SURFACE BOULDER CONCENTRATIONS OF THE LATE WISCONSINAN RAINY LOBE, MINNESOTA, USA

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Abstract

Surface boulder concentrations on the surface of till sheets are ubiquitous features of the Late Wisconsinan Rainy lobe. They occur irrespective of topography or position on the landscape and are commonly found littering the surface of uncultivated pastures and wooded areas within the Wadena and Brainerd drumlin fields of central Minnesota and the Toimi drumlin field and the Rögen moraine of northeastern Minnesota. Previous work in these locations noted the occurrence of surface boulders but dismissed them as an erosional lag or resulting from periglacial processes. Characterizations of boulder lithologies, the composition and texture of the underlying till, and mean transport length suggest that this is not the case, and that surface boulder concentrations are primary features of till deposition. We present models for surface boulder deposition in both lodgement till and deforming bed regimes.

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Introduction

Surface boulder concentrations are ubiquitous features of the central and northern Minnesota glaciated landscape and are particularly conspicuous in the Wadena, Brainerd, and Toimi drumlin fields (Figure 1). Throughout the undulating topography in these locations, boulders litter the surfaces of pastures, wooded areas, and other undisturbed locations. In places that have been plowed and cultivated, farmers have moved boulders off the fields and placed them in baskets and piles (Figure 2). Boulders are found across the landscape on hill tops, sides, and swales; concentrations can be so high that one can walk across fields stepping from boulder to boulder.

Previous investigations in the Wadena, Brainerd, and Toimi drumlin fields focused mainly on characterizing the Rainy Lobe till and describing drumlin form and fabric (Wright, 1957; Wright, 1972; Mooers, 1988, 1990a; Goldstein, 1989; Lehr and Hobbs, 1992; Lehr, 2000). Boulder concentrations have been ignored or casually interpreted as an erosional lag or the result of solifluction or other periglacial processes (*e.g.* Matsch, 1972; Goldstein, 1989). However, several studies have noted the lack of boulders within the till of the Wadena and the Brainerd drumlins (Wright, 1957; Wright, 1972; Mooers, 1988; Goldstein, 1989). Soil surveys from several central Minnesota counties (Crow Wing Co. Soil Survey Staff, 1965; Todd Co. Soil Survey Staff, 1989; Wadena Co. Soil Survey Staff, 1991) describe the suitability of soils for intensive agriculture after removal of the surface boulders. Farther to the NE, till of the Toimi drumlin field has been described as a “bouldery till,” (Wright and Ruhe, 1965; Winter et al., 1973, Lehr, 2000; Meyer, 2008) but is also characterized by dense concentrations of boulders at the surface (Figures 3 and 4).

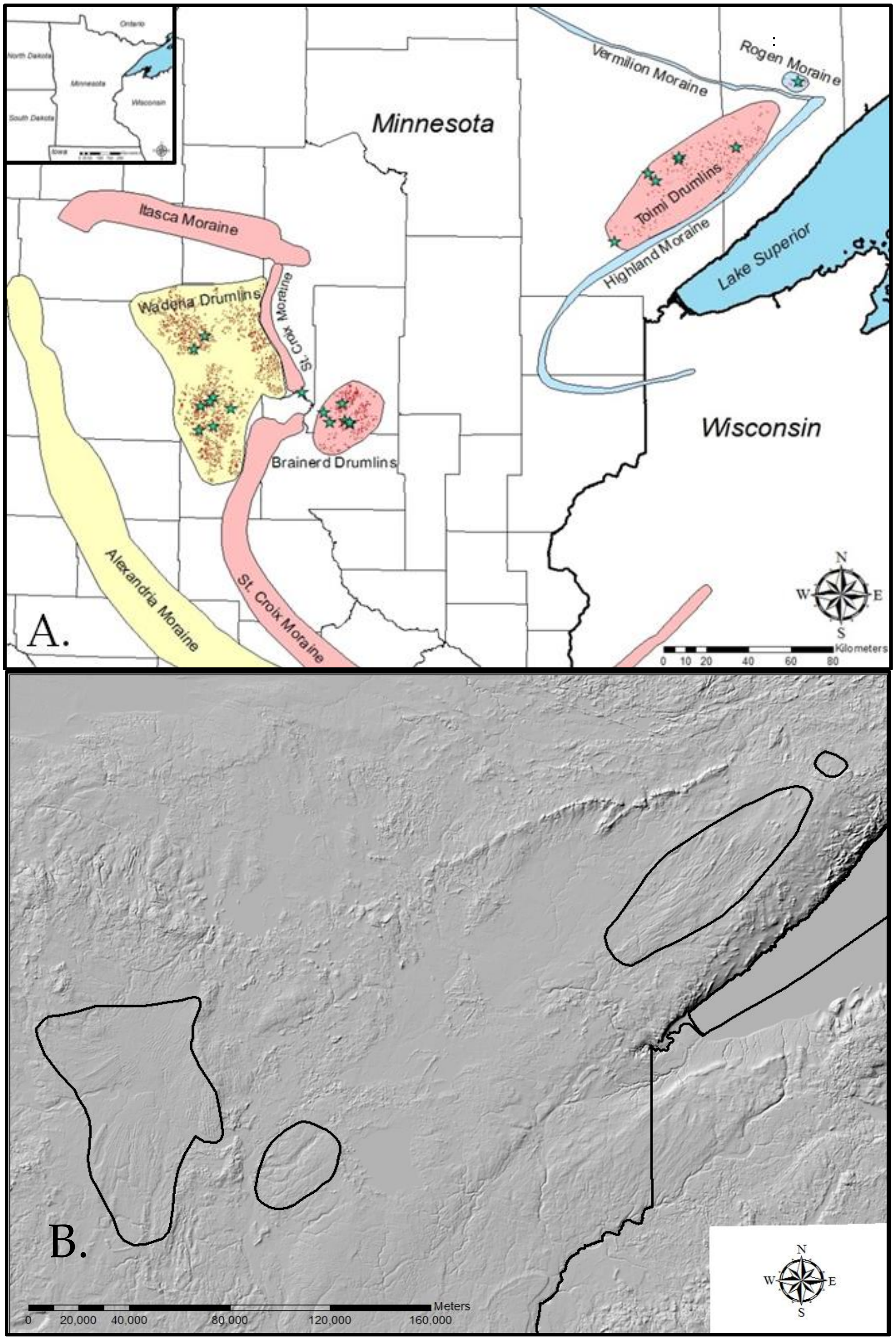

Figure 1. Study Locations. A. Study locations include the Wadena, Brainerd, and Toimi drumlin fields and Rögen moraine. Colors indicate Rainy Lobe phase-landform relationships. From oldest to youngest: Yellow = Hewitt Phase, Pink = St. Croix Phase, and Blue = Vermilion/Highland Phase. B. Lidar image with study areas outlined.

Figure 2. Occurrence of surface boulder concentrations. The nature of surface boulder concentration outcrops. A. In-situ surface boulder concentration. Many boulders reside just below the land surface with a tuft of grass marking their location (Wadena County), B. Boulders gathered into a basket at the corner of a field (Todd County), C. Push pile of boulders and corn stalks (Todd County), D. Surface boulders pushed into open field not used for agriculture (Crow Wing County).

Figure 3. Independence till exposure in the Toimi drumlins. Photo from Winter et al. (1972) of a gravel pit in the Mesabi Iron Range. The St. Louis sublobe of the Red River/Des Moines lobe deposited red clayey till above existing bouldery Rainy lobe till. A boulder pavement marks this boundary. The boulder pavement in this photo is interpreted as having existed as a surface boulder concentration before St. Louis sublobe advance.

Figure 4. Isabella till exposure in the Rögen moraine. Photo from Meyer (2008) of a till exposure dug into the Rogen moraine near Isabella, MN. The Independence till in this location is quite bouldery. Deeper exposures were not available.

I consider the hypothesis that the surface boulder concentrations are primary features of till deposition and are not erosional lags, related to solifluction, or periglacial processes. The advances of the Rainy lobe during which the till and boulders were deposited range in age from the LGM, around 23 ka BP (Mooers and Lehr, 1997), to the final wastage of ice from Minnesota about 12 ka BP (Lowell et al., 2009). Till of each successive phase is characterized by a different suite of rock types that indicates progressively shorter mean transport lengths. The boulder lithologies, texture and composition of the underlying till, and mean transport lengths are used to test various hypotheses for the origin of surface boulder concentrations. I consider the nature of transport in basal ice and the deposition of boulders in both a lodgement till and deforming bed model.

