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High-resolution lake sediment reconstruction of industrial impact in a world-class mining and smelting center, Sudbury, Ontario, Canada

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ABSTRACT

A lake sediment core from Vermillion Lake, Sudbury, Ontario was tightly sampled and analyzed for a wide range of trace elements as well as for Pb isotopes. The data resolve multiple historical events in the 140-a history of logging and mining in the Sudbury area in unprecedented detail. Lead-210 data, ^{137}Cs activity and historical information on the start of anthropogenic activities in the Sudbury area were combined to derive an age model for the sedimentary column. Using the age information, it is possible to identify sediment sections enriched and depleted in trace metal(loid)s, particularly Ni and Cu, the two most relevant metals in the Sudbury area. Maxima and minima in the chronology of Ni and Cu coincide well with local production values for both elements until environmental regulations in the 1990s resulted in a decrease in their emission and drainage into Vermillion Lake. Differences in the deposition rates of Ni and Cu, trace-metal distribution patterns throughout the sedimentary column, Pb-isotope data, and comparison with data for local rocks and ores in the Sudbury area were used to identify the sources of pollutants in the early and late periods of mining activities. In addition, the environmental impact on the sediment itself was also studied via the variation of water content and organic matter. Finally, a surficial Fe–Mn-enriched layer with elevated concentrations of the oxy-anions $(PO_4)^{3-}$, $(AsO_4)^{4-}$, and $(MoO_4)^{2-}$ was identified. This can be distinguished from accumulation of Zn and an increase in the Y / Ho ratio in the upper core sections, which likely imply increasing drainage of fertilizers into the Vermillion River watershed. The chemistry, mineralogy, and isotope composition of the Vermillion Lake sediment column thus contain a very detailed >140-a account of initial severe anthropogenic disturbance, the efforts of remediation and the effects of changing land use towards agricultural and recreational activities.

1. Introduction

Human industrial activity has severely impacted the distributions of major, minor and trace elements (including stable isotopes) in the Earth surface environment. Accumulation of elements and isotopes in sedimentary archives such as peats (e.g. Weiss et al., 2002; Shotyk and Krachler, 2010) and marine and lacustrine sediments (Kober et al., 1999; Parsons and Cranston, 2006) can serve as sensitive records of industrialization and landscape modifications by agriculture, logging, mining and urbanization. Precise and accurate geochemical mapping of lake sediment and peat cores can be used to delineate between different anthropogenic and geological sources and processes. For example, Marx et al. (2010) used trace elements in an Alpine peat bog to distinguish between Australian dust transported to New Zealand and local New Zealand dust and Marx and Kamber (2010) were able to identify different sources and processes involved in the formation of basin sediments in a low-elevation river system.

This study explored the potential of high resolution sampling of a ^{210}Pb and ^{137}Cs-dated lake-sediment core in combination with comprehensive trace-element data and Pb-isotope ratios for reconstructing the detailed chronology of the mining, smelting, logging, agricultural and recreational activities in Sudbury, Ontario, Canada (Fig. 1a).

1.1. Chronological studies of sediment cores

The distribution of major and trace elements in sedimentary columns can reveal chronological details of periods of pollution and recovery (e.g. Smol et al., 1998; Smol, 2008). The resolution of these events depends, however, on the sedimentation rate, thickness and type of sediments (Belzile and Morris, 1995), bioturbation, size and development of the corresponding watershed, mineralogical composition, grain size distribution and remobilisation of the elements in the column as well as its distance from the anthropogenic and geological sources (e.g. Tropea et al., 2010). For example, oxy-anions such as $(AsO_4)^{3-}$ and $(PO_4)^{3-}$ show a high affinity towards positively charged surfaces of Fe–Mn–oxides,

