SLOW-LOGGING SUBTLE SEQUENCES

the gamma-ray log character of glacigenic and other unconsolidated sedimentary sequences

Indiana Geological Survey
Special Report 65

INDIANA UNIVERSITY
INDIANA GEOLOGICAL SURVEY

Indiana Geological Survey Staff

Administration (812) 855-5067
John C. Steinmetz, Director and State Geologist
John R. Hill, Associate Director for Administration
John A. Rupp, Assistant Director for Research
Amanda Wilson, Administrative Secretary and Licensing Coordinator
Charlotte A. Smith, Business Manager
Helen Stephenson, Financial Records Associate

Center for Geospatial Data Analysis (CGDA) (812) 855-7428
Sally L. Letsinger, Hydrogeologist and Section Head
Chris Dintaman, Geologist and GIS Specialist
John Haddan, Field Laboratory Specialist
Denver Harper, Geologist and GIS Analyist
Kevin M. Spindler, Hydrogeologic Modeler
A. Chris Walls, Geographer and GIS Specialist

Coal and Industrial Minerals Section (812) 855-2687
Nelson R. Shaffer, Geologist and Section Head
Agnieszka Drobniak, Coal Geologist
Amy Foster, Secretary
Walter A. Hasenmueller, Geologist
Christina James, Geological Technician
Erik P. Kvale, Sedimentologist
Maria Mastalerz, Coal Geologist
Rebecca Meyer, GIS/Database Analyst
Todd A. Thompson, Sedimentologist
Licia A. Weber, Geologist
Amzie Wenning, Geological Technician

Education Extension (812) 855-1337
Jefferson R. Kirby, Education Coordinator and Web Manager

Environmental Geology Section (812) 855-7428
Nancy R. Hasenmueller, Environmental Geologist and Section Head
N. K. Bleuer, Glacial Geologist
Steven E. Brown, Glacial Geologist
Marni Dickson, Research Geologist
Jennifer Olejnik, Geologist
Robin F. Rupp, Geologist

Geochemistry Section (812) 855-2687
John B. Comer, Geochemist and Section Head
Tracy D. Branam, Geochemist
Margaret V. Ennis, Geochemist
Amy Foster, Secretary
Ronald T. Smith, Geochemist

Photography and Imaging Section (812) 855-1370
Barbara T. Hill, Section Head
John M. Day, Photographic Specialist
Donna M. Webb, Secretary

Physical Facilities and Field Services Section (812) 855-3596
Samuel S. Frushour, Section Head
Jay E. Arnold, Field Services Foreman
Drew Packman, Field Services
Donna M. Webb, Secretary

Technology Transfer Section (812) 855-3951
Richard T. Hill, Section Head
Deborah A. DeChurch, Editor
Janis Fox, Sales Office Manager
Kathleen Griffin, Network Support Specialist
David Held, Cartographic Specialist
Paul N. Irwin, GIS/Database Analyst
Karen K. Like, Cartographic Specialist
Wei Qin, Database Administrator
Kathryn R. Shaffer, Mineral Statistician
Kimberly H. Sowder, Cartographic Coordinator
Donna M. Webb, Secretary

Subsurface Geology Section (812) 855-5412
John A. Rupp, Geologist and Section Head
Sherry K. Cazee, Sample and Core Library Supervisor
Brian D. Keith, Petroleum Geologist
Premkrishnan Radhakrishnan, GIS Specialist
Wilfrido Solano-Acosta, Research Geologist
Renee Stubenrauch, GIS Technician
Charles W. Zuppann, Petroleum Geologist

Research Affiliates
Lewis M. Brown
John B. Droste
Henry H. Gray
Edwin J. Hartke
Norman C. Hester
Noel C. Krothe
Greg A. Olyphant
Richard L. Powell
Carl B. Rexroad

For sale by Publication Sales, Indiana Geological Survey,
Indiana University, 611 N. Walnut Grove, Bloomington, Indiana 47405
phone: 812 855-7636
e-mail: IGSinfo@indiana.edu
Web site: http://igs.indiana.edu

SLOW LOGGING SUBTLE SEQUENCES

the gamma-ray log character of glacigenic
and other unconsolidated sedimentary sequences

by N. K. Bleuer

Indiana University
Indiana Geological Survey Special Report 65

BLOOMINGTON, INDIANA: 2004

AUTHOR

N. K. Bleuer is a glacial geologist in the
Environmental Geology Section of the Indiana Geological Survey.

cover: The basic glacial marker sequence—part of the log representation of the glacial "advance sequence" of prograding glacial "offlap."

CONTENTS

Illustrations

CONTENTS continued on next page

Tables

Appendices

ABSTRACT

Natural gamma-ray logging is the most versatile downhole geophysical method available for use in glacial and related terrain. Log profiles illustrate lithologic variation. They illustrate vertical sequences of glacigenic deposition as well as regionally recognizable till-stratigraphic units. Expanded log profiles run at very slow speeds can illustrate cyclic variations in thick loess and in soil and soil-landscape relations.

Recognition of depositional-sequence packages can provide an ultimate basis for a natural "genetic stratigraphic" classification, a classification emphasizing whole events at all scales. Such log-based packages can provide the framework and the predictive models necessary for both regional and site-specific applications. These models can provide an objective understanding of variation that is critical to both engineering and hydrogeologic concerns.

INTRODUCTION

Downhole geophysical logs are highly visual and objective representations of subsurface materials. They facilitate elementary correlation of strata and illustrate continuous vertical profiles of lithologic variation. When run at appropriately slow speed and large scale, natural gamma-ray logs of glacigenic sediments and other unconsolidated materials illustrate stratigraphic marker beds, large-scale vertical sequences, and internal sequence components.

Realistic approaches to glacial geologic mapping and to the appraisal of many related environmental concerns lie in glacial-terrain models based upon a knowledge of whole depositional-system geometries, or "megasequences"—the records of whole, *genetic* processes of glaciation (fig. 1).

Continuous log-defined profiles of vertical lithologic change are the fundamental basis of such a megasequence approach. This report contains examples of a wide variety of log-defined vertical sequences representative of Pleistocene and recent unconsolidated materials of Indiana. Most are examples of glacial and related sequences, but examples of nonglacial and man-made sequences are included as well.

SEQUENCES, VARIABILITY, AND THE LOG BASIS

In the subsurface exploration of glacial sediments, recognition of vertical sequences—continuous vertical profiles of lithologic change—is the only effective means of identifying and packaging natural, genetic associations of sediments amidst extreme hole-to-hole variation. This documentation of variability within the body of glacial sediments—and the recognition of basinwide, systematic patterns of change within—are relatively frontier concepts in geologic study.

Considered on this basis, glacial deposits are not necessarily more complex than those of other sedimentary environments—they're just different.

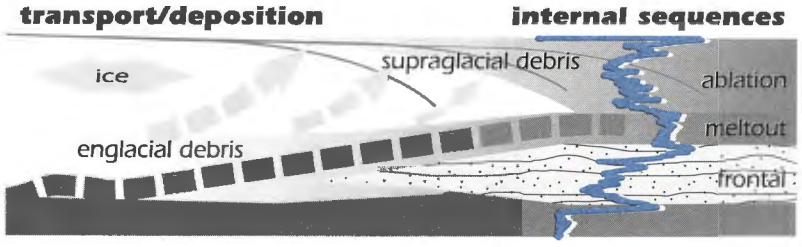


Figure 1. *Origin, depositional sequence, and ultimate log form of a simple glacial megasequence. The larger megasequence (a complete genetic, depositional sequence) is composed of component internal sequences. These include a surface ablation sequence, composed of modern soil on flow tills and other sediments; the subglacial meltout sequence, massive basal till, possibly a regionally traceable stratigraphic unit with incorporated debris at base; and a frontal sequence of flowed tills, and lake and stream sediments.*

They contain some vertical sequences not present in the rock record familiar to most geologists. Most sequences contain missing records, and whole or partial sequences may be stacked repeatedly in the manner of cyclothems. Full depositional sequence packages may be far smaller.

