 and 4). Normalizing values as in Figure 5. Inverted triangles are values below detection limits.

variable levels of Au enrichment may be attributed to particles of native gold. The PGE patterns, on the other hand, meet with mixed success where the nature and origin of the platinum-group minerals are concerned. For example, PGE abundances in three channel coals (units C1C2, 11, and 7) may be due to the presence of small amounts of Pt-Fe alloys (with minor Rh, Ir, and Os in solid solution) derived from Tulameen chromitites, possibly supplemented by Ir-Os alloy, which has been found only in the placers (Raicevic and Cabri, 1976). However, these patterns are also consistent with incorporation of either platinumiferous magnetite, derived from Lodestone Mountain in the southern part of the Tulameen Complex, or olivine clinopyroxenite which is more widespread (Figs. 1 and 5). PGE abundances in coal 25 appear more consistent with detrital fragments of hornblende clinopyroxenite or gabbroic rocks (cf. Fig. 5) which border the western margin of the coal basin. The positive slope of the pattern for deformed coal MF1 is consistent with detrital PGE-rich sulfide except for anomalously low Pd; this may have been selectively removed after deposition (e.g., Wood and Vlassopoulos, 1990). Deformed coals with the most extreme Pt and Pd concentrations (BL88-12 and -13) have Pt/Pd ratios that are inconsistent with the presence of Pt-Fe alloys from the Tulameen Complex and these signatures may indicate the presence of more than one species of platinum-group minerals. The best possibilities for detrital minerals rich in Pt include tulameenite (Pt_2FeCu) or sperrylite ($PtAs_2$) which appear fairly resistant to chemical attack (Cabri, 1981) and are found in placers and bedrock alike (Nixon et al., 1990). Palladium minerals, however,

are extremely rare in the Tulameen region and the only choice lies between kotulskite ($PdTe$) or genkinite ($(Pt, Pd)_4Sb_3$) which are both considered unlikely candidates. Kotulskite has only been found in placers and most likely was not derived from the Tulameen Complex (Raicevic and Cabri, 1976). Anomalous abundances of Ru noted earlier in the Blakeburn section may only be reconciled by detrital laurite (RuS_2) if the Tulameen Complex is the source of Ru. To date, laurite has only been found only as rare inclusions in Pt-Fe alloys (Nixon et al., 1990).

From the preceding discussion, it is clear that the PGE geochemistry contains no definitive evidence for the origin of PGE in Tulameen coals. In order to explain the PGE abundance patterns in the Blakeburn succession in terms of detritus supplied by the Tulameen Ultramafic Complex, the combined presence of a number of discrete platinum-group minerals are required. These include Pt-Fe alloys, Ir-Os alloys(?), tulameenite, sperrylite, Pt-rich magnetite, laurite, and very rare genkinite or kotulskite; in addition to possible contributions from olivine- and hornblende-bearing clinopyroxenites and gabbroic rocks. Difficulties arise, however, because some PGE patterns appear to require the presence of PGE-rich sulfides or Pt-Pd alloys with high Pd/Pt ratios which have no known counterparts in the Tulameen Complex.

Summing up, evidence for the ground-water precipitation hypothesis proposed by Van der Flier-Keller to account for anomalous abundances of PGE and Au in coals of the Tulameen basin does not stand up to detailed scrutiny. There is no conclusive evidence in the data presented for postdepositional mobility of PGE either at a local or regional scale. A detrital origin for the PGE and Au is fully consistent with the available data. In fact, it may be preferred as an explanation for the concentration of noble metals in Tulameen coal deposits if for no other reason than it provides a natural link between PGE in coals and alluvial placers. The recent Os isotope evidence for a mantle origin of PGE in Tulameen placers is particularly convincing (Hattori and Cabri, in press). A detrital origin for PGE in coal has also been favored by other authors (e.g., Finkelman and Aruscavage, 1981).

