Integrating 3-D Facies Analysis of Glacial Aquifer Systems with Ground-water Flow Models: Examples from New England and the Great Lakes Region, USA

Stone, B.D., J.R. Stone, J.P. Masterson, and D.W. O'Leary
U.S. Geological Survey; E-Mail: Byron Stone at bdstone@usgs.gov

Modern ground-water flow models, geotechnical studies, and science-based land-use planning require knowledge of the distribution of surficial earth materials from land surface to the top of bedrock (e.g., Masterson and others, 1997a,). To be useful, modern geologic maps must portray such information three dimensionally in a way that is consistent with the regional stratigraphic framework, geotechnical classifications, and the most recent understanding of geologic depositional processes (Masterson and others, 1997b, Central Great Lakes Geologic Mapping Coalition, 1999). The evolution of 3-D geologic maps of glacial meltwater deposits demonstrates new 3-D mapping and analytic techniques now available for these studies in the desktop computer environment.

The highly productive glacial aquifers in the valleys and lowlands of the northern U.S. are composed of ice-channel, glaciofluvial, glaciolacustrine, and glaciomarine deposits, which traditionally have been differentiated as lithostratigraphic formations (e.g., Willman and Frye, 1970; Lineback and others, 1983; Stone and others, 2002). Within these formation-rank units, informal allostratigraphic units comprising numerous glacial lakes and outwash systems can be distinguished (Stone and others, 2002; U.S. Geological Survey, 2001; Stone and others, in press). These individual lake and stream deposits are further related to ice-margin retreat positions in the relative stratigraphy of ice-sheet recession in various depositional basins. Detailed geologic maps (1:24,000 scale) permit precise mapping of meltwater sedimentary units within each glacial lake or valley outwash system (Jahns, 1941 and 1953; Koteff, 1966). These units, known as *morphosequences* (Koteff and Pessl, 1981), are the smallest mappable stratigraphic units on detailed geologic maps.

Morphosequences are bodies of stratified meltwater sediments that are contained in a continuum of landforms, grading from ice-contact forms (eskers, kames) to non-ice-contact forms (flat valley terrace, delta plains), that were deposited simultaneously at and beyond the margin of a glacier, and graded to a specific base level. Morphosequences each consist of a proximal part (head) deposited within or near the ice margin, and a distal part deposited farther away from the ice margin. Both grain size and ice-melt collapse deformation of beds decreases from the proximal to the distal part of each morphosequence. The head of each morphosequence is either ice marginal (ice contact) or near ice marginal. Ice-marginal morphosequences were deposited in contact with the ice margin. The heads of many ice-marginal morphosequences extended well up into the ice margin in channels and tunnels; melting of adjacent and subjacent ice caused the collapse of these headward sediments to lower positions where they commonly were buried by later sediments. Near-ice-marginal morphosequences were deposited short distances in front of the ice margin, separated from it by valley segments too steep for deposition. The surface altitude of fluvial sediments in each morphosequence was controlled by a specific base level, either a glacial-lake water plane or a valley knickpoint. Few morphosequences extend distally more than 10 km, and most are less than 2 km in length. In any one basin, individual morphosequences were deposited sequentially as the ice margin retreated systematically northward. Consequently, in many places the distal, finer grained facies of a younger morphosequence stratigraphically overlies the proximal, coarse-grained facies of a preceding morphosequence.

Six original types of morphosequences diagrammed by Koteff and Pessl (1981) are recognized across the northern U.S. Lacustrine-fan and marine-fan types are known from the northeastern U.S. (Stone and others, in press). Examples of three new types of morphosequences, deposited within holes and channels in glacial ice, are now known. Figure 1 presents these ten types of morphosequences relative to proximal-to-distal and fluvial-to-lake/marine depositional environments of the original classification. The names of these deposits have been modified (Stone and Stone, in press) from the original terminology of Koteff and Pessl (1981) to emphasize the descriptive features and the depositional environment of each morphosequence type.

