Generation of a heavy-mineral glacial indicator dispersal train from a diabase sill, Nipigon region, northwestern Ontario

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Abstract: The heavy clinopyroxene mineral pigeonite forms a glacial indicator dispersal train originating from diabase intrusions in the Nipigon region of northwestern Ontario. Analysis and interpretation of the pigeonite dispersal pattern adjacent to the up-ice portion of the diabase provides a number of insights into the nature of glacial erosion of bedrock and the generation of heavy-mineral dispersal trains. Bedrock erosion and entrainment rates at the time of pigeonite dispersal train formation were high ($3\text{--}14\text{ mm}\cdot\text{a}^{-1}$), suggesting that bedrock erosion was rapid yet spatially and temporally restricted. Contrasting erosion rates between the diabase and surrounding greenstone lithologies suggests that modern shield topography is not an assemblage of equilibrium bedforms with respect to the ice sheet. This agrees with hypothesized low total erosion of shield bedrock during the Pleistocene. Pigeonite grain size coarsens over the diabase source, indicating that most of the pigeonite was quarried from outcrops as coarse diabase fragments. Down-ice of the diabase source the mean particle size of pigeonite recovered from till decreases, suggesting most of the pigeonite was liberated from bedrock by the comminution of coarse diabase clasts during glacial transport. While the conclusions drawn from this study may not necessarily apply to all heavy-mineral dispersal trains, the interpretive framework provides a foundation for comparative studies.

Résumé : Le minéral lourd de clinopyroxène, la pigeonite, sert de minéral indicateur d'un train glaciaire; elle provient des intrusions de diabase dans la région de Nipigon du nord-ouest de l'Ontario. L'analyse et l'interprétation du patron de dispersion de la pigeonite adjacente à la portion en amont glaciaire de la diabase fournissent plusieurs aperçus de la nature de l'érosion glaciaire du socle rocheux et la formation de trains glaciaires de minéraux lourds. Les taux d'érosion du socle rocheux et d'entraînement au moment de la formation du train de dispersion de la pigeonite étaient élevés ($3\text{--}14\text{ mm}\cdot\text{a}^{-1}$), suggérant une érosion rapide du socle rocheux bien que restreinte dans le temps et l'espace. En raison des taux d'érosion différents de la diabase et des lithologies environnantes de roches vertes, la topographie moderne du bouclier n'est pas un assemblage de formes du socle en équilibre par rapport au feuillet glaciaire. Cela concorde avec l'hypothèse d'une faible érosion totale du socle rocheux du bouclier au cours du Pléistocène. La granulométrie de la pigeonite devient plus grossière au-dessus de la source de diabase, indiquant que la plus grande partie de la pigeonite a été débitée des affleurements en fragments grossiers de diabase. En aval glaciaire de la source de la diabase, la dimension moyenne des particules de pigeonite récupérées d'un till décroît, suggérant que la plus grande partie de la pigeonite ait été libérée du socle rocheux par la comminution de clastes grossiers de diabase au cours du transport glaciaire. Alors que les conclusions tirées de cette étude ne s'appliquent pas nécessairement à tous les trains de dispersion des minéraux lourds, le cadre d'interprétation fournit une base pour des études comparatives.

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Introduction

Identification and tracing of heavy-mineral glacial indicator dispersal trains is widely used as a mineral exploration tool in glaciated terrain (Peuraniemi 1990; McClenaghan et al. 2000). The method has proven to be of particular use in the search for diamondiferous kimberlites (McClenaghan and

Kjarsgaard 2001), and it also has been successfully applied to exploration for gold and base metals (Averill 2001).

Despite the long and successful history of application of heavy-mineral indicator mineralogy and dispersal studies to mineral exploration, in many respects the processes and rates by which glaciers erode and entrain, transport, and deposit indicator minerals derived from a bedrock source are poorly understood. Consequently, subjecting heavy-mineral dispersal studies to rigorous quantitative analysis and interpretation remains problematic. Most analyses of indicator dispersal data are based on the empirical observation that indicator concentrations in till tend to decrease in a quasi-exponential fashion with increasing transport length from the indicator source (Gillberg 1965; Shilts 1976; Klassen 2001; Stea and Finck 2001).

Indicator dispersal data is typically interpreted using this empirical framework, and most surveys collect an initial,

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Fig. 1. Map of field area showing till sample locations. Shaded area is the diabase outcrop. Arrows indicate the regional ice flow direction reconstructed from striation orientations (this study; Thorleifson and Kristjansson 1993).

relatively large amount of data (samples) as a basis for interpretation. Development of a more rigorous quantitative framework promises to increase the amount of useful information derived from each till sample, allowing for a lower effective sampling density. Successful application will potentially decrease the expense associated with indicator mineral surveys and encourage their wider application. We propose to adapt a new conceptual model of indicator dispersal (Larson and Mooers 2004) to the interpretation of a heavy-mineral indicator dispersal train. Herein, the general relationships presented in Larson and Mooers (2004) are adapted to the problem of interpreting a particular heavy-mineral dispersal train in a particular geologic environment with minimal discussion of the conceptual model. Interested readers are referred to Larson and Mooers (2004) for a full discussion of the conceptual model.

Study area

During the course of a regional till heavy-mineral indicator survey, Bajc and Crabtree (2001) identified a large area southwest of Lake Nipigon, Ontario, in which tills yielded anomalous quantities of non-ferromagnetic heavy-mineral concentrates (NMHMC). Here, tills yield 300–400 g of NMHMC per 10 kg of till, compared to elsewhere on the Canadian Shield where yields of 40–50 g per 10 kg are more typical (Averill 2001). Most of this anomalous NMHMC is composed of the mineral pigeonite, which is a brown, dense (specific gravity of 3.3–3.4), Ca-poor clinopyroxene. The pigeonite, in turn, is derived from the Proterozoic Nipigon diabase, a series of laterally extensive sills underlying the Nipigon Embayment (Sutcliffe 1991).

