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THE APPLICATION OF LAKE SEDIMENT GEOCHEMISTRY TO MINERAL EXPLORATION: RECENT ADVANCES AND EXAMPLES FROM CANADA

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ABSTRACT

In the glaciated Precambrian Shield areas of North America, lake sediment geochemical surveys are widely used to provide a regional geochemical framework for mineral exploration, especially in underexplored frontier areas. Most surveys are at a reconnaissance sample density of one site per 6–13 km^2*, and the results used for grassroots exploration. Higher resolution surveys with sample densities up to one site per* km^2 *have been carried out in several areas across Canada, and many have led directly to claim-staking. A secondary application of growing importance for all these survey data is their use to establish baselines for most elements of environmental concern.*

Advances in the application of lake sediment geochemical surveys over the past decade have been incremental. The number of elements routinely determined has increased to 30 or more, allowing the direct detection of most types of mineral deposit. The organisation of lake sediment geochemical data into digital databases has made the information much more useful and accessible for mineral exploration and other applications, and GIS techniques can be applied to analyse and interpret them more completely. The use of lake sediment cores by environmental geochemists to measure temporal geochemical changes provides new insights for the interpretation of the regional data for mineral exploration, and offers new approaches to exploration in contaminated areas.

INTRODUCTION

This paper briefly updates earlier, more extensive reviews of the application of regional lake sediment geochemistry to mineral exploration by Coker *et al.* (1979) and Hornbrook (1989). Fresh insights on this topic from studies of geochemical stratigraphy in lake sediment cores are summarised, and some examples of recent applications of lake sediment geochemistry in mineral exploration for gold and base metals are described.

Regional geochemical mapping is now widely used by geological surveys to support and encourage mineral exploration. Active stream sediment is the most widely used sample medium globally (Plant *et al.*, 1989), but over much of the Precambrian Shield of North America, which is characterised by low topographic relief, high water table and poorly developed drainage, geochemical surveys based on organic lake sediment are more effective. Furthermore, in this region sampling costs for lake sediment are significantly less than for alternative sample media such as glacial till.

In Canada during the past 25 years, systematic lake sediment geochemical surveys have been carried out over 2 600 000 km^2 (Figure 1), with the collection of organic lake sediment from some 181,000 sites. About half of these surveys have been carried out under the National Geochemical Reconnaissance (NGR) program (Friske and Hornbrook, 1991), led by the Geological Survey of Canada (GSC). Most of the remainder have been conducted by the Ministère des Ressources Naturelles (MRN) and other Québec government agencies.

The main application of these surveys, most of which have been at a reconnaissance sample density of one site per 6–13 km^2, has been in grassroots exploration, especially in less explored frontier areas. In some cases they have led directly to new discoveries, but in most instances they have been used in combination with other information to guide mineral exploration. Higher density surveys (up to one site per km^2) are available for several areas across Canada, and in many cases have led

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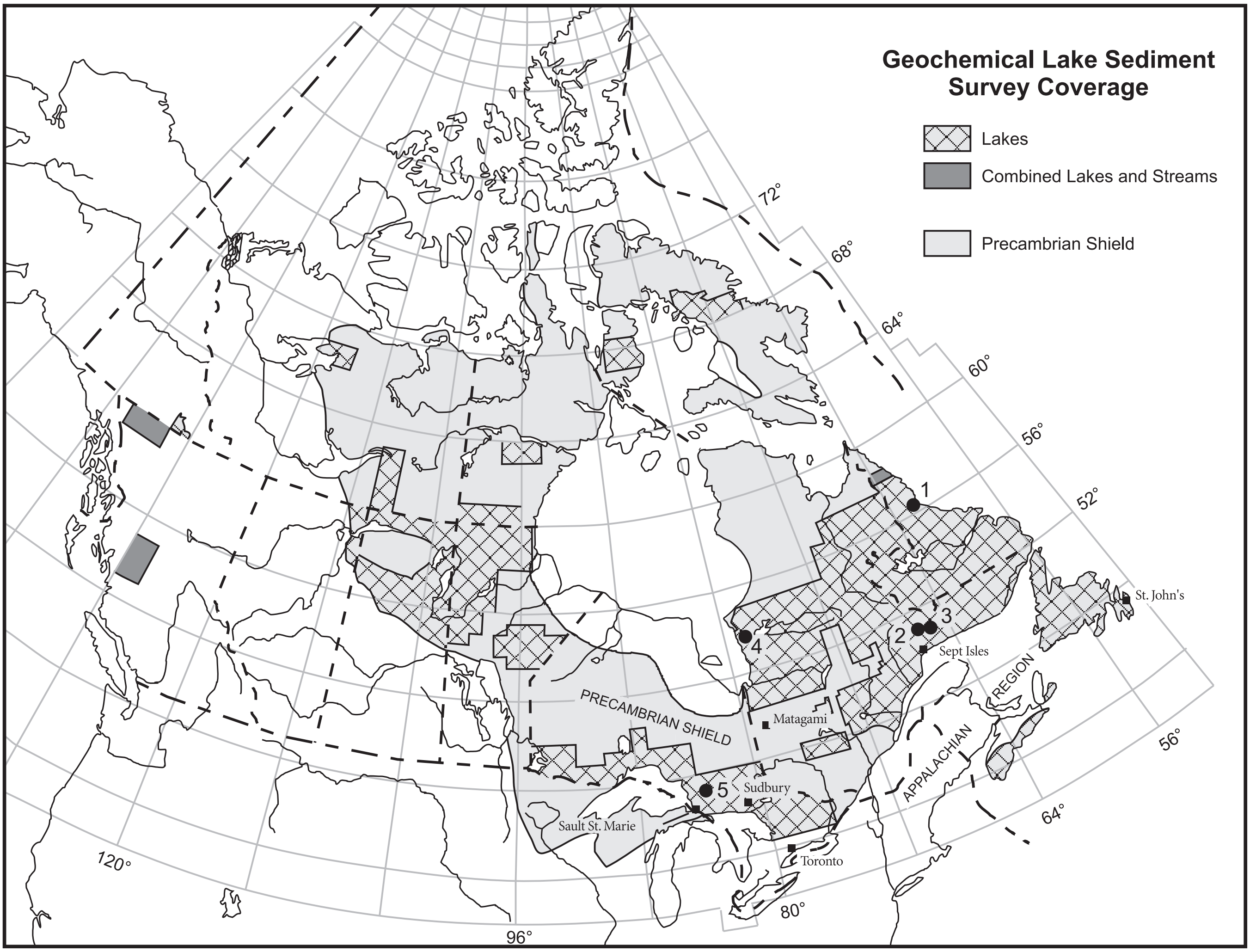