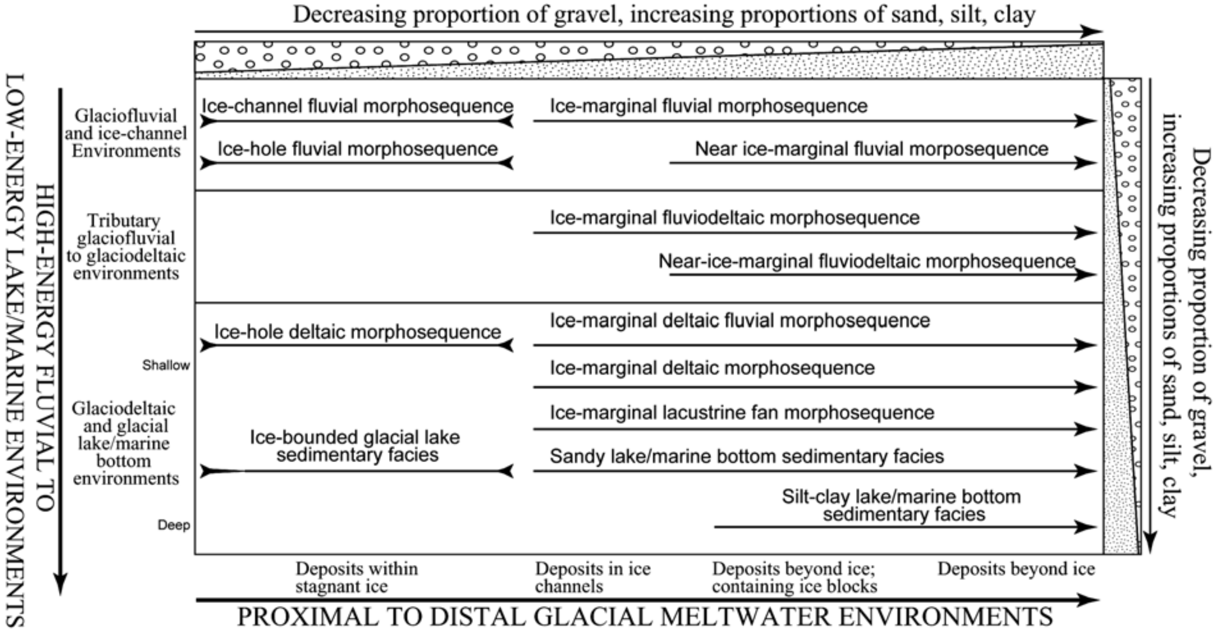


Figure 1. Relationships of ten types of meltwater morphosequences to proximal-to-distal glacial meltwater environments, and high-energy fluvial to low-energy glacial lake/marine environments. Trends in the varying proportion of gravel, sand, silt, and clay in these deposits are shown schematically.

Within the continuum of landforms, each morphosequence contains an assemblage of coarse- to fine grained *sedimentary facies* that were deposited contemporaneously. A meltwater *sedimentary facies* is a body of sediment that contains strata of similar texture and structure, and which is differentiable from other bodies of sediment possessing different lithic characteristics. Glacial meltwater sedimentary facies are combined either in facies assemblages within morphosequences, or are present as single mappable bodies of sediment in the distal parts of basins (Figure 2). Morphosequences typically consist of combinations of downstream-fining glaciofluvial and glaciodeltaic facies, which are related to specific environments of deposition along the path of meltwater flow from ice-proximal to distal environments (Figure 1). Through comparative studies of modern active environments (e.g., Boothroyd and Ashley, 1975; Gustafson and Boothroyd, 1987), these descriptive facies may be related to depositional facies within the stratigraphic framework of Pleistocene deposits (Stone and Force, 1982; Stone and others, 2002; Stone and others, in press). Recent mapping studies demonstrate how deep exposures, boreholes, geophysical surveys, and water-well records are used to subdivide morphosequences into a series of related sedimentary facies (U.S. Geological Survey, 2001).

The following section on *Sedimentary Facies in Glacial Meltwater Deposits* explains and illustrates (with diagrams) the 11 sedimentary facies (shown on Figure 2) that are recognized within the meltwater deposits of the region (modified from Stone and others, in press). Facies characteristics are distinct enough that these material units may be used as hydrostratigraphic facies in regional and local ground-water flow models (e.g., Anderson, 1989). Representative hydraulic conductivities, based on pump tests, infiltration tests, and contaminant plume flow velocities from locales with well documented 3-D stratigraphic control, are presented and highlighted (italicized) in this section.