A sequence-based approach has not been applied widely to midwestern glacigenic sediments. Partly this may be due to the common, albeit incorrect, assumption that glacial deposits are a heterogeneous morass of sediment types. This may be so in part by default, because most interest in unconsolidated deposits is found in fields related to ground water and engineering, disconnected from both glacial geologic ideas and the downhole-logging methods that are the basis of sequence packaging. But it is primarily due to tradition.

Traditional glacial geology

Glacial geologic studies in the Midwest pragmatically have relied upon surface morphology tied to stratigraphies derived from a few key exposures (typically inaccessible to the next generation) or control holes, augmented by what could be gleaned from water-well logs and sundry other subsurface records.

Material geometries commonly have been characterized through the guesswork of "counting down" correlations of presumed "key beds." These methods of correlation, whether applied to aquifers (granular beds within clay sequences) or ro old-time glacial geology (soil-defined stratigraphies), are based upon assumptions that all such markers are always present and complete in all vertical sections. Therefore, such beds are presumed to be so significant as to be notable in drilling or in sample studies, that they are always separated by other strata and are never stacked one upon another, and that they have great lateral continuity. These methods presuppose that simple correlations exist and that markers and the packages they separate cannot split: a subaqueous-fan channel cannot become multiple medial-distal fans (laterally and vertically). An upland soil, perhaps representing a continuum of multiple glacial-interglacial time spans, cannot become multiple stacked alluvial bottomland soils. None of these conditions can be assumed a priori.

Or, stratigraphies based upon till character have been defined through time-consuming laboratory analysis of samples tediously collected from surface exposures, soil cores, or rotary cuttings.

End products commonly have been accompanied by ponderously verbose core descriptions and opaque, all-inclusive map legends, and illustrated by cartoon diagram summaries.

Rock, time, and diachronic stratigraphies have been emphasized over natural, whole, genetic sequences of real materials. Rock stratigraphies encourage the separation of genetically continuous clastic progressions. Time stratigraphies cross time-transgressive rock boundaries. Diachronic stratigraphies appear to be an end run around the stratigraphic code (North American Commission on Stratigraphic Nomenclature, 1983), producing "event stratigraphies in disguise" (Clayton, 1999), promoting both cubbyholing of the material/time continuum and assumptions of event synchroneity. While such constructs are true to the strictly nongenetic precepts required of formal units by the code, they are not true to geologic reality and stultify further understanding.

Whole genetic sequences

Glacial deposits contain a physical record far too rich to be represented in traditional contexts. Instead, *both* sedimentologic and rock till-stratigraphic sequences that are present within glacial deposits beg to be recognized as such, ro be the foundation of genetic sequence-based geologic models. This is a return, without apologies, to a far simpler construct, similar to Chamberlin's concepts of the "second glacial epoch"—now the Wisconsin stage of glaciation—wherein a mass of deposits is directly representative of a glacial event (Chamberlin, 1883).

In modern terms, such a model is founded upon the recognition of vertical sequences of stratified sediments and the progressive change of depositional environment that the sequences record, and upon the three-dimensional mapping of these environments.

As a genetically interpreted package of materials representative of a depositional event, it is

effectively a "genetic stratigraphic sequence" (Galloway, 1989; Bleuer and Brown, 1999), an *informal* (not code-restricted) depositional-sequence concept applied to masses of individual log-defined vertical sequences.

The genetic stratigraphic sequence format can be applied to terrestrial glacial successions at all scales. The largest continental glacial packages (paleosol-bounded) equate with the largest marine packages (marine-flooding-unit–bounded)(Bleuer and Brown, 1999a). The internal terrestrial sequence packages (individual proglacial, subglacial, and supraglacial facies) equate with the internal facies of the shoaling-upward marine parasequence. With the addition of landscape, this is "glacial-terrain characterization" (Bleuer and Brown, 1999b). It is a construct that derives in part from the landmark "process-form model" concept (Clayton and Moran, 1974; Moran and others, 1980), and it is a form of the glacial "land-system" model that is dominated by the subsurface sequence (Eyles, 1983; Eyles and Clark, 1985; Eyles and others, 1985).

Such genetic-package models should be the foundation of glacial geologic mapping. They provide a norm for purposes of comparison and to suggest working hypotheses to guide future exploration and decision making.

The log basis

Downhole logs are the foundation of these models, providing concise graphic illustration of individual and mass vertical-sequence profiles. The single most useful and cost-effective log in glacial terrain is the natural gamma-ray log, one of the fundamental logs used in the study of the world's sedimentary basins.

Downhole logs are the basis for identifying vertical profiles of lithology (Cant, 1984; Miall, 1990) and for the regional mapping of facies geometry in sedimentary rocks—the foundation of modern basin analysis (Allen, 1975; Pirson, 1977; Selley, 1976, 1978a,b; Scholle and Spearing, 1982; Galloway and others, 1983; Cant, 1984; Serra, 1985).

Gamma-ray logs provide a highly visual and objective representation of the lithologic characteristics of subsurface materials (fig. 2; Appendix 1). They facilitate elementary correlation of strata and recognition of the subtlest vertical variation in those strata. Logs are a field-generated, immediately usable proxy for complex arrays of laboratory analyses. They can provide ready visual access to a large mass of vertical-sequence data. Logs provide an objective and permanent background record that can supplement the commonly inconsistent (and verbose and opaque) sample description process.

Perhaps most importantly, gamma-ray logs of glacigenic sediments exhibit vertical profiles of lithology, patterns characteristic of large-scale, mega-sequences and their internal sequence components (fig. 1) that are the primary foundation of the land-system model. Glacigenic sequences include examples of the same fluvial, deltaic, and subaqueous and subaerial fan environments that are well known and log-defined in nonglacial settings.

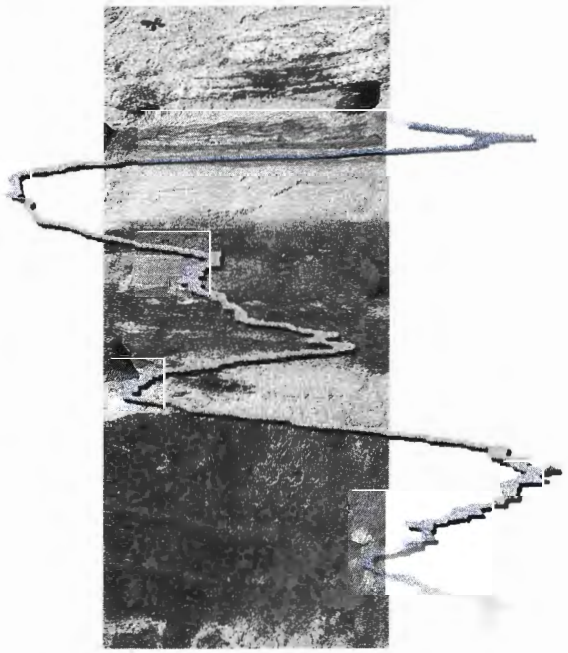


Figure 2. *A log example of a subsurface lake progression beneath Indiana's Lake Michigan rim is superposed on a photo of a similar sediment package exposed in Wisconsin's lake bluffs (selected from larger outcrop photo by S.E. Brown; lighter color = sand, darker color = clay). The natural gamma-ray log is the primary lithologic log applicable to glacial terrain and cased holes. It provides a graphic representation of continuous vertical change of grain size and some mineralogic characteristics.*

But in addition, glacigenic sequences may contain regional widespread till marker beds or packages of beds whose distinctive grain-size or mineralogic characteristics are represented by distinctive log form and (or) count rate. In this sense, the log *is* the fundamental "data" defining a till-based, rock-unit stratigraphy.

Logging history

Downhole logging of unconsolidated Pleistocene and recent materials has long been a component of site-specific engineering, ground-water, and environmental studies conducted by some consultants in some areas. But routine use in larger-scale exploration is localized at best.