Figure 1: *Extent of regional lake sediment surveys in Canada in relation to the main physiographic provinces, and location of cited examples. 1. Voisey's Bay Ni-Cu-Co; 2. Too Easy Ni-Cu; 3. Lac Volant Cu-Ni-Co; 4. Eastmain West Au-As; 5. Percy Lake Zn-Pb-Cu-Ag.*

directly to claim-staking. A secondary application for all these survey data, and one of growing importance, is their use to establish baselines for most elements of environmental concern (e.g., Friske and Coker, 1995; Friske *et al.*, 1994; Painter, *et al.*,1994).

Advances in analytical chemistry have increased the number of elements routinely determined to 30 or more (Beaumier, 1990; Friske and Hornbrook, 1991; Davenport *et al.*, 1996), allowing the direct detection of most mineral deposit types. The organisation of lake sediment data into digital databases has made the information much more useful and accessible. As digital geological maps and databases become more widespread, GIS techniques can be applied to analyse and interpret the lake sediment geochemical databases more completely. Studies of geochemical variation in lake sediment cores are providing new insights for the interpretation of the regional data, and offer new approaches to exploration in contaminated areas. Taken together, the results from environmental and mineral exploration studies emphasize some of the unique properties of organic lake sediment, and clarify the interpretation of their geochemistry for both applications.

GEOCHEMICAL VARIATION IN ORGANIC LAKE SEDIMENT

When applied to mineral exploration, it is assumed that lake sediment geochemistry reflects geologically controlled spatial variations in trace-element distributions, including geochemical dispersion from mineral deposits. This has been confirmed empirically by several workers (e.g., Friske, 1985; Kerr and Davenport, 1990; Beaumier *et al.,* 1994). The relative importance of geochemical variation due to anthropogenic inputs and other natural limnological factors is seldom quantified, however, although the same material has been widely used to study environmental change on the assumption that in their stratigraphy lake sediments preserve a faithful record of chemical (as well as biotic and physical) conditions through time (Engstrom and Wright, 1984).

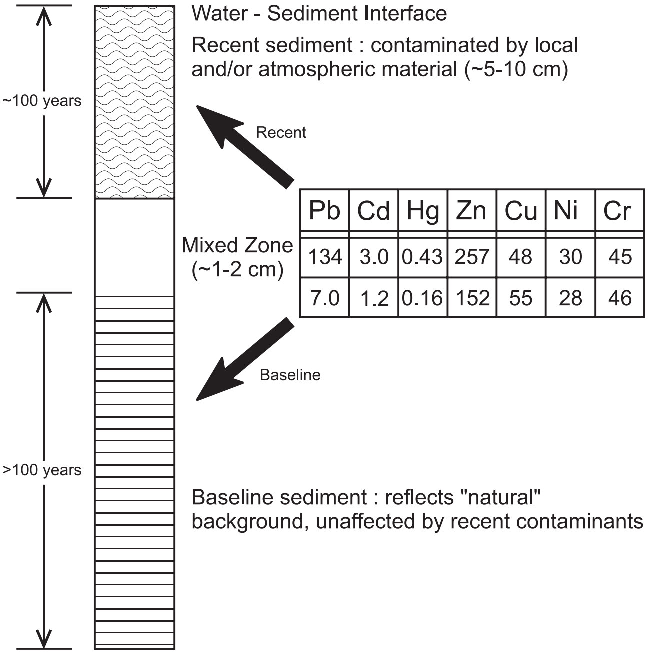
For routine geochemical mapping, *grab* samples are collected from the deeper, central basins of lakes, commonly with a tubular steel corer such as the NGR sampler (cf. Friske and Hornbrook, 1991). This sampler is allowed to freely fall from the lake surface to penetrate the sediment. The depth from which the grab sample is obtained is not known with any certainty, therefore, but typically the full length of the sampler is embedded in the sediment layers, yielding a 30–35 cm core from several tens of centimetres below the sediment-water interface. Implicit in this sampling strategy is the assumption that any variation within the sediment stratigraphy is much less than between-lake variation, yielding samples that effectively map natural geochemical features.

