Geological factors affecting the distribution of trace metals in glacial sediments of central Newfoundland

R. A. Klassen

Abstract In central Newfoundland (NTS 12A/10, 15, 16, 2H/1), As, Pb, and Zn concentrations in the clay-sized (<0.002 mm) and silt and clay-sized (<0.063 mm) fractions of till reflect compositional differences among and within rock terranes at scales of kilometers to tens of kilometers. In those fractions, till derived from volcanic bedrock of Victoria Lake Group (Tulks Hill) is notably enriched in As (50–>1000 ppm), exceeding levels commonly set for purposes of environmental protection. Near Pb-Zn mines at Buchans, geochemical variation with depth reflects the dispersal of detritus from mineralized bedrock, and differences in sediment type and provenance. There, surface sediments are rich in granitic debris derived from the Topsails igneous terrane 5 km north of Buchans and contain low concentrations of trace metals. These sediments are compositionally unrelated to either Buchans Group volcanic rock or an underlying, older till enriched in sulphide minerals and trace metals. Metal-rich till extending up to 10 km southwest of Buchans results from combined glacial and debris flow transport related to two distinct geological events. Trace metals are enriched (two- to fourfold) in the clay-sized fraction of till compared to the silt and clay-sized, and are associated with Al- and Mg-bearing minerals that preferentially concentrate in the clay fraction. The geochemistry of the silt and clay-sized fraction can approximate that of the <2-mm fraction. Background variations in till illustrate the important role of a geological framework to the interpretation of geochemical surveys and the origins of trace metals in the environment.

Key words Newfoundland · Trace metal · Arsenic · Lead · Zinc · Quaternary · Till

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Introduction

Over the past thirty years, personnel at the Geological Survey of Canada (GSC) have carried out numerous regional geochemical surveys in support of mineral exploration (Shilts 1984, Coker and DiLabio 1989; Painter and others 1994). The work has defined regional geochemical variations in surfical deposits overlying diverse geological terranes of Canada, based principally on analysis of two sediment types: lake sediments and till. Analyses of both sample media have clearly illustrated linkages between geology and surficial-sediment geochemistry at scales of tens to hundreds of kilometres (Bölviken and others 1990; Kerr and Davenport 1990; Klassen and Thompson 1993). Since these surveys were initiated, there have been significant changes in analytical instrumentation and, as a result, in the number of elements determined. In addition to Cu, Pb, and Zn of early surveys, analyses now commonly include trace metals such as As and Hg, as well as lithophile elements such as Al, K, and Mg. At the same time, there has also been an increasing awareness of the role of these elements in the environment and their effects on human and animal health, agriculture, and forestry; regional geochemical survey data have thereby assumed a wider application than mineral exploration and resource evaluation. In some studies, in particular those concerned with lake sediment geochemistry, high or 'anomalous' concentrations of trace metals have been interpreted to reflect anthropogenic input to the environment (Bölviken and others 1990). Consequently, recognition of the geological signature in geochemical surveys is important to interpret the origins and distributions of trace metals in the environment.

In 1991 and 1992, glacial history and till composition in central Newfoundland (NTS map areas 12A/9, 15, 16, and 12H/1) were studied by GSC personnel in support of mineral exploration (Fig. 1). The area straddles three distinct volcanic-sedimentary rock terranes that host volcanogenic massive sulphide (VMS) and precious metal mineralization, including former Pb-Zn-Cu mines at Buchans that had been in operation for more than 50 years (Thurlow 1981; Evans and Kean 1990). To map areal and stratigraphic variations in surficial sediments and to determine their glacial origins, till was sampled at more than 850 sites throughout the area. Geochemical analyses of those samples reflect marked compositional differences

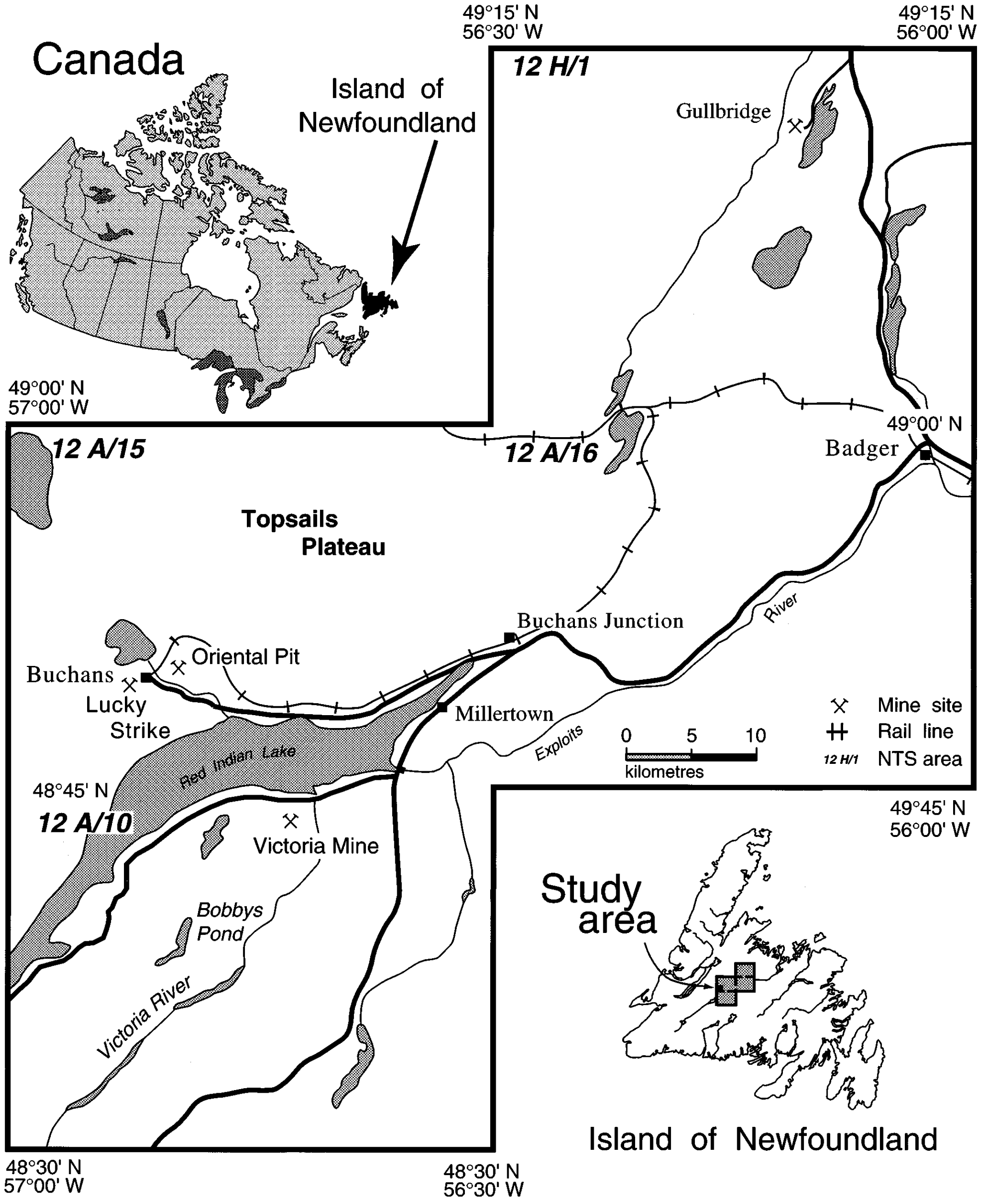

Fig. 1
Index map of the study area

among geological terranes and indicate large areas having concentrations of As, Pb, and Zn defined by some regulatory agencies as either 'contaminated' or otherwise potentially 'hazardous' (Moen 1988; Fitchko and Kingsbury 1989; Government of Canada, 1991). This report describes the till geochemistry of central Newfoundland in terms of its bedrock geology and glacial history, and illustrates some of the principal geological controls (lithology and mineralogy) on sediment geochemistry. The trace metals of environmental concern, As, Pb, and Zn (Government of Canada 1991, 1993) are examined; analysis of other elements, including Cu, Ni, and Cr, are reported by Klassen (1994a). Lithophile elements Al and Mg are used to identify linkages between trace metals and sediment mineralogy.