Exceptions are found in states and provinces of the northern Great Plains, where various logging methods have been found useful in differentiating and tracing units (Christiansen, 1967; Rutter and Wyder, 1969; Dyke and others, 1972) and in providing a framework for environmental studies (Christiansen, 1970). Electrical methods are used routinely by water-well drillers in the northern Great Plains (referenced by many county geologic and hydrogeologic reports of the North Dakota Geological Survey). In Ontario, both glacigenic sequences and stratigraphic units are log defined in a variety of studies (Greenhouse and others, 1983; Eyles and others, 1985; Farvolden and others, 1985; Greenhouse and Pehme, 1986; Karrow and others, 1986). Stratigraphy and formation characteristics have been log-defined in northern Europe (Ehlers and Iwanoff, 1983), and the relationship between gamma-ray and SP-resistivity logs and formation characteristics has been examined within a large proglacial fan sequence in Denmark (Rasmussen and Bai, 1987).

In the lower Midwest, gamma-ray logging has been a component of the controlled drilling program in Illinois (for example, Reed, 1974, 1985), and in many U.S. Geological Survey ground-water studies (for example, Norris, 1972), including significant background data for studies in Indiana (Shedlock and others, 1994). Gamma-ray logging has been extended to river-bottom surveys (Reed and others, 1983) and to the stratigraphy of municipal solid waste (Montgomery and others, 1985), and its use is expanding in ground-water and engineering fields in general (for example, Farvolden and others, 1985; Senger, 1985; and Whitley, 1983).

Indiana Geological Survey logging program

Beginning in the mid-1970s, Indiana Geological Survey (IGS) seasonal logging/sampling programs have operated across the state, relying mostly upon a "holes-of-opportunity" approach made possible by the goodwill of water-well drilling contractors and environmental consultants as IGS staff follow their day-to-day operations (fig. 3).

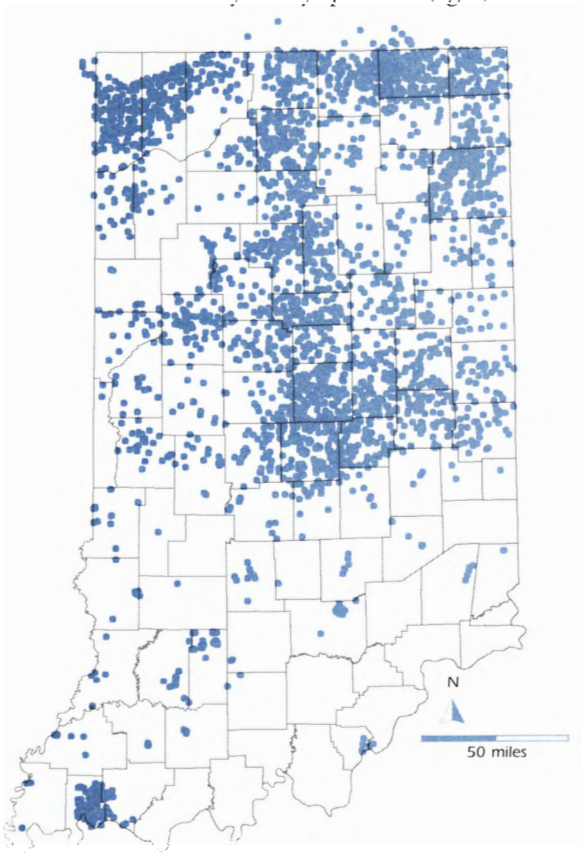


Figure 3. *Map showing the distribution of IGS gamma-ray logs and log/sample sets in Indiana and adjacent states through 2004.*

The IGS operates four MLS (Widco) units, all modified to provide digital as well as standard analog output. Scanned or digitized log plots and more recent digital logs may now be recalled and illustrated using ArcView and Adobe Illustrator.

Gamma-ray logging has become the fundamental background to the exploration of glacial materials,

whether for purposes of broad terrain mapping, ground-water sensitivity analysis, or specific environmental applications. Logging has had increasing use since 1976 beginning with studies of the Lafayette (Teays) valley fill (Bleuer, 1991; Bleuer and others, 1991). Since then, log profiles (over 4,000 collected through 2001) have provided a megasequence basis for IGS glacial-terrain analysis, including large basin-scale mapping (Bleuer and Melhorn, 1989; Fraser and Bleuer, 1991a, b) quadrangle mapping (Brown, 1994, 1996a, b; Brown and Thompson, 1995a, b), concentrated countywide environmental studies (Bleuer and Fraser, 1988, 1989; Bleuer and Woodfield, 1993; Fleming, 1993; Brown and others, 1993), a regional atlas (Brown and Bleuer, in preparation), background for local seismic risk analysis (Eggert and others, 1993), background for ground-water chemistry considerations (Hasenmueller and others, 1994, 2001) and ongoing STATEMAP products (Brown, 1994, 1996a, b, 2000; Bleuer and others, 2000).

Our first synthesis of full vertical sequence motifs derives from those Kankakee and Lake Michigan Basin studies (see Appendix 2). This work was expanded into the most robust attempts anywhere to use log-defined vertical sequences to define depositional-sequence-based glacial-geologic models and mapping units. These are the IGS Porter County and Lake County studies of the Lake Michigan rim area (Bleuer and Woodfield, 1993; Brown, 1994, 1996a, b). Individual representative vertical sequences and end-member-defined depositional sequences were outlined in detail in an effort to provide a genetic-sequence base for understanding local aquifer "sensitivity" and for providing a graphic means of illustrating institutional memory of many years of subsurface study in the region.

Logging methods

The many logging methods in use, individually or in combination, allow identification of lithology and a variety of properties of rock and its pore fluids.[1] However, the elementary bases for recognition of sedimentary sequences, that is, bed lithology and its variability, are provided by the most common logs, electric and natural gamma-ray.[2]

Gamma ray is the log of choice in midwestern glacial terrain. Gamma-ray logs can be used above or below water in uncased or cased holes (unlike electric logging), therefore a consistent log form can be maintained in regional studies involving a wide variety of hole types, sizes, and casings. No nuclear source is involved, which eliminates liability concerns.

Gamma-ray logs record photons of gamma radiation received by a detecting crystal over a time period. Gamma radiation is emitted during the radioactive decay of uranium and thorium and elements of their decay series and from the decay of the unstable isotope of potassium, ^{40}K.

In midwestern environments, the gamma log is a measure of shaliness in sedimentary rocks, reflecting radiation emitted by ^{40}K contained in illlite, which dominates the clay-mineral component of Paleozoic shales and Pleistocene tills (Appendix 1). Clays log high (that is, exhibit relatively higher gamma radiation), well-sorted granular materials log low, and quartz- or carbonate-rich materials log lowest.

---

[1]Logging methods are described in sources varying from general textbook summaries to manuals supplied by the logging industry such as Guyod (1966), Taylor and Dey (1985), Allen (1975), Keys and MacCary (1971), and Keys (1989), and log interpretation manuals from contractors such as Schlumberger, Dresser-Atlas, and BPB.

[2]Logging of glacial materials could use various methods commonly applied in petroleum and mineral exploration and rock-mechanics studies, depending upon mineralogic and hydrologic characteristics of the terrain (Commission on Standardization, 1981; Elkington and others, 1982; Hearst and Nelson, 1985). Various nuclear, sonic, magnetic susceptibility (Bristow and Bernius, 1984), conductivity, and dielectric tools (Timur and Toksoz, 1985), all capable of logging through casing, could provide information complementary to, but possibly largely redundant with respect to, that provided by natural gamma ray. Spectral gamma-ray logging would likely be a powerful tool in the discrimination of glacial deposits. But because of simplicity, cost, and availability in slimline tools, only gamma ray is in widespread use.

In addition, gamma-ray logging offers the possibility of directly logging surface exposures in situations where adequate contrast and intensity exist (for example, Ettenson and others, 1979; Chamberlain, 1984; Slatt and others, 1992; Aigner and others, 1995). (Our experience with surface-dragging a lead-shielded tool has produced generally disappoinring results, owing to uncontrollable surface irregularities of the logged faces.)

Exceptions or variations to this basic response include coarse granular beds containing significant amounts of potassium-rich granitic crystalline lithologies or, in extreme cases, uranium-rich black shale. In these cases, lithologically defined coarsening cycles may be identifiable within granular units in forms similar to those of western arcosic terrains. Exceptions include tills in which point-source erratic clasts of shale mimic grain-size variation, a situation not uncommon in basal zones of till units. And exceptions may include some buried soil materials whose well-developed, smectite-rich (illite-poor) horizons may not log as high as might be expected on the basis of grain size.

