High-resolution magnetic mapping of contaminated sediments in urbanized environments

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The remediation of contaminated sediments in industrialized harbors and waterways is a growing environmental concern in North America. More than 100 marine ports and 42 inland harbors in the Great Lakes basins are currently listed by U.S. and Canadian regulatory agencies as having severe habitat and water-quality impairments due to bottom-sediment toxicity. Current approaches to remediation include sediment dredging and removal, capping with clean sediment, and in-situ treatment with oxidants.

Regardless of the remediation approach employed, a major requirement for such projects is detailed mapping of contaminated sediment distribution, thickness, and pollutant concentrations. Conventional practice is to estimate sediment properties and pollutant levels by interpolation from a limited number of bottom core samples. However, even with relatively dense borehole spacing, this approach can lead to significant errors in estimating the distribution and total volume of sediments requiring cleanup. Core sampling and chemical analysis can also be prohibitively expensive and impractical in large contaminated basins. A geophysical approach is to use magnetic methods to remotely map the distribution of urban source sediments in coastal areas.

In this paper we highlight the preliminary results of a pilot project which is evaluating the use of magnetic property measurements for mapping contaminated harbors and waterways in western Lake Ontario (Figure 1).

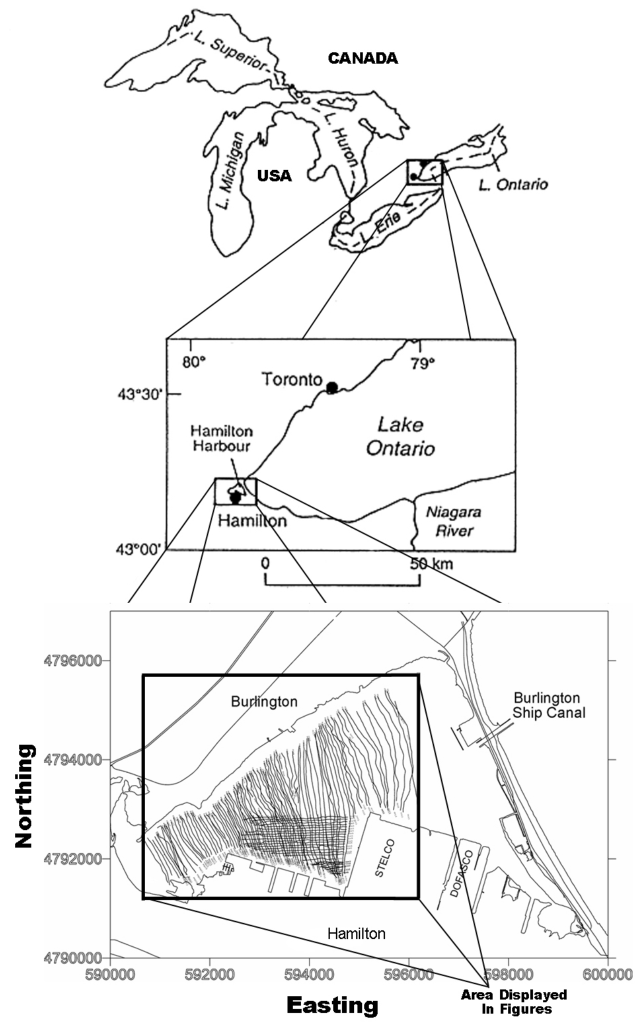

Figure 1. Map of Hamilton Harbour study area showing magnetic survey track lines.

Magnetic property measurements of contaminated sediments. Contaminated sediments in industrialized harbors and rivers are often characterized by elevated levels of magnetic oxides (principally magnetite) produced by the burning of fossil fuels. Following release into the atmosphere by combustion, the magnetic particles are deposited in lakes and rivers and ultimately become part of the sediment column. A number of studies have demonstrated that measurement of the magnetic susceptibility (κ) of bottom sediments in lakes and rivers can provide a useful indicator of the presence of urban source sediments and contaminants. Recent work in Hamilton Harbour in western Lake Ontario demonstrates that the presence of hydrocarbon compounds (e.g., coal tar), trace metals, and other priority pollutants can be reliably predicted by measuring magnetic susceptibility in bottom core samples. The levels of polycyclic aromatic hydrocarbons in sediments in particular tend to be closely tied with magnetic oxide content because they are by-products of the same combustion processes.

