INTRODUCTION

Glacial landscapes involve a complex mixture of sediment types that often have different hydrogeologic properties. The single most important factor affecting hydrogeologic characteristics of glacial deposits is the diversity of sediments and the resultant numerous lithologic discontinuities. In this chapter, the genesis, spatial arrangement, and geologic and hydrogeologic properties of these sediment types are discussed.

For the purposes of this chapter, the following terms are defined:

**Diamicton.** An increasingly popular descriptive term for poorly sorted, poorly stratified sediment. Diamicton includes sediments of varying genesis such as till, mudflow, and other mass-movement deposits. Till is a genetic term for sediment deposited directly by glacier ice without significant resorting (Dreimanis, 1982). Because earlier publications typically use "till" as the descriptive term for diamicton, we will continue that usage here.

**Glaciolacustrine deposits.** A term describing all lake deposits associated with glacial activity. These deposits may be sand, silt, or clay, and are mostly well sorted. Stratification may be well developed to absent.

**Glaciofluvial deposits.** A term describing sediments deposited by streams in association with glacier ice. Related terms are: outwash, a glaciofluvial sediment deposited by streams flowing away from the glacier; and ice-contact stratified deposits, stream sediments deposited in contact with glacier ice. Included in this category are land-forms such as eskers, ice-contact terraces, and deltas. Normally, outwash and ice-contact stratified deposits are composed of sand or of sand and gravel.

Eolian deposits, such as loess and dune sand, are not glacial deposits per se but are commonly present in the glacial landscape. Table 1 lists some generalized physical properties of glacial deposits.

Glacial deposits, primarily of Quaternary age, cover about 13 million square kilometers of North America (Flint and Sharp, 1971) and frequently constitute a major ground-water source for domestic, commercial, industrial, and agricultural purposes. Because these deposits are at or near the ground surface, they are used for waste disposal, are easily affected by spills of toxic and hazardous materials, and are subject to agricultural and other nonpoint pollutants. Many studies of glacial deposits have been published, but only a few compilations are available that address the overall character and distribution of deposits in a glacial landscape and the hydrogeologic properties of individual glacial materials. The following discussion focuses on the geologic and geochemical processes of aquifer and aquitard genesis in glacial deposits, with particular reference to midwestern North America.

SEDIMENTOLOGY OF GLACIAL DEPOSITS

The character of sediments in a glacial landscape is a function of three things: the lithology and geochemical properties of the sediment source, the nature and distance of sediment transport, and the mode of sediment deposition. For example, source terrains underlain by carbonate rocks produce sediments rich in carbonate while source terrains with silica-rich rocks generally produce glacial deposits reflecting that composition.

Texture or grain-size distribution of windblown sediment, of glaciolacustrine sediment, and of glaciofluvial deposits is controlled mostly by the environment of deposition. For glaciofluvial deposits, texture and sorting can change radically over short distances if stream energy during deposition was variable in time or space. For till and of related diamictons, texture is controlled both by source and by mode of deposition. Regional textures are commonly controlled by the position of shale outcrops or lake basins that supplied fine-grained sediment. For example, till of clayey texture is present in the flow-path direction of glacial ice in all the Great Lakes basins and most other lake basins (Mickelson and others, 1983). Sandy till is present mostly in areas where till was derived from Precambrian bedrock or younger sandstones. However, even in areas of clayey till located south of the Great Lakes, till or other diamictons of sandy texture can be found. The reason is that glaciers eroded most of the pre-existing lake sedi-
TABLE 1. GENERALIZED PROPERTIES OF GLACIAL DEPOSITS

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Till</th>
<th>Proglacial and Supraglacial Diamicton</th>
<th>Ice-contact Stratified Deposits</th>
<th>Pitted Outwash</th>
<th>Outwash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sorting</td>
<td>Poor</td>
<td>Poor</td>
<td>Moderate</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Stratification</td>
<td>None or poor</td>
<td>None or poor</td>
<td>Locally collapsed</td>
<td>Locally collapsed</td>
<td>Well developed</td>
</tr>
<tr>
<td>Surface form</td>
<td>Flat, hummocky,</td>
<td>Hummocky</td>
<td>Gently sloping with depressions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(all may be</td>
<td>or streamlined)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Where</td>
<td>Beneath ice</td>
<td>Ice margin</td>
<td>Ice margin or beneath</td>
<td>In front of or on margin in valley, apron or plain</td>
<td>In front of margin in valley, apron or plain</td>
</tr>
<tr>
<td>deposited</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grain size</td>
<td>Sandy to clayed,</td>
<td>Sandy to clayed, variable coarse</td>
<td>Variable, gravel near source, sand away</td>
<td>Uniform gravel near source, sand away</td>
<td></td>
</tr>
<tr>
<td>Rounding of clasts</td>
<td>uniform</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compaction</td>
<td>Angular</td>
<td>Moderate</td>
<td>Variable</td>
<td>Fairly well rounded</td>
<td>Well rounded</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Loose, usually not over consolidated</td>
<td>Loose, granular</td>
<td>Loose, granular</td>
<td>Loose, granular</td>
</tr>
<tr>
<td>Jointing</td>
<td>Often well developed,</td>
<td>Often closely spaced, fissile</td>
<td>Not common</td>
<td>Not common</td>
<td>Not common</td>
</tr>
<tr>
<td>Lateral continuity</td>
<td>Well developed</td>
<td>Poorly developed</td>
<td>Poorly developed</td>
<td>Well developed</td>
<td>Well developed</td>
</tr>
<tr>
<td>Aquifer potential</td>
<td>Poor</td>
<td>Poor to fair</td>
<td>Fair</td>
<td>Good</td>
<td>Excellent</td>
</tr>
</tbody>
</table>