Glacial History and Description of Study Area

Glacial History

This investigation focuses on the area glaciated by the Rainy lobe of the Laurentide Ice Sheet (LIS) in Minnesota, USA (Mooers and Lehr, 1997). During Late Wisconsin glaciations, the Rainy lobe advanced in several discrete phases (Wright, 1964) each of which can be delineated by distinct suites of landforms. The maximum limit of the lobe is marked by the prominent Alexandria moraine and the associated Wadena drumlin field (Wright, 1956, 1972; Meyer and Knaeble, 1996; Mooers and Lehr, 1997) and is dated to 23 ka BP (the Hewitt phase of Wright (1964)) (Mooers and Lehr, 1997) (Figure 5a). The Hewitt till (Wright, 1957), of which the Wadena drumlins are composed, has a sandy-loam matrix (Goldstein, 1989); clasts are dominated by granite,

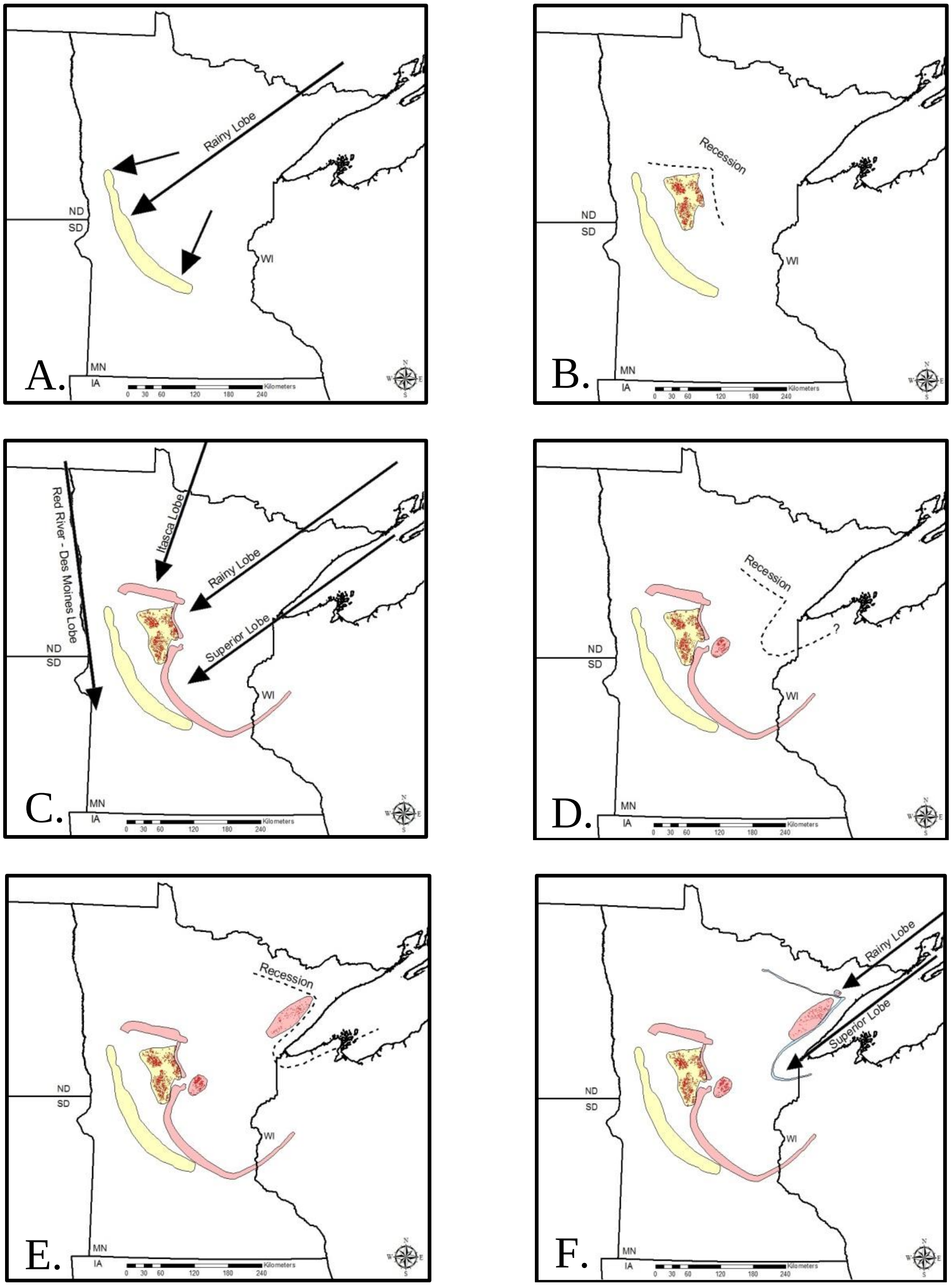

Figure 5. Phases of glaciation in Minnesota. A. Oldest Late Wisconsinan advance of the Rainy lobe which deposited the Alexandria Moraine. B. Rainy lobe recession exposing the Wadena drumlin field. C. Stagnation of the Rainy and Superior lobes forming the St. Croix Moraine. D. Recession of the Rainy and Superior lobes. E. Continued recession of the Rainy lobe exposed the Toimi drumlin field. F. Late advances of the Rainy and Superior lobes associated with the Vermilion/Highland phase with which Rögen moraine formation is attributed.

greenstone, and gneiss. In addition, the till contains abundant carbonate from Paleozoic platform sediments in the Hudson Bay lowlands and greywacke from the Paleoproterozoic Omarolluk Formation, which outcrops in eastern Hudson Bay (Mooers and Lehr, 1997; Prest et al., 2000). There is little evidence to document the retreat of the ice from the Alexandria moraine (Wright, 1972; Goldstein, 1989); however, Goldstein (1989) suggests that the ice stagnated over a wide area and wasted away (Figure 5b).

The next advance of the Rainy lobe, the St. Croix phase (Wright, 1972), is marked by the prominent St. Croix moraine (Figure 5c) (Wright, 1972; Mooers, 1988). This advance was contemporaneous with advance of the adjacent Superior and Itasca lobes (Mooers and Lehr, 1997) and formed a continuous ice margin in central and northern Minnesota (Figure 5c). The St. Croix phase culminated about 16-15.5 ka BP (Birks, 1976; Clayton and Moran, 1982; Mooers and Lehr, 1997). Unlike the general ice stagnation following the Hewitt phase, the retreat of the Rainy lobe from the St. Croix moraine is marked by numerous recessional moraines (Mooers, 1988; Johnson and Mooers, 1998). The Rainy lobe locally readvanced into areas opened by the retreating Superior lobe (Mooers, 1988). One such readvance is marked by the Platte Lake moraine and Brainerd drumlin field (Mooers, 1988; Johnson and Mooers, 1998). Following this readvance, the Rainy lobe margin retreated back into northeastern Minnesota (Figure 5d).

The Brainerd till (Schneider, 1961; Mooers, 1990), of which the Brainerd drumlins are composed, varies significantly in lithology from the earlier Hewitt till. Limestone, dolomite, and greywacke from the Hudson Bay region are rare, whereas gabbro, diabase, greenstone, and iron formation from northeastern Minnesota are common (Mooers, 1990a). Continued recession of the Rainy lobe eventually exposed the

Toimi drumlin field (Figure 5e). In contrast to the Wadena and Brainerd drumlins, bedrock underlying the Toimi drumlin field is at or very near the surface (Weiblen and Morey, 1980), and is primarily gabbro, troctolite, anorthosite, and other associated rocks of the Duluth Complex, which dominate the lithologic composition of the Independence till (Winter et al., 1973) of the drumlins.

Further to the northeast, the Independence till thins and Rögen moraine becomes a prominent landform (Meyer, 2009) (Figure 5f). The Vermilion moraine marks a prominent readvance of the Rainy lobe at about 12 ka BP (Wright, 1972; Mooers and Lehr, 1997; Lowell et al., 2009). Cross-cutting relationships evident in lidar topography indicate that Rögen formation was spatially associated with the ice margin, and thus roughly contemporaneous with the Vermilion phase (P. Larson, pers. comm.) The lithology of the till comprising the Rögen moraine is similar to that of the Toimi drumlins, but with an even greater proportion of local rock types. Rögen moraine till is henceforth referred to as Isabella till for the nearby town of Isabella, MN.

Study Area

The study area extends from the Wadena drumlin field in central Minnesota to the northeastern part of the state (Figure 1). Boulders in these locations are defined as clasts $\leq$ 30 cm in diameter. Boulder concentrations on the surface in the Wadena and Brainerd drumlin fields are expressed in much the same way. Where undisturbed, boulder concentrations are easily described by surface transects. In areas where local land owners have removed the boulders for agriculture, they are conveniently available for analysis in piles along the margins of cultivated fields (Figure 2). Given the extent of removal, overall boulder coverage is difficult to determine on a large scale. Where undisturbed in pastures, on crests and sides of drumlins and in swales between them, boulder density often exceeds 2000 ha^{-1}. Surface boulder concentrations in the Toimi drumlin field and Rögen moraine are not easily determined owing to the dense forest cover in these areas.

The Hewitt and Brainerd tills associated with the Wadena and Brainerd drumlin fields, respectively, have typically been described as lodgement till (Figure 6) (Goldstein, 1989; Mooers, 1990; Lehr, 2000), and rarely contain boulders of size comparable to those found on the surface (Goldstein, 1989; Mooers, 1988). Independence till in the Toimi drumlins (Figure 3) and Isabella till in the Rögen moraine (Figure 4) have also been described as lodgement till and are commonly referred to as bouldery tills (Wright and Ruhe, 1965; Winter et al., 1973, Lehr, 2000; Meyer, 2008).

Methods

To evaluate the possibility that the boulder concentrations are primary depositional features, their lithology, transport length, and spatial distribution must be compared with clast in the underlying till. Within this large region, four primary study locations were defined: the Wadena drumlin field, the Brainerd drumlin field, the Toimi drumlin field, and an area of Rögen moraine at the northern limit of the Toimi drumlin field near the transition to scoured bedrock terrain (Lehr, 2000; Lehr and Hobbs, 1992) (Figure 1). These four locations span the Late Wisconsinan history of the Rainy lobe from the LGM to final wastage of ice. Within these areas boulder concentrations were located on high-resolution aerial photos and by traversing the study area by vehicle. Locations and detailed descriptions of the distribution of boulders on the landscape were recorded.