Figure 2a shows a typical bottom sediment magnetic susceptibility profile from Hamilton Harbour obtained from a 1.3-m core. The approximate age of the sediments is based on ^{210}Pb dating. The onset of industrialization in the harbor in the 1890s is recorded by a rapid increase in κ at a depth of 60 cm. This horizon marks the base of the "postindustrial" sediment layer and provides a useful marker horizon for estimating the thickness of contaminated sediment within the harbor. The profile reaches a peak κ value in the late 1970s of about 2×10^{-4} cgs which, for comparison, is roughly equivalent to the susceptibility of a basalt and represents more than an order-of-magnitude increase above the background κ. The thickness and extent of the urban sediment layer in the harbor have been estimated by interpolation of the core κ data (Figures 2b and 2c). These maps identify a well defined magnetic susceptibility anomaly along the southeast shore of the harbor which is related to industrial discharges from nearby steel mills and urban effluents from the city of Hamilton. The peak κ values occur within the heavily contaminated Randall Reef area (Figure 2) in the southeast corner of the harbor. Based on the magnetic susceptibility mapping, the total volume of sediment requiring remediation within the harbor has been estimated at more than 12 $\times 10^6$ m^3.

High-resolution lake-based magnetic mapping. Although

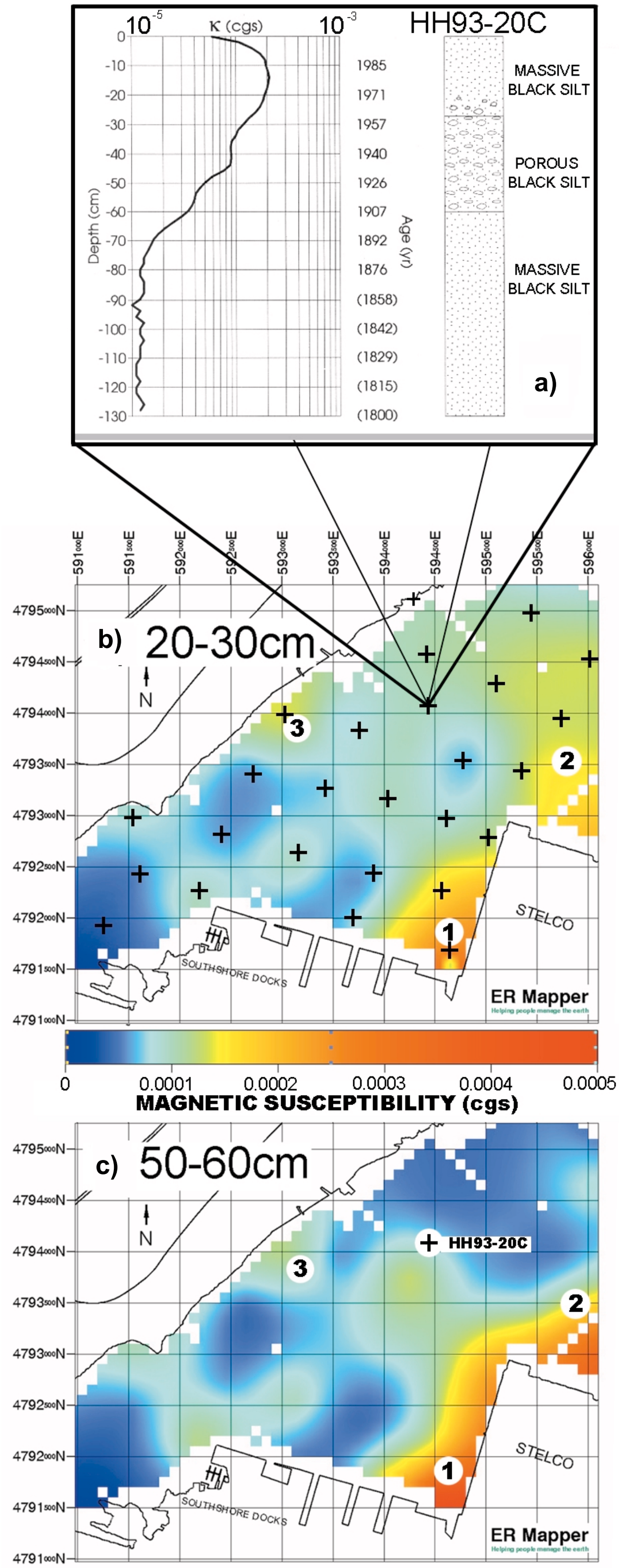

Figure 2. (a) Magnetic susceptibility (κ) versus depth in bottom sediment core sample. Approximate sediment ages based on ^{210}Pb dates (from Versteeg et al., 1995). (b) and (c) Bottom sediment magnetic susceptibility maps interpolated from 40 core samples (crosses on map) for depth intervals 20-30 cm and 50-60 cm. Magnetic susceptibility anomalies 1 and 2 identify inputs of urban source sediments from nearby steel works and sewer outfalls. Anomaly on north shore (3) identifies inputs of urban effluents from stream channel.