The combination of a heavy mineral comprising a major rock-forming component and a well-defined source area make the pigeonite dispersal train an ideal tracer for examining and quantifying the processes by which glaciers generate

heavy-mineral indicator dispersal trains. Our field area lies east of Lake Nipigon along the eastern (up-ice) contact of the Nipigon diabase (Fig. 1). Here, the easternmost outlier of the diabase is the westward-dipping sill intruding Archean metavolcanic and metasedimentary rock of the Beardmore–Geraldton greenstone belt. The map-view linear geometry of the sill, which happens to be oriented perpendicular to the ice-flow direction, allows investigation of both the incorporation of pigeonite into the glacial debris load and its evolution during transport without masking from additional pigeonite incorporation.

An examination of the up-ice portion of the Nipigon pigeonite dispersal train provides insight into the nature and rates of a number of glacial processes responsible for generation of heavy-mineral dispersal trains. These include (1) the rate of erosion and entrainment of the heavy-mineral indicator into the glacial debris load (i.e., how quickly the indicator dispersal train is resolvable from background values), (2) the particle-size distribution of eroded and entrained indicator material (i.e., if the indicator mineral is incorporated as monomineralic grains or within lithic fragments), and (3) the effect of comminution of the indicator during transport on the down-ice dispersal of the indicator dispersal plume (i.e. if comminution enhances or attenuates the heavy-mineral indicator signal).

Bedrock geology

The Nipigon diabase consists predominantly of olivine tholeiite diabase dikes and sills (Sutcliffe 1991). The diabase is associated with the Midcontinent Rift and was intruded at ~ 1108 Ma. Major silicate mineral phases in the diabase include plagioclase, variable amounts of augite and pigeonite, olivine, minor orthopyroxene, magnetite, and biotite and micrographic quartz – alkali feldspar intergrowths (Mackasey 1975; Sutcliffe 1991).

Table 1. Till sampling data.

Sample No.	Sample locations		Substrate	Sample size (kg)	<i>T</i> from down-ice contact (m)	<i>T</i> from up-ice contact (m)	<i>L</i> (m)
	Latitude (°N)	Longitude (°W)					
NIP-02	49.7114	87.9197	Greenstone	11.2	−2040	−413	
NIP-03	49.7101	87.9258	Greenstone	8.5	−1615	−42	
NIP-07	49.6723	87.9692	Greenstone	12.1	3473	6227	2754
NIP-08	49.6665	87.9710	Greenstone	9.9	3928	6810	2881
NIP-09	49.6931	87.8428	Greenstone	13.0	−5585	−3944	
NIP-10	49.6892	87.8539	Greenstone	9.6	−4614	−3006	
NIP-13	49.6773	87.8960	Diabase	11.1	−859	690	690
NIP-14	49.6775	87.8985	Diabase	13.7	−1027	854	854
NIP-15	49.6797	87.9008	Diabase	13.9	−784	889	889
NIP-16	49.6793	87.9063	Diabase	12.1	−406	1265	1265
NIP-17	49.6785	87.9073	Diabase	12.4	−300	1371	1371
NIP-18	49.6782	87.9098	Diabase	13.3	−116	1554	1554
NIP-20	49.6792	87.9156	Greenstone	9.1	208	1873	1665
NIP-21	49.6651	87.9388	Greenstone	12.3	2438	4108	1669
NIP-22	49.6645	87.9444	Greenstone	9.6	2830	4497	1667
NIP-23	49.6638	87.9494	Greenstone	10.1	3195	4860	1665
NIP-25	49.6935	88.0026	Greenstone	9.9	3241	4832	1591
NIP-26	49.6565	87.9725	Greenstone	11.5	4895	6746	1850
NIP-27	49.6532	87.9707	Greenstone	13.5	5123	6766	1745
NIP-28	49.6550	87.9718	Greenstone	10.2	5020	6788	1666
NIP-29	49.6489	87.9694	Greenstone	11.2	5255	6927	1671
NIP-30	49.6434	87.9778	Greenstone	12.2	6082	7756	1673
NIP-31	49.6388	87.9904	Greenstone	8.4	7136	8808	1672
NIP-33	49.6310	88.0069	Greenstone	6.1	8611	10284	1672

Note: *T*, transport length; *L*, flowline outcrop thickness.

In the study area, the easternmost outlier of the Nipigon diabase consists of a westward-dipping 120–200 m thick sill (Mackasey 1975) (Fig. 1). The sill forms an east-facing scarp with up to 50 m of relief; locally, cliffs over 30 m high display columnar jointing.

The diabase sill intrudes a sequence of Archean metavolcanic and metasedimentary rocks (greenstone) (Mackasey 1975). In contrast to the diabase, these rocks are extensively metamorphosed, folded, and faulted. Abundant secondary mineral phases, such as chlorite and sericite, well-developed foliation, and local shearing result in a lithic assemblage that is significantly mechanically weaker than the younger diabase.

An indication of the relative strengths of the diabase and the greenstone country rock is provided by a comparison with engineering studies of similar rock types in northeastern Minnesota, USA. Unconfined compressive strengths (UCS) for the Silver Creek and Lafayette Bluff diabases ranged from 68 to 83 MPa for weathered rock and from 99 to 248 MPa for dense unweathered rock (CNA Consulting Engineers 1989, 1991). In comparison, the UCS of unweathered metavolcanic and metasedimentary rocks in the Soudan Mine ranged from 64 to 132 MPa (CNA Consulting Engineers 1999).

Glacial geology

Thorleifson and Kristjansson (1993) described in detail the glacial geologic setting of the Beardmore–Geraldton region, including the study area. Till and other glacial sedi-

ments in the study area are associated with the final retreat of the Laurentide ice sheet (LIS) at the end of the Wisconsin glacialiation. The probable time of till formation in the study area is bracketed by the minor readvance of the LIS to the Nipigon moraine to the west at about 9300 BP and a minor readvance of the LIS to the Nakina moraine to the east at about 8300 BP. As the ice retreated from the Nipigon moraine, topographically lower areas adjacent to Lake Nipigon in the western portion of the study area were inundated by Glacial Lake Kelvin (Zoltai 1965). Glacial Lake Kelvin was confluent with the Minong levels of Lake Superior and persisted from the retreat of the ice sheet from the Nipigon basin until 9000 BP.