ment and derived much of their basal load from bedrock composed of sandstone, limestone, and crystalline rocks.

Mode of deposition also affects texture, the presence of fractures, consolidation, and other properties. If debris is carried near the base of the ice and deposited as basal till, little or no change in texture occurs during the process of deposition. If, however, debris is carried high enough in the ice so that it melts out and is deposited from the ice surface, various mass-wasting processes and some washing may affect the material, producing other diamictons that are often more variable than basal till, and perhaps more sandy (Fig. 1).

In the discussion above, the differences in till and related sediments that can occur during a single glacial advance have been described. It is important to recognize, however, that in most glaciated areas, several advances have taken place. The record of glacial advances varies from place to place because of processes within the glacier. For example, valley glaciers commonly downcut their valleys during each advance and erode away older deposits in the valley bottom. Thus, only the thin deposits are preserved high on valley walls or moraines and terraces that were outside the limit of later advances. The ice sheet that covered the flatter terrain of much of central and eastern North America left a complex record of earlier advances. In general, central areas of the ice sheet experienced severe erosion during each advance. Although isolated valleys contain a stratigraphic record, much of the Canadian Shield has thin, very young till over bedrock. In the other parts of the ice sheet, however, deposition generally prevailed and several stratigraphic units are commonly present.

DOCUMENTATION OF GLACIAL DEPOSITION

As described above, deposits in a glaciated region are rarely uniform and isotropic. Ground-water studies require information about the vertical and horizontal distribution and hydraulic characteristics of sediments in the landscape. Traditional mapping of
Glacial deposits, although providing some ground-water resource information, has often fallen short of providing details necessary to make sound interpretations in ground-water studies. Part of the reason is that many studies have concentrated on the distribution of materials or landforms at the surface without providing detailed and widespread subsurface information. Other studies do not provide sufficient information about the sediments and depositional environments necessary to make reasonable interpretations of the continuity and hydrogeologic characteristics of units, nor do these reports contain quantitative geotechnical or hydraulic data. Among approaches to deal with this problem, two appear to be developing along parallel lines; both appear valid at different map scales and different levels of interpretation.

In the central United States, where the stratigraphy is fairly well known, lithostratigraphic units have been defined and described (e.g., in Illinois: Willman and Frye, 1970; in Minnesota and North Dakota: Harris and others, 1974; in Iowa: Hallberg, 1980; in Wisconsin: Mickelson and others, 1984). Normally, units exposed at the surface are mapped and also shown in cross sections. In some cases, a more useful approach is that of stack-mapping—the mapping of units that include an indication of all of the materials in the section present to a certain depth (Kempton and Cartwright, 1984). This approach has been used successfully in the county scale (Berg and others, 1984a) and at the state level as a basis for maps showing susceptibility to contamination (Berg and others, 1984b). Moreover, this approach provides the most useful information for the purposes of ground-water studies, partly because stratigraphic extrapolation is done by the stratigrapher instead of by a map user, as in the case of widely spaced cross sections. However, this method of evaluating glacial deposits is expensive and time-consuming.

Another approach, which is particularly useful for more generalized studies or in situations where glacial deposits are fairly thin, is land-systems mapping. The land-systems approach consists of mapping areas that have similar landforms and sediment types as units that can be further subdivided. For example, a subglacial land system can be subdivided into several categories, including drumlin areas. A drumlin area can then be subdivided into units based on sediment type, slope position, or other features. Intended to be a hierarchical, integrative resource inventory system, land-systems mapping has been used for many years in various parts of the world (Stewart, 1968; Haantjens, 1972). Several reviews of general land-systems approaches are given, for example, in Wright (1972), and Cook and Doornkamp (1974). Eyles (1984a, 1984b), Eyles and Menzies (1984), and Paul (1983) have provided a detailed outline of glacial land systems in low-relief and high-relief areas.