Bedrock geology

The region near Buchans is underlain by the Ordovician Buchans Group consisting largely of a bimodal suite of basalt and rhyolite (Fig. 2; Thurlow 1981; Kirkham 1987; Thurlow and Swanson 1987). These rocks are equivalent to the Roberts Arm Group northeast of Buchans. The ophiolitic Skidder Basalt occurs west and southwest of the Buchans Group, and Cambro-Ordovician volcanic and sedimentary rocks of the Victoria Lake Group occur south of Red Indian Lake (Kirkham 1987). The Victoria Lake Group is lithologically subdivided into three parts: (1) Tulks Hill volcanic rocks to the southwest, (2) Tally Pond volcanic rocks to the southeast, and (3) volcanically-derived sedimentary rocks to the northeast, which are in part the lateral equivalent of the two volcanic units

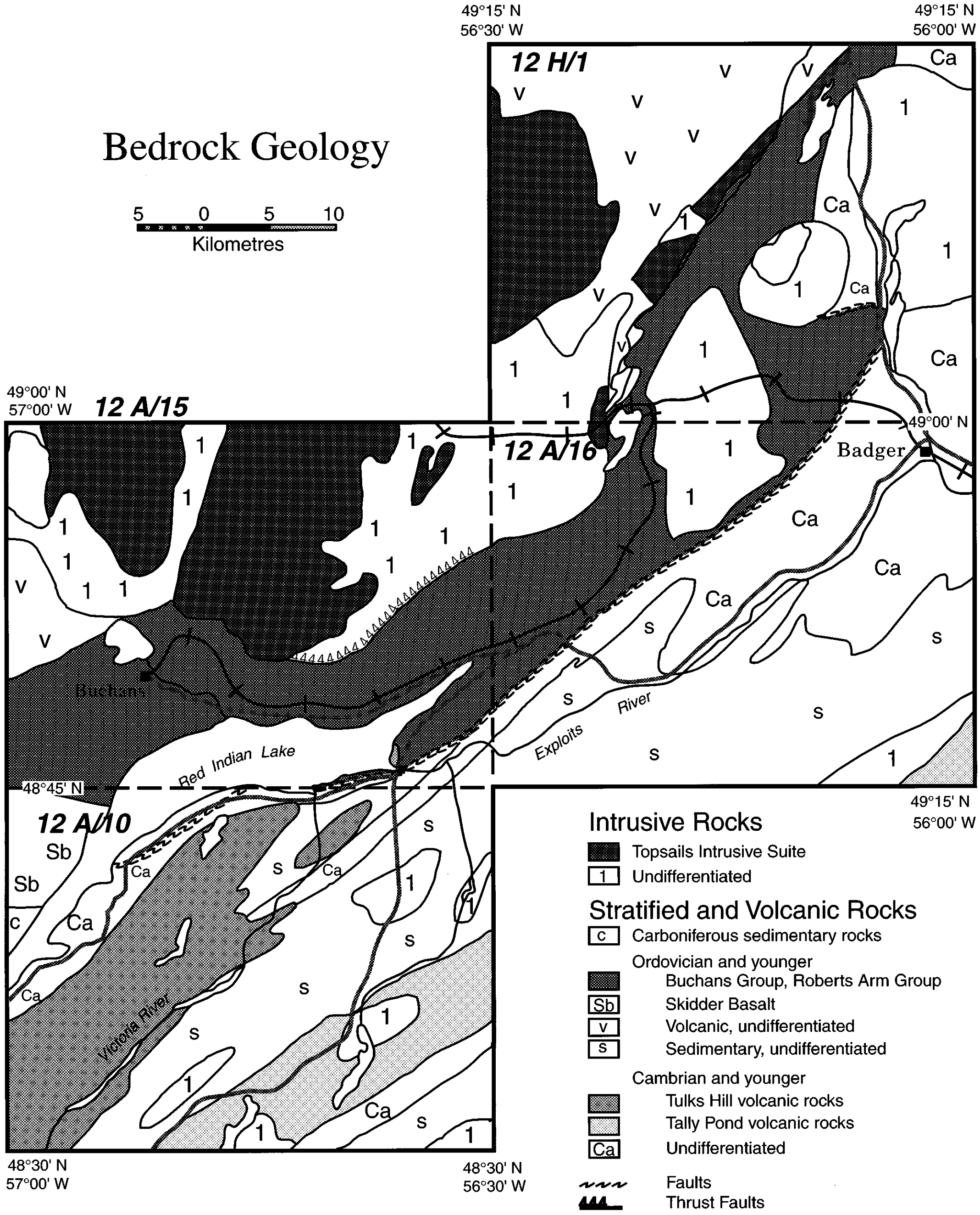

Fig. 2
Simplified pre-Quaternary geological map of the study area

(Evans and Kean 1990). The volcanic belts include felsic pyroclastic rocks intercalated with mafic flows; mafic volcanic rock is more common with Tally Pond rock.

VMS deposits occur in the Buchans River Formation of the Buchans Group, which comprises felsic tuff, rhyolite breccia, pyritic siltstone, greywacke, breccia and conglomerate (Kean and others 1981; Thurlow and Swanson 1987). Some of the deposits, for example at the Oriental and Lucky Strike mines, subcrop beneath glacial drift (Fig. 1). Ore-bearing rocks of the Buchans Group contain more Ba, Pb, and Zn than equivalent rocks unrelated to mineralization (Thurlow and others 1975). VMS mineralization also occurs at Victoria Mine and Bobby's Pond in Tulks Hill volcanic rocks, and at Duck Pond in Tally Pond volcanic rocks (Squires and others 1990; Stewart and Beischer 1993).

To the north and northeast of the Buchans Group lies the early Silurian Topsails igneous terrane, which includes peralkaline and granitic rocks of the Topsails igneous suite, volcanic and sedimentary rocks of the Springdale Group, as well as intrusive and metamorphic rocks of the Hungry Mountain Complex (Kean 1977; Whalen and Currie 1987, 1988). Silurian and Carboniferous sedimentary and volcanic rocks occur in Red Indian Lake basin (Thurlow 1981).

Quaternary geology

Central Newfoundland is characterized by broad hills with relief of tens to more than a hundred metres, and elevations of 150–500 masl. North and south of Red Indian Lake, topographic trends in the volcanic terrane of the Buchans and Victoria Lake Groups are elongate northeast–southwest, parallel to the principal structural trends. The highest elevations are associated with the Topsails Plateau (Fig. 1), an upland of rounded hills and scattered monadnocks, and are underlain by the Topsails igneous terrane which lies above treeline and is characterized by tundra vegetation. Red Indian Lake occupies part of a northeast-trending fault zone (Kirkham 1987), and Buchans townsite lies within a northwest-trending saddle containing Hinds and Buchans Lakes.

The glacial history of central Newfoundland was summarized by Grant (1974), Grant and Tucker (1976), Vanderveer and Sparkes (1982), and Klassen (1994b). Prominent streamlined landforms define ice flow toward the northeast and the southwest (Prest and others 1968; Graham and Grant 1991). Striations indicate four ice flow events that include, from oldest to youngest: (1) regional southward flow from the Topsails Plateau (Events Ia and b); (2) regional northeastward flow, possibly followed by a local westward to southwestward flow near Buchans (Events II a and b); (3) northward and southward flow in the topographic saddle near Buchans (Event III); and (4) southwestward and northeastward flow in Red Indian Lake basin (Event IV) (Klassen and Henderson 1992; Klassen 1994b). Ice divides near Buchans are inferred during Events II–IV. Multiple ice flow directions associated with a single event are identified by lowercase letters.

In terms of drift composition and the geological record of ice flow, these ice flows did not affect the study area uniformly. South of Red Indian Lake, for example, northeastward ice flow removed the record of an older regional southward flow (Murray 1955; Grant and Tucker 1976; Klassen 1994a), whereas in the Buchans area to the north the record is more complex, with ice flow toward the west and southwest, south and southeast, and northeast reflected both in till composition and ice flow lineations (Grant and Tucker 1976; Sparkes 1985; Klassen and Henderson 1992; Klassen 1994b). From Buchans, a Zn-rich glacial dispersal train extends 8 km southwest (James and Perkins 1981). At Buchans, the Quaternary stratigraphic succession includes: (1) an older till containing Buchans Group volcanic rock deposited by northeastward-flowing ice, and (2) glacial lake deposits, including subaqueous debris flow sediments, and (3) a surficial subaerial debris flow deposit containing granitic debris derived from southward to southwestward-flowing ice, and redistributed in debris flows (Klassen and Murton 1996).

During deglaciation, ice margins receded toward an ice divide arcing across central Newfoundland, which later split into separate, shrinking ice caps (Grant 1974). In the Buchans saddle, glacial landforms indicate that ice margins receded both eastward toward a cap on the Topsails Plateau and southward from Hinds Lake toward Red Indian Lake basin, where final ice disintegration took place (Grant 1974). A glacial lake extended to about 59 m above the present level of Red Indian Lake, dammed by the last remnants of ice within Exploits River valley (Vanderveer and Sparkes 1982; Mihychuk 1985).

Sample collection and compositional analysis

To determine drift provenance and model glacial dispersal trains, till was sampled from hand-dug pits and existing exposures throughout the study area and analysed for geochemical and lithological properties. The least weathered sediment accessible in shovel pits and road cuts was sampled from the lowermost B and upper C soil horizons, typically at depths below surface of 0.5–1 m. For analysis, the clay-sized (<0.002 mm) fraction was obtained by wet centrifuge methods (Lindsay and Shilts 1995), and the silt and clay-sized (<0.063 mm) by dry sieving in stainless steel sieves. For stratigraphic sections, analysis of the ball-milled <2 mm fraction was also done; that fraction is commonly used to characterize bulk soil composition (Jackson 1969). Geochemical analysis was by inductively coupled plasma-atomic emission spectrometry (ICP-AES), following hot nitric and hydrochloric acid (LeForte) attack; regional survey results are given by Klassen (1994a), and those for stratigraphic sections in Table 1.