In the study area, till occurs as a thin, discontinuous mantle overlying bedrock and is generally about 1 m thick. Striation orientations indicate a flow direction of ~235° during the last glacialiation. In the western portion of the study area, the till is overlain by subaqueous outwash and glaciolacustrine silts and sands deposited in Glacial Lake Kelvin.

Sampling and methods

Sampling

Basal till samples were collected along a transect roughly parallel to the ice-flow direction over the diabase sill and up to 9 km down-ice. A total of 24 samples were collected: four from tills up-ice of the mapped extent of the diabase sill, six

Table 2. Till granulometry.

Sample No.	< 0.125 mm	0.125–0.25 mm	0.25–0.5 mm	0.5–1.0 mm	1.0–2.0 mm	2.0–4.0 mm	4.0–8.0 mm	8.0–16.0 mm
NIP-02	0.647	0.033	0.021	0.041	0.035	0.047	0.076	0.099
NIP-03	0.602	0.115	0.061	0.096	0.029	0.019	0.033	0.044
NIP-07	0.240	0.145	0.102	0.085	0.090	0.095	0.117	0.125
NIP-08	0.312	0.159	0.103	0.096	0.092	0.066	0.077	0.094
NIP-09	0.328	0.108	0.121	0.068	0.072	0.107	0.111	0.084
NIP-10	0.372	0.142	0.137	0.081	0.068	0.055	0.075	0.070
NIP-13	0.315	0.117	0.102	0.073	0.077	0.088	0.111	0.117
NIP-14	0.312	0.135	0.127	0.100	0.076	0.089	0.076	0.084
NIP-15	0.509	0.185	0.097	0.052	0.040	0.037	0.039	0.040
NIP-16	0.349	0.193	0.095	0.068	0.069	0.066	0.071	0.090
NIP-17	0.297	0.177	0.129	0.096	0.074	0.067	0.076	0.085
NIP-18	0.460	0.168	0.111	0.071	0.052	0.057	0.038	0.044
NIP-20	0.366	0.142	0.104	0.066	0.065	0.081	0.091	0.085
NIP-21	0.338	0.201	0.166	0.103	0.050	0.043	0.047	0.051
NIP-22	0.297	0.121	0.115	0.075	0.063	0.104	0.108	0.118
NIP-23	0.434	0.122	0.094	0.062	0.039	0.039	0.126	0.085
NIP-25	0.465	0.117	0.103	0.068	0.053	0.051	0.068	0.074
NIP-26	0.417	0.150	0.126	0.084	0.060	0.055	0.053	0.055
NIP-27	0.481	0.145	0.095	0.071	0.053	0.051	0.054	0.050
NIP-28	0.381	0.154	0.120	0.091	0.076	0.062	0.060	0.058
NIP-29	0.384	0.159	0.131	0.099	0.069	0.057	0.054	0.046
NIP-30	0.377	0.134	0.108	0.088	0.085	0.065	0.068	0.074
NIP-31	0.301	0.085	0.112	0.086	0.072	0.090	0.116	0.139
NIP-33	0.419	0.222	0.132	0.067	0.055	0.030	0.036	0.040

Note: Values are mass fraction of < 16 mm till particle-size fractions.

from tills directly overlying the sill, and 14 from tills down-ice of the sill (Fig. 1, Table 1).

Sample locations included road cuts and hand-dug pits. All samples were dense, semi-fissile lodgement tills collected from unweathered C-horizon material. Samples were collected as close to the bedrock surface as possible; most were collected from a depth of 0.5–1.0 m. Samples were screened in the field to remove clasts > 16 mm. Mean till sample size was 11 kg (Table 1).

Transport lengths corresponding to each sample location were determined by measuring the distance in the flow direction from the down-ice edge of the diabase sill to the sample location (Table 1). The flowline outcrop thickness was similarly determined by measuring the distance between the up-ice and down-ice contacts of the diabase sill along a line extending from the sample location in the flow direction (Table 1). Bedrock contact locations were taken from Ontario Geological Survey (1993) bedrock mapping.

Till granulometry

Till particle-size distribution was determined by dry screening the > 2 mm fraction from the bulk sample. The relative proportions of the > 2 mm fractions were determined by further dry screening at 1 ϕ intervals. The particle-size distribution of the < 2 mm fraction was determined by dry screening an ~ 400 g split. Till particle-size distributions are summarized in Table 2.

Heavy-mineral concentrate from till

Heavy-mineral processing of the till samples was performed

by Overburden Drilling Management Limited, Nepean, Ontario. The bulk samples were dried and weighed before screening to remove the 2–16 mm fraction; this material was retained to determine the concentration of coarse diabase clasts. The < 2 mm fraction was initially concentrated by wet-gravity tabling. The table concentrate was further concentrated to a > 3.2 specific gravity, heavy-mineral concentrate (HMC) using density-dependent settling in methylene iodide diluted with acetone. Ferromagnetic minerals were separated from the HMC using an automagnet. The non-ferromagnetic fraction was dry-sieved at 0.125, 0.25, 0.5, and 1.0 mm. The mass fraction of NMHMC in each individual till particle-size fraction is summarized in Table 3.

One hundred-grain mineral counts were performed to establish the volume percentage of pigeonite for the 0.125–0.25, 0.25–0.5, 0.5–1.0, and 1.0–2.0 mm fractions of each sample (Table 4). The resulting volume percent of pigeonite is assumed to be equivalent to the mass percent.

Pebble counts

The concentration of diabase clasts in the > 2 mm fractions were determined by visually identifying and manually separating diabase clasts from splits comprising more than 500 grains from the 2–4, 4–8, and 8–16 mm fractions. The splits were weighed, and the mass concentration of diabase in each particle-size fraction calculated (Table 5).

Heavy-mineral yield from diabase

Four boulders of unweathered diabase were collected from outcrop and from till in the diabase dispersal train in the

Table 3. Non-ferromagnetic heavy-mineral concentrate as a mass fraction of individual till particle-size fractions.