An alternative hypothesis for the origin of anomalous PGE in Tulameen coal is offered. Fine-grained detrital gold and platinum-group minerals brought into coal swamps by periodic floods are preferentially trapped by mosses and similar vegetation during a radical change in depositional environment, thereby promoting a close association between organic matter in coal and concentrations of noble metals occurring as rare heavy mineral grains. Geochemical correlations and relative abundance patterns cannot adequately establish the origin or

source(s) of the noble metals. Whether the noble metals actually traveled as dissolved species or colloids in surface waters to be deposited as organically bonded complexes in Blakeburn coals, or whether they were introduced as detrital grains remains to be firmly established. This could be effectively accomplished, for example, by detailed electron and/or ion microbeam examination of coal ash for Au and platinum-group minerals where information on mineral species, textures, solid solutions, and Os isotope ratios should elucidate a low- versus high-temperature origin for the noble metals.

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PLATINUM-GROUP ELEMENTS IN TULAMEEN COAL, BRITISH COLUMBIA, CANADA

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Sir: Recently, Van der Flier-Keller (1991) has attributed enhanced Pt values in coals of the Tulameen coal basin to transport of Pt in ground water and its precipitation in an organic-rich, low pH environment. The Tulameen Ultramafic Complex, several kilometers to the west, is proposed as the source of the platinum-group elements (PGE). Although we cannot comment on the overall scope of Van der Flier-Keller's conclusions, we present evidence for (limited) hydromorphic transport of Pt in the present weathering environment of the Tulameen Ultramafic Complex (Cook, 1991; Cook and Fletcher, in press).

The Tulameen Complex comprises a dunite core surrounded by crudely concentric shells of olivine pyroxenite, hornblende clinopyroxenite, and gabbroic rocks (Findlay, 1969; Nixon and Rublee, 1988). The PGE, which occur mainly as inclusions of Pt-Fe-Cu-Ni alloys in chromite grains and as interstitial Pt arsenides, are preferentially associated with chromitite segregations in the dunite (St. Louis et al., 1986; Nixon et al., 1990).

Our study area is on the dunite core (peridotite in fig. 4 of Van der Flier-Keller, 1991) of the complex north of the Tulameen River. Here Pt-bearing chromitites are well exposed near the summit and in cliffs on the southern side of Grasshopper Mountain (elev 1,500 m). An apron of dunitic talus beneath the cliffs locally overrides the thin glacial till that covers the lower slopes and a base of slope bench (1,100 m). The base of slope zone is characterized by ground-water seepage, bogs, and gleysolic soils. Elsewhere eutric brunisols and humoferric podzols are developed on dunitic and nondunitic tills, respectively. However, soil development is generally minimal because of active colluvial processes, climatic conditions, and the short time (ca. 10,000 yr) since deglaciation.

Sampling involved collection of organic-LFH and mineral horizons from 47 profiles; the uppermost 20

to 35 cm of organic material from three bogs (two in the base of slope zone and one perched bog close to Pt mineralization near the summit); and surface waters from 17 sites. Water samples (1 l) were filtered through 0.45- μ m filters within a few hours of collection and preserved by addition of hydrochloric acid.

C horizon soils were wet sieved to -212μ m, dried and representative (200–300 g) splits pulverized in a tungsten carbide ring mill. LFH horizon and organic samples were dried and ashed at 700°C in a muffle furnace. Pt and Pd content of 10-g splits was then determined by lead fire assay and inductively coupled plasma emission spectroscopy. Pt content of

TABLE 1. Pt Content (ppt) and pH of Waters

Location and water type	Pt (ppt)	pH	Color	
Grasshopper Creek, stream water	0.9	8.2	Clear	
	0.8	7.9	Clear	
	0.8	8.1	Clear	
	0.9	8.0	Clear	
	0.9	8.0	Clear	
	0.5	7.1	Clear	
	0.9	7.3	Light brown	
	Base of slope zone	1.0	6.3	Light brown
Bog 1		0.7	8.0	Light brown
Bog 2		0.9	6.9	Light brown
Soil pit		0.6	7.3	Light brown
Soil pit		0.9	7.0	Clear
Soil pit		2.2	6.7	Light brown
Summit	Bog 3	3.2	7.4	Brown
	Bog	3.5	7.3	Light brown
	Pond	1.8	7.6	Clear

All samples filtered to 0.45 μ m