The fine sand fraction (0.063–0.250 mm) was retained for heavy mineral separation (methylene iodide, >3.3 s.g.) and mineralogical analysis, and the pebble fraction (4.0–5.6 mm) for rock identification. Heavy minerals are reported as percentages of grains counted (100), and pebbles as weight percentages. Pebble sample weights were typically 20–40 g, representing 50–150 clasts, and estimates based on replicate analysis indicate reproducibility of about ±5 weight percent. The principal indicator of glacial transport and drift provenance is unmetamorphosed, pink, medium-grained granite of the Topsails igneous terrane.

Trace metal distribution between size fractions

For till in the study area, concentrations of trace metals Pb, Zn, and As, and lithophile elements Al and Mg are typically two- to fourfold greater in the clay-sized fraction than in the silt and clay-sized (Table 2). For Pb, Zn, and As concentrations there are strong linear correlations ($r \geq 0.6$, $n = 837$–841) between size fractions (Fig. 3); within size fractions correlations are also evident between Pb and Zn. For lithophile elements a linear correlation be-

Table 1
Geochemical and lithological data, Oriental and Lucky Strike mine sections (Lithology: *A* crystalline rock, *B* pink granitic rock, *C* sedimentary rock)

Sample no	Depth m	Arsenic ppm			Lead ppm			Zinc ppm			Aluminum %			Magnesium %			Lighology wt %			Pyrite
		< 0.002	< 0.063	< 2	< 0.002	< 0.063	< 2	< 0.002	< 0.063	< 2	< 0.002	< 0.063	< 2	< 0.002	< 0.063	< 2	A	B	C	
Oriental mine																				
92KY0002A	7.0	8	4	30	800	1060	636	1648	1200	1265	4.14	2	1.76	2.28	0.9	0.91	45	1	1	83
92KY0002B	6.5	12	4	6	570	532	258	900	584	394	4.63	2.27	1.84	2.27	0.9	0.89	45	1	3	10
92KY0002C	6.0	14	4	6	420	382	246	1642	1064	750	4.85	1.99	1.84	2.35	0.82	0.9	46	1	3	8
92KY0002D	5.5	18	1	4	350	284	204	1160	434	410	4.7	2.22	1.9	2.14	0.9	0.89	44	1	5	5
92KY0002E	5.0	6	2	4	470	300	196	894	414	330	4.99	2.22	1.92	2.29	0.9	0.88	52	1	3	6
92KY0002F	4.5	1	1	6	740	496	354	972	536	420	4.87	2.2	1.93	2.16	0.85	0.84	40	3	2	7
92KY0002G	4.3	52	28	24	1260	800	600	5502	1788	1655	4.44	1.61	1.78	2.17	0.75	0.87	32	2	3	11
92KY0002H	4.3	82	76	30	1920	2312	934	7562	2182	1525	4.27	1.41	1.56	2.02	0.68	0.83	40	1	4	18
92KY0002I	4.3	4	16	16	818	684	442	4502	2118	1645	4.29	1.96	1.75	2.22	0.87	0.89	39	1	1	12
92KY0002J	3.8	8	2	6	1625	740	764	7032	1354	1015	2.76	0.82	0.77	1.31	0.33	0.37	61	3	2	12
92KY0002K	3.4	14	1	6	1570	806	476	4496	716	588	2.98	0.78	0.83	1.48	0.31	0.42	65	14	4	1
92KY0002L	3.0	8	1	4	682	278	162	2728	482	314	3.02	0.81	0.76	1.49	0.3	0.35	70	9	1	1
92KY0002M	2.5	1	1	2	798	250	204	974	140	106	2.71	0.64	0.61	1.13	0.22	0.25	75	13	1	0
92KY0002N	2.0	14	1	1	66	32	18	390	66	48	2.84	0.58	0.53	0.98	0.17	0.2	80	14	0	0
92KY0002O	1.5	12	1	2	44	22	8	286	56	38	3.24	0.58	0.51	1.1	0.19	0.2	73	16	1	1
92KY0002P	1.0	16	1	2	45	20	14	356	72	54	2.77	0.59	0.52	0.99	0.18	0.21	74	17	0	1
92KY0002Q	0.5	1	1	4	44	20	14	202	52	44	2.61	0.53	0.51	0.64	0.15	0.17	77	22	0	0
Lucky Strike																				
92KY0008A	0.1	12	1	2	125	58	46	1574	542	310	10.61	3.61	2.05	0.3	0.2	0.32	48	3	2	10
92KY0008B	0.2	34	1	2	80	36	32	600	252	200	7.26	1.72	1.21	0.6	0.22	0.32	53	5	4	4
92KY0008C	0.4	16	1	2	74	28	158	610	182	2260	5.27	1.13	1.11	0.82	0.21	0.68	56	7	2	3
92KY0008D	0.6	18	4	4	117	42	34	686	158	144	4.23	0.91	0.84	0.85	0.21	0.3	62	6	1	5
92KY0008E	0.8	4	2	2	130	42	28	658	148	126	3.85	0.8	0.74	0.99	0.2	0.27	76	10	0	2
92KY0008F	1.2	1	2	2	60	22	14	724	108	98	4.4	0.71	0.69	1.09	0.19	0.26	63	9	0	1
92KY0008G	1.8	20	1	2	49	20	16	1330	378	262	5.47	0.89	0.75	0.92	0.22	0.26	81	6	0	1
92KY0008H	2.8	10	1	6	82	84	62	1386	836	672	2.82	1.45	1.27	1.6	0.73	0.71	55	3	4	26
92KY0008I	3.3	52	22	12	1145	1566	740	4492	1146	812	3.98	0.99	1.18	2.17	0.57	0.86	33	0	3	11
92KY0008J	3.8	14	1	2	23	18	18	174	82	90	2.83	1.29	1.34	1.58	0.67	0.78	38	4	7	3
92KY0008K	5.6	6	8	4	245	256	182	3790	982	904	3.43	1.06	1.11	1.77	0.58	0.65	54	8	0	5
92KY0008L	8.2	6	4		177	142		5942	1890		2.96	1.01		1.59	0.56		65	0	0	6
92KY0008M	8.6	8	8	4	480	338	340	5386	1738	2190	2.77	0.96	1.08	1.43	0.47	0.57	76	0	0	24
92KY0008N	8.7	108	46	28	10 000	6624	2990	1008	850	1000	1.56	0.91	1.09	0.67	0.51	0.89	56	2	1	3

Table 2
Summary of univariate statistics for till geochemistry, central Newfoundland

	Fraction mm	Mean	Min	Max	Range	Median	Mode	Std. Dev.	Std. Error	Count
Arsenic	< 0.002	47.6	1	2138	2137	24	1	98.10	3.38	841
	< 0.063	21.1	1	1762	1761	8	1	66.20	2.29	837
Lead	< 0.002	40.9	1	510	509	30	16	40.93	1.41	841
	< 0.063	14.1	1	112	111	12	6	11.98	0.41	837
Zinc	< 0.002	161.4	18	2270	2252	130	–	137.29	4.73	841
	< 0.063	62.9	14	804	790	50	22	49.11	1.70	837
Aluminum	< 0.002	5.82	1.69	15	13.31	5.4	–	1.743	0.060	841
	< 0.063	1.88	0.28	10.11	9.83	1.81	–	0.775	0.027	837
Magnesium	< 0.002	1.19	0.16	4.19	4.03	1.21	1.21	0.493	0.017	841
	< 0.063	0.53	0.05	2.39	2.34	0.51	0.61	0.267	0.009	837

tween size fractions is evident only for Mg ($r = 0.616$, $n = 840$). For the silt and clay-sized fraction, subdivision of trace metal data according to the concentration of Al and Mg indicates the following general trends: (1) an increase in the mean concentration of trace metals with increase in Al, most evident for Zn, and (2) trace metal concentrations are lower with intermediate concentrations of Mg (0.5–1%), and (3) the range of trace metal concentrations increases with decrease in Al and Mg (Fig. 4).