Figure 6. Hewitt till and Brainerd till exposures. A. Hewitt till exposed as the uppermost unit in a gravel pit in northwestern Wadena County Pit operator described removing large boulders only from the surface (Ryan Berttunen, personal communication). B. Gravel pit in Crow Wing County exposing Brainerd till bounding coarsening upward outwash.

Boulder sampling locations were selected on the basis of ease of access and permission from land owners. Sampling locations included in situ boulder concentrations in pastures and wooded lots and rock piles in areas that had been cleared for cultivation (Figure 2). Areas with sub-surface till exposure, such as aggregate mines, were selected for detailed study of underlying till. Lithologic categories were established that characterize the provenance of the Rainy lobe. In particular, suites of rocks that occur at various distances along flow from the Labradorean accumulation center were considered (Figure 7). Some lithologic types are ubiquitous on the Canadian Shield and yield widely varying mean transport lengths. For example, granite, gneiss and greenstone occur commonly along flow lines from the Labradorean ice dispersal center. Other types are easily assigned to specific localities or a range of localities based on the limited extent of their outcrop. These types include dolomite from the Hudson Bay Lowlands, greywacke from the Omarolluk formation (Omars) of eastern Hudson Bay (Prest, 1990; Prest et al., 2000), and a variety of distinctive lithologies from well-known source areas in NE Minnesota and adjacent Ontario, Canada (Figure 7).

At each locality, boulder size and lithology were tabulated. Clasts in till samples were sorted and the lithologic makeup of cobbles and pebbles recorded. The lithology of the 1-2 mm sand fraction was condensed from investigations by the Minnesota Geological Survey (MGS) and from Mooers (1988, 1990b). The lithology of the 1-2 mm fraction of the till matrix has proven extremely useful for discriminating tills (Matsch, 1972; Mooers, 1990b; Hobbs, 1998). Textural data for till in the study locations was gathered from Mooers (1990), Goldstein (1989), and the USDA Natural Resources Conservation Service (NRCS) (Soil Survey Staff, 1965, 1989, 1991, 2007). Additional

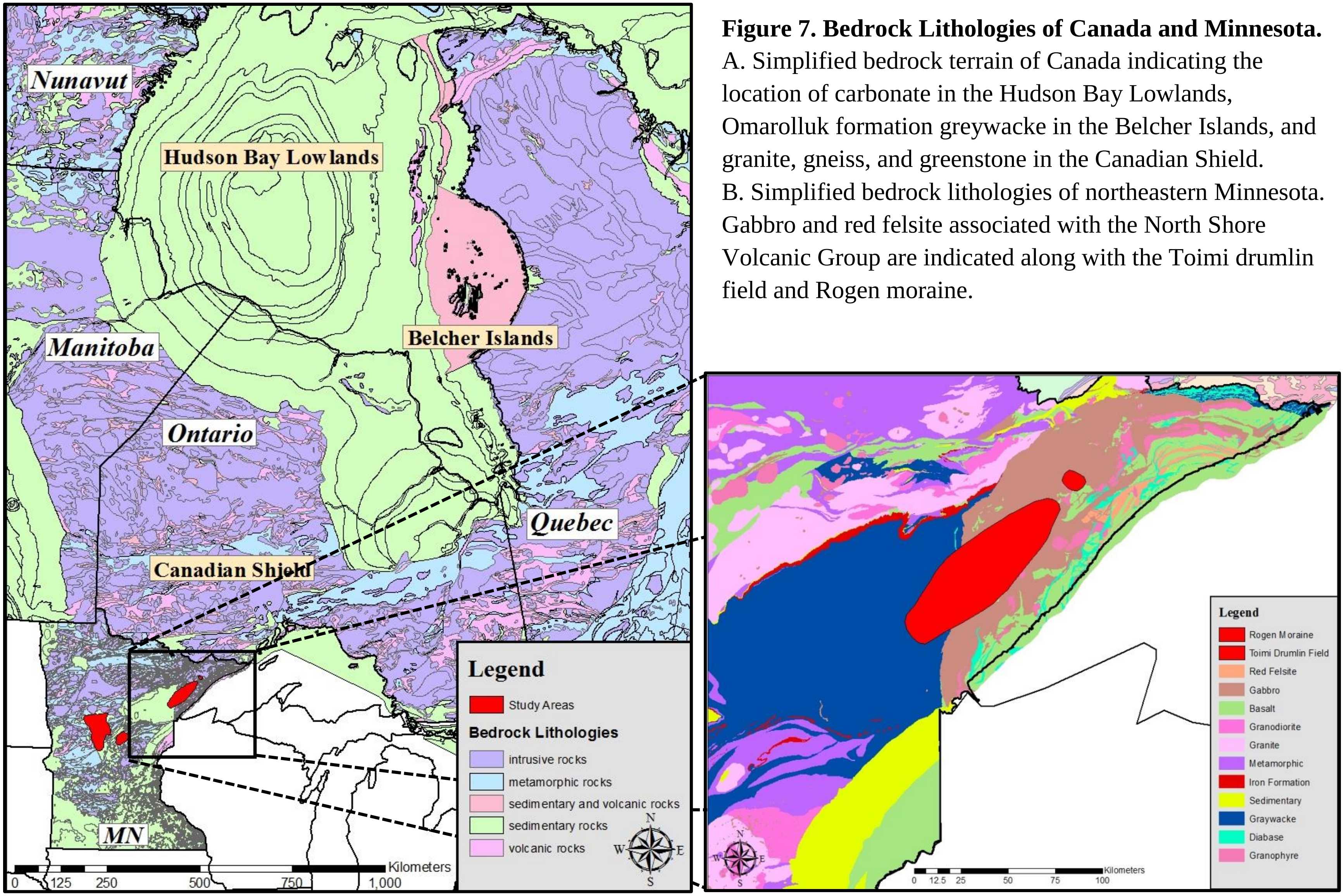

Figure 7. Bedrock Lithologies of Canada and Minnesota. A. Simplified bedrock terrain of Canada indicating the location of carbonate in the Hudson Bay Lowlands, Omarolluk formation greywacke in the Belcher Islands, and granite, gneiss, and greenstone in the Canadian Shield. B. Simplified bedrock lithologies of northeastern Minnesota. Gabbro and red felsite associated with the North Shore Volcanic Group are indicated along with the Toimi drumlin field and Rogen moraine.

work was done to characterize the stone density of the till using photometric analysis. Figures 8 and 9 are photographs of Hewitt till in the Wadena drumlin field and Brainerd till in the Brainerd drumlin field, respectively. Figure 3 is a photograph of an exposure of Independence till associated with the Toimi drumlin field (Winter et al., 1973), and Figure 4 is of Isabella till in the area of Rögen moraine (Meyer, 2008). Lithologic categories to which clasts of each size fraction were assigned are listed in Table 1.

For each category a mean transport length was calculated following the work of Salonen (1986) and Larson and Mooers (2004). Transport length is defined as the distance a particular lithology has traveled from its source area. Transport length in terms of distance can be used as a proxy for transport length in terms of time. It follows that material with a longer transport length has undergone comminution for a longer period of time than material with a shorter transport length. A maximum, minimum, and resulting mean transport length was determined for each lithology using the bedrock geology of Ontario, Canada (Ontario Geological Survey, 2011), and Minnesota (Minnesota Geological Survey, 2011) (Figure 7). Using boulder counts from a particular location within a study area, the fraction of each lithology (m) was calculated as

$$m = \frac{n_i}{N}, \qquad (1)$$

where n_i is the number of a particular lithology i, and N is the total number of rocks counted. The mean transport length ($\bar{x}$) for each lithology was then calculated as

$$\bar{x} = \frac{L_{min} + L_{max}}{2}, \qquad (2)$$

where L_{min} and L_{max} are the minimum and maximum transport lengths, respectively. Overall weighted mean transport length ($\bar{X}$) was then calculated as

$$\bar{X} = \sum_{i=1}^{n} \bar{x}_i m. \qquad (3)$$

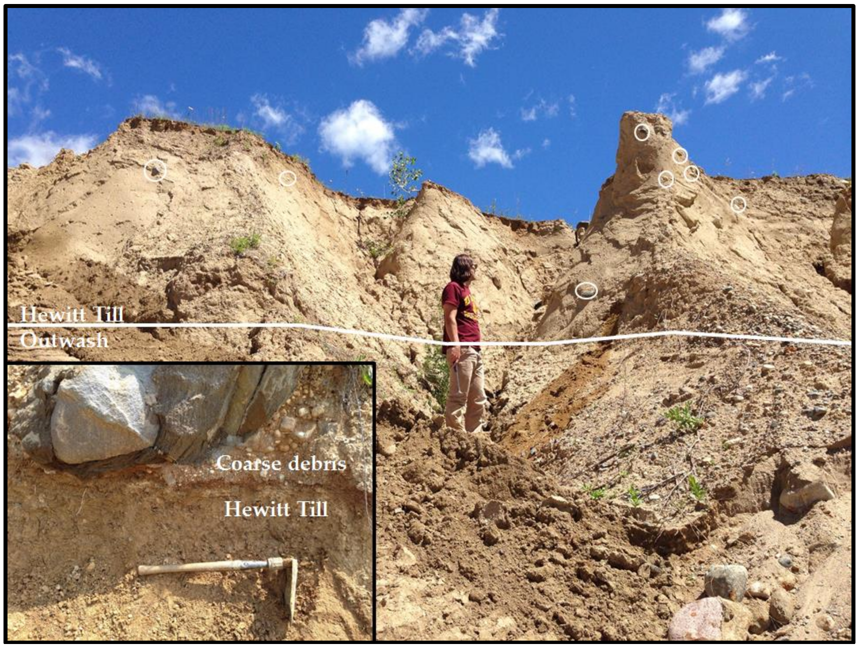

Figure 8. Stone density in the Hewitt till. Gravel pit near Menagha, MN. Hewitt till caps the outwash deposit targeted for aggregate. Individual rocks larger than about 10 cm are circled. Note the lack of them and their general location nearer to the surface. Inset photo is a close-up exposure of the Hewitt till capped by a layer of coarse sediment. Very few, if any, larger clasts were found within the till.