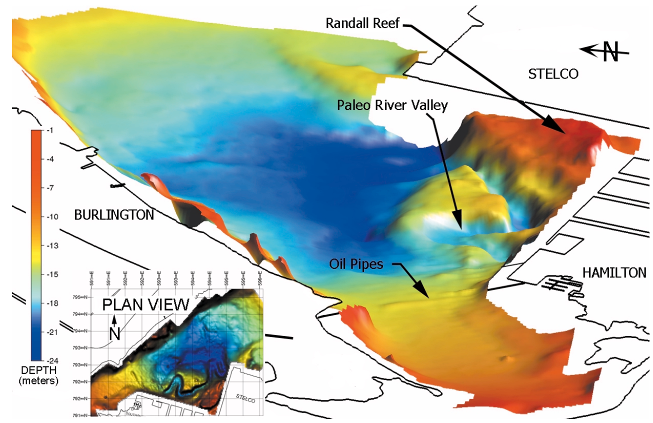

Figure 3. 2.5-D representation of harbor bathymetry (viewed from west to east) showing Randall Reef and submerged river channel on harbor bottom. Water depths in meters below lake level. Inset on lower left shows map view.

measurement of sediment κ provides a more rapid "proxy" method for assessing contaminant levels than conventional chemical assay methods, it suffers from several drawbacks. First, it requires collection of core samples, and second it provides only "at-a-point" data which must be interpolated to produce maps of urban sediment distribution. An alternate geophysical approach, currently under development, is to remotely measure sediment magnetic properties and the presence of contaminants using a towed marine magnetometer. Core data indicate that the κ of the contaminated layer is 1-2 orders of magnitude greater than the clean underlying precolonial sediments. The κ contrast is large enough to produce a well-defined magnetic anomaly (typically 1-30 nT) which can be mapped with a total-field magnetic survey using a marine magnetometer. Total-field data, through several processing steps, can in turn be used to determine the apparent (relative) susceptibility of the bottom sediments. The major advantage over direct core κ measurements is the much higher sampling density that can be achieved. Towed magnetic data can be collected as a grid of closely spaced survey lines that systematically cover the lake bottom (Figure 1). In recent work, we have conducted surveys with nominal line spacings of 25 to 75 m and a magnetometer sampling rate (measurement interval) of 4 Hz. This yields about one measurement every meter at boat speeds of 10 km/hour. The high density of data that is achieved allows for greatly enhanced spatial resolution and recording of magnetic anomalies with spatial frequencies as small as 0.5-12.5 m (in-line and cross-line, respectively). In real terms, this translates into highly detailed images of bottom sediment magnetic response that can be used to map the postindustrial sediment distribution.

Recent survey work in Hamilton Harbour has been conducted using a single Overhauser marine magnetometer (Marine Magnetics "SeaSpy") deployed from a small boat. SeaSpy is a fully digital system which provides high sensitivity (about 0.015 nT) and is an omnidirectional sensor free from heading errors which complicate the use of optically pumped magnetometers. High sensitivity is a critical requirement for detecting small variations in the magnetic field produced by κ contrasts in lake-bottom sediments.

The survey is acquired by towing the magnetometer about 30 m behind a small survey launch with the sensor at a constant elevation above the harbor bottom. Survey positioning is provided by an onboard D-GPS and navigational chart plotting system which directly encodes survey posi-