In a study to measure geochemical variability in long cores of lake sediment, Davenport *et al.* (1993) showed that the variation between cores (sites) is much larger than within-core variation for a wide range of elements in a five-lake transect across an area of high geochemical relief in south-central Newfoundland. Similar results were reported from long cores from six widely spaced lakes in northern Ontario (Fortescue, 1986). Exceptions were noted in the top 10–15 cm, where enrichment in Pb was observed in five lakes in Ontario and three in Newfoundland, and in Cu and Ni in two lakes in Ontario, northeast of Sudbury. These variations in near-surface lake sediment have been confirmed in other studies (e.g., Fortescue and Vida, 1991; Johnson *et al.*, 1986), where enrichments in Pb and probably also Hg are widespread, locally accompanied by other elements.

In southern Sweden enrichment in Pb extends to sediment depths of over 50 cm in some headwater lakes (Renberg *et al.*, 1994), a feature attributed to a long history of pollution from classical Greek and Roman civilizations dating from 2600 B.C. Such thick sections of surface sediment enrichment are more typical of localised, highly disturbed areas where greatly increased sedimentation rates are combined with increased trace-element inputs. In the Snow Lake area of Manitoba, Friske and McCurdy (1996) have documented heavy-metal contamination to depths of 30 cm from gold and base-metal mining since 1948. These unusual thicknesses of highly contaminated sediment are sufficient in places to contaminate grab samples collected by the NGR sampler. Perhaps the most extreme documented example is from lakes near the Falun Mine in south-central Sweden (Qvarfort, 1983), where contamination in Cu, Zn, Pb, Ag, Cd and Hg extends to depths of up to 200 cm, corresponding to the start of mining in 700 A.D. Thick sections of contaminated sediment may also be encountered in lakes in urban and long-established industrial settings. In St. John's, Newfoundland, sediments from urban lakes are contaminated in a range of heavy metals to depths of up to 80 cm (Christopher *et al.*, 1993), thick enough to affect routine grab-sample collection.

Less work has been done to assess lateral continuity of lake-sediment stratigraphy. Christopher *et al.* (1993) found the chemical stratigraphy to be remarkably consistent in four urban lakes in St. John's. Engstrom *et al.* (1994) in a study of 81 cores from seven lakes in Minnesota and Wisconsin showed that smaller and shallower lakes exhibited more consistent geochemical stratigraphy than large and steep-sided ones, and those with major stream inflows and outflows that lead to heterogeneous sediment deposition. Friske (1995) observed significant differences in the geochemical profiles of three sediment cores from Tatin Lake in British Columbia. This lake is irregular in shape, relatively steep-sided with several sub-basins and inflow streams, resulting in not only inhomogeneous sediment deposition, but variable degrees of oxygenation of the bottom waters. Where bottom waters are oxygenated, diagenetic recycling of Mn and Fe, together with As, Co and Zn is apparent in the upper 10 cm of the sediment section. These enrichments are absent where the bottom waters are reducing and oxygen-poor. Grab samples taken with the NGR sampler would likely not incorporate the Mn- and Fe-rich sediment to a great extent.

Taken together these studies suggest that while lateral variation in lake sediment composition may introduce a component of sampling noise in grab samples, this variation affects mainly the near-surface sediment. The available evidence indicates that in most *relatively undisturbed areas* in North America, metal enrichment is restricted to the upper 10–15 cm of sediment (Figure 2), and can usually be avoided by sampling below 20 cm, e.g., with the NGR sampler. In areas where thicker contaminated sections of sediment are suspected (where human disturbance is usually obvious), short-core surveys offer a way to sample beneath the contaminated layer (Fortescue and Vida, 1991; Friske and McCurdy, 1996).



Pb	Cd	Hg	Zn	Cu	Ni	Cr
134	3.0	0.43	257	48	30	45
7.0	1.2	0.16	152	55	28	46

Figure 2: *Schematic representation of a typical lake sediment section showing trace-element data from Turkey Lake, northwestern Ontario (from Johnson et al., 1986).*

RECOGNITION OF ANOMALIES DUE TO MINERALISATION

The effectiveness of regional lake sediment geochemical surveys to reveal geochemical dispersion from mineralisation will vary according to the size and contrast of the dispersion patterns developed. At the low sample densities typically employed, the chance of detecting an individual massive sulphide deposit is low, but clusters of deposits would likely be apparent (Cameron and Hornbrook, 1976). Similarly large scale alteration systems associated with mineralisation will be reflected if they have a geochemical signature (Davenport and Nolan, 1991). Glacial dis-