Knowledge of the sediments in the glacial setting is essential to the interpretation of the hydrogeology of glaciated terrains. Figure 2 shows a hypothetical mountain and valley landscape that has been glaciated. Except in valley bottoms, the surficial cover is thin and composed of weathering residue and isolated patches of till from earlier advances. Alluvial fans and talus cones are common near the base of slopes, and these extend into the basin fill that is typically better-sorted sand or sand and gravel. In some cases, these talus cones are active features, but periglacial conditions during glaciation probably greatly enhanced these processes, producing thick accumulations of mass-movement debris near the valley walls. Lateral moraines along valley sides extend across the valley floor as end moraines, showing in the subsurface as lenses of till and boulders.

In areas of continental glaciation, particularly in areas of clayey or silty till, major ground-water sources are commonly in valleys, some of which are entirely filled with deposits of the youngest glacial advance (Fig. 3). Thus, depth to bedrock and the stratigraphy of deposits above the bedrock greatly influence considerations for water supply and for the disposal of waste that must be isolated from a lower Quaternary aquifer or older bedrock aquifer. Because in many areas lithostratigraphic units can be defined and traced, and ranges in properties can be obtained, a lithostratigraphic approach to defining the hydrogeologic setting is often appropriate.

These lithostratigraphic units should, however, be inter-
interpreted with genesis in mind. Till and related diamictons have
different hydrogeologic properties than do water-laid deposits.
Even within deposits traditionally called till, differences in envi-
ronment of deposition create differences in characteristics of the
sediment (Lutengger and others, 1984). Sediments deposited in
the subglacial environment commonly show streamlined forms at
the surface (Fig. 3). This drumlin topography normally indicates
uniform basal till at the surface (although not necessarily at
depth), probably with few sand lenses and similar discontinuities.
However, joints might be common, depending on the texture of
the till (Grisak and Cherry, 1975; McGown and Radwan, 1975;
McGown and Derbyshire, 1977; Connell, 1984). Uniform basal
till might also be present as nearly flat plains that have little
original relief. In areas that have deposits older than Wisconsinan
age, the surface has commonly been fluvially dissected, but glacial
deposits in the subsurface still greatly affect hydrologic conditions
(Sharp, 1984). In areas where bedrock is near the surface, for
example in much of the Canadian Shield, till is commonly so thin
that use of the surficial deposits for either waste disposal or water
supply is impossible (Fig. 3).

End moraines are ridges that are roughly parallel to the
former ice margin, that formed in different ways, and therefore,
that are variable in composition. In places where ice evidently
had a wet bed during till deposition (e.g., in Illinois, Indiana,
Iowa, and Ohio, along the margins of the Great Lakes, and in
southern Ontario), the till in the moraines is generally fairly uni-
form, and probably is mostly basal till (Mickelson and others,
1983). In other areas, particularly farther north in parts of Wis-
consin, Minnesota, North Dakota, Michigan, and in many parts
of New England and Canada, end moraines are much more
complex and generally have higher-relief hummocky topography.
In these cases, basal till is commonly intermixed with silt, sand,
gravel, supraglacially derived diamictons, and sediment melted
out in situ from higher in the ice.

Stream deposits vary in character with distance from the ice
margin at the time of deposition. Commonly, sediments deposited
near the ice margin are poorly rounded, less stratified, and less
well sorted than those deposited away from the ice. Ice-contact
stratified sediments generally contain collapse of bedding and
interbedded lenses or amorphous masses of diamicton. Because of
their discontinuity and often limited extent, these deposits provide
limited opportunity for high capacity wells, although frequently
used for domestic supplies. Sand and gravel deposited by streams
flowing away from the glaciated area are generally better strati-
fied, better sorted, and more continuous than that deposited near
the ice and, thus, provide greater potential for water supply.

HYDROGEOLOGY OF GLACIATED TERRAINS

Because many glacial terrains are composed of heteroge-
neous mixtures of sediments, complex hydrogeologic environ-
ments result. Hydraulic properties of the deposits show consid-
erable variability, both between different glacial terrains and for a particular type of deposit. The diversity of these deposits results in numerous lithologic discontinuities and is perhaps the single most important factor affecting the overall hydrogeology of glaciated terrains. In an attempt to examine the hydrogeology of glacial terrains, the remainder of this chapter addresses: (1) The hydraulic and hydrogeochemical properties of specific types of glacial materials; and (2) The flow systems and hydrostratigraphy that characterize different glacial depositional systems as a result of the intercalation of various glacial sediments.

Glacial deposits may be grouped into two general hydraulic categories: (1) materials that transmit water readily, such as outwash and ice-contact stratified deposits and sandy diamicton; and (2) materials that have relatively low hydraulic conductivity, including many tills, loess, and lacustrine sediment (mainly silt and clay). The majority of glacial aquifers consists of the first type, and because these deposits have been widely exploited for water supplies, much is known about their hydraulic characteristics. Hydrogeologic data for the second group are relatively scarce, although their low hydraulic conductivity has recently made these materials attractive for waste-disposal sites. Therefore, much of the available data has come from investigations related to waste disposal. The following discussion of hydraulic properties is directed chiefly at materials of the second category—low hydraulic conductivity—because: (1) the hydraulic properties of outwash are fairly well known and are similar to those of alluvium, which is discussed in detail elsewhere in this volume; (see chapters by Heath, Lennox and others, Cartwright and others, Cherry and Farvolden, Rosenshein, and Sharp); and (2) of the need to evaluate systematically the hydrogeology of till and related deposits within a wide range of glacial terranes.