In exposures near Buchans, trace metal concentrations in the < 2 mm fraction are equivalent to half those of the

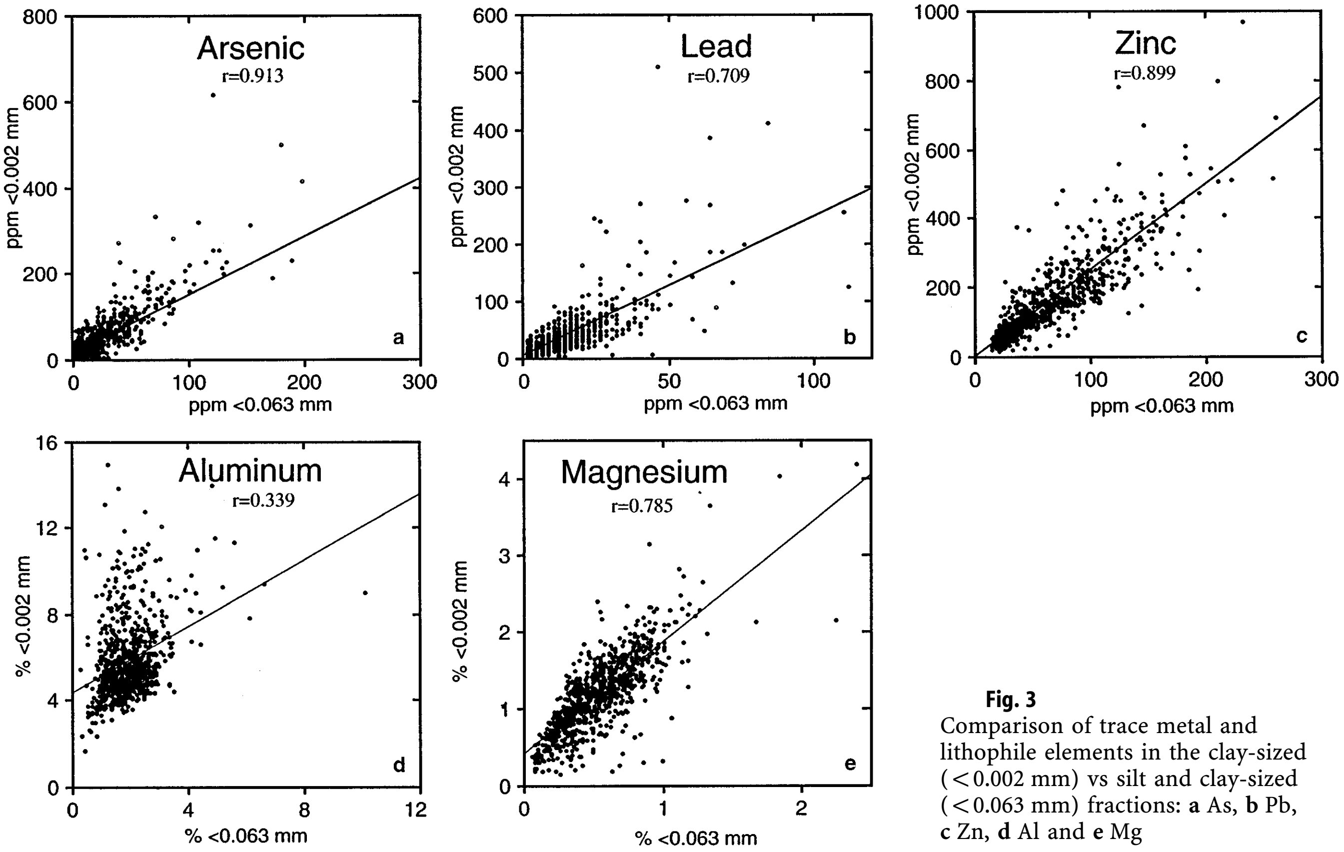

Fig. 3
Comparison of trace metal and lithophile elements in the clay-sized (<0.002 mm) vs silt and clay-sized (<0.063 mm) fractions: **a** As, **b** Pb, **c** Zn, **d** Al and **e** Mg

<0.063 mm fraction, and one-half to one quarter of those of the <0.002-mm fraction. Linear correlations are better defined between the <2-mm and the <0.063-mm fractions than between the <2-mm and <0.002-mm fractions (Fig. 5).

Till composition: regional trends

Subdivison of geochemical data according to pebble lithology reveals the effects of bedrock provenance on geochemistry. In the <0.002-mm and <0.063-mm fractions, concentrations of As and Zn (Fig. 6) and of Al and Mg (Fig. 7) tend to decrease with an increase in the proportion of intrusive and metamorphic ('crystalline') rock; conversely, they increase directly with the proportion of sedimentary and volcanic rocks. As an exception, no clear relation exists between Al and crystalline rock concentrations in the clay-sized fraction. The linear relations are most evident for Mg (Fig. 7); data scatter reflects mineralogical differences among crystalline rock types, which include peralkaline igneous rock of the Topsails igneous terrane, metamorphic rock of the Hungry Mountain Complex, and varied gabbroic sources, among others.

Areal variations in till geochemistry (<0.002 mm) reflect compositional differences among diverse geological terranes (Fig. 8). Trace metal concentrations are greatest in areas of volcanic and sedimentary bedrock, most notably the Tulks Hill volcanic rocks of the Victoria Lake Group south of Red Indian Lake. There, As concentrations are typically 50–100 ppm; elsewhere in the study area they are less than 20 ppm. Over Topsails igneous terrane north of Buchans, all trace metals in till are low, commonly near their lower detection limit.

The effects of glacial dispersal on geochemical patterns are best described near Buchans. There, a glacial dispersal train defined by the 5 wt.% isopleth of red granitic rock pebbles extends southward as a tongue across minesites to the northern shore of Red Indian Lake, with Lucky Strike mine near its southwestern margin (Fig. 9). Within the train trace metal levels are lower than elsewhere over Buchans Group bedrock. Up to 10 km west and southwest of Oriental Mine, however, glacial sediments are enriched in Pb (>120 ppm, 200 ppm; <0.002 mm) (Fig. 8b, c); the zone coincides with the glacial dispersal train mapped by James and Perkins (1981; Fig. 9). There, geochemistry reflects dispersal of sulphide minerals in till and debris flow deposits derived from subcropping VMS mineralization at Buchans. Elsewhere in the region, trace metal patterns occur at scales consistent with the areal extent of bedrock units, and they are not known to indicate glacial dispersal from single sources of sulphide mineralization. At Victoria Mine south of Red Indian Lake, for example, As and Zn concentrations are elevated over volcanic rocks for tens of

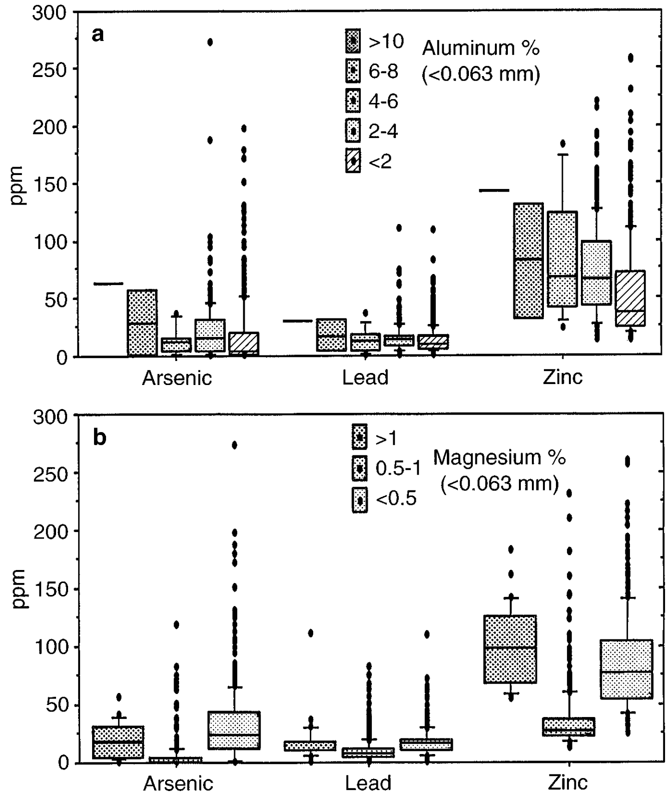

Fig. 4
Box-and-Whisker plots illustrating trace metal concentration in the silt and clay-sized fraction, subdivided according to **a** Al and **b** Mg concentrations. The upper and lower *bounding lines of the boxes* represent the 25th and 75th percentiles, with the median value indicated by a *central line*; *single bar lines* outside the box represent the 90th and 10th percentiles; outlying data are represented as *individual points*

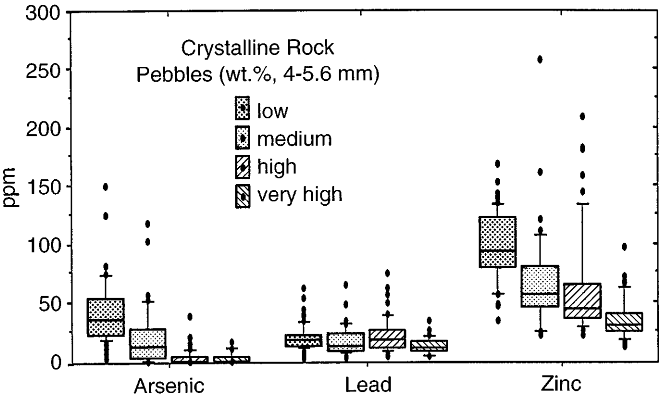

Fig. 6
Box-and-Whisker plot illustrating trace metal variations in the silt and clay-sized and in the clay-sized fractions, subdivided according the concentration of crystalline rock pebbles (explanation of plot given in Fig. 4)

kilometres along strike, a distribution reflecting general enrichment in Tulks Hill volcanic rocks (Fig. 8a, c)

Till composition: vertical trends

At the margins of the Oriental and Lucky Strike mines at Buchans, exposures (Klassen and Murton 1996) permitted determination of vertical compositional variations in multiple till units and dispersal of VMS detritus in glacial, glacial lake, and debris flow deposits beneath surface deposits (Fig. 10a, b). The dispersal of mineralized detritus can be traced by sulphide-bearing clasts and by pyrite grains; it is also reflected by elevated trace metal concentrations. Although pyrite is used as an indicator of mineralized detritus, trace metals Pb, Zn, and As are hosted by galena, sphalerite, and arsenopyrite.

