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Mercury and other trace metals in the seasonal snowpack across the subarctic taiga-tundra ecotone, Northwest Territories, Canada

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A B S T R A C T

In Canada's Northwest Territories, mining for base metals and diamonds are vital economic activities which carry risks of adverse environmental impacts. To gather baseline geochemical data against which the impact of future mining activities may be measured, a survey of trace metal concentrations in snow was carried out in 2012 along a 285-km stretch of winter mining road crossing the taiga-tundra ecotone between latitudes 62.8 and 65.5° N. The distribution of 17 elements, including mercury (Hg), was measured and mapped. Results indicate that road traffic along the winter road has only a modest impact on the metal content of the nearby tundra-taiga snowpack, and that this impact is largely due to the mobilization of soil dust and associated elements. However, some enrichment of As, Pb, Sr and Zn in snow was detected near former gold mine sites, likely reflecting the windborne dispersion of contaminated soils. The Hg concentrations in snow across the study area were generally low ($\leq$3.01 ng L^{-1}), and did not covary with any other metals, which suggests atmospheric deposition from distant/diffuse sources. An analysis of air back-trajectories pointed to the most likely distant (>10^3 km) anthropogenic source regions being eastern Asia or Russia. Using Hg data from the present survey and another source, in combination with gridded maps of snowpack water equivalent, we calculated the potential flux of atmospherically-derived Hg that could be released by spring snowmelt into the Mackenzie River to be in the order of ~195–404 kg a^{-1}, which may represent a substantial fraction of the estimated total Hg discharge to the Beaufort Sea.

1. Introduction

Mineral/metal exploration and mine development have increased markedly in the Canadian subarctic and Arctic in recent decades, and will likely continue to do so as the warming climate allows for longer exploration seasons and better sea-route access (Furgal and Prowse, 2008). The Northwest Territories (NWT) in western Canada is an important region of active and prospective mining development which contributes substantially to the territorial economy. In 2014, the last year for which data are available, a total of CAD$ 101.7 million was spent in the NWT on mineral exploration and deposit appraisal, primarily for diamonds and gold (NRCan, 2016).

The Tibbitt to Contwoyto Winter Road (TCWR) is a major south-north transport route from Yellowknife to several exploration camps, or to operating or developing mining operations in the NWT (Fig. 1). Opened in 1982, the TCWR is the longest winter road in the world (varying between 400 and 600 km long, depending on mining activities), and is re-established each winter to pass over hundreds of frozen lakes and intervening permafrost terrain (EBA, 2005; Nuna Logistics Ltd, 2016). The TCWR is the main shipping and supply route for the operating Ekati, Gahcho Kué and Diavik diamond mines in the NWT (NRCan, 2016). Up to 10,000 transport truck loads are delivered along the ice road in February and March each year (Nuna Logistics Ltd, 2016).

The transport traffic along the TCWR, and the active and planned mine developments, are potential sources of trace metals to the surrounding regional environment through airborne emissions, transport and deposition. Heavy transport trucks and mining

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machinery have long been known to emit a variety of metals, such as Cr, V, Pb, Zn, Cu and Hg, derived from the combustion of fuel and wear of tires, brakes, and engine components (Huber et al., 2016; Morawska and Zhang, 2002), while fugitive dust generated during mining operations and containing trace metals may be dispersed by winds (Csavina et al., 2012). In subarctic regions where snowfall amounts are relatively low, metal contamination by dust dispersion may occur even in winter, and, in the absence of proper remediation steps, may persist long after mining operations are discontinued (e.g., Houben et al., 2016). The snowpack is not only the receiving medium for aeolian deposition; snowfall is an efficient scavenger of airborne particulate and aerosol metals (AMAP, 2005, 2011). During spring thaw, metals contained in the snowpack are likely to enter adjacent water bodies where they may become available to aquatic biota, including fish and waterbirds which are traditionally important subsistence foods for First Nations people in the NWT. For example, trace metal emissions from the former Giant gold mine near Yellowknife, including those in the form of fugitive dust, have led to elevated As levels in nearby lakes and fish (Cott et al., 2016; Houben et al., 2016). Mercury (Hg) is of particular concern in freshwater ecosystems because it is the only metal that biomagnifies (i.e., increases in concentration) at higher levels of food-chains (AMAP, 2011). Concerns have been raised about unsafe Hg levels (>0.2 to > 0.5 mg/kg wet wt.) in trout (*Salvelinus namaycush*) from Lac de Gras, near the Diavik diamond mine, although reasons for these elevated levels are as yet unknown (Health Canada, 2009).

The aim of this study was to develop an understanding of the concentrations and origins of trace and major elements in the snowpack of the region around the TCWR, in order to provide baseline data and perspective for future monitoring of possible metal contamination from the TCWR and regional mining activities. Previous measurements of trace elements in the snowpack of this area are rare, and limited to a few metals. These include an early assessment of As contamination in snowpack of the Yellowknife area (Hazra et al., 1977) and, more recently, a survey of Hg levels in snow across parts of the NWT and nearby Nunavut (Sturm et al., 2008), which will be discussed later. The most comprehensive report to date includes measurements on eight trace elements (As, Ba, Cr, Cu, Ni, Pb, Sb, and Zn) in Korosi et al.'s (2016) study of vehicle-derived contaminants in snow, lake sediments and waters at 14 stations along the TCWR and in Yellowknife.