Sample No.	< 0.125 mm	0.125–0.25 mm	0.25–0.5 mm	0.5–1.0 mm	1.0–2.0 mm	Yield (g·10 kg ⁻¹)
NIP-02	0.004	0.010	0.007	0.002	0.002	38
NIP-03	0.005	0.007	0.002	0.000	0.001	33
NIP-07	0.009	0.015	0.016	0.016	0.009	101
NIP-08	0.010	0.011	0.008	0.004	0.003	72
NIP-09	0.008	0.019	0.008	0.006	0.004	102
NIP-10	0.007	0.009	0.004	0.002	0.002	53
NIP-13	0.010	0.018	0.012	0.012	0.009	116
NIP-14	0.012	0.028	0.028	0.018	0.009	172
NIP-15	0.009	0.015	0.018	0.027	0.019	117
NIP-16	0.014	0.016	0.024	0.034	0.031	187
NIP-17	0.014	0.018	0.016	0.017	0.018	154
NIP-18	0.008	0.015	0.012	0.014	0.017	102
NIP-20	0.017	0.029	0.027	0.033	0.027	215
NIP-21	0.014	0.020	0.019	0.015	0.010	145
NIP-22	0.010	0.021	0.015	0.019	0.024	158
NIP-23	0.016	0.051	0.062	0.048	0.012	269
NIP-25	0.013	0.031	0.022	0.022	0.019	156
NIP-26	0.008	0.013	0.009	0.009	0.006	79
NIP-27	0.004	0.008	0.009	0.008	0.006	54
NIP-28	0.009	0.015	0.013	0.011	0.007	94
NIP-29	0.009	0.014	0.009	0.006	0.005	85
NIP-30	0.005	0.008	0.005	0.004	0.002	47
NIP-31	0.003	0.010	0.006	0.004	0.002	43
NIP-33	0.005	0.008	0.007	0.009	0.003	51

study area in order to establish the recoverable NMHMC content of diabase. A portion of each boulder weighing ~200 g was disaggregated to < 2 mm fragments by electric-pulse disaggregation (EPD) (Weiblen 1994; Saini-Eidukat and Weiblen 1996). The EPD tends to disaggregate rocks along grain boundaries among the constituent minerals, rather than across grains as with most mechanical crushing methods. In this respect, EPD closely reproduces the effects of glacial comminution, in which clasts tend to break along mineral grain boundaries and the final size distribution is dependent on the grain size of the parent rock (Haldorsen 1981).

The disaggregated diabase was dry sieved at 0.125, 0.25, 0.5, and 1.0 mm. A > 3.2 specific gravity HMC was separated from each of the resulting fractions using density-dependent settling in methylene iodide diluted with benzyl benzoate. Ferromagnetic minerals were separated from the HMC using a hand magnet.

The resulting NMHMC is composed almost entirely of pigeonite or pigeonite enclosing smaller plagioclase grains. The EPD NMHMC grains recovered from the boulders and pigeonite grains recovered from till are visually indistinguishable. The EPD NMHMC in the 0.125–2.0 mm particle-size fraction derived from comminution of diabase to < 2 mm comprises 42% ± 8% of the original diabase mass. Using this factor, diabase concentrations in the > 2 mm clasts were converted to “pigeonite” concentrations. The mass fraction of pigeonite in each individual till particle-size fraction is summarized in Table 6. Henceforth, “pigeonite” refers to both pigeonite recovered from till in the 0.125 to 2.0 mm

fractions and the inferred pigeonite concentration of diabase clasts in the 2.0 to 16.0 mm fractions.

Results

Indicator dispersal train

Pigeonite concentrations in till define an indicator dispersal train extending down-ice from the outcrop of the diabase sill (Fig. 2). The dispersal pattern displays a quasi-exponential decay with increasing transport length from source, which was empirically observed by Gillberg (1965) and many subsequent workers and predicted by Larson and Mooers (2004). The maximum concentration of pigeonite in till occurs near the down-ice edge of the indicator outcrop, suggesting that incorporated indicator material was rapidly mixed into a relatively thin basal debris layer.

Pigeonite concentrations in individual particle-size fractions in till generally mimic the quasi-exponential decay observed in the till as a whole (Fig. 3, Table 6). With the exception of the coarsest size fraction (8.0–16.0 mm), pigeonite concentrations increase rapidly over the diabase source and decrease with increasing transport length from the source.

Erosivity

Erosion and entrainment of bed material into the glacial debris load is quantified as erosivity represented by E (unit of mass per cubic unit of length) (Larson and Mooers 2004). Erosivity describes the coupling between the glacier's bed and debris load, and it is the mass of bed material incorpo-

Table 4. Volume percent pigeonite in non-ferromagnetic heavy-mineral concentrate.

Sample No.	0.125–0.25 mm	0.25–0.5 mm	0.5–1.0 mm	1.0–2.0 mm
NIP-02	2	0	0	1
NIP-03	1	0	0	0
NIP-07	17	55	66	77
NIP-08	9	32	45	39
NIP-09	3	4	3	3
NIP-10	2	0	1	1
NIP-13	25	45	50	63
NIP-14	50	58	78	73
NIP-15	28	47	78	72
NIP-16	36	52	76	74
NIP-17	39	50	69	72
NIP-18	16	35	36	40
NIP-20	43	54	59	65
NIP-21	45	67	58	33
NIP-22	43	61	66	72
NIP-23	71	84	92	79
NIP-25	57	68	83	75
NIP-26	33	43	54	25
NIP-27	24	37	43	38
NIP-28	47	64	52	30
NIP-29	16	47	43	27
NIP-30	7	13	7	3
NIP-31	24	19	22	12
NIP-33	10	52	54	39

rated into the debris load per unit bed area per unit of length along the flowline. Over any flowline interval T , erosivity is related to an absolute erosion rate of e (unit of length per unit of time) by

$$[1] \quad E = \frac{e\rho_b}{u}$$

where ρ_b is the density of bed material and u is the mean velocity of the basal debris load.