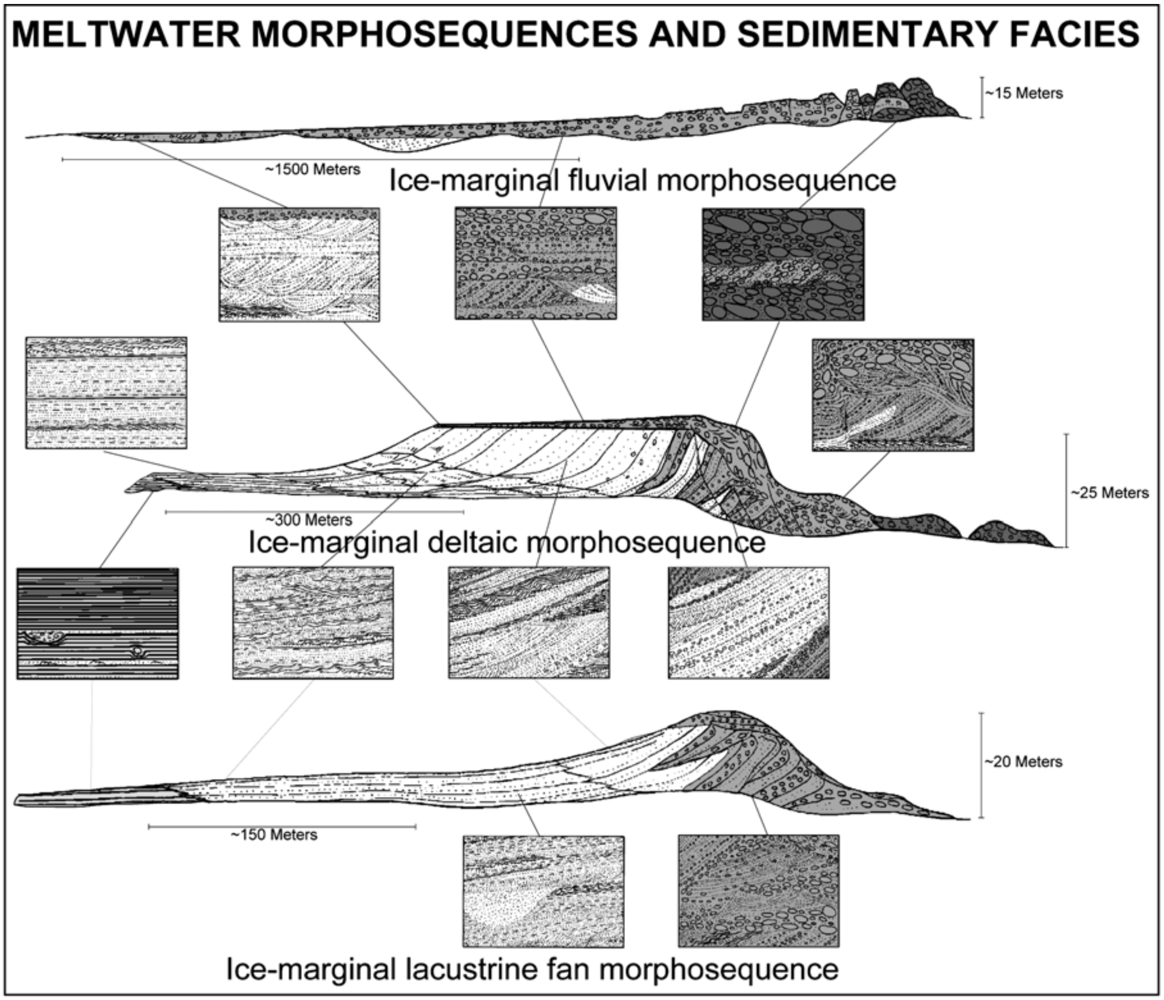
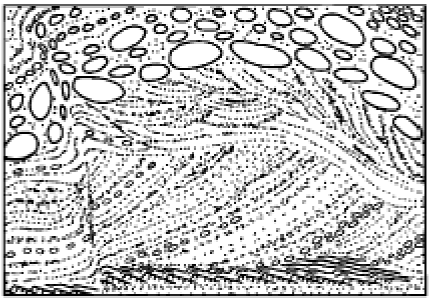


Figure 2. Assemblages of meltwater sedimentary facies within selected types of morphosequences (modified from Stone and others, in press). See section below on *Sedimentary Facies in Glacial Meltwater Deposits* for a detailed description of the 11 sedimentary facies.