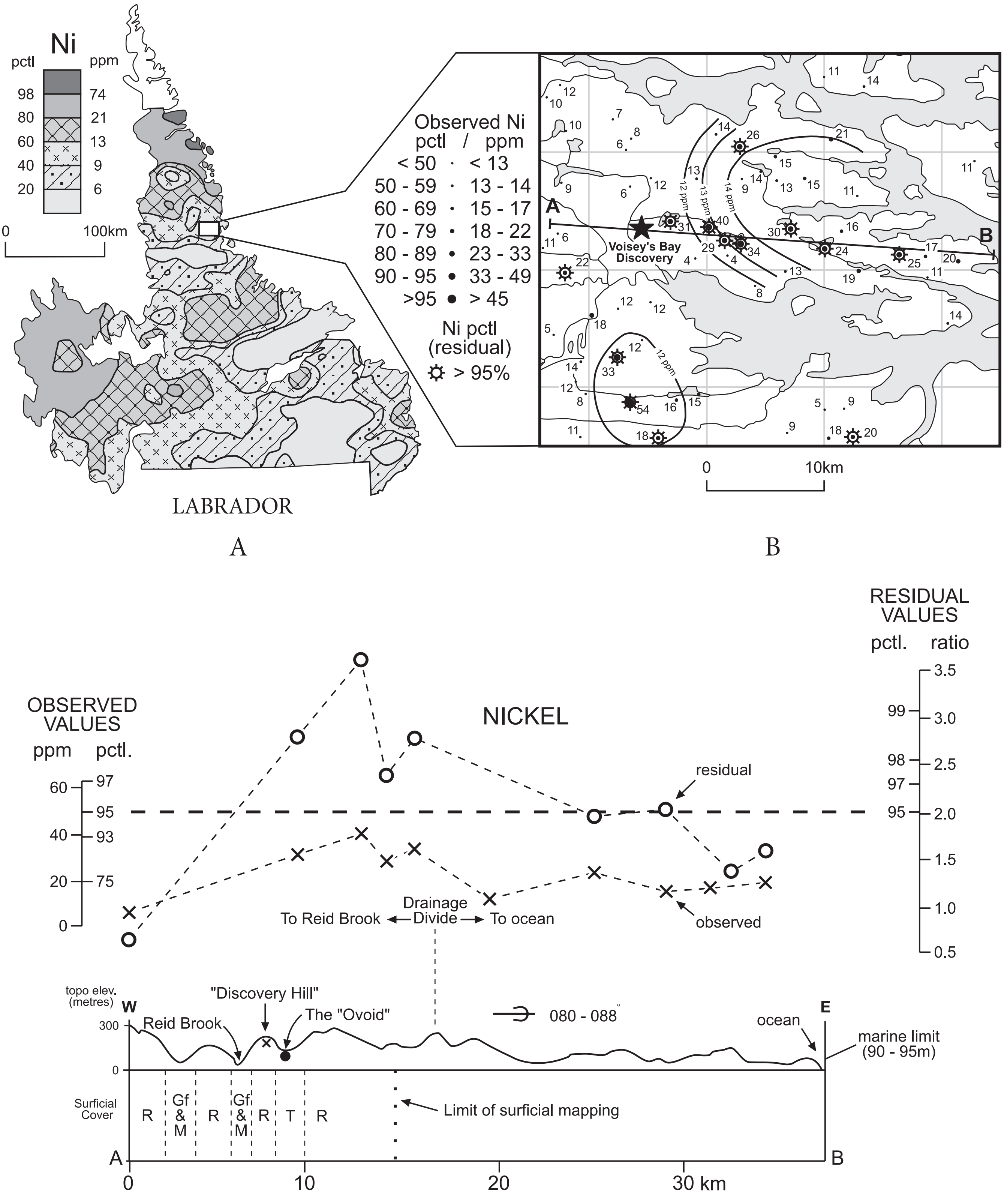


Figure 3: *Distribution of Ni in lake sediment: (A) generalised for all Labrador; (B) near the Voisey's Bay Ni-Cu-Co deposit (Ni values in ppm); and (C) in profile along a transect across the Voisey's Bay deposit. (Key to surficial cover types—R: exposed rock; Gf: glaciofluvial sediments; M: marine sediments; T: till.) Residual Ni values are the ratio of the observed values to the interpolated values from the regional surface shown by contours.*

persion may modify the primary geochemical patterns, sometimes substantially (e.g., McConnell and Batterson, 1987), but commonly not very significantly with respect to the sample spacing employed in the regional surveys. The nature and thickness of the glacial deposits modifies the intensity of the geochemical response, subduing it in areas of extensive marine, lacustrine, fluvial and outwash deposits. The target dispersion patterns are only a small component of natural geochemical variation that result from geological, limnological and anthropogenic factors. As already discussed, sampling strategy can minimize the last two. Some recent and successful applications of lake sediment geochemistry in mineral exploration from Québec and Ontario, and a review of the lake sediment response to the Voisey's Bay Ni-Cu-Co deposit in Labrador, illustrate some of these points.

NICKEL-COPPER MINERALISATION

The Voisey's Bay Ni-Cu-Co deposit in northern Labrador was discovered by two prospectors who in 1993 were attracted to the site by an extensive hillside gossan. Subsequent geological and geophysical exploration followed by diamond drilling in 1994 located the richest part of the deposit (the "ovoid") which is concealed beneath 10–30 m of till (Naldrett *et al.*, 1996), and other major blind ore bodies to east and west. The massive sulphides of the ovoid contain published reserves of 31 200 000 t grading 2.83% Ni, 1.74% Cu and 0.12% Co, but despite their impressive metal content, they occupy a remarkably small area at subcrop (only about 150 000 m^2). Topographic relief in the area is rugged, with hills of exposed rock and till veneer and steep-sided valleys whose bottoms are filled with tens of metres of glacio-fluvial and marine sediment. The area was covered by reconnaissance lake sediment sampling under the NGR in 1978 and 1985 (Geological Survey of Canada, 1993).