The Oriental section comprises four stratigraphic units, which include in ascending order: (1) Lower till , (2) Meltout till, (3) glacial lake sediment, and (4) subaerial debris flow sediment (Fig. 10a). Lower till is dominated by Buchans Group volcanic rock, including mineralized debris derived from nearby VMS deposits and was deposi-

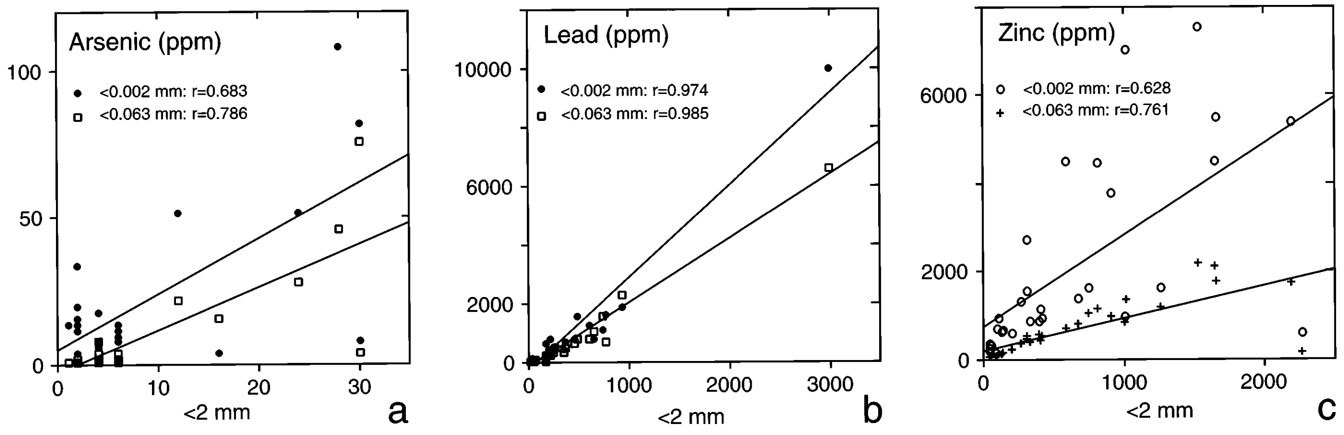

Fig. 5
Comparison of **a** As, **b** Pb, and **c** Zn in the <2 mm fraction and in the silt and clay- (<0.063 mm) and the clay-sized (<0.002 mm) fractions in samples from stratigraphic sections at Oriental mine and Lucky Strike (see Fig. 10a, b)

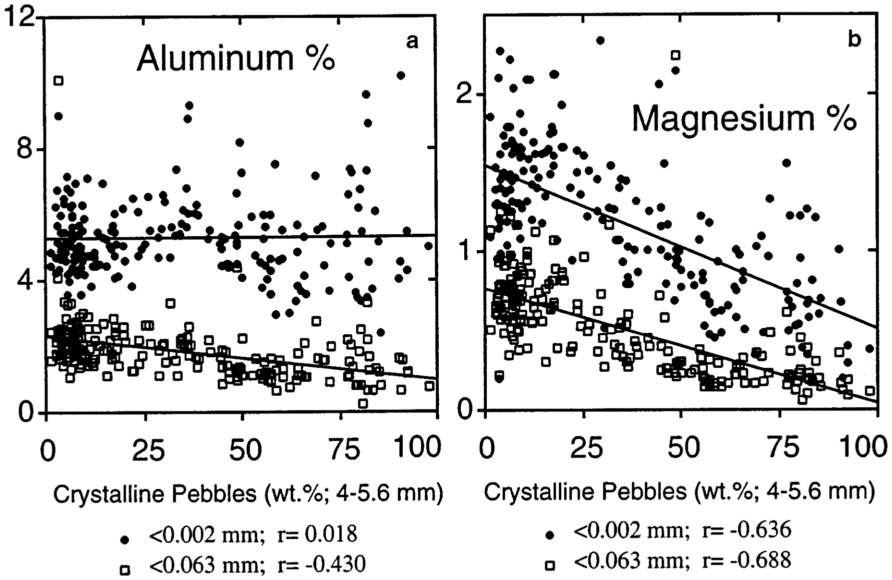

Fig. 7
a Al and **b** Mg concentrations in the silt and clay-sized and in the clay-sized fractions compared to the concentration of crystalline (igneous and metamorphic rock, undifferentiated) pebbles in till

ted by northeastward-flowing ice. The subaerial debris flow deposit capping the section is enriched in granitic debris derived from the Topsails igneous terrane to the north and northeast. Lower till is enriched in pyrite (5%), Pb (200–1000 ppm), and Zn (400–1500 ppm), with concentrations decreasing upward. Arsenic concentrations increase upward in the <0.002-mm fraction and decrease in the <0.063- and <2-mm fractions, although overall they are low (10–20 ppm), consistent with till derived from unmineralized volcanic bedrock of the Buchans Group elsewhere. Crystalline rock comprises 45 wt.% of the pebble fraction and varies little with depth in the Lower till. The upwards decrease in trace metal concentrations indicates till higher in the section contains less detritus derived from underlying mineralized bedrock. The highest concentrations of pyrite (10–20%), Pb (750–>2000 ppm), Zn (2000–>8000 ppm), and As (30–90 ppm) occur in the Meltout till and sediments directly overlying it, indicating a provenance distinct from the Lower till. In the subaerial debris flow deposit, crystalline rock concentrations increase upward from ~55–>80 wt.%; red granite pebbles indicate a corresponding increase in the proportion of debris from the Topsails igneous terrane. Near the base of the debris flow deposit, trace metal levels are high, comparable to those in the underlying Meltout till, and they decrease exponentially upward to levels comparable to till elsewhere in the Buchans Group terrane. In samples where Pb concentrations in the <2-mm and <0.063-mm fractions are either equivalent to or greater than those of the <0.002-mm fraction, the coarser fractions likely contain either mineralized rock fragments or sand-sized sulphide grains, or both. The vertical compositional variations reflect erosion and mixing of metal-rich sediment, derived either from nearby VMS mineralized bedrock and older, overidden glacial deposits, with granite-rich sediment derived from the Topsails Plateau and comprising the bulk of the debris flow deposit.

In ascending order, the Lucky Strike section comprises three distinct stratigraphic units: (1) glaciofluvial sediment, (2) glacial lake sediment, and (3) subaerial debris flow sediment that is stratigraphically and compositionaly equivalent to the surface unit at Oriental Mine (Fig. 10b). In the glacial-lake sequence, influx of debris from either subcropping mineralized bedrock or older glacial deposits is reflected by high concentrations of Pb (>1000 ppm) and Zn (1000–4000 ppm) in the subaqueous debris flow diamictons. In them, concentrations of As are comparable to those in Meltout till at Oriental mine, indicating they could be derived from the same bedrock source. Compared to underlying glacial-lake sediments, concentrations of crystalline pebbles and of indicator erratics of red granite are greater in the subaerial debris flow deposit, and trace metal concentrations are lower. Compared to the subaerial debris flow deposit at Oriental mine, concentrations of crystalline pebbles are less, trace metals greater, and pyrite is present (>2%) indicating a Buchans Group provenance. In addition, the proportions of crystalline pebbles decrease upward in the deposit, whereas at Oriental mine they increase. Between sections the compositional differences likely reflect local changes in debris source of the debris-flow deposit, the distribution of subcropping VMS sources, and possibly local topographic diversion of debris flows (Lucky Strike Mine is 40 m higher than Oriental Mine).