Slow logging

Gamma-ray logs can illustrate grain-size variations as small and subtle as horizons within surface soils, and as gross and obvious as major lithologic breaks within thick bedrock sections. However, the extremes of glacial-sequence and bedrock log responses require different balances of logging speed, time constant, and depth and count-rate scalings.

Petroleum industry norms for gamma-ray logging are inappropriate for most unconsolidated materials, or even for logging fine details of bedrock lithologies. Those norms include logging speeds greater than 20 ft/min, low time constants (TC), and analog outputs plotted to narrow 2.5-inch-wide rate scales for 150 to 200 API units (Table 1). (Gamma ray is typically part of a tool string including the electric tools which can be run at any speed.) Run at such fast speeds, a gamma-ray log is useful only for logging extreme differences of count rates of grossly differing rock types such as limestone and shale, relatively thick rock units, and deep holes.

	glacial terrain	loess terrain	petroleum industry
line speed ft/min	5–10	2.5	20+
time constant (TC) secs	5	10	3
horizontal scale API units/inch	5	5	80

Table 1. *Common logging-speed, time-constant, and output-scaling relationships.*

In contrast, slow logging speeds with relatively high TC are necessary for the definition of thin beds and subtle grain-size or mineralogic changes characteristic of unconsolidated sequences. Routine logging at the IGS uses a TC of 5 and a speed of 5 ft/min (with variations dependent upon hole diameter and casing type). Analog output is plotted at a depth scale of 10 ft/in and a rate scale of 100 counts/s (100 counts equals 75 API units) on a 5-inch-wide plot. Even slower logging speeds and repeat logs are necessary for the highest quality product. For instance, detailed logging of subtle loess cycles has utilized a TC of 10, a speed of 2.5 ft/min, with expanded depth and rate scales (see soil and loess cycles, fig. 20). Something less than this ideal is generally dictated by time, money, and diminished returns.

LOG FORMS

Simplest log forms

Log forms can be characterized in terms that describe the simplest shapes and orientations (figs. 4 and 5); most represent internal components of larger megasequences, while some may represent complete glacial-depositional megasequences in themselves.

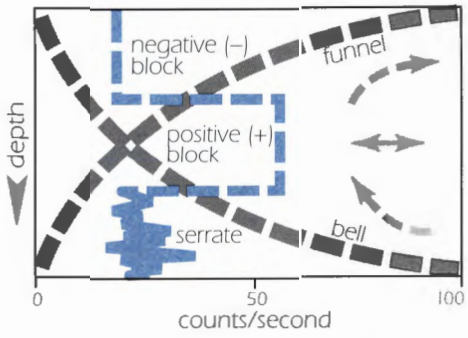


Figure 4. *General gamma-ray log forms. Funnel, bell, serrated, and positive and negative blocks are vertical-sequence characteristics; positive blocks are also till-stratigraphic unit characteristics. Arrows indicate coarsening-upward (bells) and fining-upward (funnels).*

The terms "bell" and "funnel" (fig. 4) describe gradational patterns of lithologic change (forms of "gradational evolutions" or "ramps" of the "electrosequences" of Serra, 1985). The most common interpretations of such patterns in the glacial examples that follow are as prograding or retrograd-

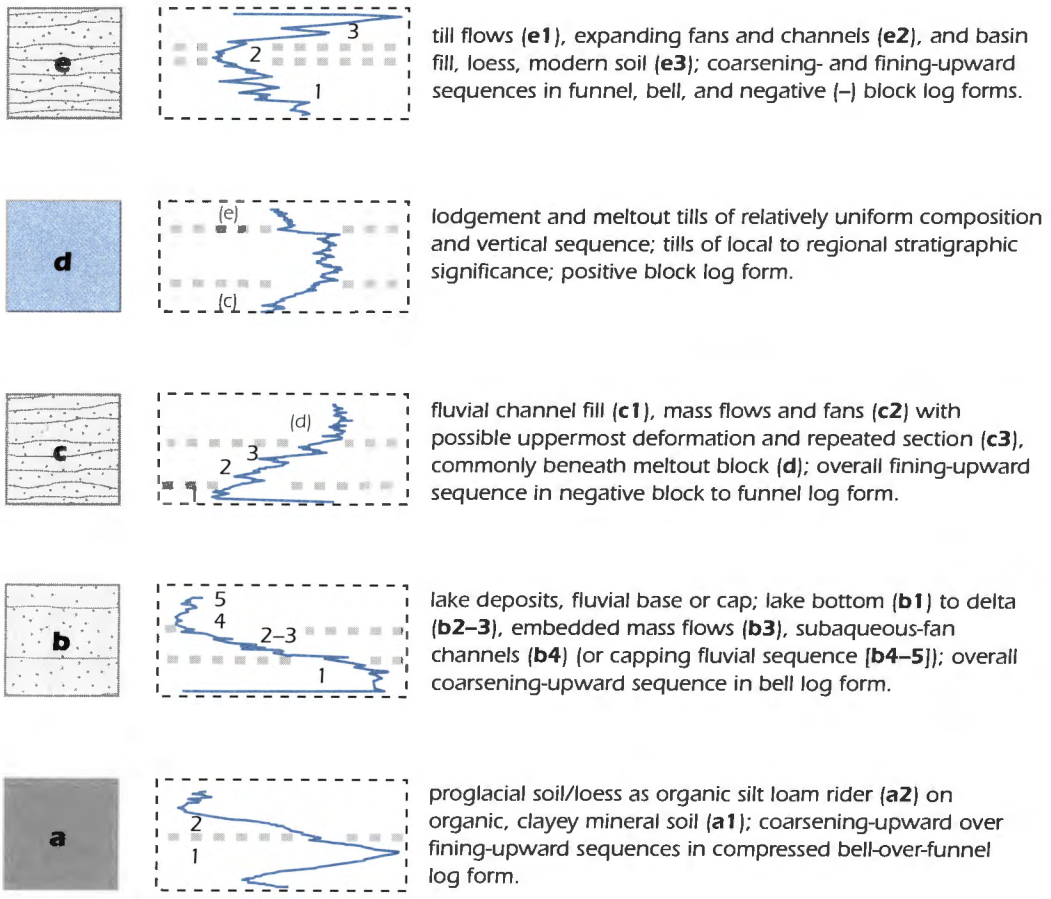


Figure 5. *Gamma-ray log forms—internal, position-dependent marker sequences and marker units common within the larger glacial megasequences (compare to earlier suggestions of overall motifs, Appendix 2). Horizontal counts/second are illustrated in the range of typical IGS glacial logs. Note that for gamma-ray logs, with baseline left, "bell" infers a coarsening-upward sequence, "funnel" a fining-upward sequence (the inverse of traditional usage for SP-log curves; see Serra, 1985).*

ing deltaic, subaerial and subaqueous fan, and true glacier-edge (sediment-gravity-flow) environments; these are the internal, position-dependent *marker sequences*.

"Positive block" patterns primarily describe sharp-based, lithologically homogeneous masses of till representative of subglacial meltout environments; these are the till-stratigraphic *marker units*. "Negative block" patterns primarily describe channel-fill environments in both subaqueous and subaerial settings.

The basic glacial megasequence

Glacial sequences include deposits representative of ice-frontal, subglacial, and supraglacial deposition. These sequences have in common an association with poorly sorted deposits derived primarily from melting ice, the so-called tills and till-like sediments (diamicts). Tills are commonly classified according to their presumed modes of origin with respect to glacial ice. Included are the broad categories of supraglacial tills, englacial or subglacial (basal) lodgement tills, and incorporation/deformation tills (fig. 1). The widespread, blanketing aspect of many such deposits is well known.

Glacigenic sequences also include (and are in some instances dominated by) stratified, sorted fluvial and lake sediments of a wide variety and extent. But even these sequences commonly contain till-like sediments, diamicts, deposited in environments less directly associated with melting ice. These include, for instance, sediment-gravity-flow and rainout deposits representative of glacial-lake and glacial-fluvial environments.