The Ni distribution in lake sediment around the Voisey's Bay deposit is shown in Figure 3. Five lakes up to 12 km due east of the deposit contain locally elevated values of Ni (29–40 ppm), but these values are less than the 95th percentile for all of Labrador. The Cu and Co values in these lakes are even less pronounced. A topographic and geochemical profile A-B drawn at 095° through the deposit and through or close to this string of lakes illustrates the dispersion more clearly.

The local background for Ni in the Voisey's Bay region is close to the median for Labrador. To compensate for variations in the regional background, the observed Ni values were divided by the interpolated regional values to give residual ratios. Residual Ni ratios are markedly enhanced in the four lakes closest to the deposit (between the 97 and 99th percentiles), and values above the 95th percentile extend over 20 km to the east. This approach did not reveal any dispersion pattern in Cu or Co.

The Too Easy Cu-Ni-Co showing, Québec, was one of many new Cu-Ni showings discovered in 1992 by Falconbridge Ltd. while following up several Cu-Ni lake sediment geochemical anomalies west of the Manicouagan reservoir. The showing, in granulite facies mafic intrusive rocks of the Grenville Province, contains up to 1.89% Cu and 1.49% Ni, and is situated approximately 100 km north-northeast of Sept-Îles. The area lies within a high, deeply incised plateau with extensive bedrock outcrop. Lakes are small and scarce.

The results of a 1976 lake sediment survey at an average density of one site per 11 km^2 by SOQUEM published by Choinière (1986) included a geochemical anomaly consisting of two adjacent sample sites containing 108 ppm Cu and 378 ppm Ni, and 72 ppm Cu and 38 ppm Ni (Figure 4), well above the local background of 25 ppm Cu and 20 ppm Ni. In subsequent exploration around the more anomalous lake several new showings of disseminated or vein-type mineralisation were discovered in the granulite-grade noritic gabbros (Clark and Gobeil, 1996). Exploration around the second anomalous lake led to the discovery of similar mineralisation.

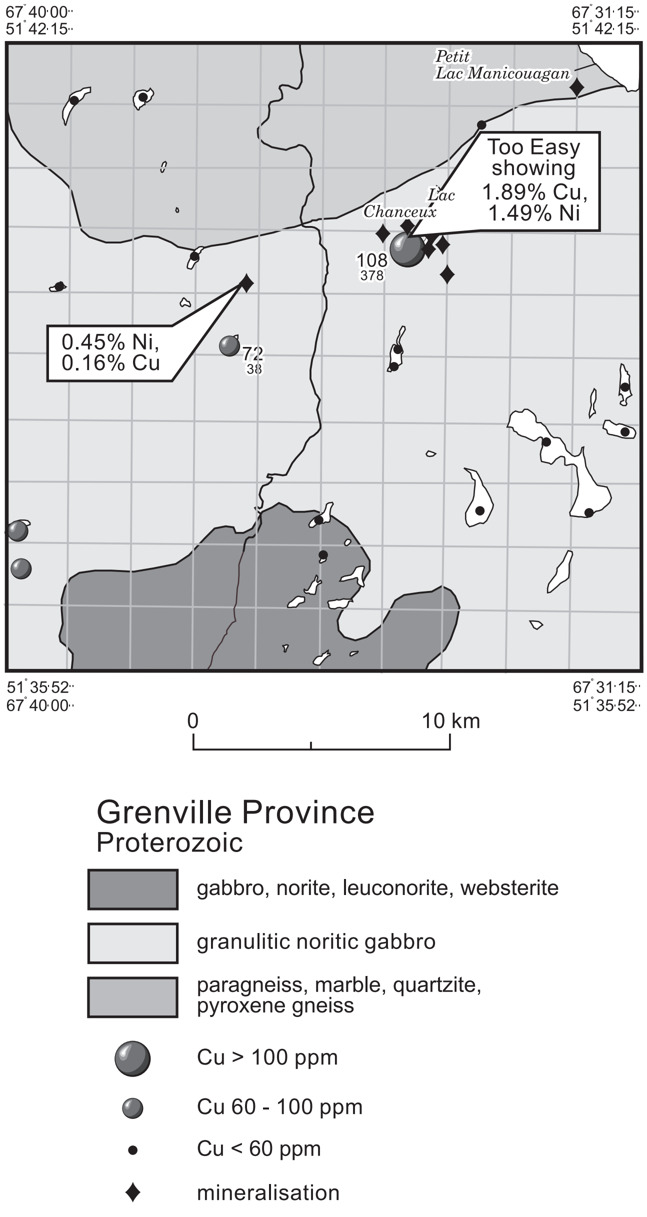


Figure 4: *Lake sediment geochemistry and mineral occurrences, Too Easy Cu-Ni showing, north of Sept-Îles Québec (geology simplified from Gobeil, 1995). Values are for Cu (above) and Ni (below) in ppm.*

In these two examples, dispersion from magmatic Ni-Cu deposits is quite limited. Similarly, the recently discovered Lac Volant Cu-Ni-Co showing near Sept-Îles, Québec, where channel samples assay up to 2.96% Cu, 1.97% Ni and 0.14% Co (Perreault *et al.*, 1996), is reflected only by a modest anomaly in lake sediment. The values of 23 ppm Ni and 35 ppm Cu at the closest lake sediment site are less than the 98th percentile for the whole survey, but are nonetheless elevated relative to the regional backgrounds of 11 and 25 ppm and local backgrounds over mafic intrusions of 13 ppm Ni and 30 ppm Cu, and are quite comparable to those at Voisey's Bay. Other Ni-Cu showings in the adjacent Lac Tortue and Lac Manitou areas (Clark *et al.*, 1996) are more strongly reflected in the lake sediments.