**Hydraulic Properties**

Data on the hydraulic properties of glacial deposits are usually provided as follows:

**Hydraulic conductivity**, the most widely reported hydrologic property of glacial deposits, shows much variation among the different types of deposits. Intergranular porosities, where reported, show much less variation and are commonly in the range of 25 to 40 percent for most glacial deposits (see Morris and Johnson, 1967; Grisak and Cherry, 1975).

**Transmissivity** is commonly used to describe the amount of ground water flowing in primarily confined sand and gravel aquifers.

**Values of specific storage** have in some cases been reported for confining layers of till and lacustrine deposits that overlie outwash aquifers (Norris, 1959; Grisak and Cherry, 1975).

Reported values of hydraulic conductivity are frequently calculated by different methods. Field-determined values, from aquifer tests or single-hole methods, are often much greater than laboratory-determined values for the same material. Likewise, different laboratory methods may produce differing values of hydraulic conductivity. Where hydraulic properties are compared in this chapter, an attempt was made to differentiate between the results of different methods. However, some of the scatter in the data is due to the different procedures used.
TABLE 2. HYDRAULIC CONDUCTIVITY RANGES OF GLACIAL DEPOSITS

<table>
<thead>
<tr>
<th></th>
<th>Unweathered (m/day)</th>
<th>Weathered (m/day)</th>
<th>Fractured (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basal till</td>
<td>$10^{-8}$ to $10^{-4}$</td>
<td>$10^{-7}$ to $10^{-4}$</td>
<td>$1.0$ to $10^{-4}$</td>
</tr>
<tr>
<td>Supraglacial till*</td>
<td>$1.0$ to $10^{-4}$</td>
<td>$1.0$ to $10^{-4}$</td>
<td>$1.0$ to $10^{-4}$</td>
</tr>
<tr>
<td>Lacustrine silt and clay</td>
<td>$10^{-6}$ to $10^{-4}$</td>
<td>n.a.</td>
<td>$10^{-3}$ to $10^{-6}$</td>
</tr>
<tr>
<td>Loess</td>
<td>$1.0$ to $10^{-4}$</td>
<td>$10^{-2}$ to $10^{-5}$</td>
<td>n.a.</td>
</tr>
<tr>
<td>Outwash</td>
<td>$102$ to $10^{-2}$</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

*Includes some poorly stratified sediments and debris flow.

The hydraulic properties of glacial deposits show a systematic variation that can be related to differences between depositional environments and, to some extent, post depositional modification. Two types of hydraulic conductivity are recognized: (1) Primary hydraulic conductivity, which is a property of the predominant material itself that is in turn the result of its genetic history; and (2) Secondary hydraulic conductivity, which arises through post depositional modification, such as fracturing and weathering. These secondary features, considered with the intercalation of two (or more) lithologies that have entirely different primary hydraulic conductivities, result in a bulk hydraulic conductivity that may be different from the primary hydraulic conductivity and from the conductivity that ultimately predominates in the landscape.

To separate quantitatively these two kinds of hydraulic conductivity is often problematic, but some attempt has been made to do so in the following discussion.

The values given in Table 2 are compiled from many sources in the literature. Despite the large number of sources and methodologies represented, distinct differences occur among the ranges of hydraulic conductivity for each type of material. These distinctions are especially noticeable in the values for till, both for the genetic categories (basal and supraglacial) as well as for primary (unweathered) and secondary (weathered, fractured) hydraulic conductivities.

In the case of primary hydraulic conductivity, several genetic controls appear to influence the range of values. A particularly strong relationship is evident between laboratory-determined hydraulic conductivity and grain-size distribution, as shown in Figure 4. The major influence here appears to be the amount of clay present. Haeefeli (1972) has suggested that as little as 2 percent clay in otherwise clean sand can reduce hydraulic conductivity by two to four orders of magnitude. In Figure 4, a clay content of between 15 and 20 percent appears to mark a threshold above which conductivities are uniformly low. At clay contents below this threshold, a major factor appears to be the sand-silt ratio (higher conductivities associated with a larger ratio).