Together, these sequences are typically stacked in a sequential order within larger megasequences, and megasequences may be stacked one atop the other. However, as in the traditional cyclothems of the Paleozoic record, the simple larger sequence is commonly incomplete internally. An important variable is the relative position of the erosional horizon(s) representing the glacier base, at the base of or within the basal till mass, or both (the gamma-ray block, log form **d**, fig. 5b).

Glacial genetic-sequence mapping of such deposits depends upon recognizing individual vertical profiles of lithology from which the three-dimensional geometry of lithologic associations, or megasequences, can be conceptualized in a land-system model.

Glacial genetic-sequence mapping requires (1) a basis for recognizing individual marker sequences. For example, these may be genetic packages representing glacial advance: the subaqueous-fan to subaerial-fan package (equivalent to prograding offlap of marine sequences) or the proglacial-sediment to basal-till package. They may be packages representing glacial retreat (equivalent to retrograding onlap of marine sequences): the ablation-material to loess to postglacial-soil package. These define, *by position,* large, whole, genetic megasequences.

Such mapping further requires (2) a basis for recognizing till-stratigraphic marker beds. These define, *by association,* larger, whole genetic megasequences.

Basin examples—the glacial offlap sequence

The total stack of sedimentary deposits representing any single glacial event is most commonly a prograding sequence, one becoming more ice-proximal upward (fig. 1) (Brodzikoweski and van Loon, 1991, figs. 66-A, -B). This is true within glacial and glacial-marine basin-fill examples from the Paleozoic (fig. 6), and it is true within examples from the midwestern Pleistocene (fig. 7).

In notable examples from two continents, log-defined glacial sequences occur within oil-bearing Paleozoic Gondwana sediments. These are packaged within regional rock-stratigraphic contexts thousands of feet thick (Levell and others, 1988; Françá and Potter, 1991). Three primary facies associations are described by Levell and others (1988): (1) those of glacial and glacial-fluvial environments (sands to diamictites), (2) those of ice-marginal glacial-lake and meltwater-delta environments (sands, varved shales, dropstones), and (3) those of glacial-lake environments (shales to turbidite sandstones). These are dominantly prograding "offlap" sequences (fig. 6) (terminology of Levell and others, 1988; in bedding-relationship terminology of seismic stratigraphy, offlap is "the progressive offshore shingling of ... units within a conformable sequence...." [Miall, 1990, p. 342]).

Across Indiana (and presumably the glaciated Midwest), log-defined glacial sequences occur within ground-water-bearing Pleistocene sediments. These are packaged within regional rock-stratigraphic contexts up to 500 feet thick (aggregate of Wedron, Trafalgar, and Jessup Formations in Indiana). Packages represent multiple, stacked, stratigraphically defined events of the till-plain terrain of central Indiana or single multicomponent events characteristic of fan terrain of northern Indiana, or both (fig. 7). Facies associations include those of glacial frontal, basal, supraglacial,

glacial environments, and nonglacial-lake and eolian environments. Most may also be characterized as "offlap" sequences.

In the Paleozoic examples, accommodation space was provided within tectonic, marine, and lake basins. In Indiana examples, space was provided within ice-dammed, subaerially eroded basins (Teays-Mahomet and equivalent valleys), within drift-defined proglacial basins, and in ice-dammed, glacially eroded basins (southern rim of Lake Michigan). Space was also provided atop the land surface, with upward stacking limited only by physics of the glacier bed (central till plain).

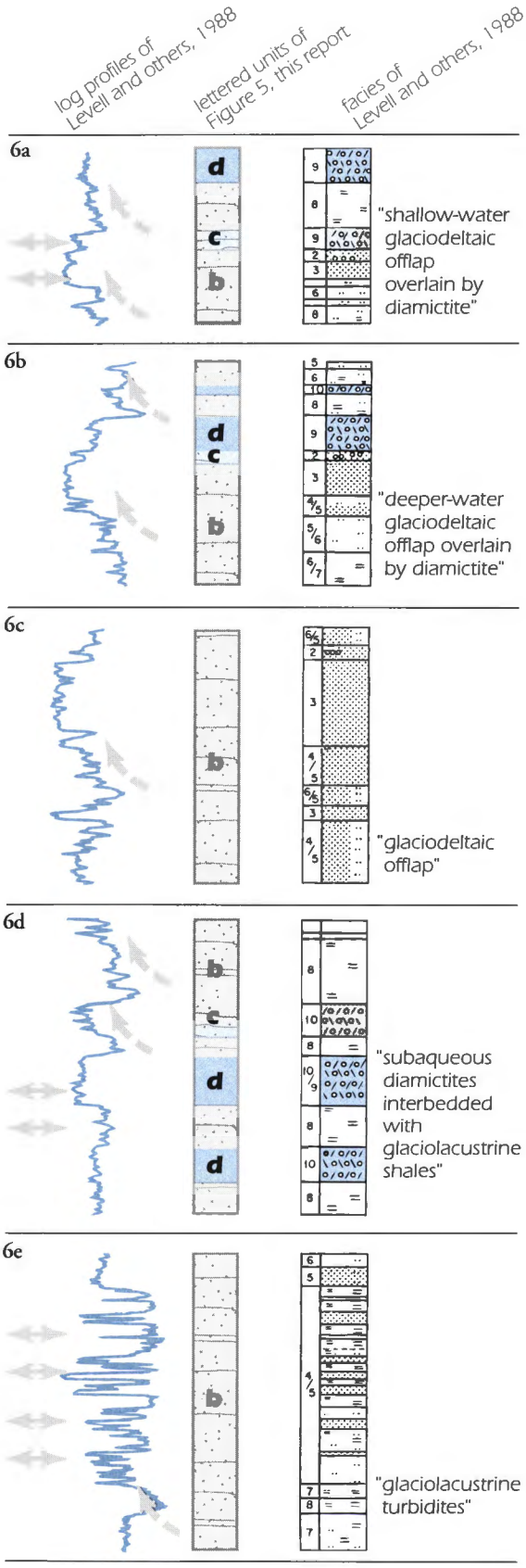


Figure 6. *Log-profile and facies-sequence examples of Gondwana glaciation in Oman (after Levell and others, 1988, selected examples from their figs. 16, 17, and 18). Lettered equivalents from Figure 5 (this report) are indicated in the middle column and with arrows; lithofacies profiles, facies (numbered) and terminology of Levell are on the right (in quotation marks). Note their association of log response with vertical sequences of lithofacies types identified in core—the basic mode of large-scale basin studies. Both specific lithofacies types and embedded internal sequences (their ideal offlap sequence) are recognized within log profiles.*