This type of deposit lacks an alteration envelope of any significant size, and hence the only source of dispersion in the surficial environment is the outcropping or sub-cropping sulphides themselves, which in structurally complex areas of the Shield are likely to represent only a small proportion of an ore system (cf. Naldrett *et al.*, 1996). They do occur commonly in clusters, however, so some indication of a Ni-Cu province would be expected in regional geochemical data, although with the wide sampling interval used the signature will be diffuse and subtle, and approaches such as examining both observed and residual values relative to the local background may help to identify anomalous dispersion patterns.

GOLD-ARSENIC MINERALISATION

The Eastmain Au-As showing was discovered during follow up of a lake sediment As anomaly in late 1995 by Virginia Exploration and SOQUEM. Located some 300 km north of Matagami, Québec, the area is characterised by rolling topography with moderate outcrop and thin till-cover. The lake sediment survey was carried out in 1975 at a sample density of one site per 9 km^2, and released as maps and reports by Gleeson (1978). The archived samples were reanalysed by ICP-ES and instrumental neutron activation, and released as digital data (Beaumier, 1990), and as a series of colour geochemical maps (Beaumier and Kirouac, 1994). The broad anomaly is over 70 km east-west and 7 km wide (Figure 5), comprising over 50 sites where As>6 ppm (mean of 23 ppm), with associated Sb and W.

By the end of 1996, four separate mineralised zones had been found in the Eastmain West area, the most significant of which are the LA zone, the K zone and the PP-51 zone (Figure 5). Mineralisation extends throughout a structurally controlled zone 70 km in length, and is associated with iron formation within volcano-sedimentary rocks of the Eastmain greenstone belt. The western part of the area is dominated by a major shear zone which shows some similarity to the Cadillac Break in the Rouyn-Val d'Or area, where a similar geochemical anomaly in till is developed (LaSalle and Henry, 1987). The geochemical response in this mineralised area, as well as with the Escale Au-As showing about 100 km to the north, reflect the major alteration zones associated with this style of mineralisation. Major hydrothermal alteration zones are excellent targets for definition by regional lake sediment geochemical surveys (Davenport and Nolan, 1991).

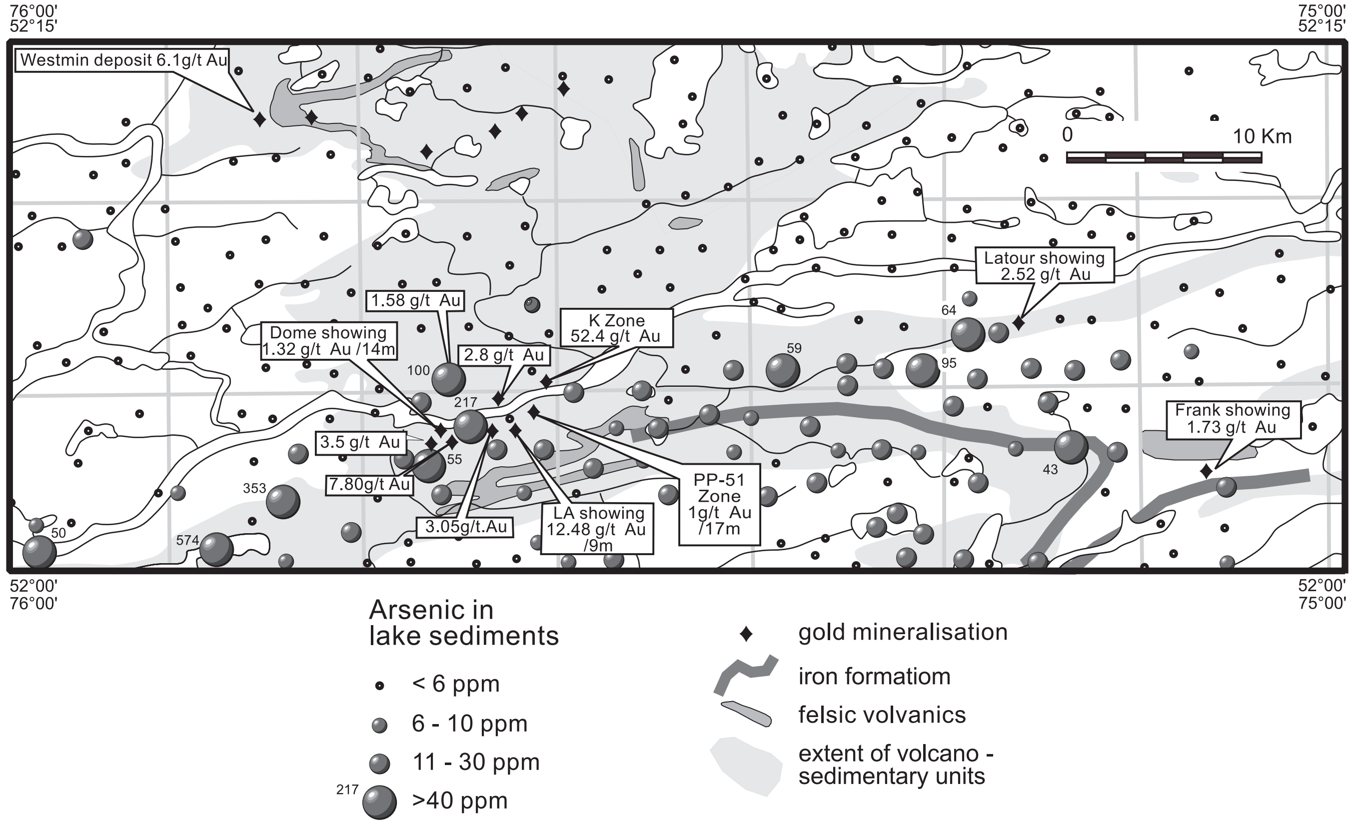


Figure 5: *Lake sediment geochemistry and simplified geology, Eastmain West Au-As showing, James Bay region, Québec.*