For tills along the flowline interval extending from the up-ice to the down-ice contacts of the diabase outcrop, erosivity is estimated by

$$[2] \quad E = \frac{\left[\frac{m}{(1 - c_i)} - m \right]}{L}$$

where c_i is the indicator (diabase) mass concentration, L is the transport length from the up-ice diabase contact, and m is the debris mass per unit bed area at the up-ice contact. Assuming m was $1000 \text{ kg}\cdot\text{m}^{-2}$ at the up-ice contact (an amount of debris sufficient to produce a till layer $\sim 0.5 \text{ m}$ thick upon deposition), erosivity values recorded in tills overlying the diabase average $0.028 \text{ kg}\cdot\text{m}^{-3}$ (Fig. 4A, Table 7).

Erosivity values for tills down-ice of the diabase outcrop are calculated by first estimating the mass of indicator material eroded and entrained per unit bed area (m_i)

$$[3] \quad m_i = E_d \cdot L$$

where E_d is the average erosivity estimate of $0.028 \text{ kg}\cdot\text{m}^{-3}$

Table 5. Diabase clasts as a mass fraction of 2–16 mm particle-size fractions.

Sample No.	2–4 mm	4–8 mm	8–16 mm
NIP-02	0	0	0
NIP-03	0	0	0
NIP-07	0.013	0.008	0.009
NIP-08	0.028	0.007	0.018
NIP-09	0	0	0
NIP-10	0	0	0
NIP-13	0.005	0.004	0.001
NIP-14	0.162	0.036	0.013
NIP-15	0.071	0.087	0.014
NIP-16	0.053	0.023	0.016
NIP-17	0.114	0.075	0.029
NIP-18	0.058	0.035	0.010
NIP-20	0.175	0.134	0.099
NIP-21	0.066	0.036	0.042
NIP-22	0.077	0.021	0.004
NIP-23	0.423	0.767	0.645
NIP-25	0.219	0.144	0.159
NIP-26	0.023	0.018	0.017
NIP-27	0.021	0.010	0
NIP-28	0.023	0.009	0.003
NIP-29	0.051	0.018	0
NIP-30	0.001	0.001	0
NIP-31	0.004	0.003	0.017
NIP-33	0.005	0.009	0.013

and L in this case is the flowline length of the indicator outcrop. The resulting m_i estimate is incorporated into the following equation to yield the erosivity values recorded in tills overlying the greenstone down-ice of the diabase

$$[4] \quad E_g = \frac{\left(\frac{m_i}{c_i} - m_i - m \right)}{T}$$

where T is the transport length down-ice of the diabase outcrop. Using these assumptions, erosivity values recorded in tills overlying the greenstone average $0.854 \text{ kg}\cdot\text{m}^{-3}$ (Fig. 4A, Table 7).

The contrasting erosivity values recorded in tills overlying the diabase and the greenstone indicate that the ice sheet was able to erode and entrain weak, foliated, and fractured greenstone material at ~ 31 times the rate of hard, massive diabase (Fig. 4A).

Erosion length scales

Erosion length scale (λ) (units of length) describes the influence of debris derived from up-ice on the magnitude and down-ice persistence of an indicator dispersal train (Larson and Mooers 2004). High values indicate that up-ice debris dominates the debris load, whereas low values indicate that locally derived indicator material is able to form dispersal trains with high signal to background contrast. Erosion length scales for tills overlying the diabase are calculated from

Table 6. Pigeonite as a mass fraction of individual till particle-size fractions.

Sample No.	0.125–0.25 mm	0.25–0.5 mm	0.5–1.0 mm	1–2 mm	2–4 mm	4–8 mm	8–16 mm	0.125–16.0 mm
NIP-02	0.000	0	0	0.000	0	0	0	0.000
NIP-03	0.000	0	0	0	0	0	0	0.000
NIP-07	0.003	0.009	0.011	0.007	0.005	0.003	0.004	0.005
NIP-08	0.001	0.003	0.002	0.001	0.012	0.003	0.007	0.004
NIP-09	0.001	0.000	0.000	0.000	0	0	0	0.000
NIP-10	0.000	0	0.000	0.000	0	0	0	0.000
NIP-13	0.005	0.005	0.006	0.006	0.002	0.002	0.001	0.003
NIP-14	0.014	0.016	0.014	0.007	0.068	0.015	0.005	0.020
NIP-15	0.004	0.009	0.021	0.014	0.030	0.037	0.006	0.012
NIP-16	0.006	0.012	0.026	0.023	0.022	0.010	0.007	0.013
NIP-17	0.007	0.008	0.011	0.013	0.048	0.032	0.012	0.016
NIP-18	0.002	0.004	0.005	0.007	0.024	0.015	0.004	0.007
NIP-20	0.012	0.014	0.020	0.018	0.074	0.056	0.042	0.032
NIP-21	0.009	0.013	0.009	0.003	0.028	0.015	0.017	0.012
NIP-22	0.009	0.009	0.013	0.017	0.032	0.009	0.002	0.012
NIP-23	0.036	0.052	0.044	0.010	0.178	0.322	0.271	0.146
NIP-25	0.018	0.015	0.018	0.014	0.092	0.060	0.067	0.036
NIP-26	0.004	0.004	0.005	0.002	0.010	0.007	0.007	0.005
NIP-27	0.002	0.003	0.003	0.002	0.009	0.004	0	0.003
NIP-28	0.007	0.008	0.006	0.002	0.009	0.004	0.001	0.006
NIP-29	0.002	0.004	0.003	0.001	0.021	0.007	0	0.005
NIP-30	0.001	0.001	0.000	0.000	0.000	0.000	0	0.000
NIP-31	0.002	0.001	0.001	0.000	0.002	0.001	0.007	0.002
NIP-33	0.001	0.004	0.005	0.001	0.002	0.004	0.006	0.003

Note: Values are mass fraction of pigeonite in 0.125–16.0 mm particle-size fractions.

$$[5] \quad \lambda = \frac{m}{E_d}$$

Assuming m was $1000 \text{ kg} \cdot \text{m}^{-2}$ at the up-ice contact, and using the values for E_d presented in Table 7, erosion length scales recorded in tills overlying the diabase average 49 700 m (Fig. 4B, Table 7).