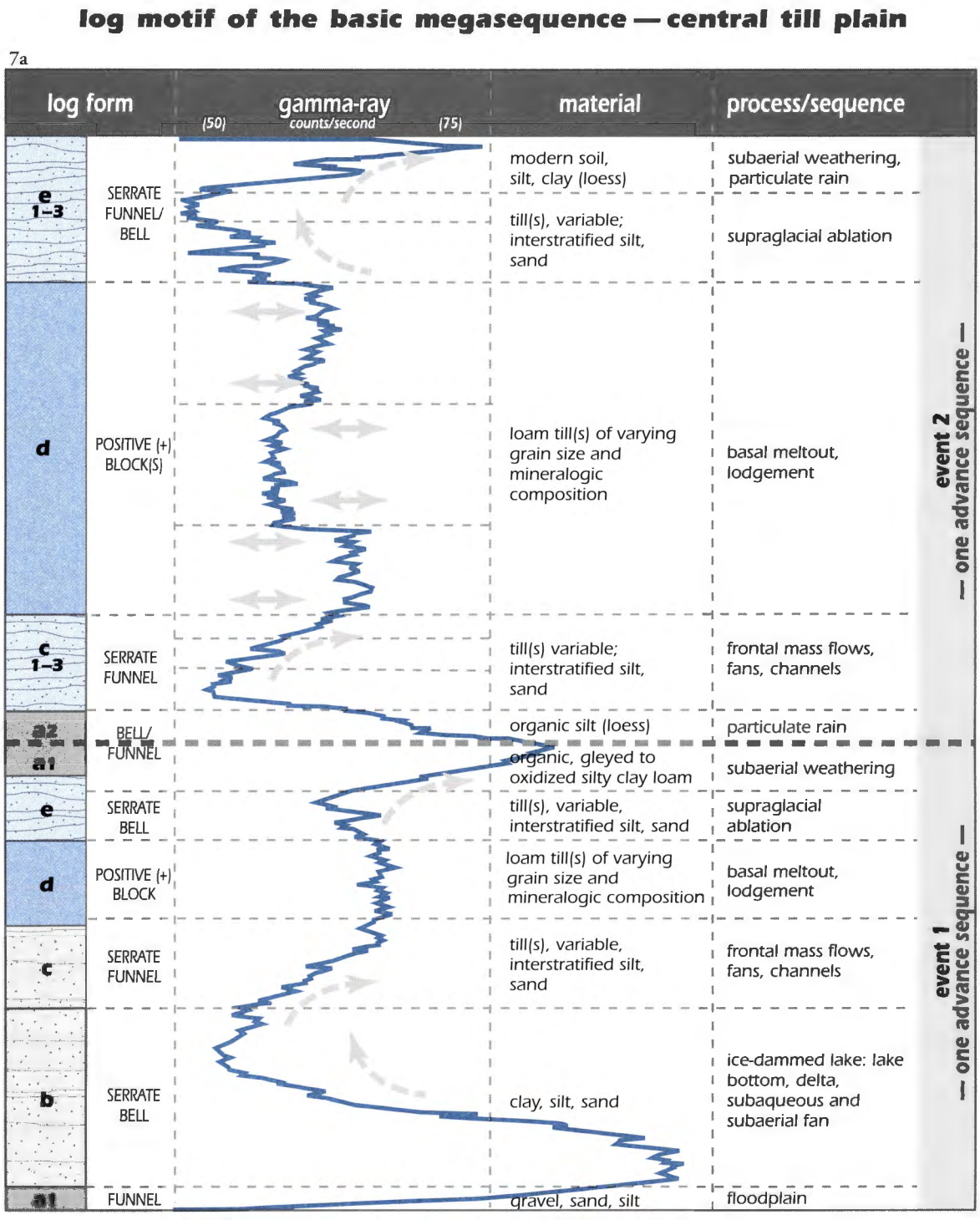


Figure 7. *Gamma-ray log motif of simple and stacked glacial megasequences and their internal sequences (compare to Figures 5 and 6 and Appendix 2; for log-form designations, see Figure 5).* **a.** *Hypothetical log illustrating stacked megasequences of similar general character, as representative of the central till plain; multiple internal sequences dominated by basal tills (positive blocks) with associated proglacial and supraglacial sequences.*

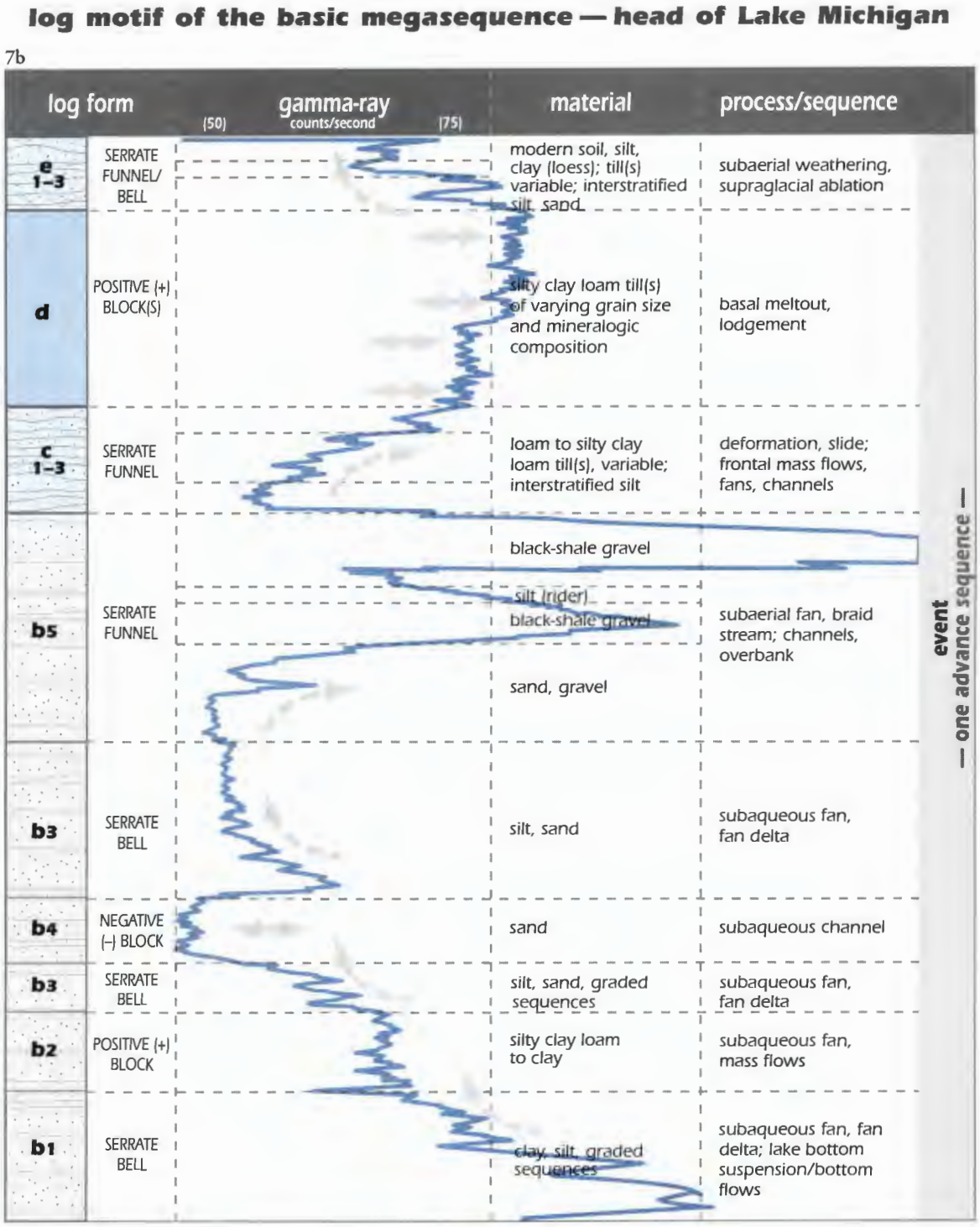


Figure 7 (continued).
b. *Hypothetical log illustrating the single, large-scale megasequence of the head of Lake Michigan (the quintessential Valparaiso Moraine), dominated by massive coarsening-upward (subaqueous/subaerial) fan sequence (bell, serrate bells), capped by thin basal till (positive block) and proglacial/supraglacial debris (funnel-bell).*

	region	surface	sequence	source	figure
1a	Illinois till plain	loam to silt loam	loess/till/older drifts	Lake Michigan	———
1b	Valparaiso moraine and fan	silty clay loam/ gravel	till/subaerial–subaqueous fan	Lake Michigan	10,17
1c	Lake Border moraines, lake plain	silty clay loam to clay	till/subaqueous fan/ lake	Lake Michigan	11,17
2a	west-central till and lake plain	loam	till (loam)/till (silty clay loam)/lake clay	Huron-Erie, Lake Michigan	13,17
2b	central till plain	loam	till/paleosol/ older drifts	Huron-Erie	12,18, 24, 25, 26
2c	east-central trough terrain	loam	loess/till/paleosol/ older drifts	Huron-Erie	9b
2d	eastern trough terrain	loam	till/paleosol/older drifts	Huron-Erie	9
3	northeastern moraine, fan, and trough terrain	loam till, gravel	tills/fans/channels	Michigan, Lake Michigan, Huron-Erie	14
4	northeastern moraine terrain	silty clay loam to clay loam	clayey tills/loam tills/ older valley fills/rock	Huron-Erie	15
5	St. Joseph, Kankakee, Tippecanoe plains	sand	fan–braid stream/ lake	Michigan, Lake Michigan, Huron-Erie	16,17
6	Lake Maumee plain	silty clay loam to clay loam	clayey till/loam tills/ rock	———	———
7a	southwestern loess/rock hills and lake terrain	silt loam	silt loam loess/ paleosol/drifts/rock	———	20
7b	south-central unglaciated terrain	silt loam/clay	silt loam loess/clay	———	19
7c	southeastern dissected loess/till/rock terrain	silt loam	silt loam loess/ paleosol/drifts/rock	———	———

Table 2. *Characteristics of Indiana terrain regions (using an informal terminology for this report) and index to figures.*

GLACIGENIC SEQUENCES

A wide range of glacigenic and other sequences from across Indiana are illustrated in examples below (indexed in Table 2 and fig. 8).[3] Examples are grouped loosely according to simplest and familiar concepts of origin (fig. 1). They reflect a simplistic set of depositional environments that seem to correspond with a familiar arrangement of log forms, which together make up an overall log motif. Individually, they are recognizable entities; together, they are the offlap megasequences (figs. 6 and 7).