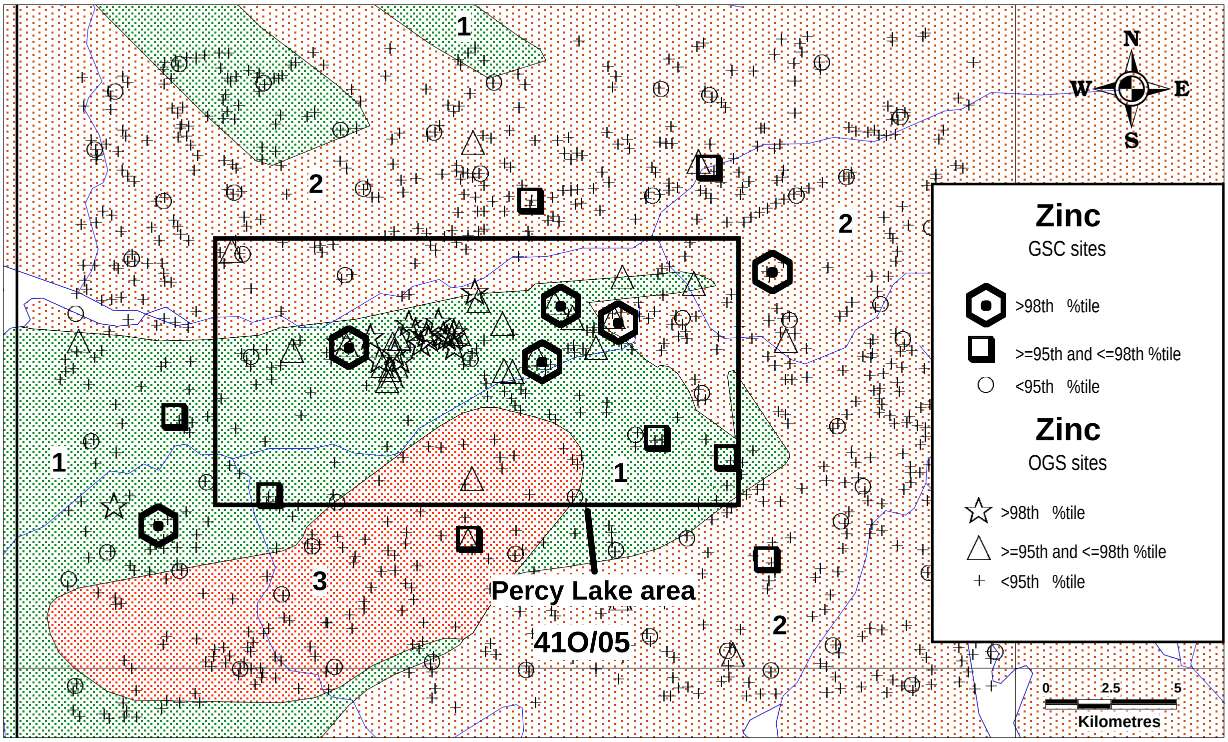


Figure 6: *Distribution of Zn in lake sediment samples of the Cow River in-fill survey (Ontario Geological Survey) and Chapleau NGR survey (Geological Survey of Canada) in the Percy Lake area.*