Erosion length scales for tills overlying the greenstone down-ice of the diabase outcrop are calculated with

$$[6] \quad \lambda = \frac{(m + m_i)}{E_g}$$

Assuming m was $1000 \text{ kg} \cdot \text{m}^{-2}$ at the up-ice contact, and using values for E_g and m_i presented in Table 7, erosion length scales recorded in tills overlying the greenstone average 2016 m (Fig. 4B, Table 7).

Calculated erosion length scales recorded in tills overlying the diabase outcrop are ~25 times higher relative to those of tills overlying down-ice greenstone. Similar to the erosivity values, this comparison indicates that greenstone was eroded and entrained at a significantly higher rate than diabase. Consequently, the down-ice propagation of the pigeonite indicator dispersal train is significantly retarded — more than it would have been if the greenstone were as strong as the diabase. Conversely, the maximum concentration of pigeonite in till at the down-ice contact of the diabase outcrop is significantly lower than it would have been if the diabase were as weak as the greenstone.

Erosion rates

A range of absolute erosion rates for both the diabase and the greenstone are calculated from the erosivity estimates using basal ice velocities of $10\text{--}50 \text{ m} \cdot \text{a}^{-1}$. This represents a range of basal velocities that are consistent with reasonable balance velocities near the margin of an ice sheet with a diameter of 900 km and characterized by a parabolic profile and uniform radial flow (see Paterson 1994). Diabase and greenstone densities were assumed to be 3000 and $2700 \text{ kg} \cdot \text{m}^{-3}$, respectively (eq. [1]). The apparent diabase erosion rate was $0.1\text{--}0.5 \text{ mm} \cdot \text{a}^{-1}$, whereas the greenstone erosion rate was $2.8\text{--}14.2 \text{ mm} \cdot \text{a}^{-1}$. The erosion rate calculated for the greenstone is comparable to the highest erosion rates estimated for modern large, temperate glaciers (Hallet et al. 1996).

The greenstone was apparently eroded at a rate ~30 times higher than the diabase. The disparate erosion rates of the two substrates, and the inverse correlation between erosion rate and substrate strength, suggest bed mechanical strength was the dominant control on erosion rates.

It is well established that LIS basal erosion rates varied both spatially and temporally over the course of a glacial cycle. Cold-based ice results in little, if any, erosion over significant areas in the interior of the ice sheet (Dyke 1993; Kleman 1994; Kleman and Bergstrom 1994). While at its maximum extent, expansion of cold-based ice towards the margin of the ice sheet insulates significant areas of the bed from erosion; these areas are subject to erosion during growth and decay of the ice sheet.

In addition, subglacial debris limits the spatial extent of

Fig. 2. Pigeonite concentration in the 0.125–16 mm till particle-size fractions. Transport length is calculated along flowlines from the down-ice contact of the diabase outcrop. NIP-23 (0.146 pigeonite) not shown.

the bed subject to active erosion and entrainment; it also limits the duration of the erosion and entrainment. Debris deposited by earlier glacial cycles will insulate the underlying bedrock from glacial erosion during a later glacial cycle until the older debris is eroded and entrained. On a shorter time scale, deposition of subglacial debris early in a glacial cycle may insulate portions of the bed from erosion later in the glacial cycle.

Both cold-based ice and insulation by subglacial debris serve to restrict active glacial erosion at any given location on the bed of an ice sheet to some time period less than the entire length of the glacial cycle. Landscapes formed by glacial erosion therefore record only a portion of the history of a glacial cycle.

While not addressing the causes of spatial and temporal restriction of active erosion and entrainment processes beneath an ice sheet, the greenstone and diabase erosion rates estimated by this study can be used to quantify the extent of this restriction. The calculated erosion rates indicate that the relief of the diabase sill increased between 3 and 14 m per thousand years with respect to the surrounding landscape. Relief of the sill with respect to the surrounding landscape is only 50 m today, indicating 4000 – 18 000 years of active erosion at most during the Pleistocene.

Bedrock erosion and entrainment at such high rates would have resulted in enormous sediment fluxes to the margin. A conservative sediment flux estimate, assuming average erosivity values of $\sim 0.5 \text{ kg} \cdot \text{m}^{-3}$ over only 100 km of flowline length and a mean basal velocity of only $10 \text{ m} \cdot \text{a}^{-1}$, results in the delivery of 500 tonnes of debris per metre of width per year to the ice margin. Regionally, moraines deposited over the course of a few hundred years during the retreat of the LIS, such as the Nipigon moraine, may have been constructed by sediment fluxes of this order. However had erosion occurred at such rates over many hundreds of kilometres of flowline length, or if the mean basal velocity were higher, the correspondingly greater sediment flux would have constructed moraines significantly larger than those observed. Active erosion and entrainment of bedrock was thus probably restricted

to on the order of 10–100 km of flowline length. The LIS advanced and retreated over hundreds of kilometres of scoured Canadian Shield bedrock landscape during the last glacial cycle. Therefore, apparently only a portion of the shield was subjected to active erosion and entrainment at any given time during the glacial cycle.

When subjected to active glacial erosion and entrainment during the Pleistocene, significant erosion of hard crystalline bedrock on this portion of the Canadian Shield apparently occurred at high rates comparable to those of modern temperate glaciers. However, such high erosion rates must have been restricted to a relatively small area of the bed of the ice sheet at any given time. The continuous scoured bedrock landscape observed on the Shield today is likely the cumulative product of localized bedrock erosion and entrainment processes acting successively over thousands of years of the last ice sheet's history.

Pigeonite grain size

The particle-size distribution of the pigeonite indicator is calculated from till granulometry (Table 2) and the mass fraction of pigeonite in individual till particle-size fractions (Table 6). Mean pigeonite grain size ranges from 0.34 to 8.69 mm, with a mean of 2.18 mm. The proportion of the pigeonite in individual till fractions from 0.125 to 16 mm is summarized in Table 8.