[3]Logs reproduced here were initially analog records of holes of various sizes and casing types. "Test holes" are mostly IGS 4-inch auger holes logged though 2-inch PVC pipe. "Water wells" are logged through 5- or 6-inch PVC pipe. Digital traces have been reduced by varying amounts depending upon the scale of feature illustrated. Several are reduced so drastically (to illustrate large sequence forms) that a significant amount of real (nonstatistical) detail is lost.

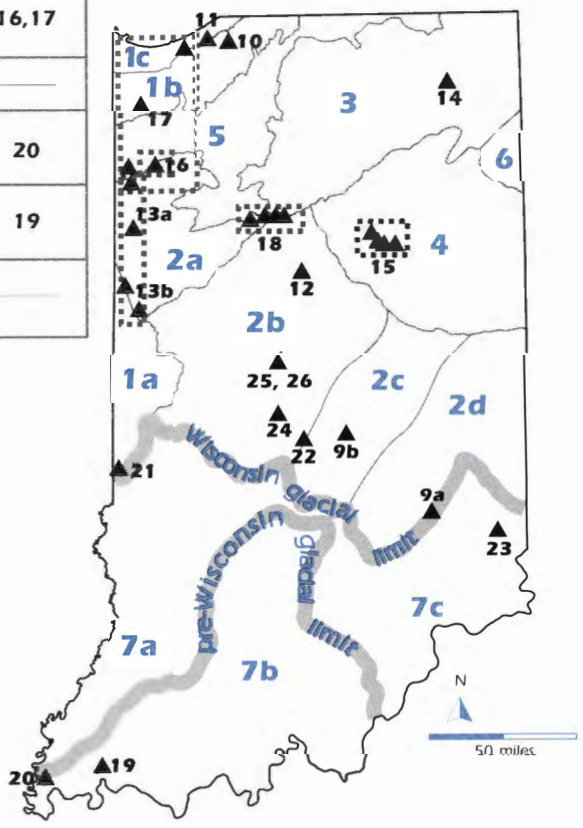


Figure 8. *Map showing the locations of the log examples in this report's illustrations with respect to general glacial-morphogenetic terrain regions of Indiana. Black triangles indicate locations of log examples; black numerals refer to the figure numbers. Dashed boxes represent sections of multiple logs. Terrain-region designations (Table 2) are in blue (for example, 1a, 2b.)*

The frontal sequence

The frontal sequence (fig. 9) represents a prograding, "proximalling-upward" fan environment. It consists of a fining- and thickening-upward sequence within which "fine" flowtill diamicts become increasingly common or thicker upward toward the base of the overriding tills of the melt-out sequence, or both. This gradation is common in both terrestrial and subaqueous frontal (morainal bank) environments. The flow units are discontinuous wedges interspersed with sand and gravel as fan-lobe and channel deposits.

In position and in log form, the frontal sequence may have been so affected by glacial override that it would be considered in the category of incorporation/deformation tills or the "deforming bed" of current debates. Outcrop examples of deformed materials include discrete interlayering of till with slices of overridden and subsequently incorporated sediments. The units display evidence of shear deformation, particularly along lithologic boundaries. The most extreme examples are those from glacial-lake environments of the northwestern lake plain, where large-scale boudinage and rafts of interlayered lake and subaqueous flow material, many feet in thickness, may be present.

The gamma-ray log motif of such frontal/basal sediments may appear gradational (reflecting interlayered thin beds) or be distinctly serrate with major peaks and troughs. Where gradational, the log commonly is funnel shaped

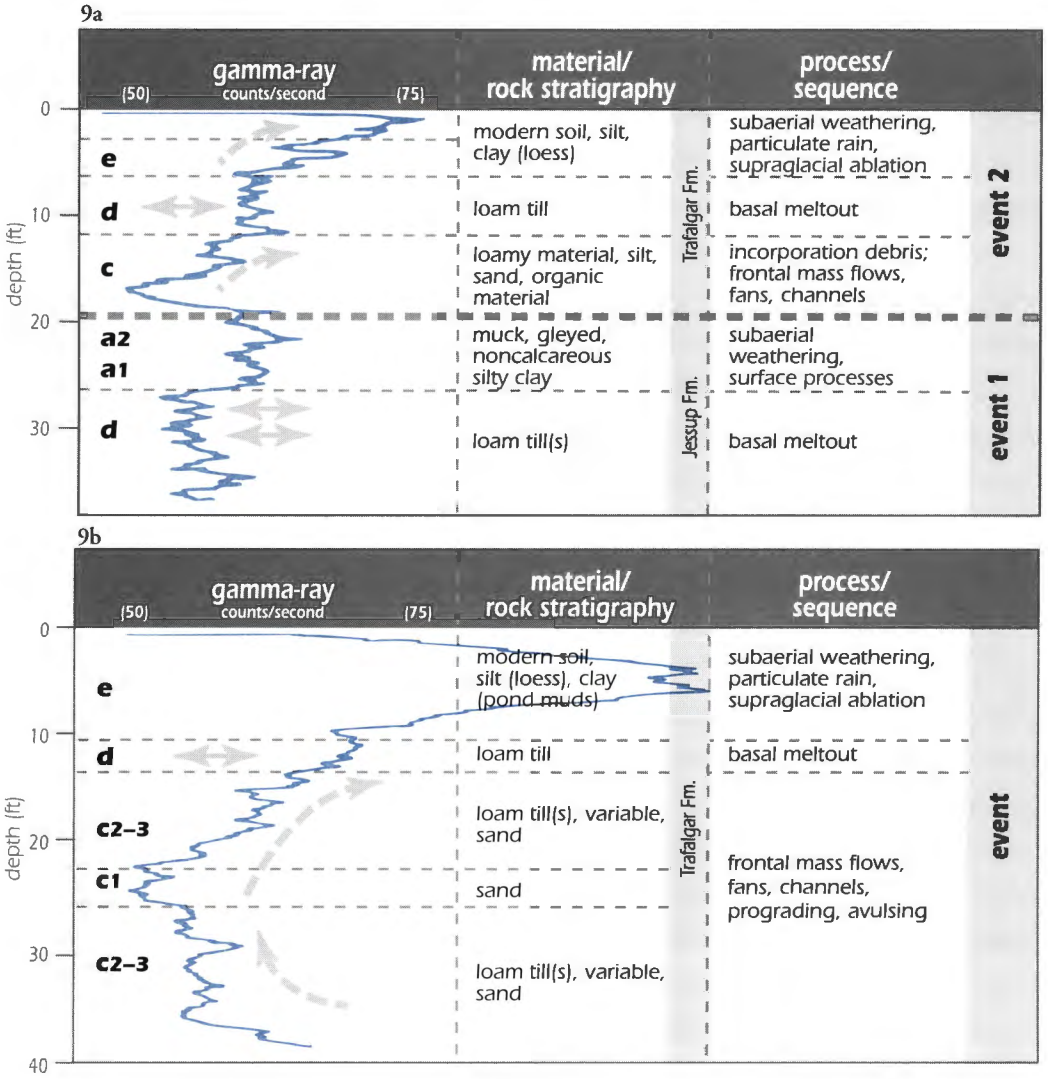


Figure 9. *Logs illustrating simple advance sequences of the central till plain. (Refer to Figure 5 for log-form designations.)*

a. *Log of a test hole on the front slope of the Wisconsin terminal moraine, Decatur County, southeastern Indiana, showing the depositional sequence of the absolute ice margin. The base is defined by the in situ, pre-advance soil.*

b. *Log of a water well, Hancock County, central Indiana, in which a significant basal till block is absent. The sequence is dominantly mixed flows of frontal or earlier ablation origin.*

(log form **c**, fig. 5), reflecting a fining-upward gradation to the overlying till, or possibly bell-shaped where overriding till more directly overlies clayey section in lake environments (log form **b1**, fig. 5). This generally fining-upward sequence is equivalent to the lower part of tillite facies 9 in the glaciodeltaic offlap sequences of Levell and others (1988) (fig. 6).