Also evident is that some conductivity values for till differ by as much as two orders of magnitude, even though the samples reflected similar grain-size distributions, indicating the effect of other factors. One such factor is suggested by a comparison of the conductivity ranges of basal till and supraglacial diamicton, as given in Table 2. Although both types of till show similar spreads of about four orders of magnitude, the values for supraglacial diamicton cluster approximately about two orders above those for basal till. This difference stems directly from contrasts between the subglacial and supraglacial environments. Deposition of till in the subglacial environment often occurs under great confining pressure, due to the weight of the overlying ice. Thus, many basal tills are characterized by a high degree of consolidation and have fine-grained types often referred to as "overconsolidated" (Sladen and Wrigley, 1983; McGown and others, 1975). The product of this process is a dense, compact basal till in which voids are poorly interconnected, resulting in reduced hydraulic conductivity. The degree of consolidation can be influenced by a number of variables, including the ratio of basal shear stress to normal stress, basal porewater pressure, the amount of reworking due to basal meltwater, and the amount of overburden that has been removed by erosion (Bouton and Paul, 1976; Sladen and Wrigley, 1983). Because these factors commonly vary from place to place, not all basal till has the same degree of consolidation; therefore, the effect on conductivity can also be expected to vary.

Supraglacial deposition, on the other hand, occurs at the ice margin, and the deposits are not subject to intense compaction. Thus, pore spaces can be expected to be better connected than those in basal till. Moreover, the supraglacial environment is typified by abundant rainfall and meltwater, which can have an effect that ranges from minor washing of fines from the sediment to complete reworking and sorting (Paul, 1983). Both the lack of consolidation and better sorting tend to increase the hydraulic conductivity of supraglacial diamictons as compared to basal till. However, this sorting process also tends to be irregularly localized in the supraglacial environment, producing a complex mixture of till, sand and gravel, and debris-flow sediment that may have little lithologic continuity. This condition has major implications for
Sources

Till O

Loess ▲

Lacustrine Deposits △

Outwash ●

Gordon and Huebner (1983)
1.6, 2, 3, 4, 5, 6, 7,
8.6, 10, 26, 70, 170,
1000, 4500

Morris and Johnson (1967)
0.08, 2.4, 3.2, 4.1,
9, 80, 960, 2800,
3900, 5200, 56000

Prudic (1982) 6

Herzog and Morse (1984)
10

0.7, 1, 1.2, 1.5, 1.7,
1.9, 3, 5, 100

0.0004, 0.4, 8, 80

6500, 64000

Figure 4. Relationship between hydraulic conductivity (in units of $1 \times 10^{-5}$ m/d) and glacial-deposit type.
the large-scale hydrogeology of the supraglacial land system, as will be discussed later.

Secondary hydraulic conductivity in glacial deposits is typically difficult to detect using laboratory methods alone, simply because of the larger scale involved than that encompassed by conventional laboratory specimens. Causes of secondary hydraulic conductivity include jointing, weathering, and ground-water erosion. The magnitude of secondary hydraulic conductivity is commonly two or three orders greater than the laboratory-determined primary hydraulic conductivity of a given glacial sediment. Thus, the presence of secondary hydraulic conductivity is frequently identified by comparing laboratory and field tests (Table 3).

For many years, fractures have been considered to influence the movement of ground water in fine-grained glacial till and lacustrine sediment (Williams and Farvolden, 1967). However, the idea that fractures are common to many of these deposits has emerged mostly within the last decade, due in part to problems associated with waste-disposal sites (e.g., Herzog and Morse, 1984; McGown and Radwan, 1975; Grisak and others, 1976). Fractures appear to be particularly prevalent in fine-grained basalt till and other deposits that have been overridden by ice (Connell, 1984; Grisak and Cherry, 1975), but fractures are not limited to fine-grained materials. Knutson (1971), for example, reports that a strong fissility is frequently developed in the sandy basalt till in the Midwest and New England. Moreover, fracture genesis may not be limited to the subglacial environment. Connell (1984) has summarized several mechanisms that may generate fractures in a variety of glacial environments.

Data in Tables 2 and 3 show that a well-connected fracture network can considerably elevate the hydraulic conductivities of otherwise low permeability materials. Sharp (1984) has described localized fracture-flow systems in pre-Illinoian till from Missouri where fractures yield sufficient water to meet domestic and some agricultural needs. Similar fracture systems are responsible for the good soil drainage found in some clay-rich tills and lacustrine sediments in parts of Alberta (Hendry, 1982). Fractures can produce strongly anisotropic permeability (Snow, 1969).

Grisak and Cherry (1975) also found fractured tills to be characterized by two specific storage values: intergranular specific storage ranges from $1 \times 10^{-2}$ to $9 \times 10^{-3}$ m$^{-1}$, whereas specific storage associated with the fracture network is on the order of $1 \times 10^{-5}$ m$^{-1}$. The distinction between the two types of specific storage became evident during water-level observations in a till confining bed overlying a sand and gravel aquifer (Fig. 5). During pumping, changes in total head are rapidly transmitted through the fractures, producing rapid responses in piezometers that intersect open fractures. On the other hand, piezometers screen in unfractured till blocks respond much more slowly, because water is released by the delayed process of intergranular consolidation (Grisak and Cherry, 1975). Interbedded lenses of sand and gravel probably produce a similar effect on specific storage.