Geochemical partitioning among size fractions

For till of central Newfoundland, Pb, Zn, and As concentrations are typically two- to four-fold greater in the clay-sized fraction than in the silt and clay-sized fraction, with correlations between size fractions generally linear. Com-

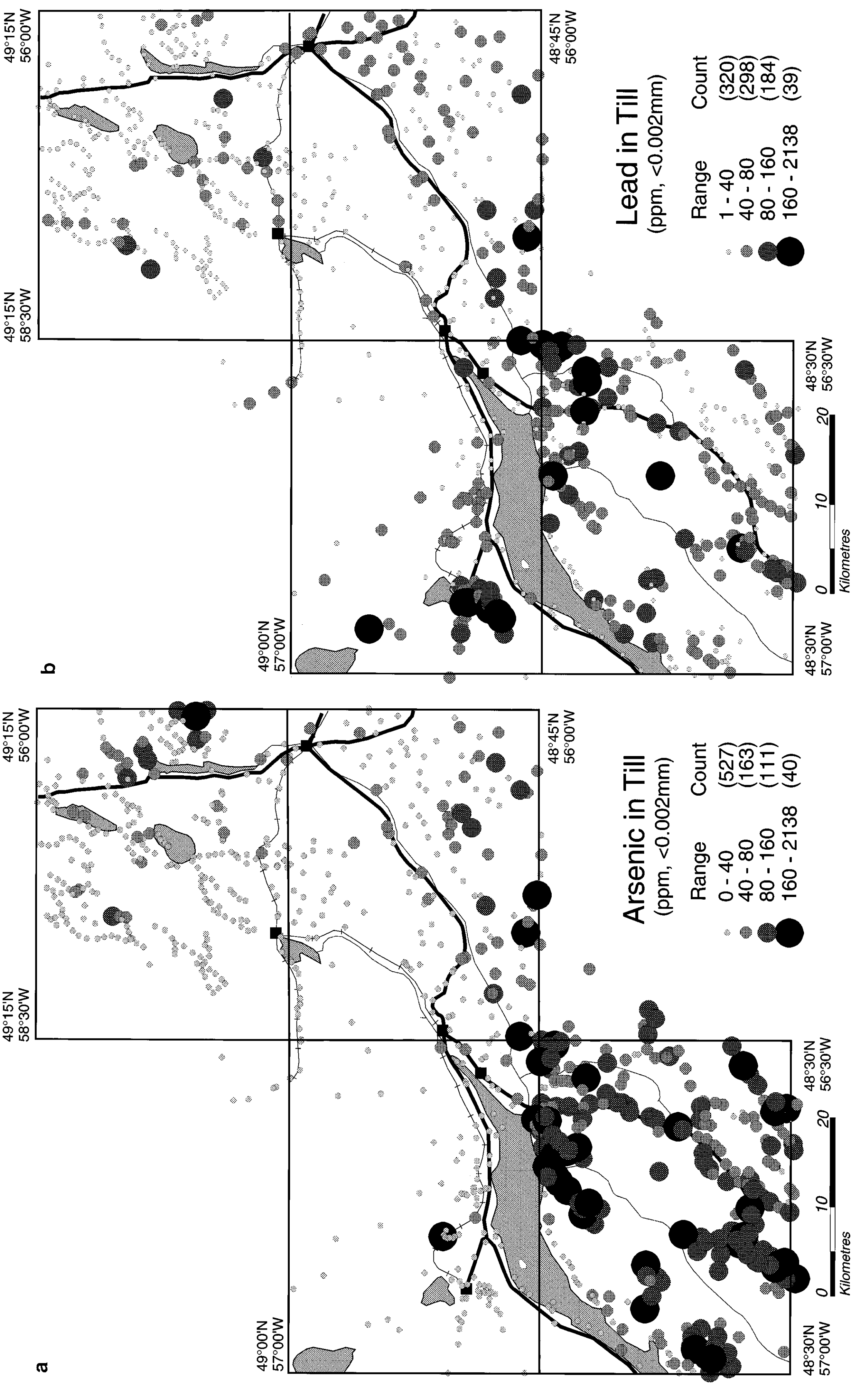
b
49°15'N 56°00'W
49°15'N 58°30'W
49°00'N 57°00'W
48°45'N 56°00'W
48°30'N 56°30'W
48°30'N 57°00'W
Lead in Till
(ppm, <0.002mm)
Range Count
1 - 40 (320)
40 - 80 (298)
80 - 160 (184)
160 - 2138 (39)
0 10 20
Kilometres
a
49°15'N 56°00'W
49°15'N 58°30'W
49°00'N 57°00'W
48°45'N 56°00'W
48°30'N 56°30'W
48°30'N 57°00'W
Arsenic in Till
(ppm, <0.002mm)
Range Count
0 - 40 (527)
40 - 80 (163)
80 - 160 (111)
160 - 2138 (40)
0 10 20
Kilometres

Fig. 8a, b

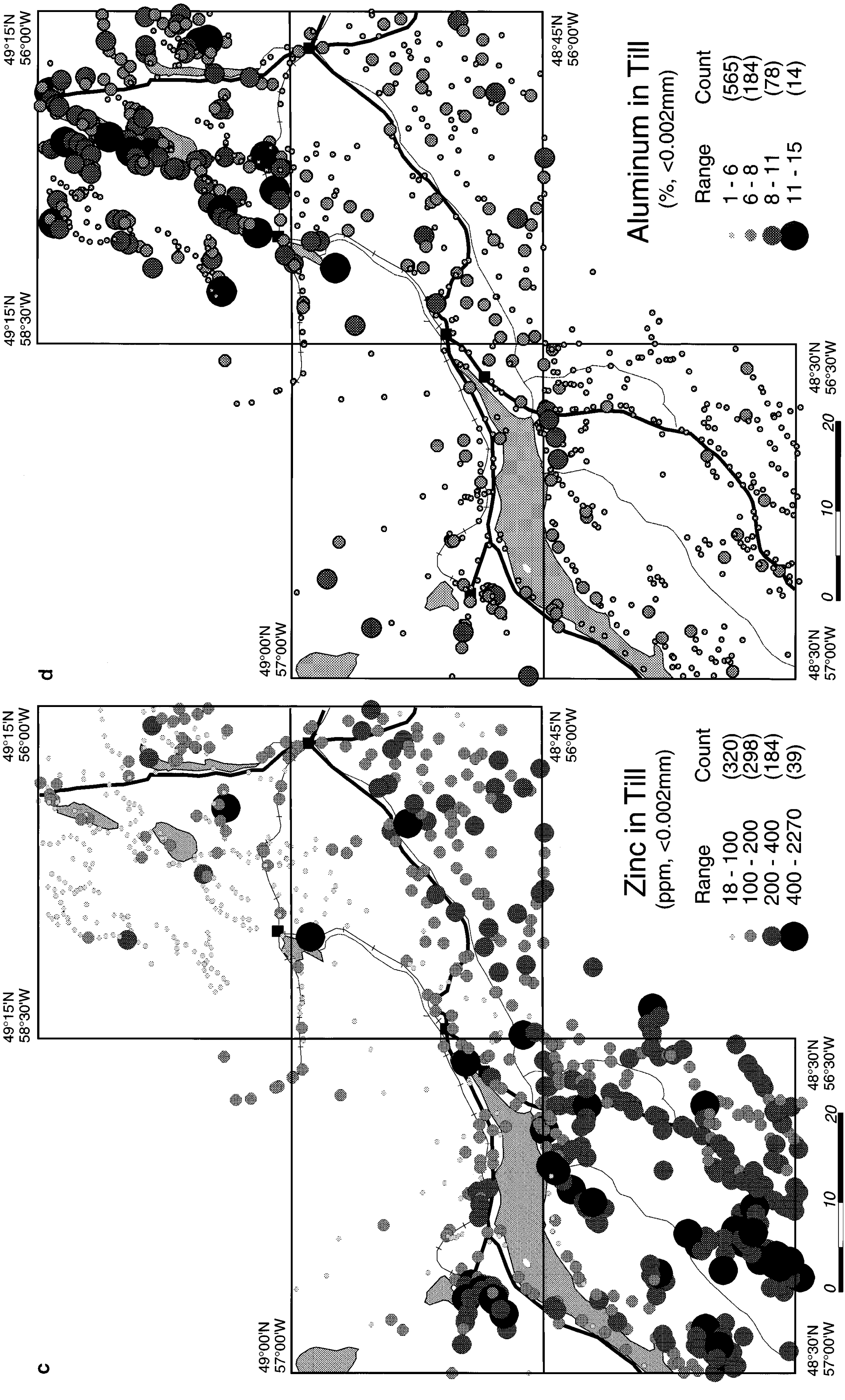
c
d
Zinc in Till
(ppm, <0.002mm)
Range Count
18 - 100 (320)
100 - 200 (298)
200 - 400 (184)
400 - 2270 (39)
Aluminum in Till
(%, <0.002mm)
Range Count
1 - 6 (565)
6 - 8 (184)
8 - 11 (78)
11 - 15 (14)
49°15'N 56°00'W
49°15'N 58°30'W
48°45'N 56°00'W
49°00'N 57°00'W
48°30'N 57°00'W
48°30'N 56°30'W
0 10 20
Kilometres