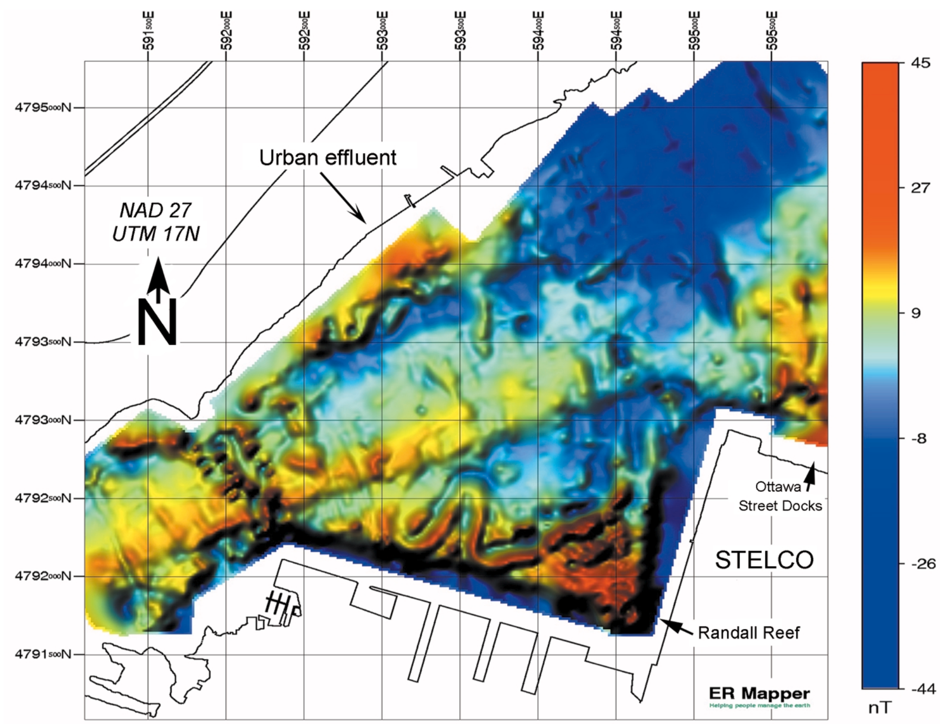

Figure 4. Preliminary residual total field magnetic map of Hamilton Harbour. Note positive magnetic anomaly associated with Randall Reef and steel works docks on southeast shore.

tions with the digital magnetic data. Digital bathymetry data (Figure 3) are collected simultaneously using a 200 kHz echo sounder system. The digital bathymetry data are crucial for precise correction of variations in the magnetic field strength related to changes in water depth. Prior to the start of surveying, several base station magnetometers are deployed in "magnetically quiet" areas around the survey site to record the diurnal field variations. Locating base station areas free from cultural magnetic noise can be a major challenge in urban waterways but is essential for accurate diurnal corrections.

Several postcruise processing steps are applied to the magnetic total field data to obtain a residual magnetic map (Figure 4) which emphasizes the contributions from shallow magnetic sources. The general processing flow includes:

- base station corrections for diurnal field variations
- tie-line and microleveling of survey data to remove corrugation noise
- gridding of data using a minimum curvature algorithm
- removal of depth-related changes in signal intensity by downward continuation to a constant elevation datum (draping)
- regional separation (removal of long-wavelength signals associated with deep structure)
- Butterworth band-pass filtering to remove high-frequency noise

Results. Preliminary testing was completed last year with collection of 80 line-km of magnetic and digital bathymetry data in Hamilton Harbour (Figure 1). The bathymetry data reveal a central harbor basin with maximum water depth of 24 m and identify a previously unrecognized meandering feature on the south shore of the harbor (Figure 2). The feature records a partially buried paleo river valley which existed during an earlier phase of low lake levels (-30 m) in Lake Ontario. The bathymetry also clearly images several buried oil pipelines which cross the southwestern end of the harbor and the mound-like Randall Reef area on the south shore. Figure 4 shows the residual magnetic map for the harbor which is the result of subtraction of a 10-m upward continuation of the data from the corrected total-field data. Tie-line data have not yet been collected for the entire harbor area and some short wavelength line corrugation is present in the data. The residual map identifies a number of magnetic anomalies on the harbor bottom, including well defined positive anomalies over Randall Reef and the adjacent paleoriver channel. The magnetic anomaly pattern within the basin corresponds generally with the trend of magnetic susceptibility maps (Figures 2b, 2c) but provides greatly enhanced detail. Randall Reef stands out as the region of highest magnetic intensity and shows considerable magnetic relief. Other distinctive features in the residual field map include a broad, linear magnetic anomaly which parallels the axis of the harbor. This feature does not appear to have bathymetric expression but is aligned parallel with a known west-east trending fault which offsets bedrock below the harbor. The anomaly is enigmatic, but may record a local thickening of sediments within a fault-controlled topographic depression (graben?) in the bedrock surface below the harbor. The residual field map also identifies several smaller magnetic anomalies on the north shore of the harbor which include known areas of bottom sediment contamination. The source of these urban sediment inputs is not yet well understood but they likely represent influx of contaminated sediment from urbanized streams draining southward into the harbor.