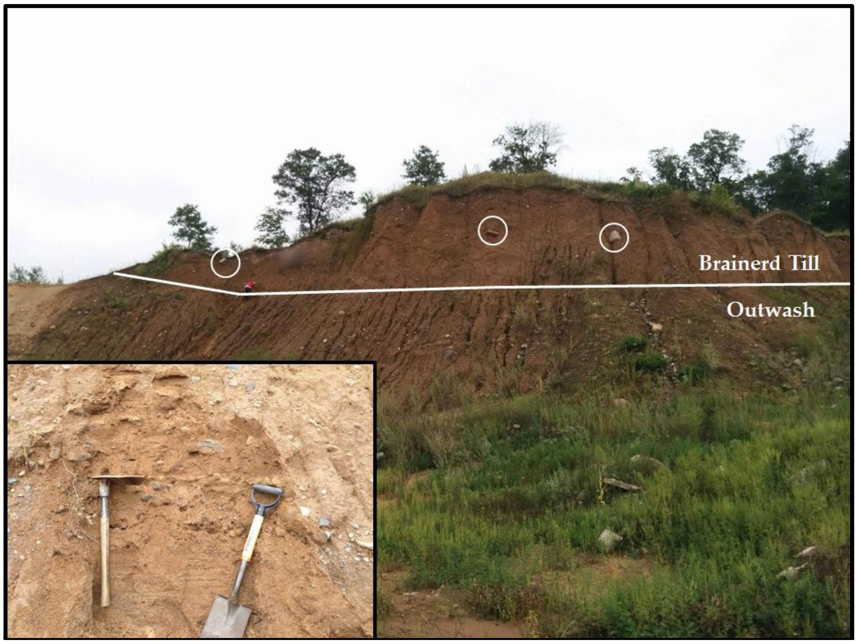

Figure 9. Stone density in the Brainerd till. Gravel pit southwest of Brainerd, MN. Brainerd till is generally coarser than the Hewitt till. Note large boulders circled greater than 60 cm in diameter. Inset photo is of a fresh surface of the Brainerd till overlying coarse outwash. Cobbles are generally in the 15-20 cm range and are numerous.

Mafic Igneous
Felsic Igneous
Metamorphic
Red Felsite
Limestone/Dolomite/Chert
Sedimentary
Iron Formation
Omar

Table 1. Lithologic categories. These are simplified categories. Mafic igneous includes: gabbro, diabase, anorthosite and basalt. Felsic igneous includes: granite, granodiorite, quartz and diorite. Metamorphic includes: gneiss, metasedimentary and metavolcanic greenstone, quartzite, schist, non-specific greywacke, phyllite, and slate. Red felsite includes rhyolite and syenite associated with the North Shore Volcanic Group (NSVG). Sedimentary includes interflow red sandstone from the NSVG and conglomerate.

Study Area	Mean TL (km)
Wadena	438
Brainerd	364
Toimi	82
Rögen	37

Table 2. Generalized transport lengths. Transport lengths (TL) for each of the four study areas.

Mean transport lengths for each location within a study area were then averaged and an overall transport length for all rocks counted within each of the four study areas was calculated (Table 2).

Results

Spatial Distribution of Boulder Concentrations

Surface boulder concentrations are ubiquitous throughout the four study areas. In locations where boulders have not been removed for agricultural use, concentrations are sometimes so dense that one can step from boulder to boulder across a field (Figure 2a). Where boulders were removed, obvious boulder piles in the middle or corners of fields or within wire baskets were commonly observed (Figures 2b, 2c, and 2d). By traversing numerous roads in the study areas, confirmation was made of previous observations of boulders outcropping on the surface regardless of drumlin topography (Mooers, 1988; Goldstein, 1989).

Lithologic Composition

Lithologic composition and sizes of clasts are tabulated in Table 3. Figure 10 shows the proportions of rock types in each of the four areas. In the Wadena drumlin field, large clasts (30-180 cm fraction) are dominantly granite (felsic igneous) and gneiss, greenstone, and schist (metamorphic) with a minor component of mafic igneous lithologies. These rock types are ubiquitous in the Superior Province of Ontario and Quebec west of the Labradorean ice accumulation center (Ontario Geological Survey, 2011). In the smaller fractions (<16mm) dolomite dominates. In the Brainerd drumlins, dolomite and Omarolluk formation greywacke (Hudson Bay lithologies) are rare. Iron

Wadena	1-2 mm	8-16 mm	15-30 cm	30-180 cm	Total
Mafic Igneous	0	0	15	20	**35**
Felsic Igneous	1593	31	109	263	**1996**
Metamorphic	175	47	120	287	**629**
Red Felsite	14	1	4	1	**20**
LS/Dolo/Chert	317	55	23	14	**409**
Sedimentary	4	0	0	5	**9**
Iron Formation	0	1	1	1	**3**
Omar	41	4	10	1	**56**
					3157
Brainerd					
Mafic Igneous	19	29	36	71	**155**
Felsic Igneous	1217	55	136	196	**1604**
Metamorphic	318	122	119	94	**653**
Red Felsite	115	42	8	6	**171**
LS/Dolo/Chert	2	4	2	0	**8**
Sedimentary	8	1	1	0	**10**
Iron Formation	37	1	7	4	**49**
Omar	0	0	1	0	**1**
					2651
Toimi				30-300 cm	
Mafic Igneous	115	54	116	259	**544**
Felsic Igneous	285	87	54	50	**476**
Metamorphic	186	135	36	47	**404**
Red Felsite	182	29	30	8	**249**
LS/Dolo/Chert	0	0	0	0	**0**
Sedimentary	2	2	4	1	**9**
Iron Formation	3	0	7	1	**11**
Omar	0	0	0	0	**0**
					1693
Rögen				30-300 cm	
Mafic Igneous	283	141	8	34	**466**
Felsic Igneous	79	11	4	2	**96**
Metamorphic	44	97	9	1	**151**
Red Felsite	89	115	13	0	**217**
LS/Dolo/Chert	0	0	0	0	**0**
Sedimentary	0	0	0	0	**0**
Iron Formation	8	1	2	0	**11**
Omar	0	0	0	0	**0**
					941

Table 3. Lithologic composition according to clast size. Number of clasts counted of each lithology in each size category. 1-2 mm counts were performed by the Minnesota Geological Survey (MGS). LS = limestone and dolo = dolomite.