Many glacial terrains, particularly in the north-central United States, exhibit strong weathering profiles that may extend to depths of 10 m or more. Because of the un lithified nature of the parent material, weathering changes and pedological structures can be difficult to recognize at depth (Follmer, 1984). Moreover, glacial sequences sometimes show the effects of more than one pedogenic episode. The effects may be superimposed on one particular stratigraphic level, or may be associated with different horizons, or both. Follmer (1984) emphasized the potential complexity of the weathering profile in glacial terrains, and the variable effect that this can have on ground-water flow and geochemistry, especially where the soil is developed on several glacial deposits.

Weathering results from a complex interaction of chemical
Glacial deposits

Figure 5. Schematic diagram showing water-level behavior typical of piezometers in fractured and unfractured till overlying a pumped aquifer (from Grisak and others, 1976).

and mechanical processes, the intensity of which varies both spatially and temporally. This interaction is reflected in the wide range of conductivity values associated with weathered glacial deposits (Table 2). Where direct comparisons have been made, however, weathered deposits tend to show greater conductivity than their unweathered counterparts (Herzog and Morse, 1984; Lloyd, 1983). Much of the increased hydraulic conductivity is probably due to the disaggregation of material produced by surficial mechanical weathering and to changes in soil structure due to pedogenesis and fracturing (Bouma, 1973). Some studies suggest that hydraulic conductivity decreases with depth in weathering profiles of till (Lloyd, 1983; Sharp, 1984). In cases where the translocation of clay is an important weathering process, claypans and other argillic horizons can significantly impede vertical conductivity and infiltration (Janson and Peters, 1967; Quigley and Ogunbadejo, 1976). Likewise, the clay-rich B-horizon of the Sangamon paleosol has been reported to behave as a low hydraulic conductivity layer in the glacial deposits of Illinois (Follmer, 1982).

Many glacial sequences are capped by a blanket of loess, derived by wind from rock flour deposited by meltwater in major outwash valleys. Loess consists chiefly of silt-sized grains of quartz and feldspar that typically have a very loose packing arrangement when unsaturated. Thus, porosity of unsaturated loess can be high, reaching 50 or 60 percent in some places. This condition might suggest that recharge rates should be significantly greater in areas mantled by thick loess deposits. However, this is not so. The high porosity of loess will collapse if saturated. Since the porosity of deposits in thick loess can still be measured as high, one could conclude that loess has never been saturated. Recharge is probable in thick loess areas only through prominent joints and root channels (S. N. Davis, personal communication, 1985).

Because loess is frequently at the surface, it is also a principal parent material of soils in glaciated regions. Infiltration tests indicate that weathering and pedogenesis significantly decrease the hydraulic conductivity of loess (Prill, 1977; Van Bavel and others, 1968). The cause of the decrease is probably due to several factors, including compaction, leaching of carbonates, and the filling of pores by clay minerals derived from the weathering of feldspar (Prill, 1977; Morrow, 1964).

Weathering may also affect the specific storage of glacial deposits. Many midwestern U.S. tills contain abundant fine-grained carbonates. Over time, these carbonates are leached from the till, resulting in losses as high as 50 percent of the original volume. Specific storage is probably reduced as volume is lost
and consolidation occurs. Sharp (1984) has suggested that time-dependent consolidation may be a factor in comparatively low specific storage values for deeply weathered till in Missouri.

Irregularly shaped bodies of sand and gravel are commonly present in most glacial sequences and range in thickness from less than a centimeter to many meters. Where laterally extensive, these bodies can transmit significant quantities of water (Lloyd, 1983). More commonly, they are discontinuous, discrete bodies that act as local high hydraulic conductivity zones amidst materials of lower hydraulic conductivity. Such deposits create a higher bulk hydraulic conductivity because their effects are beyond the scale of that measured in laboratory samples. Like fractures, the presence, size, and frequency of high-conductivity lenses play a critical role in the ability of fine-grained glacial deposits to yield water for small users, as well as in attempts to isolate toxic wastes from the general hydrogeologic environment (Norris, 1961; Engquist and others, 1978; Gordon and Huebner, 1983).

A particularly striking example of secondary hydraulic conductivity comes from southeastern Sweden, where permeable zones have developed through weathering processes in fissile layers in sandy basal till and in thin lenses of outwash (Knutson, 1971). These permeable zones control the flow of water to a majority of springs and domestic wells that were developed in deposits of both the subglacial and supraglacial land systems. The velocities are sufficiently high to cause significant ground-water erosion, marked by cones of sand and gravel at their outlets (Knutson, 1971).