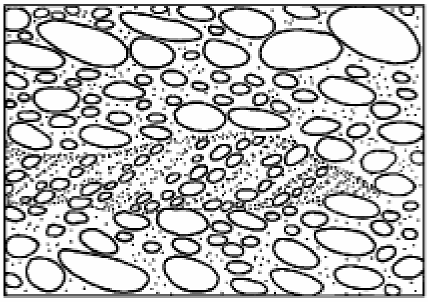
SEDIMENTARY FACIES IN GLACIAL MELTWATER DEPOSITS

GLACIOFLUVIAL SEDIMENTARY FACIES



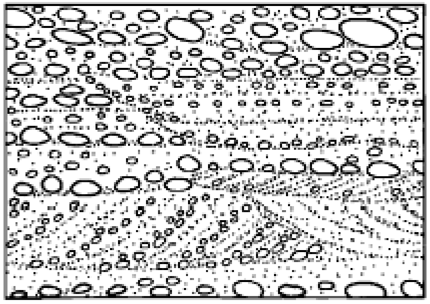
Sand and Gravel Ice-Channel Glaciofluvial Facies

Pebble-cobble gravel beds, massive planar bedded, planar-tabular crossbedded
Interbedded medium-coarse sand, planar bedded, planar-tabular and trough crossbedded, ripple laminated
Minor sets of silt and clay laminae
Three to 30 m total thickness
Horizontal hydraulic conductivity 88 m/day,
Ratio of horizontal to vertical conductivity 3:1
In ice-contact esker and ice-channel deposits



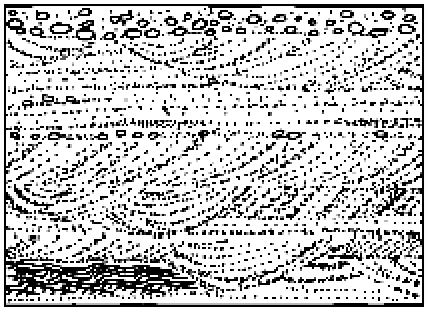
Coarse Gravel Glaciofluvial Facies

Cobble-boulder gravel beds, coarse sand matrix, massive planar bedded, planar-tabular crossbedded
Minor interbedded medium-coarse sand beds, planar-tabular and trough crossbedded, ripple laminated
No silt or clay beds
Two to 15 m total thickness
Horizontal hydraulic conductivity 106 m/day,
Ratio of horizontal to vertical conductivity 3:1
At ice-marginal head of morphosequences



Sand and Gravel Glaciofluvial Facies

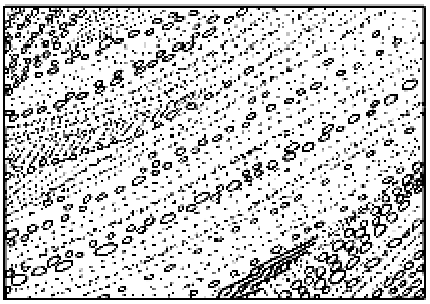
Pebble-cobble gravel beds, massive planar bedded, planar-tabular and trough crossbedded
Interbedded medium-coarse sand beds, planar-tabular and trough crossbedded, ripple laminated
Minor sets of silt laminae, minor clay
One to 15 m total thickness
Horizontal hydraulic conductivity 88 m/day,
Ratio of horizontal to vertical conductivity 3:1
In outwash deposits and as delta topset beds



Coarse Pebbly Sand Glaciofluvial Facies

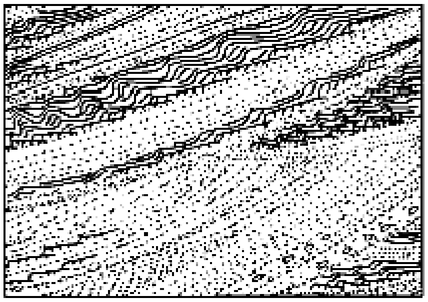
Coarse pebbly sand beds, massive planar bedded, planar-tabular and trough crossbedded
Interbedded pebble gravel beds, and medium-coarse sand beds, planar bedded and ripple laminated
Minor sets of silt laminae, minor clay
One-half to 8 m total thickness
Horizontal hydraulic conductivity 73 m/day,
Ratio of horizontal to vertical conductivity 3:1
In distal outwash or delta topset deposits

\GLACIODELTAIC SEDIMENTARY FACIES



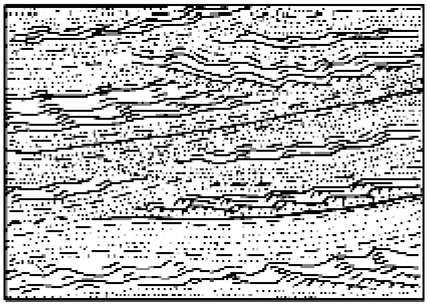
Sand and Gravel Glaciodeltaic Foreset Facies