The present study complements and expands the work of Korosi et al. (2016) by: (a) measuring the concentrations of total Hg and 16 other major and trace elements (Al, Ba, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Sc, Sr, Ti, U, V and Zn) in the snowpack along the TCWR; (b) collecting a large number of snow samples with ultra-clean techniques ($N = 68$) from a wider geographical area around the TCWR (37 sites across an area of approximately 38,000 km^2); (c) assessing the likely geochemical sources of trace metals in snow using metal-pair correlations and enrichment factors; and (d) calculating air back-trajectories to identify potential source(s) of metal aerosols deposited in snow across the study area. Finally, we used our measurements of Hg in snow and those of Sturm et al. (2008), combined with regional maps of snow water equivalent (SWE), to estimate a range of potential Hg releases from snowmelt into

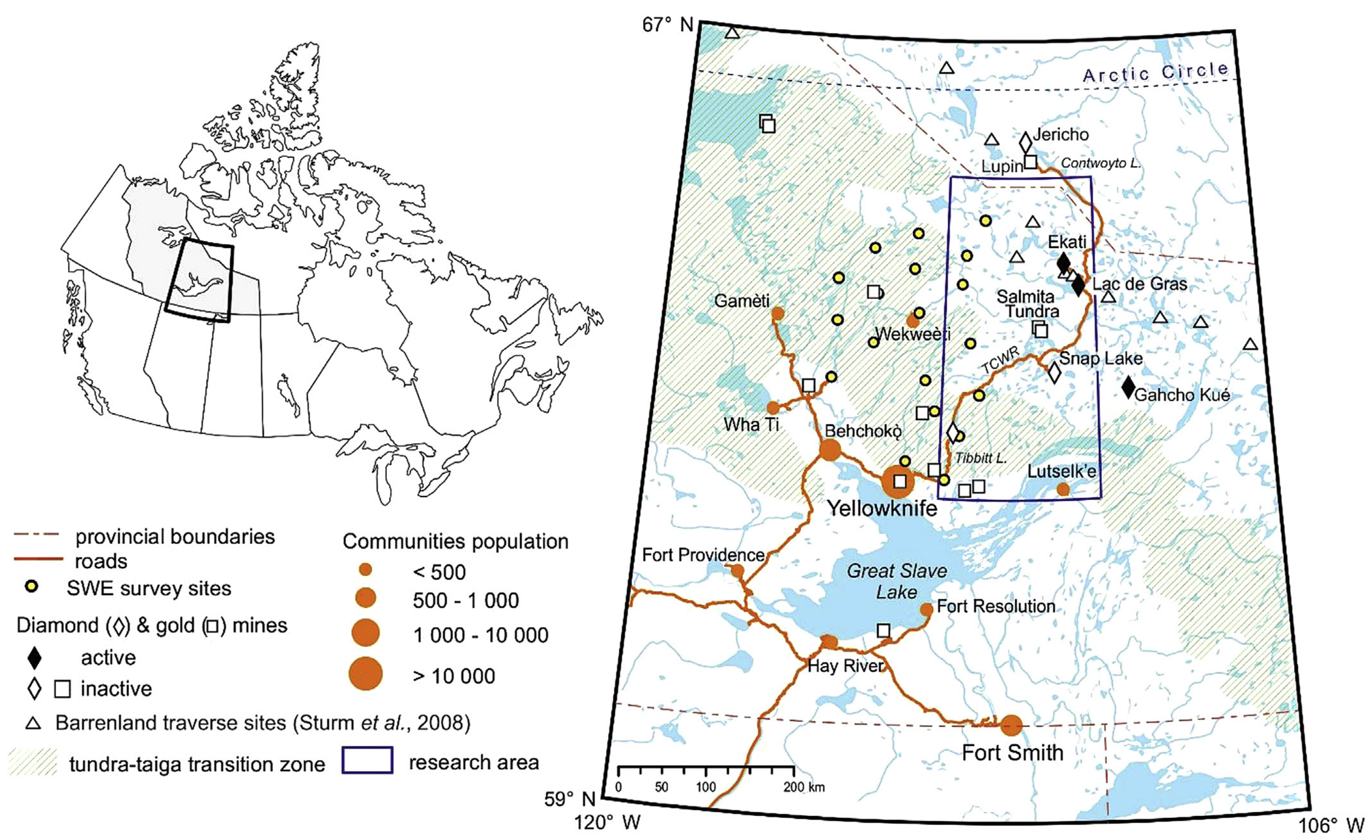

Fig. 1. Location map of part of the Northwest Territories, Canada. TWCR = Tibbitt-Contwoyto Winter Road. The study area (blue quadrangle in right-hand panel) is enlarged in Fig. 2. Population figures from 2011 census, mine status as of 2016. Yellow circles identify hydrometric survey sites from which historical data on snow water equivalent (SWE) were obtained. The extent of the taiga-tundra ecotone (green hatching) is based on MODIS vegetation cover mapping over the period 2000–2005 (Ranson et al., 2011). Also shown are some of the locations sampled for snow chemistry by Sturm et al. (2008) as part of the Barrenland traverse. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)