Figure 5 shows the results of a detailed survey of the Randall Reef area acquired with a nominal line spacing of 25 m. The closer line spacing provides much enhanced resolution of magnetic boundaries defining the edge of the reef and the adjacent paleoriver channel. It is noted that the meander channel is defined by a positive magnetic anomaly which is intuitively the reverse of what should be expected for a topographic depression on the harbor bottom (due to fall-off of amplitude with distance from the source). The positive anomaly indicates that the former river channel is at least in part infilled by a layer of relatively high magnetic susceptibility sediment. The likely source of the sediment is the downslope movement of sediment from the adjacent Randall Reef. The general decline in magnetic intensity within the meander channel northward from Randall Reef is suggestive of the basinward transport and thinning of the postindustrial sediment cover into the basin.

Interpretation of magnetic data is further aided by 2-D forward modeling of the observed anomaly patterns in the harbor. Figure 6 shows a modeled profile across the southern portion of Randall Reef (location in Figure 5). In the model, uncontaminated precolonial sediments are assigned

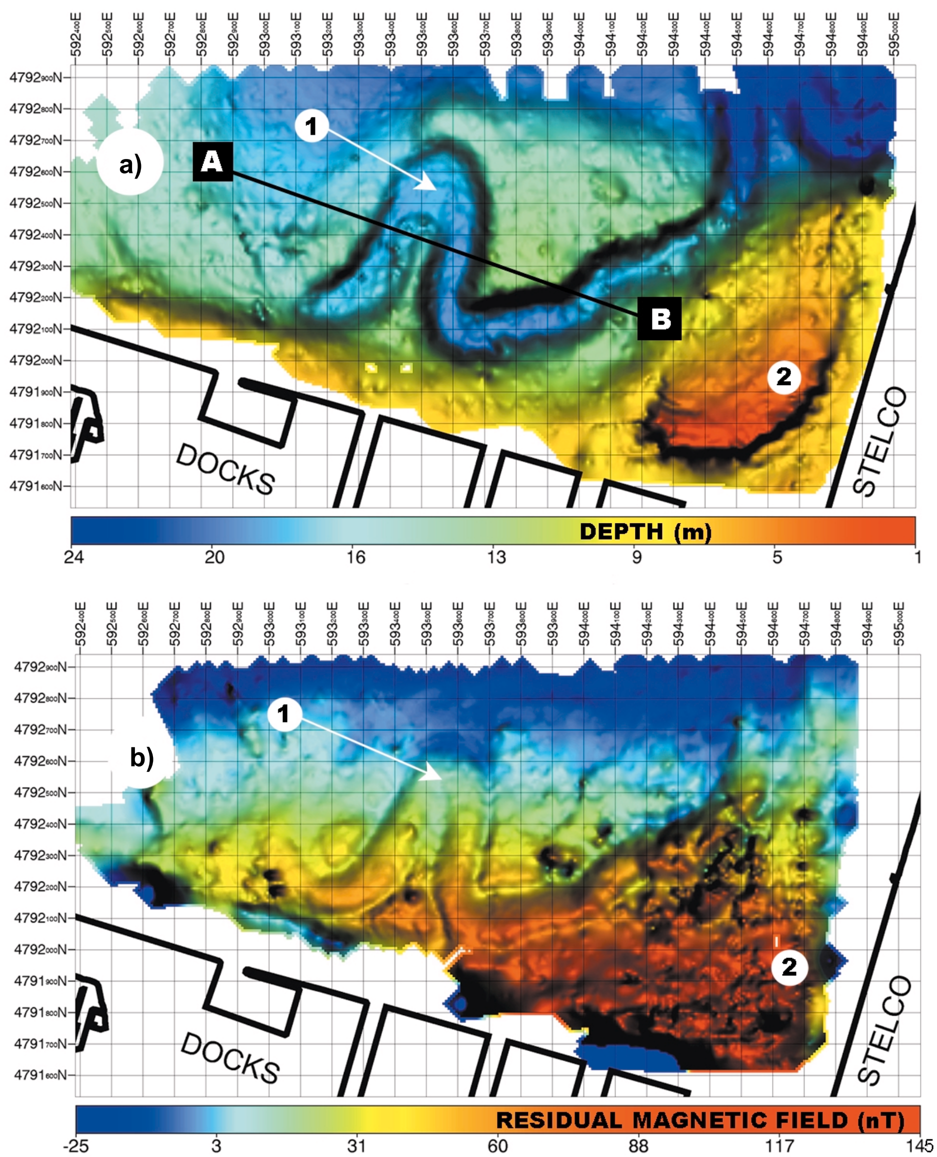

Figure 5. (a) High-resolution bathymetry obtained from detailed survey (25-m line spacing) of Randall Reef area. (b) Residual total-field map obtained from same area. Note positive anomaly due to accumulation of urban sediments in former river valley.

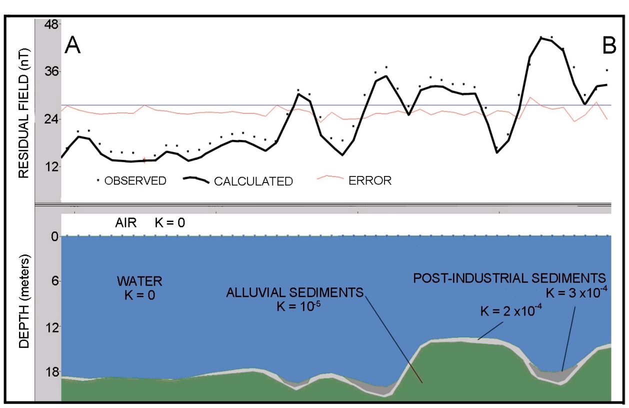

Figure 6. 2-D modeled magnetic field variations across Randall Reef (see Figure 5a for location of profile). Positive anomalies recorded in field data are consistent with the presence of 0.5-1 m layer of contaminated sediment (10^{-4} cgs) overlying low susceptibility precolonial sediments (10^{-5}-10^{-6} cgs).

a κ value of 10^{-5} and the upper contaminated sediment layer a κ value 10^{-4} cgs. Comparison of the field data with the modeled sediment magnetic response confirms that a contaminated sediment layer about 0.5-1.0 m in thickness is sufficient to generate the observed magnetic anomaly patterns. This thickness is consistent with the average thickness in core samples (Figure 2).

The primary limitation of the method is that it is applicable only in areas in which the natural (precolonial) bottom sediments have a relatively low magnetite content and low magnetic susceptibilities when compared with urban source sediments. The method is likely to be less successful in areas where high susceptibility igneous or metamorphic bedrock is close to the surface.