Fig. 8c, d

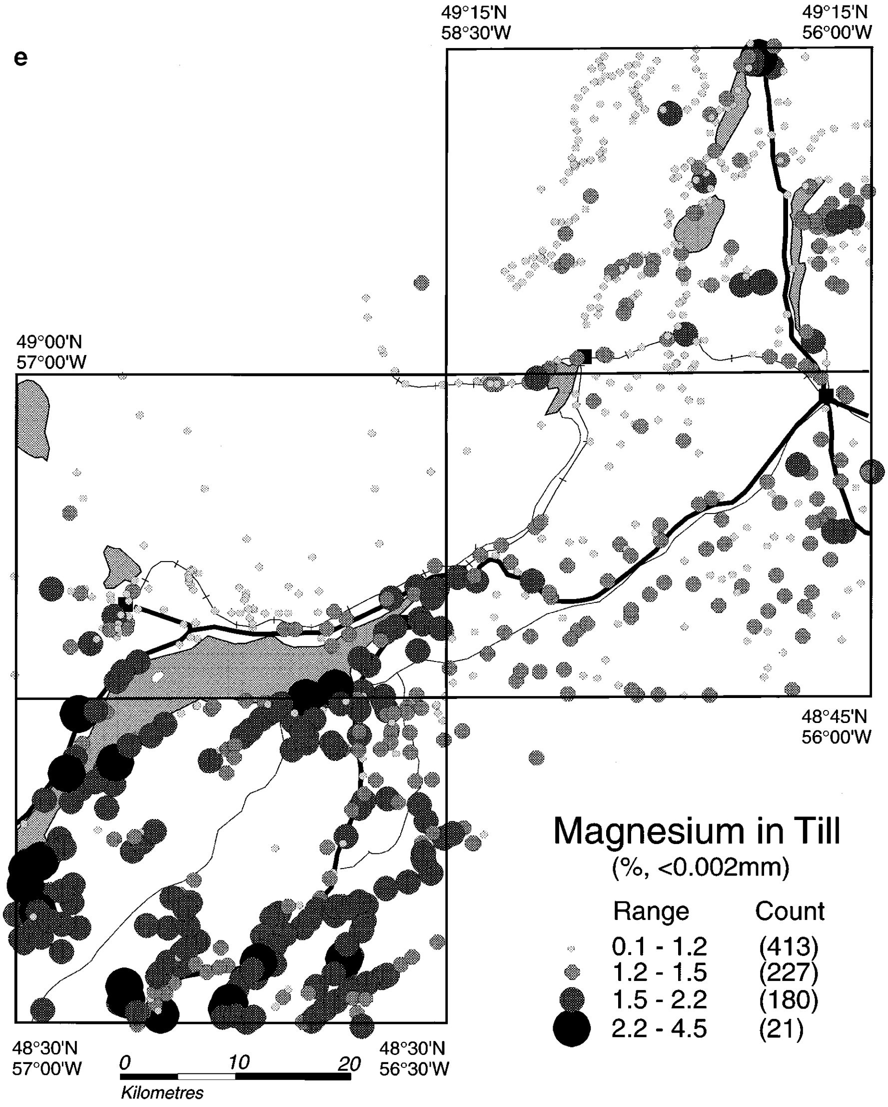

Fig. 8
Maps of **a** As, **b** Pb, **c** Zn, **d** Al and **e** Mg in the clay-sized (<0.002 mm) fraction of till

parable correlations between size fractions have also been determined in till of central Labrador (Klassen and Knight 1996) and the District of Keewatin (Klassen 1995). Geochemical differences between size fractions reflects mineralogical partitioning resulting from glacial comminution, and the differences in mineral hardness and cleavage affecting their resistance to glacial comminution (e.g. Eriksson 1973; Perttunen 1977; Shilts 1984; 1995; DiLabio 1995). For glacial sediments of the Canadian Shield, the >2-mm fraction is typically composed of rock fragments derived from bedrock along the path of glacier flow (Shilts 1993). The sand fraction (2–0.063 mm) consists of separate mineral grains, whereas the silt- and clay-sized fractions consist of both mineral grains and grain fragments. Quartz and feldspar tend to concentrate in the silt-sized fraction (0.063–0.002 mm), and softer minerals such as phyllosilicates (e.g. chlorite, muscovite, bitotite) and mafic minerals (e.g. amphibole, pyroxene) tend to be occur in the clay-sized fraction (Allen and Johns 1960; Darmody and others 1987; Haldorsen and others 1989; Mäkinen 1995; Nevalainen 1989). For that reason, the proportions of clay-sized material in the <0.063-mm fraction are approximated by Al concentrations. Assuming uniform application of glacial process, the texture and mineralogy of bedrock controls the compositional differences observed among size fractions. In contrast to till derived from crystalline rock, till derived from sedimentary and volcanic rock is finer grained, containing greater proportions of silt and clay. Within it, mineralogical and geochemical partitioning among size fractions is minimal because minerals of the rock matrix are silt or finer size, and the differential effects of glacial comminution on mineral grains tend to decrease with decrease in grain size. Till derived from coarser crystalline rock is sandy, with quartz and feldspar concentrated in the silt-sized fraction.

In common with other studies (Shuman 1979; Nikkarinen and others 1984; Nevalainen 1989; Esser and others 1991; Horowitz 1991; DiLabio 1988, 1995; Shilts 1984, 1993, 1995), this work illustrates that grain size and lithology are important to the determination of geochemical 'background', with geochemical differences among size frac-

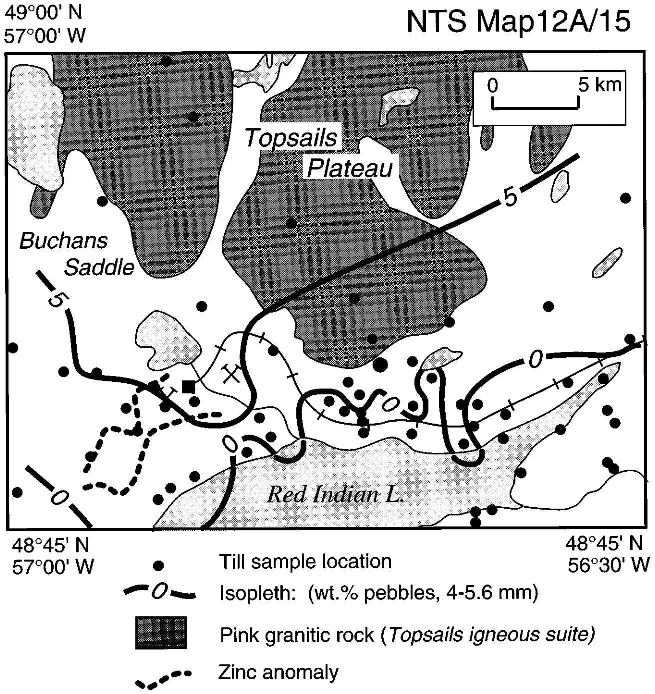

Fig. 9
Glacial dispersal train of red granitic pebbles derived from the Topsails igneous terrane north of Buchans outlined by the 5 wt.% isopleth. Stratigraphic sections shown by Fig. 10 a, b are located at Oriental and Lucky Strike mines at Buchans

tions reflecting more than net surface area (Horowitz 1991). Although no mineralogical analyses of either the silt and clay-sized or the clay-sized fractions have been done, the positive correlations between trace metal concentrations and Al and Mg are inferred to indicate that trace metals are preferentially associated with either phyllosilicates or mafic minerals, or both (Figs. 4 and 5). The tendency for trace metal concentrations to increase with Mg concentrations either greater or lesser than 0.5–1% (Fig. 5) indicates that more than one mineral species could serve as trace metal hosts. Because quartz and feldspar typically contain low trace metal concentrations, they serve as geochemical 'dilutents' that lower trace metal concentrations in the silt fraction (Shilts 1995). Through sequential extraction studies, Shilts (1995) concluded that phyllosilicates are important trace metal hosts because: (1) they have a large reactive surface area, (2) their mineral lattice structures accommodate a wide range of trace metal cations, and (3) they are easily cleaved and can readily concentrate in the clay-sized fraction. Trace metals also occur in mafic minerals (Foster 1971; Allen and Nichol 1984), and can serve as important geochemical controls in glacial sediments (Mäkinen, 1995). In this report, the effects of weathering and trace metal movement are assumed minimal, an interpretation supported, but not proven, by the preservation of pyrite grains in the soil horizons sampled (upper C, lower B) during the regional survey. Weathering, however, can affect trace metal residence sites, indicated by trace metals associations with weathered phyllosilicates (vermiculite), clay minerals, and secondary oxides of iron and alumina (Farrah and others 1980; Larocque 1991; McBride 1978; Cole and Rose 1984).

Bedrock geology, glacial history, and till geochemistry

The geochemical maps (Fig. 8) reflect the composition of common rock-forming minerals from different geological terranes, and their partitioning by glacial transport and comminution to different size fractions. Compositional profiles of the two sections exposed in mine workings at Buchans (Klassen and Murton 1996) illustrate the effects of sediment provenance, glacial history, and depositional environment on geochemistry. They illustrate that glacial processes are an important factor in the redistribution of sulphide minerals and trace metals in sediments, a conclusion that has long been successfully used in mineral exploration based on sampling glacial sediments (Coker and DiLabio 1989). At Buchans, the scale of glacial transport is measured in kilometres to tens of kilometres, similar to dispersal from deposits elsewhere (Coker and DiLabio 1989). Sulphide-rich detritus and high trace metal concentrations in subaerial and subaqueous debris flow deposits as well as glacial lake sediments indicate that other geologic processes are also important agents of dispersal. The dispersal of sulphide-rich debris up to 10 km southwest of Buchans was originally identified as a glacial dispersal train (James and Perkins 1981). The Buchans stratigraphy, however, indicates that surficial deposits associated with the train underwent a final phase of transport in debris flows confined in a southwest-trending topographic low. In contrast, sulphide-bearing sediment and subcropping VMS mineralization at Buchans are masked by granite-rich debris derived from the Topsails igneous terrane >5 km north. The metal-poor sediments are compositionally unrelated to bedrock of the Buchans Group.