Pigeonite over the diabase source

The region overlying the diabase outcrop is the zone of erosion and entrainment of pigeonite into the glacial debris. Here, the mean particle size of pigeonite in the 0.125–16.0 mm till particle-size fraction increases across the diabase outcrop (Fig. 5). In general, one would expect the mean particle size of an indicator to stay constant or decrease with increasing degree of comminution during glacial transport. The changing particle size of an indicator due to glacial comminution is described by

$$[7] \quad \frac{dx_i}{dT} = -k_i x_i + \sum_{j=1}^{i-1} a_{ij} k_j x_j$$

where x_i is the fraction of the indicator material in particle-size fraction (i), T is the transport length, and k and a_{ij} are constants that describe the rate of comminution and the particle-size distribution of comminution daughter products (Larson and Mooers 2004, adapted from Horst and Freeh 1970).

Inspection of eq. [7] indicates two scenarios that might result in an increase in i : (1) particles in the size fraction i break down at a higher rate than particles in size classes coarser than i , which would result in an apparent decrease in the amount of intermediate size particles relative to coarser and finer fractions; (2) if indicator material is added to the debris load in size fractions coarser than i , the breakdown of this material might add material to size fraction i and result in an apparent coarsening of indicator material in that fraction.

With respect to scenario (1), fracture mechanics posits that fractures initiate at volume flaws within the clast (Lawn 1993). Such flaws in geologic materials may take the form of preexisting fractures, grain boundaries, or mineral cleavage planes. In general, the larger the flaw, the less energy required

Fig. 3. Pigeonite concentrations in individual till particle-size fractions.

to propagate the fracture and result in breakage of the clast. During glacial comminution, coarser clasts might thus be expected to comminute at a higher rate than finer clasts

(Sharp and Gomez 1986). Therefore, scenario (1) is unlikely to have occurred.

With respect to scenario (2) and the pigeonite case in

Fig. 4. Erosivity (A) and erosion length scale (B) values for tills overlying and down-ice of the diabase outcrop. Each data point represents a unique solution over the flowline, extending either from the up-ice or down-ice contact of the diabase outcrop. Note that, while erosivity and erosion length scale are inversely proportional, the exact relationship depends on the value selected for m , which is the amount of englacial debris per unit bed area. The absolute value of erosion length scale is independent of the estimate of m and is the more robust parameter describing erosion and entrainment in a glacial system. Erosivity can be used to calculate an absolute erosion rate.

particular, the apparent increase in pigeonite grain size with transport length in tills overlying the diabase outcrop is probably indicative of incorporation of additional pigeonite as diabase clasts > 16 mm. This, combined with the relative coarse mean size in this interval (0.5–2.5 mm) indicates that most of the erosion of diabase was taking place by the quarrying of larger lithic clasts rather than by the abrasion of smaller monomineralic clasts. Most of the pigeonite grains separated from till are the product of comminution of diabase clasts during transport and were not directly eroded from the outcrop.

Pigeonite down-ice of the diabase source

For transport lengths beyond the down-ice edge of the diabase outcrop, the mean pigeonite size decreases from ~4 to ~0.5 mm over 9 km of glacial transport (Fig. 6). This is a consequence of both breakdown of the coarser diabase–

Table 7. Erosivity and erosion length scale estimates.

Sample No.	Substrate	E_d erosivity ($\text{kg}\cdot\text{m}^{-3}$)	λ Erosion length scale (m)
013	Diabase	0.012	82724
014	Diabase	0.057	17423
015	Diabase	0.034	29345
016	Diabase	0.025	39910
017	Diabase	0.028	35561
018	Diabase	0.011	93322
007	Greenstone	1.405	767
008	Greenstone	2.153	502
020	Greenstone	*	
021	Greenstone	0.250	4184
022	Greenstone	0.187	5604
023	Greenstone	*	
025	Greenstone	*	
026	Greenstone	0.661	1592
027	Greenstone	1.097	956
028	Greenstone	0.445	2350
029	Greenstone	0.586	1786
030	Greenstone	*	
031	Greenstone	0.974	1074
033	Greenstone	0.776	1348
Average	Diabase	0.028	49714
Average	Greenstone	0.854	2016

Note: The estimated concentration of diabase at $T = 0$ for tills overlying the greenstone is calculated using the average erosivity value for tills overlying the diabase ($0.028 \text{ kg}\cdot\text{m}^{-3}$). * indicates NIP-20, NIP-23, and NIP-25 are excluded from erosivity estimates because the diabase concentrations are higher than predicted. NIP-30 is excluded because it contains anomalously low diabase concentrations.

pigeonite clasts at a higher rate than the finer pigeonite clasts, and the lack of addition of new diabase–pigeonite to the debris load.

Theoretically, comminution of pigeonite grains proceeded until the grains reached the terminal grade (Dreimanis and Vagners 1971), likely fine sand. However, in as much as the samples collected for this study came from within 9 km of the source, it is likely that the bulk of the pigeonite was not comminuted to the terminal grade.

Comminution enhancement of the pigeonite dispersal train

Heavy-mineral indicator surveys commonly analyze indicator mineral concentrations in the 0.25–2.0 mm size fraction of till (Averill 2001; McClenaghan et al. 2000). The resulting concentration of indicator mineral in a restricted particle-size range is the dispersal concentration (c_{DISP}) (Larson and Mooers 2004). In contrast, the concentration of indicator mineral in the entire till particle-size range is the dilution concentration (c_{DIL}). Dispersal concentration is related to dilution concentration by

$$[8] \quad c_{\text{DISP}} = \frac{c_{\text{DIL}} x_i}{x_{\text{till}}}$$

where x_{till} is the fraction of till in size fraction i .

In the case of the pigeonite dispersal train, the fraction of

Table 8. Pigeonite granulometry.