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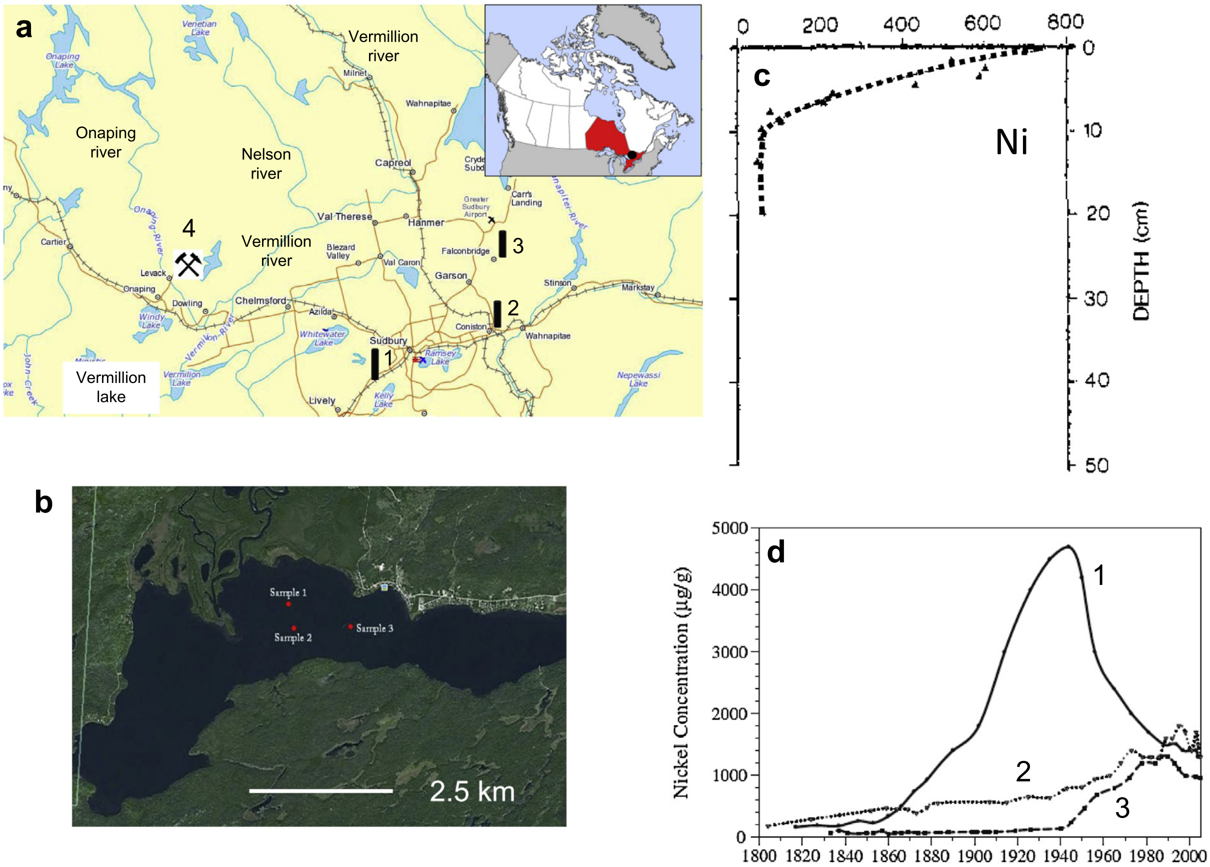

Fig. 1. (a) Map of the upper and middle part of the Vermillion River water shed with the locations of the smelter centers at Copper Cliff (1), Coniston (2) and Falconbridge (3) (indicated with sketched chimneys) and the mine tailings areas at Levack (4); an index in the upper right corner shows the location of Sudbury within Ontario, Canada; (b) satellite images of Vermillion lake with the sample locations for three sediment cores; (c) and (d) Examples of previous studies on the distribution of metals in sedimentary cores: depth profile for Ni in sedimentary cores from (c) the center of Vermillion lake (modified from Nriagu et al., 1982) and (d) Daisy lake (labeled 1), Swan lake (2) and Tilton lake (3) (modified from Tropea et al., 2010).

whereas cationic aqueous species either adsorb to negatively charged organic material or precipitate in the form of sulfides or oxides within organic-rich layers of low pe (Belzile and Tessier, 1990; Tessier et al. 1994; Belzile and Morris, 1995; Stumm and Morgan, 1996). The concentration of trace elements in these layers is controlled by their concentration in the water column as well as by adsorption and redox processes on the micron scale (Tessier et al., 1994; Belzile and Morris, 1995; El Bilali et al., 2002). Hence, the higher abundance of a trace element in an organic- or Fe–Mn–oxide-rich layer relative to a clay- or sand-rich layer may not necessarily reflect a higher concentration of this element in the water column at the time of sedimentation. The distribution and nature of metal-enriched layers must, therefore, be carefully investigated before element distribution chronologies can be linked to anthropogenic activities or climate change.

1.2. Objectives and approach

The major goal of this study was to test whether high-resolution sampling of a lake sediment core could resolve multiple environmental events over the last 140 a in the Sudbury area. The important environmental factors that have affected Sudbury are tightly linked to its mining history and were mainly felt through emissions from local smelters. The chronology of emissions may at first glance seem to be of local relevance only. However, because the Sudbury mining district is a major global supplier of Ni and Cu, emissions from its smelters varied strongly with global metal demand. Therefore, it is conceivable that the environmental fallout surrounding Sudbury could reflect global events such as the beginning of World War I (WW I), the Great Depression in the 1920s, World War II (WW II), the Korea boom, and the Vietnam War. In addition, this study wanted to test whether a highly resolved chronology could detect societal changes, such as workplace improvements achieved through union strikes (and concomitant smelter shutdowns) and an increased focus on the agricultural and recreational value of the land (via increased use of fertilizers). Several of these events occurred within less than a 10-a period, which imposes a series of requirements for the archive (sufficiently high sedimentation rate, size of the watershed and proximity to smelters, absence of complicating organic-rich surface layers) and the applied method (sampling interval, age dating frequency, data precision). A location that may fulfill these requirements is the Vermillion River delta at Vermillion Lake, approximately 32 km west of the city center of Sudbury (Fig. 1a and b). The lake has the highest sediment influx of all lakes in the Sudbury area with 425 g m^{-2} a^{-1} (Nriagu et al., 1982). Although the lake itself may have had limited exposure to smelter emissions transported by the prevailing northeasterly wind directions, its associated watershed encompasses an area that was heavily impacted by deposition of atmospheric emissions as well as mining activities (Fig. 1a and b).

2. Background and methods

2.1. Recent history of the Sudbury area

Although the Hudson's Bay Company established a fur-trading post in the Sudbury area in 1824, it was not until the 1871 great