Geochemical background

Despite potential mineralogical differences, geochemical maps based on silt and clay- and clay-sized fractions reflect comparable differences within and among geological terranes of central Newfoundland. The highest trace metal concentrations are associated with volcanic and sedimentary rocks, especially volcanic terrane of the Victoria Lake Group south of Red Indian Lake. The close spatial associations between till geochemistry and bedrock lithology indicates that trace metals reflect geological variability and glacial process, and that trace metals associated with atmospheric input from anthropogenic sources are not significant in comparison.

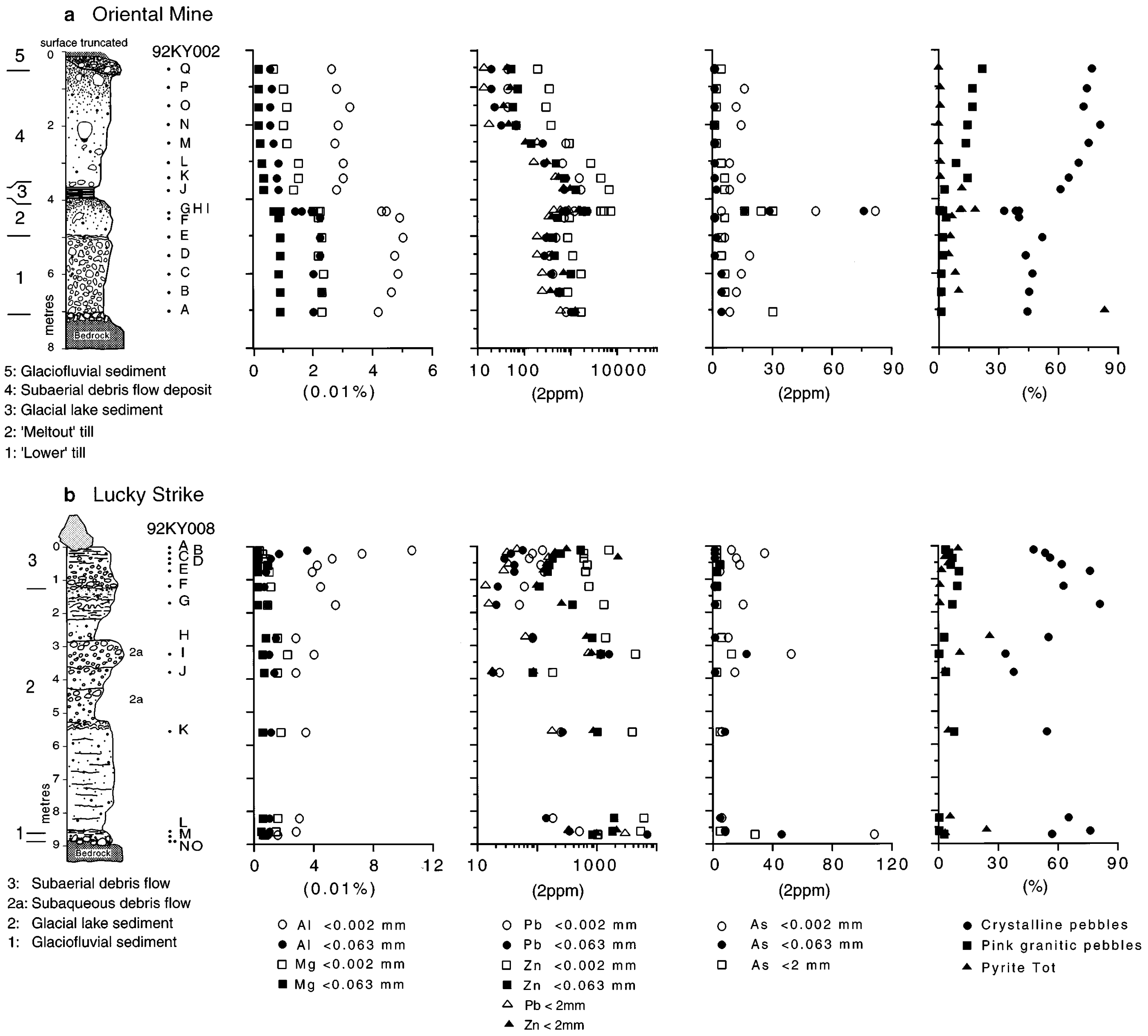

Fig. 10
Lithofacies and geochemical profiles of surfical deposits at **a** Oriental mine and **b** Lucky Strike mine

In Canada, and elsewhere, regulatory agencies set trace metal 'benchmarks' intended to be protective of human and environmental health; they are approximately <50 ppm As, <1000 ppm Pb, and <1500 ppm Zn, and are commonly based on analysis of the <2-mm fraction (Fitchko and Kingsbury 1989; Environment Canada 1991). Because the highest trace metal concentrations occur in the clay-sized fraction, the proportion of clay-sized material in the <2-mm fraction is important for the interpretation of trace metal geochemistry and environmental hazards (Tarvainen 1995). This is recognized in the Netherlands where both clay and organic matter concentrations are used to define environmental standards for soil geochemistry (Moen 1988).

In this study, there are strong positive linear correlations of trace metal concentrations among the <0.002-mm, <0.063-mm and <2-mm fractions. From those linear relations, the regional geochemical survey results, which are based on the <0.063- and <0.002 mm fractions, can be used to characterize trace metal concentrations for environmental purposes, although indicating higher overall trace metal levels than the <2-mm fraction. For example, at more than half of sites overlying Victoria Lake Group rocks, the silt and clay-sized fraction of till contains As concentrations greater than identified as significant environmental thresholds (>50 ppm; Fig. 9b). Graphs in Figure 5 indicate that equivalent concentrations in the <2-mm fractions would be >25 ppm. Elsewhere in the study area samples also exceed threshold concentrations for Pb and Zn.

Not only is the clay-sized fraction the most reactive soil component (Horowitz 1991), it is most likley to be eroded and furthest transported by aeolian or fluvial processes. The removal of clay by geological processes, such as winnowing, will leave a coarser lag enriched in quartz and feldspar and having lower trace metal concentrations than the finer transported component (Shilts 1971, 1995). For this study, the depth of sample collection (<50 cm; typically 80–100 cm) and the preservation of primary sedimentary structures at sample sites both indicate that the texture and mineralogy of the sampled sediments reflects glacial processes of erosion, transport, and comminution, with minimal to no postglacial modification and textural change. Thus, the geochemical patterns are interpreted to reflect bedrock composition, modified by the effects of glacial history and ice flow dynamics. At Buchans, stratigraphic variations illustrate that sediment characterized by low trace metal concentrations can overlie and mask older sediments and bedrock enriched in trace metals. There, trace metal levels in surface till are as much as 10 times less than elsewhere over Buchans Group rock, reflecting glacial dispersal of granitic debris from the Topsails igneous terrane and compositional masking of underlying bedrock. In contrast, older buried sediments are more locally derived. They are enriched in sulphide minerals and trace metals, with concentrations well above environmental risk thresholds. Exposure and weathering of that sulphide-rich sediment, either through natural erosion or excavation of older deposits, could lead to environmental problems typically associated with mine tailings and acid mine drainage. Although stratigraphic complexity in the subsurface has long been known in mineral exploration, its recognition for environmental studies, where terrane is commonly described according to use (agricultural, parkland, or industrial) or vegetation (deciduous woodland) is less certain (Environment Canada 1991).

Conclusions

Marked geochemical variations characterize glacial sediments in central Newfoundland that reflect bedrock source and geological history. Geochemical analyses of till from this region indicate that background concentrations of trace metals in the environment vary over three orders of magnitude. Over large parts of the area, As, Pb, and Zn in both clay-sized and silt and clay-sized fractions exceed levels associated with environmental risk (Moen 1988; Fitchko and Kingsbury 1989; Government of Canada 1991, 1993;). The close linkages between geochemistry and pebble lithology, spatial associations between geochemical patterns and geological terranes, and stratigraphic associations with distinct till units demonstrate that distributions and concentrations of trace metals reported here are of geological origin, and the effects of anthropogenic inputs are not evident. In common with numerous other studies, the work emphasizes the importance of size fraction and lithology to the interpretation of geochemical analysis and description of geochemical landscape. It further illustrates that the definition of geochemical 'background' must recognize the geologic provenance and stratigraphic origins of surficial sediments, and the intrinsic geochemical variations that occur both within and among geological terranes.

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