Sample No.	0.125–0.25 mm	0.25–0.5 mm	0.5–1.0 mm	1.0–2.0 mm	2–4 mm	4–8 mm	8–16 mm	0.25–2.0 mm	Mean grain size (mm)
NIP-07	0.09	0.21	0.22	0.15	0.13	0.09	0.11	0.58	0.93
NIP-08	0.07	0.11	0.08	0.04	0.32	0.10	0.29	0.23	3.11
NIP-13	0.22	0.23	0.18	0.19	0.07	0.08	0.03	0.59	0.60
NIP-14	0.14	0.15	0.10	0.04	0.45	0.09	0.03	0.29	2.22
NIP-15	0.13	0.14	0.18	0.09	0.18	0.24	0.04	0.41	1.45
NIP-16	0.14	0.14	0.21	0.19	0.17	0.08	0.07	0.54	1.05
NIP-17	0.12	0.09	0.10	0.09	0.29	0.22	0.10	0.28	2.58
NIP-18	0.11	0.13	0.10	0.10	0.37	0.15	0.05	0.32	2.28
NIP-20	0.09	0.07	0.06	0.06	0.29	0.25	0.17	0.19	3.36
NIP-21	0.23	0.28	0.12	0.02	0.15	0.09	0.11	0.41	0.49
NIP-22	0.13	0.12	0.11	0.12	0.38	0.11	0.02	0.36	2.06
NIP-23	0.05	0.06	0.03	0.00	0.08	0.49	0.28	0.10	5.83
NIP-25	0.11	0.08	0.06	0.04	0.24	0.21	0.25	0.18	3.63
NIP-26	0.22	0.16	0.13	0.03	0.18	0.13	0.14	0.33	0.92
NIP-27	0.18	0.19	0.15	0.07	0.28	0.14	0.00	0.41	0.94
NIP-28	0.29	0.27	0.15	0.04	0.16	0.06	0.02	0.46	0.42
NIP-29	0.13	0.20	0.09	0.03	0.42	0.14	0.00	0.32	2.20
NIP-30	0.35	0.34	0.10	0.03	0.10	0.09	0.00	0.46	0.34
NIP-31	0.12	0.07	0.04	0.01	0.09	0.09	0.57	0.13	8.69
NIP-33	0.13	0.33	0.21	0.05	0.04	0.10	0.15	0.59	0.58

Note: Values are mass fraction of pigeonite in 0.125–16.0 mm particle-size fractions.

Fig. 5. Mean particle size of pigeonite in the 0.125–16 mm till particle-size fractions overlying the diabase source. Linear regression line indicates an increase in mean particle size with increasing transport length from the up-ice contact ($r^2 = 0.36$, $p = 0.03$; both values are small because of clustering).

pigeonite in the 0.25–2.0 mm size fraction generally increases from ~0.20 at the down-ice contact of the diabase source to ~0.45 after 9 km of glacial transport. The fraction of till in the 0.25–2.0 mm size fraction stays roughly constant over the same transport interval.

The dispersal concentration of pigeonite in the 0.25–2.0 mm

Fig. 6. Mean particle size of pigeonite in the 0.125–16 mm till particle-size fractions overlying and down-ice of the diabase source. A linear regression line indicates a decrease in mean particle size of $> 2 \phi$ over 8 km of transport from the up-ice contact. Although the coefficient of determination is very low ($r^2 = 0.08$, $p = 0.31$), it is greatly influenced by a single value at $T = 7136$ m.

size fraction, if no comminution had taken place, can be estimated from eq. [8]. Assuming the pigeonite concentration in the 0.125–16.0 mm size fraction is that of the till (the dilution concentration), using the known x_{till} , and assuming a constant x_i of 0.20, the resulting calculated dispersal concentrations are only 40% of the values measured at the 9 km transport length. That is, at 9 km from the down-ice contact of the diabase, the actual pigeonite concentrations in the

0.25–2.0 mm till particle-size fraction are ~250% higher than if no comminution taken place during transport.

Conclusions

Analysis and interpretation of a heavy-mineral indicator dispersal train using the conceptual model of indicator dispersal presented in Larson and Mooers (2004) provides a number of insights into the nature of bedrock erosion and entrainment by the LIS and the generation and down-ice propagation of indicator dispersal trains.

Erosivity and erosion length scale values calculated from indicator dispersal data indicate that the contrast in composition and mechanical strength between the indicator source and surrounding bedrock were reflected in the relative rates of erosion and entrainment. The inferred high erosion rates suggest that significant erosion of bedrock on the Canadian Shield was spatially and temporally restricted.

The inverse correlation between mechanical strength and erosion rates indicates that the bedrock topography is not an assemblage of equilibrium bedforms with respect to the ice sheet. The persistence of non-equilibrium landforms, despite multiple glaciations, supports the conclusions of Flint (1971), Gravenour (1975), Sugden (1976), and Kaszycki and Shilts (1987) that only a limited amount of bedrock erosion occurred on the Canadian Shield over the course of the Pleistocene. Bedrock landforms here and elsewhere on the shield likely reflect the geometry of the unweathered bedrock surface underlying a mantle of preglacial regolith (Feininger 1971; Lidmar-Bergström 1997; Patterson and Boerboom 1998; Olvmo and Johansson 2002).

Analysis of the particle-size distribution of indicator material in the 0.125–16 mm till particle-size fraction suggests that erosion of the indicator source occurred predominantly by quarrying of coarse fragments of the indicator material. Therefore, most of the heavy-mineral indicators recovered from the dispersal train were released from the bedrock by the comminution of entrained rock fragments. Similarly, the contribution of heavy minerals liberated from comminuted rock fragments down-ice of the indicator source greatly increases the distance down-ice over which the heavy-mineral dispersal train can be detected and resolved from the background.

The conclusions drawn from investigation of the Nipigon pigeonite dispersal train are not necessarily directly applicable to analysis and interpretation of other heavy-mineral indicator dispersal trains, such as those related to gold mineralization or diamondiferous kimberlites. However, the conceptual framework presented in Larson and Mooers (2004) and used to quantify and interpret pigeonite dispersal in this study provides a basis for investigating, quantifying, and interpreting the erosion, entrainment, and transportation of indicator material in any glaciated region.

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