The importance of secondary hydraulic conductivity becomes quite apparent in a comparison of average linear ground-water velocities (Table 4). These data suggest that ground-water flow in fine-grained glacial deposits is effectively controlled by the secondary hydraulic conductivity. The extremely low average ground-water velocities of the till matrix imply that the intergranular porewater at depth should be very old. Desaulniers and others (1981) obtained radiocarbon dates from lacustrine clays in southern Ontario that indicate ground-water ages in excess of 8 ka. Ground-water ages of 9 to 10 ka have also been found in clayey till from two sites near Superior, Wisconsin (Bradbury and others, 1985). Ground-water in the underlying sandstone bedrock near these sites has been dated at 16 ka. Similar dates are probably typical of porewater at depth from other clay-rich glacial deposits, suggesting that such water may have originated at the time the till was deposited (Grisk and others, 1976). On the other hand, ground water within the upper few meters of these deposits, and within fractures, shows modern oxygen isotope ratios and tritium values, indicative of the much greater velocities in weathered and fractured zones (Grisk and others, 1976; Bradbury and others, 1985; Desaulniers and others, 1981).

**Hydrogeochemical Properties**

Because the chemical composition of ground-water in glacial deposits can be quite variable, generalizations are difficult. The hydrogeochemistry at any given site is a function of several related variables, including lithology, depth, hydraulic conductivity, residence time, and weathering. Ground water within basal till typically shows higher total dissolved solids than in other adjacent deposits (Eyles and Sladen, 1981; Lloyd, 1983; Grisk and others, 1976). This hydrogeochemistry is thought to be due to the relatively low permeability that enhances the slow movement of ground water from the matrix into fractures and inhibits
oxidation of pyrite. Pyritic shales and carbonates are both important constituents of many tills; thus, many pore waters are of the calcium-sulphate or calcium-bicarbonate-sulphate facies (Spears and Reeves, 1975; Rozkowski, 1967; Lloyd, 1983; Sharp, 1984). Ground water from till in the midwestern U.S. and in Canada is commonly super-saturated with respect to calcite and dolomite (Grisak and others, 1976). Small, but widespread amounts of chloride in ground water from till of the Interior Plains Region have been ascribed both to local concentrations of chloride salts in incorporated shale and to the upward movement of brines from bedrock due to ice loading (Cherry, 1972; Grisak and others, 1976). High iron contents have occasionally been reported in ground water from older, deeply weathered till (Drew and Sharp, 1981; Gilkeson and others, 1977).

Grisak and others (1976) suggest that diffusion is the predominant transport process in deposits of low hydraulic conductivity. Where these materials are cut by fractures or other zones of relatively high ground water velocity, strong ionic gradients exist between the till blocks and the open fractures. The flux across these boundaries can be significant and may produce locally saline conditions in the fractures (Grisak and others, 1976). The ion exchange capacities of many clay-rich glacial deposits can provide an important measure of attenuation for contaminants emanating from waste disposal sites (Grisak and others, 1976). Finally, hydrogeochemical characteristics have provided significant information concerning recharge and the hydraulic relationships between glacial deposits and underlying bedrock aquifers in some areas (Walton, 1970; Sage and Lloyd, 1978; Lloyd, 1980).

Hydrostratigraphy

The degree of lithological heterogeneity is the major determinant affecting the hydrostratigraphy of glacial terrains. The most productive aquifers are associated with thick, widespread blankets of outwash that were deposited in front of advancing or retreating ice sheets (Fig. 3). In many places, this outwash filled sizable proglacial river valleys, commonly to depths of over 100 m. These buried valley aquifers tend to yield large volumes of ground water and may constitute the only significant source of ground water in many glaciated regions (Norris and White, 1961). The glacial stratigraphy in these valleys can be quite complex, however, especially where multiple advances or a fluctuating ice margin affected deposition (Norris and Spieler, 1966; Winter, 1973; Stephenson, 1967).

In many areas, much of this proglacial outwash is overlain by extensive sheets of basal till (Fig. 3). Fine-grained types commonly produce confined conditions in the underlying aquifers and can greatly impede recharge (Penman, 1950; Lloyd and others, 1981). Where the till is coarse-grained and relatively homogeneous over a wide area, small quantities of water might be yielded to domestic users and small farms (Olsson, 1974; Engquist and others, 1978). Moreover, abundant basal meltwater beneath temperate glaciers can produce longitudinally extensive deposits of sand and gravel within the till. The above observations suggest that, despite their typically low hydraulic conductivity, sequences of subglacial deposits have appreciable hydrogeologic continuity. Even where the till is predominantly fine-grained and is considered an aquitard, considerable recharge can occur through time to underlying aquifers by vertical movement (Norris, 1959; Walton, 1960; Lloyd, 1983).

In contrast, deposits of the supraglacial environment commonly exhibit great internal diversity and, except for some large ice-contact stratified deposits, have little lithologic continuity. Although many of the better-sorted deposits have high primary permeabilities, they are of small extent and discontinuous, and, thus, will act only as ground water reservoirs, not conduits. Therefore the supraglacial deposits might be expected to exhibit relatively low bulk permeability, characterized by many highly localized, poorly connected aquifers.