Pebble-cobble gravel in planar-tabular and trough foreset beds, parallel bedded, minor openwork gravel
Interbedded fine-coarse sand in trough foreset beds, parallel bedded, planar-tabular crossbedded, and ripple laminated
Some sets of silt laminae, minor clay, minor flowtills
Two to 30 m total thickness
Horizontal hydraulic conductivity 85 m/day,
Ratio of horizontal to vertical conductivity 3:1
In proximal parts of deltaic deposits



Sandy Glaciodeltaic Foreset Facies

Fine-coarse sand in planar-tabular and trough foreset beds, parallel bedded, ripple laminated
Interbedded fine pebble gravel in planar-tabular foreset beds, parallel bedded
Interbedded sets of draped silt and minor clay laminae
Two to 30 m total thickness
Horizontal hydraulic conductivity 61-45 m/day,
Ratio of horizontal to vertical conductivity 5-10:1
In central and distal parts of deltaic deposits



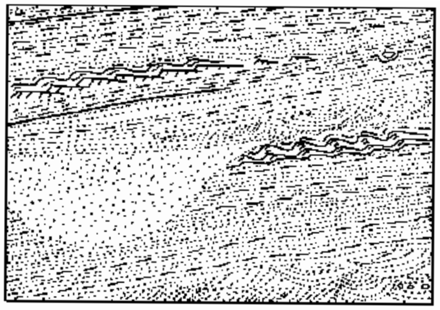
Fine Sand Glaciodeltaic Bottomset Facies

Fine-medium sand in planar and trough bottomset beds, parallel bedded, ripple laminated
Interbedded sets of draped silt and minor clay laminae
Two to 10 m total thickness
Horizontal hydraulic conductivity 45-21 m/day,
Ratio of horizontal to vertical conductivity 10-30:1
In distal parts of deltaic deposits

GLACIAL LAKE/MARINE-BOTTOM SEDIMENTARY FACIES

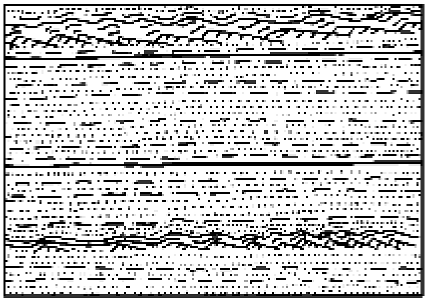
Sand and Gravel Glaciolacustrine Fan Facies

Pebble-cobble gravel, coarse sand, and minor flowtill in planar-tabular and trough foreset beds, parallel bedded, planar-tabular crossbedded
Local compact till at top of section
Minor interbedded fine-medium sand, parallel bedded, ripple laminated
Minor interbedded sets of draped silt and minor clay laminae
Two to 20 m total thickness
Horizontal hydraulic conductivity 85 m/day,
Ratio of horizontal to vertical conductivity 3:1
In proximal parts of lacustrine/marine fan deposits



Sand-Silt Glaciolacustrine Fan Facies

Fine-medium sand in planar and trough bottomset beds, parallel bedded, ripple laminated
Interbedded sets of draped silt and minor clay laminae
Two to 20 m total thickness
Horizontal hydraulic conductivity 45 m/day,
Ratio of horizontal to vertical conductivity 10:1
In distal parts of lacustrine/marine fan deposits



Sandy Glacial Lake or Marine Bottom Facies

Fine sand-silt, irregularly spaced parallel laminae, ripple laminated
Interbedded sets of silt and clay laminae
Marine facies contains massive silt-clay
10 to 60 m total thickness
Horizontal hydraulic conductivity 9 m/day,
Ratio of horizontal to vertical conductivity 100:1
In lake-bottom deposits proximal to deltaic deposits

Silt-Clay Glacial Lake-Bottom Facies

Silt-fine sand and clay in irregularly spaced parallel laminae or regularly spaced varve couplets, minor ripple laminated
Minor interbedded fine sand, parallel laminated, ripple laminated
2 to 60 m total thickness
Horizontal hydraulic conductivity 3 m/day,
Ratio of horizontal to vertical conductivity 100:1
In distal lake-bottom deposits

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