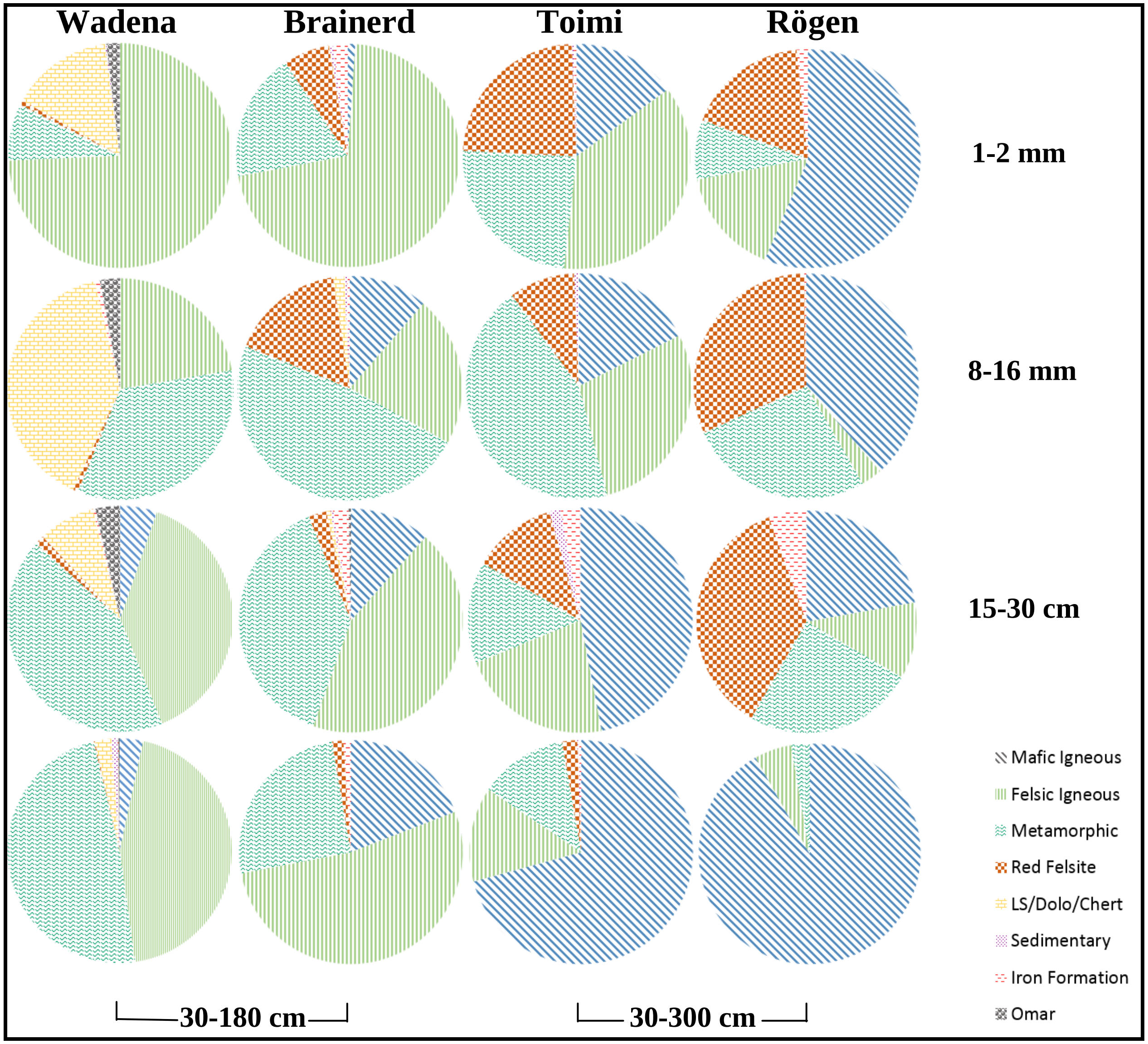

Figure 10. Lithologic proportions according to clast size. Pie charts showing the proportions of various lithologies throughout four size fractions. Size fractions above 15 cm were counted in more than two specific sizes but are grouped here for simplicity. 1-2 mm coarse sand grain counts were provided by the Minnesota Geological Survey. All other rock counts were performed either in the field or in the sediment laboratory at the University of Minnesota-Duluth. Results for the 30-90 cm fraction in the Rögen moraine are lacking because of limited exposure in the study area. LS = limestone and dolo = dolomite.

formation, Duluth Complex gabbro, and North Shore Volcanic Group diabase, rhyolite and basalt (northeastern Minnesota rock types) are abundant throughout all size fractions.

Further northeast, the Toimi drumlins carry an even stronger northeastern Minnesota signature where more than 70% of the biggest boulders, ranging in size from 60-300 cm, are gabbro from the Duluth Complex (Figure 10) that underlies the drumlins. The largest boulders encountered anywhere in this entire study were gabbros in the Toimi region (Figure 11). The marked increase of gabbro in the Toimi drumlins was accompanied by an increase in the red felsite proportion. Red felsite is associated with the Felsic Series of the Duluth Complex, which is considered the roof of the complex (P. Larson, pers. Comm). Granite, gneiss, and greenstone of Canadian Shield provenance still occur and are more abundant in the smaller size fractions (Figure 10). Isabella till in the Rögen moraine to the northeast is very similar to the Independence till with some exceptions. The dominance of Duluth Complex gabbro is abundantly clear, especially in the 90-300 cm boulder fraction (Figure 12). The proportion of red felsite continues the trend of increasing to the northeast while granite and granodiorite proportions decrease substantially. In some cases, the number of rocks of intermediate size was limited; however the till was rich in pebbles, in accordance with previous investigations (Wright and Ruhe, 1965; Winter et al., 1973; Lehr, 2000; Meyer, 2008), and provided additional data.

The lithologies present in the boulder fraction are biased toward homogeneous lithologies that form large, roughly equidimensional clasts that are quarried along widely spaced joints and fractures. In contrast, dolomite is typically softer and finer-grained, and quarries along fractures in sizes equivalent to bed thickness (Hallet, 1996; Dühnforth et

Figure 11. Boulders in the Toimi drumlin field. Many large gabbro boulders were encountered in the Toimi drumlin field (rock hammer for scale).

Figure 12. Boulders in the Rögen moraine. Gabbro boulders exposed in the Rögen Moraine northeast of Isabella, MN. Boulders appear to have been pushed aside to build a railroad no longer in existence.

al., 2010; Krabbendam and Glasser, 2011; Lucas et al., 2013). As a result, dolomite is more likely to constitute a higher proportion of smaller size fractions than the boulder fraction (Dreimanis and Vagners, 1971; Lucas et al., 2013), and granite, greenstone and gneiss will dominate larger clast sizes (Kirkbride, 1995; Hallet, 1996; Dühnforth et al., 2010; Krabbendam and Glasser, 2011; Iverson, 2012; Lucas et al., 2013). Once incorporated into the glacier ice, comminution of boulders will be limited to abrasion rather than crushing (Haldorsen, 1983; Sharp and Gomez, 1986). This is because when two large clasts collide within the ice, the point load or force on each clast is balanced by plastic deformation of the ice (Tulaczyk et al., 1998). Since tensile strength for common rocks and minerals is greater than the yield strength of ice and tensile stress and point load scale with clast diameter, ice cannot produce the tensile stress necessary to crush larger clasts (Tulaczyk et al., 1998). Therefore, the larger the clast, the more difficult it is to crush (Haldorsen, 1983; Sharp and Gomez, 1986). Abrasion, however, removes surface irregularities on the surface of boulders and effectively rounds them while also producing gravel and sand size clasts (Sharp and Gomez, 1986). Once rounded, further abrasion is minimal (Haldorsen, 1983).

The lithologies common in the boulder fraction can of course be entrained in smaller sizes and be therefore more susceptible to comminution by crushing, but they typically only break down to the 1-2 mm fraction where they begin to dissociate into their mineralogical components (Dreimanis and Vagners, 1971; Haldorsen, 1983). Because of this, felsic igneous sediments tend to show an overrepresentation in the 1-2 mm fraction. This is because monomineralic quartz grains are included in the felsic igneous counts when in fact some may have been derived from gneisses and should actually be counted as metamorphic (Mooers, 1990a).

Transport Length

Determination of mean transport length was based on averaging the distance over which each assemblage could have traversed. Generalized transport lengths for each of the four study areas are listed in Table 2. Additionally, minimum, maximum and mean transport lengths for each lithologic category are listed in Table 4. Figure 13 shows the lithologic proportions counted in each study area based on transport length.

Granite and greenstone were found in all study locations; however, outcrops of these rock types occur over a large distance along a flow line of the Rainy Lobe and lack distinguishing characteristics necessary to trace individual samples to specific outcrops or formations. As a result, the transport lengths of these more ubiquitous lithologies, while included in the mean, do not constrain transport length and were not included in Figure 13. The lithologies that are significant are those that can be related to specific formations; these include Omarolluk erratics and limestone/dolomite/chert samples from Hudson Bay, and lithologies associated with the Duluth Complex and North Shore Volcanic Group including gabbro, diabase, and red felsite. Some igneous and metasedimentary rocks were recognized and interpreted as members of specific formations associated with the Vermilion greenstone belt and other Archean terrain in northeastern Minnesota.

The lithologic proportions of glacial sediments of various size fractions will vary based on transport length (Dreimanis and Vagners, 1971; Drewry, 1986; Kirkbride, 1995;

Wadena	TL Min (km)	TL Max (km)	Mean TL (km)
Mafic Igneous	90	320	205
Felsic Igneous	1	810	405.5
Metamorphic	1	810	405.5
Red Felsite	210	290	250
LS/Dolo/Chert	810	1180	995
Sedimentary	1	810	405.5
Iron Formation	62	480	271
Omar	1425	1600	1512.5
Brainerd			
Mafic Igneous	80	310	195
Felsic Igneous	1	802	401.5
Metamorphic	1	802	401.5
Red Felsite	200	280	240
LS/Dolo/Chert	802	1190	996
Sedimentary	1	802	401.5
Iron Formation	1	470	235.5
Omar	1415	1590	1502.5
Toimi			
Mafic Igneous	1	82	41.5
Felsic Igneous	82	520	301
Metamorphic	82	520	301
Red Felsite	1	76	38.5
Sedimentary	82	520	301
Iron Formation	82	244	163
Rögen			
Mafic Igneous	1	64	32.5
Felsic Igneous	64	502	283
Metamorphic	64	502	283
Red Felsite	1	58	29.5
Iron Formation	64	226	145

Table 4. Transport lengths according to lithology. Transport lengths calculated using the bedrock geology of Minnesota and Ontario (Minnesota Geological Survey, 2011; Ontario Geological Survey, 2011). LS = limestone and dolo = dolomite.