Little direct evidence is available to test these conclusions. In southern Sweden, the yields of wells and springs situated in drumlin terrane are about one to two orders of magnitude greater than those of wells located in hummocky moraine, which is presumably supraglacial (Knutson, 1971; Engquist and others, 1978). Knutson (1971) has attributed this difference to observable contrasts between the stratigraphic continuity of the two types of terrane, with some of the basal lithologies being traceable for several kilometers. However, many of the supraglacial deposits are rarely greater than a few meters in extent. Tracer experiments conducted by Knutson (1971) in both kinds of terrane also suggest greater hydraulic continuity in the subglacial deposits.

CONCLUSIONS

Glacial deposits in North America are primarily Quaternary in age, cover about 13 million km², and constitute both a sediment source for ground water and, increasingly, a sink for waste disposal. The term "glacial deposits" includes:

- Till: sediment deposited directly by glacier ice without significant sorting;
- Glaciofluvial: sediments deposited by streams in association with glacier ice;
- Glaciolacustrine: lake sediments deposited in association with glacial activity; and
- Loess: not strictly a glacial deposit but often present in a glacial landscape.

All glacial deposits comprise silt, sand, or sand and gravel in addition to clay fractions and cobble/boulder fractions.

Hydrogeologic aspects of glacial deposits have not been overly emphasized to date in North American geological research. This oversight has developed because large-volume water supplies frequently have been pumped from bedrock aquifers that have received most study. In more recent years, as practices developed to utilize glacial deposits for waste disposal and increasingly for smaller-scale water supplies, the paucity of information on relationships between glacial geology and ground-water occurrence and movement has been apparent. Programs are being developed to produce quantitative information on sediment, hydraulic, and index properties of glacial deposits.

Continently glaciated areas are of major concern when
researching relationships between ground water and geology. However, whether in alpine or continental glaciated terrains, the most characteristic geologic feature is the diversity in lithology, both laterally and vertically. Definition of the three-dimensional configuration of materials that have high values of hydraulic conductivity is one of the major challenges facing a glacial-deposit stratigrapher.

The character of glacial sediments is a function of (1) lithology and geochemical properties at the sediment source; (2) the nature and distance of sediment transport; and (3) the mode of sediment deposition. In a given geographic area, differences in till and other glacial sediments may be the result of single or several glacial episodes. Thus, aquifer systems are frequently of more concern than individual aquifers or aquitards.

A knowledge of sedimentary environments in the glacial setting is essential to interpretation of the hydrogeology of glacial terrains. Ground-water studies should include information on vertical and horizontal distribution and hydraulic characteristics of sediments in a glacial landscape. Traditional mapping of glacial deposits has often not included hydrogeologic aspects. New mapping approaches address the issue of heterogeneity and complexity of glacial deposits as related to hydrogeology. These mapping techniques include “stack mapping” and land-systems mapping.

Glacial deposits are grouped into two general hydraulic categories: (1) those that transmit ground water readily, such as outwash and ice-contact stratified deposits; and (2) those that have low hydraulic conductivity, such as till. Complicating transmissive properties, especially of number 2 above, is the presence of fractures. The concept that fractures are common in many unconsolidated glacial deposits has received recent emphasis because of interest in contaminant movement through glacial deposits.

The most widely reported aquifer characteristic of glacial deposits is hydraulic conductivity. The method of evaluating this hydraulic property must be carefully selected. The hydraulic properties of glacial deposits show a systematic variation related to both depositional environment and postdepositional modification.

The chemical composition and age of ground water in glacial deposits are frequently quite variable over small distances. Ground water in fine-grained deposits, such as basal till, generally contains higher total dissolved solids and is older than ground water in coarse-grained materials and fractures that have smaller residence times for the water. The sometimes extreme variability in chemical composition of glacial-deposit ground water makes generalizations exceedingly difficult. This condition is especially true in areas that received multiple glaciations, especially when each advance was from a different source.

Innumerable opportunities for research exist for the person interested in hydrogeology or hydrogeochemistry of glacial deposits. A few of these opportunities include:

1. Development of new generations of vertical variability mapping techniques that emphasize center-of-gravity of high or low hydraulic conductivity zones;
2. Comparison of natural ground-water flow (time-independent) versus aquifer system flow (time-dependent) characteristics;
3. Vadose-zone geologic characteristics in glaciated areas as they affect contaminant distribution and movement or ground-water recharge; and
4. Hydrogeochemical characteristics of naturally occurring ground water in glacial deposits as a mechanism in site selection for hazardous-waste disposal. Brackish ground water in glacial deposits does occur in some portions of the Interior Plains of Canada and the United States. The origin of sulfate as the dominant anion is not known.

The importance of the hydrogeology of glacial deposits in the northern U.S. and in Canada is in contrast to the paucity of data that quantitatively define this geologic environment. This is a paradox in an age where ground-water quality is almost a household concern. Glaciated portions of North America include many of the large population centers, and in many of these population centers, glacial deposits serve as both water supply and waste-disposal medium. Many opportunities exist for increased research, which the authors hope will lead to better understanding of the hydraulic and geochemical characteristics of glacial deposits.

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