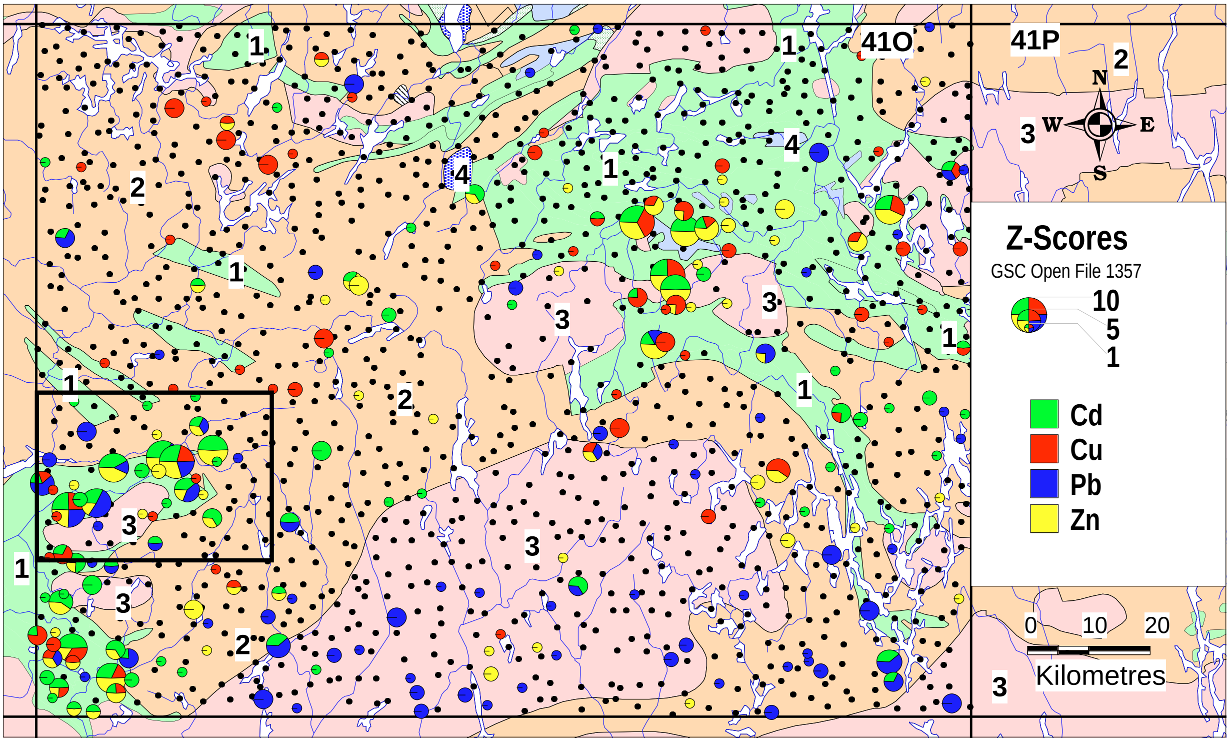


Figure 7: *Distribution of Cd, Cu, Pb and Zn for 1335 lake sites from the NGR Chapleau survey (NTS 41O), with the area of the Cow River in-fill survey (Figure 6) for reference.*

COPPER-ZINC VMS MINERALISATION

The Percy Lake Zn-Pb-Cu-Ag discovery, about 90 km northeast of Sault Ste. Marie, Ontario, was triggered by the release of lake sediment geochemical results from the Cow River Geochemical Mapping project (Hamilton *et al.,* 1995), which covered an 800 km^2 area. This survey, at a sample density of one site per km^2, confirmed and more closely delineated a strong Zn anomaly revealed in an earlier NGR lake sediment of the region at a sample density of one site per 13 km^2 (Geological Survey of Canada, 1987). Both surveys highlight the 10 km^2 Percy Lake area (Figure 6), where in addition to Zn, Cd and Cu are also anomalous. This element association and the geological environment suggested the presence of VMS mineralisation (Hamilton *et al.,* 1995). Up to December 1996, over 600 mineral claims had been staked in the Batchawana greenstone belt, an assemblage of predominantly mafic to felsic metavolcanics and clastic metasediments, and follow-up exploration led to the discovery of Zn-Pb-Cu-Ag mineralisation throughout the area (Hamilton, pers. comm., 1996).

The NGR survey covered other geological environments potentially favourable for VMS mineralisation, and Figure 7 shows the distribution of the indicator elements Zn, Cd, Cu and Pb for the whole reconnaissance lake sediment data set (1335 sites). To present the information as a single figure, Z-scores were calculated for each site as follows. For each of the four metals, values between the 95th and 98th percentile were assigned a score of 1, between the 98th and 99th percentile a score of 2, and at or above the 99th percentile a score of 3. Values below the 95th percentile were assigned a score of 0. Each site is represented by a circle whose size is proportional to the sum of the Z-scores for the four elements. The relative contribution of each element to this sum is shown as a pie chart within the circular symbol. In addition to the Percy Lake area, the Batchawana greenstone belt in the southeast corner of the survey area stands out with anomalous base-metal geochemistry, and, in the northeastern part of the region, the supracrustal rocks of the Abitibi greenstone belt in the Swayze area. The use of multi-element signatures enhances the signal in the reconnaissance data and clarifies targets for follow up.

CONCLUSION

Regional lake sediment surveys provide a systematic, well-controlled geochemical framework for over 2 600 000 km^2 of the Precambrian Shield and Appalachian regions of Canada, where they are the most cost-effective approach to reconnaissance geochemical mapping. They have also been used to good effect in similar physiographic regions in the northeastern United States and Finland (Tenhola, 1988), as well as the Interior Plateau of British Columbia (Cook *et al.*, 1997).

Lake sediment surveys provide multi-element geochemical data similar to stream sediment surveys, although the data may not be directly compared without transformation (Davenport, 1990). Although in common with other drainage sample media, lake sediments are subject to anthropogenic contamination, unlike stream sediment and surface waters, sampling strategies can be adopted to avoid it.

The NGR lake sediment database contains data for up to 50 elements from almost 100,000 sites, and almost as much data again available from MRN for Québec. All of these results were reviewed cursorily when first released and some of the most obvious anomalies followed up, but their volume is such that they remain an information resource to be evaluated over and over again in the future. To facilitate their use for mineral exploration, the data have been organised into digital databases, which can be readily integrated with other geological and geophysical information to define exploration targets, either through formal geomathematical modelling using GIS, or by informal visual superimposition of the different layers in a data viewer. For potential users who have limited computer resources, digital compilations of geochemical data with bedrock and surficial geology, mineral deposit, aeromagnetic and topographic information are being prepared, such as the Digital Geochemical Atlas of Newfoundland (Davenport *et al.*, 1996).

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