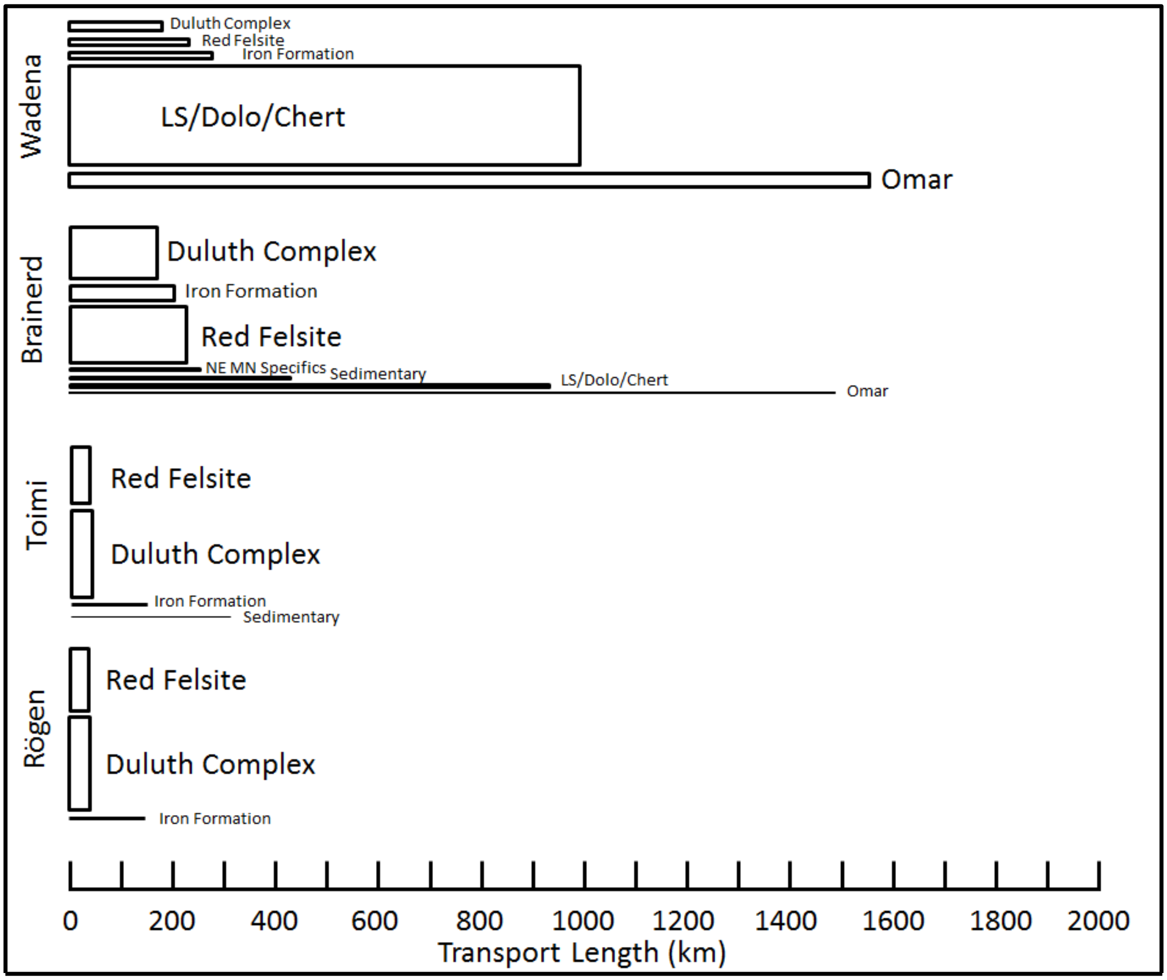

Figure 13. Transport lengths according to lithology. Average transport lengths are shown for the indicator lithologies in each study area. The size of each bar represents the percentage of each lithology composing the sediments in each study area. Canadian Shield lithologies including granite, greenstone and gneiss are excluded. NE MN specifics are lithologies immediately recognizable as associated with the Mesabi Iron Range in northeastern Minnesota. Gabbro and anorthosite are grouped and labeled as Duluth Complex. LS = limestone and dolo = dolomite.

Lucas et al., 2013) and mechanical properties (Haldorsen, 1983; Larson and Mooers, 2005). Dreimanis and Vagners (1971) show that basal till containing dolomite with a short transport length (0-3 km) has a peak in dolomite in the coarse pebble fraction (16-31.5 mm). On the other hand, basal till with a long transport length (300-500 km) has a dolomite peak in the medium silt to very fine sand fraction (0.016-0.125 mm). The same trend was found in two other basal tills consisting primarily of igneous and metamorphic rocks (Dreimanis and Vagners, 1971). Longer transport length implies a longer duration of transport thereby increasing the duration of comminution on a particular particle. Based on this evidence, basal till with a longer transport length is expected to contain smaller clasts overall than basal till with a shorter transport length.

In the Wadena drumlin field, the higher proportion of dolomite and chert found, particularly in the smaller size fractions (Figures 10 and 13), indicates that the till there has the longest transport length. The transport length of till in the Brainerd drumlins decreases by more than just the difference in distance along a flow line of the Rainy lobe between the Wadena and Brainerd drumlins (about 10 km) (Figure 13 and Table 2). This is indicated by a significant decrease in dolomite and chert and an increase in red felsite and iron formation, lithologies indicative of a northeastern Minnesota provenance in the Brainerd till (Wright, 1972; Mooers, 1990b) (Figure 10). Still shorter transport lengths are found in Toimi, as indicated by the higher amount of gabbro in all size fractions; even shorter transport lengths are found in the Rögen moraine of Isabella which has even higher amounts of gabbro and red felsite (Figure 10). Clearly, as northeastern Minnesota provenance rocks constitute a higher proportion of the lithologies counted in each successive study area moving up glacier, the overall transport length decreases (Figure 13).

Till Matrix, Bulk Density, and Stone Density

The matrices of the tills in each of the four study areas are distinct. Hewitt till has been previously described as a sandy loam with high carbonate content (Goldstein, 1989; Soil Survey Staff, 1989, 1991). The texture of the Brainerd till matrix is also a sandy loam but slightly coarser than the Hewitt till (Mooers, 1990a; Soil Survey Staff, 1965) because of the lack of carbonate in the <62µm fraction (H.D. Mooers, unpublished data). Independence till in the Toimi drumlins and Isabella till in the Rögen moraine is again slightly coarser and classified as sandy loam or loamy sand; however, they differ from the Hewitt and Brainerd till by being quite bouldery (Figures 3 and 4) (Winter et al., 1973).

Bulk densities in each study area were measured by the USDA Natural Resources Conservation Service. Typical bulk densities for the Hewitt till in the Wadena drumlin field range between 1.80-2.00 g/cm^3 (Soil Survey Staff, 1989, 1991). Bulk densities for the Brainerd drumlins range between 2.08-2.15 g/cm^3 (Soil Survey Staff, 1965), and for the Independence till in the Toimi drumlins and Isabella till in the Rögen moraine, between 1.80-2.00 g/cm^3 (Soil Survey Staff, 2007). The NRCS provides a chart showing typical ranges for bulk density and the ability of the soil to sustain plant growth (Soil Survey Staff, 2008). Sandy textured soils capable of supporting plant growth typically have bulk density values less than 1.60 g/cm^3; sandy soils can no longer support root growth when the bulk density values are greater than 1.80 g/cm^3. The bulk densities of the Hewitt, Brainerd, Independence and Isabella tills are close to the theoretical limit for granular material of similar grain size distribution (Sivrikaya et al., 2008; DiMatteo et al., 2009). In addition, the grain size distribution of Class 3 to Class 5 aggregate used in highway construction is very similar to the grain size distribution of these tills, and maximum dry densities at optimum moisture content range from 2.05 to 2.1 g/cm^3 (Minnesota Department of Transportation, 1996). Therefore these tills are highly overconsolidated, which is a reflection of the preconsolidation stress imposed by glacier ice (Horn et al., 1998; Tulaczyk et al., 2001a).

Stone densities of the till associated with each study area are shown in Figures 3, 4, 8, and 9. Figures 8 and 9 are of Hewitt till from the Wadena drumlin field and Brainerd till from the Brainerd drumlin field, respectively. Throughout its entire thickness, Hewitt till rarely contains rocks larger than 10-15 cm in diameter (Figure 8). Brainerd till, however, has far more clasts in the 10-15 cm fraction, and even contains a few boulders (Figure 9). Figure 3 shows the Independence till in an exposure in an iron mine on the Mesabi Iron Range (Winter et al., 1973). Boulders are clearly seen within the till in addition to the obvious boulder concentration on the surface. Isabella till in the area of Rögen moraine is shown in Figure 4 (Meyer, 2008).

Discussion

Boulder concentrations on the surfaces of tills in the area glaciated by the Rainy lobe are ubiquitous features of the landscape in central and northeastern Minnesota. Any potential hypothesis for the formation of surface boulder concentrations in the Wadena, Brainerd, and Toimi drumlin fields and the Rögen moraine must explain the observed characteristics of the boulders and of the sediments within the till beneath them. Hewitt till, with its provenance in Hudson Bay and the Canadian Shield, has the longest transport length of any of the tills studied (Figure 13 and Table 2), a greater proportion of dolomite in the smaller size fractions (Figure 10), and a lack of any boulders larger than 15 cm within it (Figure 8). Additionally, the smallest surface boulders of any study area were found in the Wadena drumlin field (Figures 2a, 2b and 2c). Brainerd till has a higher proportion of northeastern Minnesota lithologies and a shorter transport length than the Hewitt till, resulting in coarser rocks within the till (Figure 9) and larger surface boulders (Figure 2d). Average transport lengths for the bouldery Independence till in the Toimi drumlins and Isabella till in the Rögen moraine (Figures 3 and 4) were even shorter, based on the high proportion of locally derived gabbro and red felsite. The largest boulders encountered as part of this study were almost exclusively locally-derived gabbro associated with the Independence till (Figures 11 and 12).

These observations indicate that progressively shorter mean transport length through time is associated with increasing clast size in the till and suggest that transport length and lithology control the size of clasts. I will now examine the formation of surface boulder concentrations. I suggest that there are only a limited range of mechanisms that can account for the origin of surface boulder concentrations on till of a single glacial advance and retreat. These include:

1. Formation as a lag or the result of erosion by meltwater or solifluction/periglacial processes,
2. Erosion and subsequent transport higher in the debris load such that the stratigraphic superposition of boulders is maintained upon ice wastage, or
3. Vertical sorting during till transport or deposition in either a deforming till or lodgement till system.