Areas which have favorable geology for shallow magnetic mapping include much of the lower Great Lakes basins and other areas where the Precambrian basement rocks are overlain by a substantial thickness of low-susceptibility Paleozoic sedimentary cover rocks.

Under these conditions the measured field strength will be dominated by the bedrock response.

Conclusions. The results of this pilot study indicate that strong magnetic susceptibility contrasts associated with the presence of magnetic oxides in contaminated lake sediments may be measured using a towed Overhauser magnetometer. Detection of shallow magnetic anomaly patterns in harbor sediments depends on collection of closely spaced survey lines (< 25 m) and careful postcruise processing. A key requirement is removal of regional and depth-related variations in the magnetic field intensity which would otherwise mask subtle magnetic anomalies.

Preliminary results from Hamilton Harbour demonstrate that magnetic survey methods have the potential to provide an improved and more rapid means of mapping contaminated sediment distribution in harbors and urban waterways. A primary advantage over conventional core-based analyses is that entire basin areas can be mapped with a high density of physical property measurements. The method is not likely to replace the use of conventional chemical assay methods for determining contaminant concentrations, but it has good potential to be used as a reconnaissance method for assessing the distribution of urban source sediments prior to collection of core data.

Suggested reading. "Heavy metal and magnetic relationships for urban source sediments" by Beckwith et al. (*Physics of the*

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(Boyce, from p. xxx)

Earth and Planetary Interiors, 1986). "The utility of magnetic properties as proxy for mapping contamination in Hamilton Harbour sediment" by Versteeg et al. (*Journal of Great Lakes Research*, 1995). "Magnetic susceptibility mapping of roadside pollution" by Hoffmann et al. (*Journal of Geochemical Exploration*, 1999). "Low-field magnetic susceptibility—a proxy method of estimating increased pollution of different environmental systems" by Petrovsky et al. (*Environmental Geology*, 2000).

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