Lag from erosion or solifluction/periglacial processes

The idea that boulder pavements in SW Minnesota were erosional lags was proposed by Matsch (1972) and Wright (1972). Many hypotheses have been postulated for the existence of boulder pavements between two distinct till units (Holmes, 1944; Matsch, 1972; Clark, 1991; Hicock, 1991; Boulton, 1996; Benn and Evans, 2010); most of these are not applicable in our case because of the lack of a unit on top of the boulders, but an erosional lag hypothesis is pertinent to this study. The erosion event could occur subglacially just before complete recession of the Rainy Lobe from each location or subaerially sometime after recession. Boyce and Eyles (2000), in an attempt to explain boulder pavements between successive sequences of till near Toronto, Ontario, suggest that boulders are the result of subglaciofluvial reworking of underlying till producing a lag of coarse rocks/boulders. This hypothesis requires a concentration of boulders within the till sufficient to form a layer with a significant density of boulders after removal of fine sediments.

In the Wadena and Brainerd drumlin fields, there are no boulders of comparable size and density within the till (Figures 8 and 9). In the Toimi drumlins and Rögen moraine, Independence and Isabella tills are considered bouldery, but in the limited exposures examined, the largest of the boulders outcropped at the surface (Figures 11 and 12). In order to produce the dense surface concentrations of boulders observed in these study areas, erosion and removal of the finer size fractions within a thickness of till on the order of tens of meters would have to occur. Given the volume of sediment removal required and the lack of large boulders within the underlying till, the potential “parent material,” the erosional lag hypothesis is highly unlikely.

The same line of evidence can be used to evaluate freeze/thaw hypotheses. Frost or stone heave is a well-documented phenomenon in which large cobbles and stones appear on the surface as the sediment below is rearranged and its permeability changed during repeated freezing and thawing (Vilborg, 1955; Viklander and Eigenbrod, 2000). If freezing and thawing processes produced surface boulder concentrations in the Wadena and Brainerd drumlin fields, permafrost active layer thickness or frost depth on the order of many tens of meters was necessary. With the observed boulder paucity in the till, stone heave capable of uplifting nearly the entirety of the boulders throughout the complete thickness of the till is required. In the Independence till, stone heave would have to preferentially concentrate on the surface only the largest of the boulders in the till, leaving smaller boulders unaffected. For all of these things to have occurred seems highly unlikely given the variable nature of freeze/thaw processes. In addition, the process of solifluction has also been proposed as a means to concentrate boulders (Goldstein, 1989). However, there were no observed slumping structures on the slopes of drumlins, and boulders do not preferentially outcrop on either the tops or swales of the drumlin fields.

Boulders carried higher in glacier ice

The Rainy lobe eroded and entrained sediment over thousands of years along a flow line extending from northern Ontario and Quebec to northeastern Minnesota. Bedrock from further up glacier in Ontario was subjected to glacial erosion before material further down glacier in Minnesota as shown by the lithologic assemblages distinct to each study area through time (Figure 10). According to this hypothesis, granite and greenstone with tendencies to quarry in larger blocks owing to joint spacing will end up at a higher stratigraphic position in the ice than sediment entrained further down glacier, resulting in a concentration of large granite and greenstone boulders higher in glacier ice isolated from comminution.

In the Wadena drumlins, this hypothesis is credible because the boulder fraction is clearly dominated by a high proportion of felsic igneous and metamorphic lithologies while the smaller fractions show more variety in lithologic composition. Brainerd drumlin boulders are also dominantly felsic igneous and metamorphic, but the proportion of mafic igneous boulders is higher. In the Toimi drumlins and Rögen moraine, boulders are distinctly large and are dominated by Duluth Complex gabbro while the felsic igneous proportion decreases substantially. This transition, while most obvious in the boulder fraction, is also represented in the underlying till (Figure 10).

While the boulders in these four study areas may only represent a few particular lithologies, much of that bias can be explained by how different types of rock are eroded from their bed and subsequently comminuted in the glacier (Dreimanis and Vagners, 1971; Drewry, 1986; Kirkbride, 1995; Hallet, 1996; Dühnforth et al., 2010; Krabbendam and Glasser, 2011; Iverson, 2012; Lucas et al., 2013). Despite the lithologic control on size, surficial boulders are clearly representative of the material in the underlying till and continued to be even as the erosional center of the Rainy lobe migrated south (Mooers and Lehr, 1997). If they were eroded and entrained further up glacier, boulders in the Toimi drumlins and Rögen moraine would have a lithologic signature more indicative of a Canadian Shield provenance instead of their observed Duluth Complex and North Shore Volcanic Group provenance. These results indicate that erosion of the surface boulders and till matrix material in each of the study areas was contemporaneous, meaning boulders were not eroded further up glacier and carried higher in glacier ice. Rather, it appears more likely that boulders were actively transported and the lithologies that remain boulder-sized are the ones most capable of withstanding comminution within basal ice.

Vertical sorting during till transport or deposition

Deforming till

The occurrence and significance of deforming subglacial till has been debated vigorously among glaciologists for the last few decades (Boulton and Jones, 1979; Boulton and Hindmarsh, 1987; Clayton et al., 1989; Boulton, 1996; Boulton et al., 2001; Piotrowski et al., 2001; van der Meer et al., 2003; Piotrowski et al., 2004; Evans et al., 2006, Menzies et al., 2006; Benn and Evans, 2010; van der Meer and Menzies, 2011). The hypothesis that a sheet of deforming till exists beneath glaciers challenges the classic dichotomy of tills as lodgement, meltout or flow. Some studies go so far as to say tills in the classical sense do not exist and that all tills were deforming based on microfabric analysis (van der Meer et al., 2003; van der Meer and Menzies, 2011). In addition, arguments have been made stating that drumlins are formed under deforming bed conditions (Boulton, 1996; Boulton et al., 2001; Kjaer et al., 2003). Without jumping too far into the debate, both deforming till and lodgement till provide a mechanism to concentrate boulders on the surface of till sheets, yet each has their limitations.

G.S. Boulton has been at the forefront of the deforming bed paradigm shift, presenting a model for the formation of boulder pavements between two till sheets involving separate horizons of deformation (Boulton, 1996; Evans et al., 2006; Benn and Evans, 2010). Figure 14 illustrates a subglacial layer of deforming till shearing in the

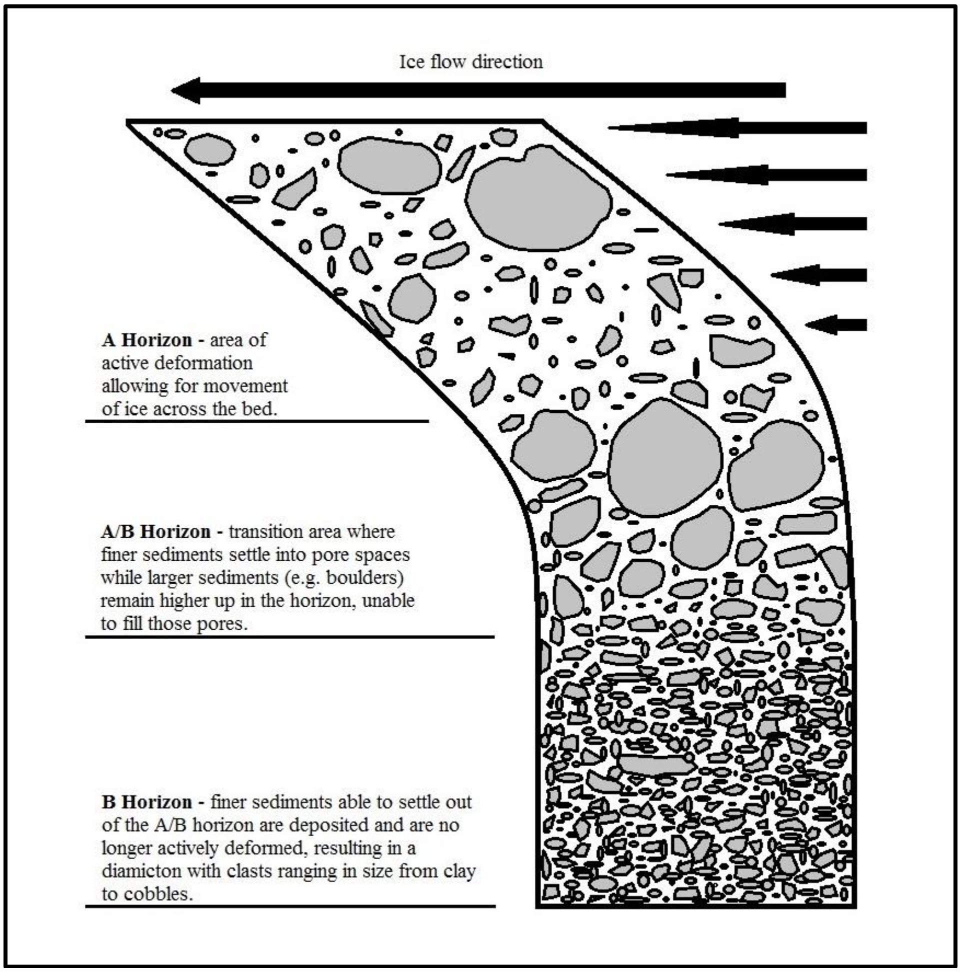

Figure 14. Deforming bed model. Example of a deforming bed below an ice sheet showing the hypothesized "Brazil nut effect" concentrating large boulders at the surface while finer material settles into pore spaces below. Modified from Evans et al. (2006).

direction of ice flow and creating three distinct horizons. The A horizon is the location where active deformation and shearing occurs, and the B horizon is where actual deposition occurs as sediments settle out of active transport with the A/B horizon representing the transition between the two (Boulton, 1996, Evans et al., 2006). In the A horizon where sediments of all lithologies and sizes are dilated, shearing and mixing, deformation can occur episodically or pervasively.

I suggest that active deformation occurring in the dilated A horizon produces what has been termed in soil engineering literature as a “Brazil nut effect” where fines settle into pore spaces beneath larger particles, thereby concentrating coarser particles above finer ones (Rosato et al., 1987; Jullien and Meakin, 1990; Möbius et al., 2001). Finer sediment will therefore settle further and further down toward the A/B horizon where it can eventually be incorporated into the B horizon; fines continuously filling in the pore spaces would cause larger particles (i.e. boulders) to stay in traction in the A horizon rather than settle into the B horizon. If the glacier were to build up this deforming bed sequence and eventually stagnate or deplete its sediment reservoir, the resulting subglacial till would appear relatively devoid of larger size fractions and would coarsen upward with the coarsest material on top. This model is in stark contrast to the model of Clark (1991) where boulders settle to the bottom of a soupy deforming till thereby forming a boulder pavement.

One potential limitation of this method of concentrating surface boulders is that the tills in all four study areas are overconsolidated and have high bulk densities (Mooers, 1988; Goldstein, 1989; Soil Survey Staff, 1965, 1989, 1991; Lehr, 2000; Meyers, 2008). In order to consolidate, sediments in the B horizon must dewater and develop a till-matrix framework where porosity decreases and density increases. Evans et al. (2006) argue that some degree of consolidation can occur with increasing depth of sediment resulting from the increasing load and normal stress from the ice above or from an increase in subglacial drainage decreasing pore water pressure; however, this may not be enough to consolidate till to near its theoretical limit of consolidation.

Lodgement till

The tills in the Wadena, Brainerd, Toimi drumlins and the Rögen moraine are highly overconsolidated with high bulk densities, so they have traditionally been interpreted as lodgement tills (Wright, 1972; Mooers, 1988; Goldstein, 1989; Lehr, 2000; Meyer, 2008). The high bulk densities reported for all locations (Soil Survey Staff, 1965, 1989, 1991) are generally attributed to lodgement in which pore space is minimized as the glacier smears sediment directly onto its bed (Evans et al., 2006; Benn and Evans, 2010). This requires some degree of basal melting to liberate the sediments and make them available for deposition. As a result, finer sediments with smaller diameter and surface area will generally melt out from glacier ice and become lodged more frequently than larger clasts. The Hewitt and Brainerd tills both have a high degree of fine material in them as opposed to larger cobbles which would fit this explanation. The Independence till is coarser, but again, most of that difference can be explained by the shorter transport length of the sediments.

Once a particle of any size begins to protrude from basal ice, it will plough into existing basal sediment until the resistance of the till below is strong enough to arrest the forward motion of the particle and it becomes lodged (Iverson, 1999; Benn and Evans, 2010). It is easy to see how this can occur for fine fractions and is essentially the main mechanism behind the formation of lodgement till, where the drag force exerted on clasts is governed by clast size. Smaller clasts (<8 mm in diameter) are easily accommodated by regelation whereas larger clasts (<50 cm in diameter) are accommodated by enhanced creep (Iverson and Hooyer, 2004; Benn and Evans, 2010). However, obstacles in the 0.5 to 2 m size range impose the largest drag on basal ice because this range cannot be accommodated by either regelation or enhanced creep (Weertman, 1964; Nye, 1969; Kamb, 1970; Fowler, 1981; Benn and Evans, 2010). Thus, I suggest that for a boulder greater than about 0.5 m in diameter, it would be difficult for the already dense and consolidated sediment below to plough up in front of the boulder enough to overcome its forward motion. A boulder of significant size could simply be dragged along, roll over, or do work on the unconsolidated sediment below (Tulaczyk et al., 2001b) and never be incorporated into it. When ice stagnates, boulders would settle into the location where the glacier last moved them. The term I deem for this phenomenon is “selective lodgement,” where clasts smaller than those in the boulder fraction are easily deposited or “selected” for deposition whereas larger clasts are not and remain actively transported by glacier ice.

Conclusion

The data on lithologic composition of boulders and of till along with transport distance and the general nature and occurrence of boulder concentrations on the surface, support a “selective lodgement” process for the origin of surface boulder concentrations. Deforming and lodgement tills are more closely related than may have been previously interpreted. The separate dichotomy between deforming till and the other classical terms

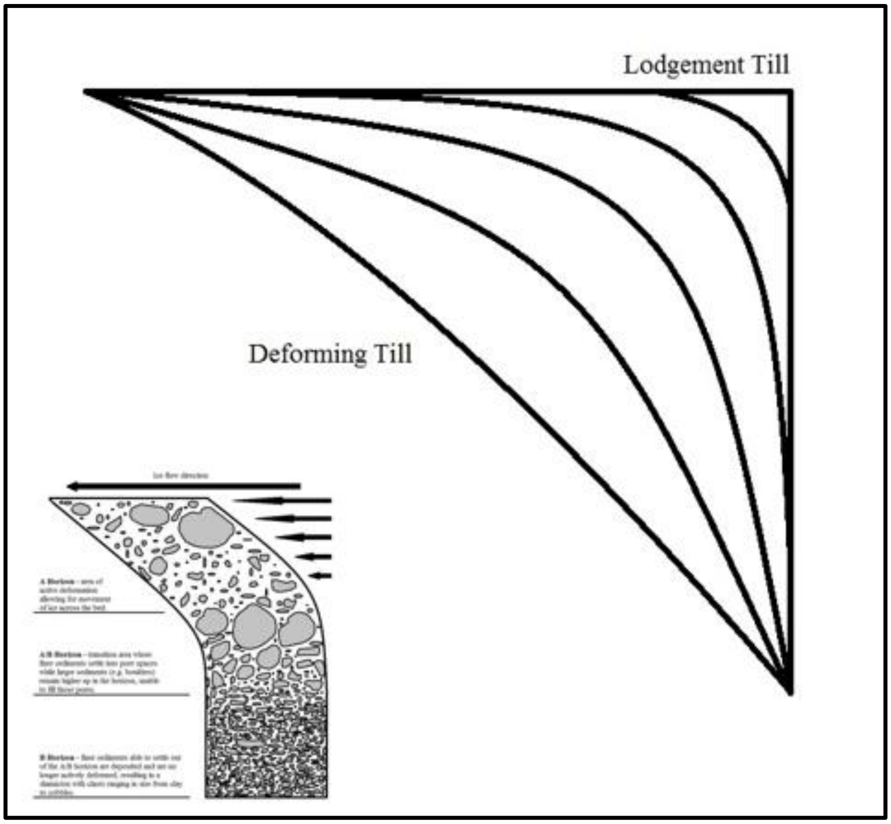

Figure 15. Deforming bed to lodgement till spectrum. Diagram showing the deforming and lodgement tills as end members of a deformation spectrum. As the thickness of deforming till decreases, the thickness of the A horizon or active layer of dilated sediment also decreases. Eventually, the thickness of the deforming layer becomes small enough to where deposition of sediment occurs a lodgement regime. Sediment is actively deposited by glacier ice and smeared onto the bed because the sediment below no longer compensates for movement of ice by shearing in the direction of flow. The separate dichotomy of deforming versus lodgement till is therefore unnecessary as lodgement till deposition can be considered a specific type of deformation process.

for describing till formation serves no purpose other than to isolate and create debate about two things that are inherently related. I suggest that lodgement and deformation are two end members along the same continuum of deposition of subglacial sediment (Figure 15).

Begin with a pervasively deforming bed with an A/B horizon at the transition between the actively deforming sediment (A horizon) and the horizon where deposition occurs (B horizon). As the A/B horizon migrates up, the zone of active deformation becomes thinner and net deposition occurs. Continued deposition, in turn, decreases the thickness of the deforming layer. Once this A horizon becomes too thin, the dominant depositional process becomes lodgement as sediment can no longer dilate to the same extent and is essentially smeared onto the A/B horizon. The converse can occur with lodgement transitioning to deformation, as sediment can more readily dilate if a greater thickness is deforming. Thinking along a continuum in this way rather than within strict boundaries allows for even more interpretation about depositional processes rather than limiting discussion to one mechanism or the other.

No matter where surface boulder concentrations associated with the Rainy lobe fit along this spectrum, it is clear that boulders remained in the active sediment layer instead of being deposited within the till below. The lithologic composition of the boulders and the till is unique to each study area, indicating all sediments from all size fractions were eroded contemporaneously despite the fact that the primary locus of erosion by the Rainy lobe migrated south through time. The particle size distribution of till sediments and boulders is the result of lithologic and transport length differences. The largest boulders observed in the Wadena, Brainerd, and Toimi drumlin fields and in the Rögen moraine do not occur within the underlying till. Given the similarities of the lithologies of the boulders and the till and the general lack of large boulders within the till itself, erosional processes are unlikely to be responsible for the formation of surface boulder concentrations, whether they occur at the point of initial entrainment or after deposition by the Rainy lobe. Boulders found on the surface of till sheets that directly reflect the same provenance as the till below are ultimately best explained by selective lodgement processes throughout an entire spectrum from pervasive deformation to lodgement deposition.

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