In moraine-front positions, the frontal sequence may be a component of a simplest, but complete, terrestrial advance sequence (fig. 9a, "Shelbyville" moraine, central Indiana; fig. 9b, Valparaiso Moraine composite, northwestern Indiana). In these examples, either a buried soil (fig. 9a) or a thick, continuous, obviously "proximalling" fan sequence (fig. 7b) helps define position. Within the stacked stratigraphies of the central till plain, interbedded funnel and bell sequences may represent a combination of proglacial advance materials atop similar ablation materials relating to a just-earlier advance (fig. 9b). Such shallow mixed zones are common near-surface aquifers within the till plain.

A complete frontal sequence, however, is more than the immediately ice-proximal fan progression just described. It also consists of the underlying coarsening-upward granular deposits representing more distal fan and outwash channel deposits. Whether of very local or vast areal extent they were ultimately buried by ice to become part of the full progression. A remarkable example is the giant proglacial fan complex that lies within the core of, or that entirely comprises, the Valparaiso Moraine at the head of Lake Michigan. The Valparaiso Moraine example consists of an entire progression from lake bottom through subaqueous fan to subaerial fan and subsequent glacial override. (Log profiles of the upper, subaqueous/subaerial fan elements are illustrated in Figure 10. Profiles of the lowest parts of the progression are illustrated in following figures.)

Because of the unique lithology of the upper granular materials, particularly in the northern head-of-fan area, the overall coarsening-upward, prograding nature of this complex is strikingly documented in gamma-ray log profiles. Coarse clasts in much of that unit are composed of uranium-rich Devonian black shale, apparently derived from subglacial channels eroding black-shale bedrock of the basin immediately to the north. The shale-rich gravel logs far higher than sand, and log profiles illustrate remarkably well-defined fining and coarsening sequences within the massive sand and gravel section (fig. 10).

Log profiles in these materials are outwardly similar to those of fining-upward proglacial successions or to avulsing fan/lake progressions (log forms **c1–3** or **b1–3**, fig. 5); the meaning of the profiles is just the opposite. The inverted pattern, an upward coarsening-"shaling" (the shale increases upwards) throughout the entire sequence with many internal coarsening-shaling cycles suggests prograding fan lobes; these, in turn, appear to contain even smaller fining-"deshaling" (shale decreases) cycles suggestive of internal channel fills. This upper part of an overall coarsening-upward sequence is the log equivalent of facies 3 of the glaciodeltaic offlap sequences of Levell and others (1988) (fig. 6a, b, c).

The coarsest material that is richest in shale, the highest log peaks, are locally capped by a thin silt "rider." If the coarsest materials logged low, as is normal, the silt would be the top of a thin funnel-shaped log trace (as uppermost log form **b4–5**, fig. 5), a form characteristic of an overbank silt-capped fluvial sequence.

Within the deposits of the ice-contact lake environment, a similar prograding advance sequence exists. Examples from Indiana's northwestern lake plain (fig. 11) illustrate blocky logging till units confined between a variety of lake sequences. These sequences contain interbedded flows of varying grain-size, berg-drop debris, and sandy subaqueous channels suggestive of deposition in morainal bank or ice-proximal lake. The package of sediments is remarkably similar overall to the lake-sediment to diamict progressions, particularly facies 10 of the glaciodeltaic offlap sequences of Levell and others (1988) (fig. 6b, c).

Subglacial meltout sequence

The subglacial meltout sequence (fig. 12) includes tills that are more homogeneous masses, commonly of loam to clay-loam matrix. Units commonly have abrupt, glacially planed erosional bases and possibly water- or ice-planed top surfaces. They may contain scattered lenses of

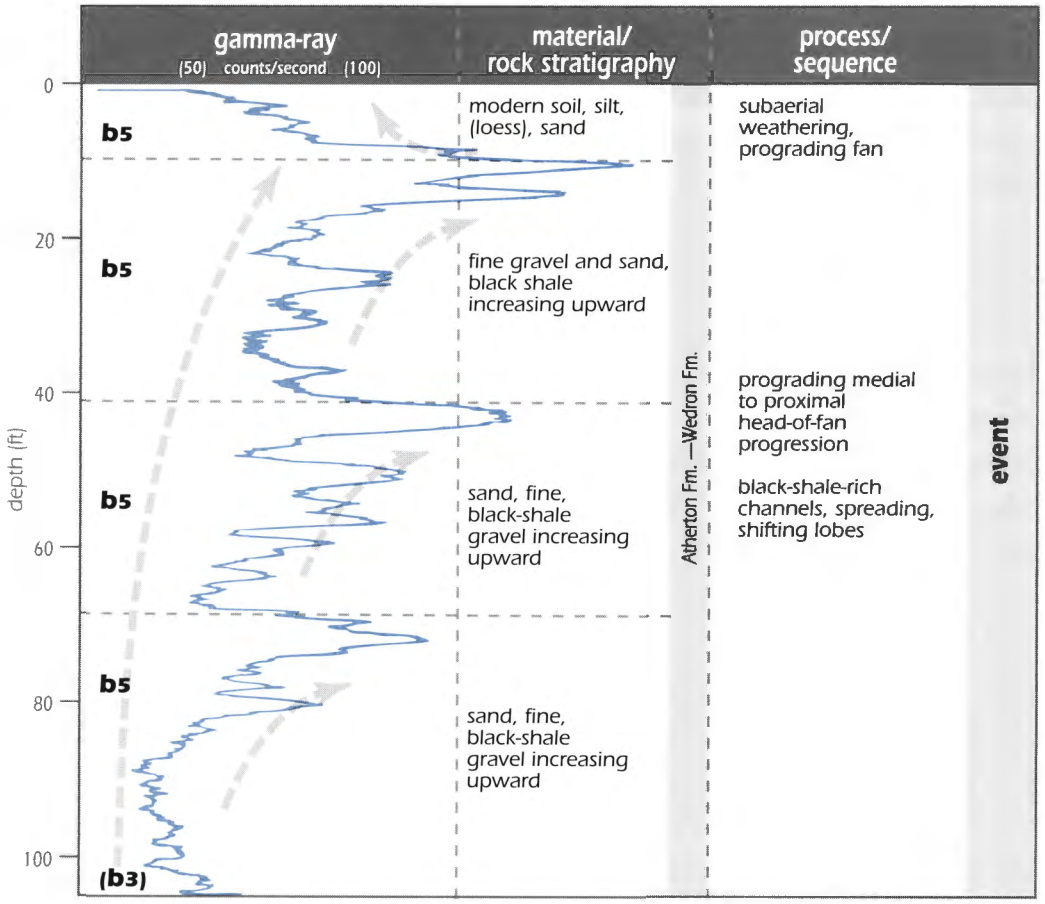


Figure 10. *Log illustrating multiple internal and overall coarsening-upward sequences in outwash fan materials, created by the abundance of uranium-rich, black-shale clasts in the coarse fractions of the outwash in a localized area. Log is from a water well penetrating the Valparaiso megasequence, LaPorte County, northwestern Indiana. (Refer to Figure 5 for log-form designations.)*

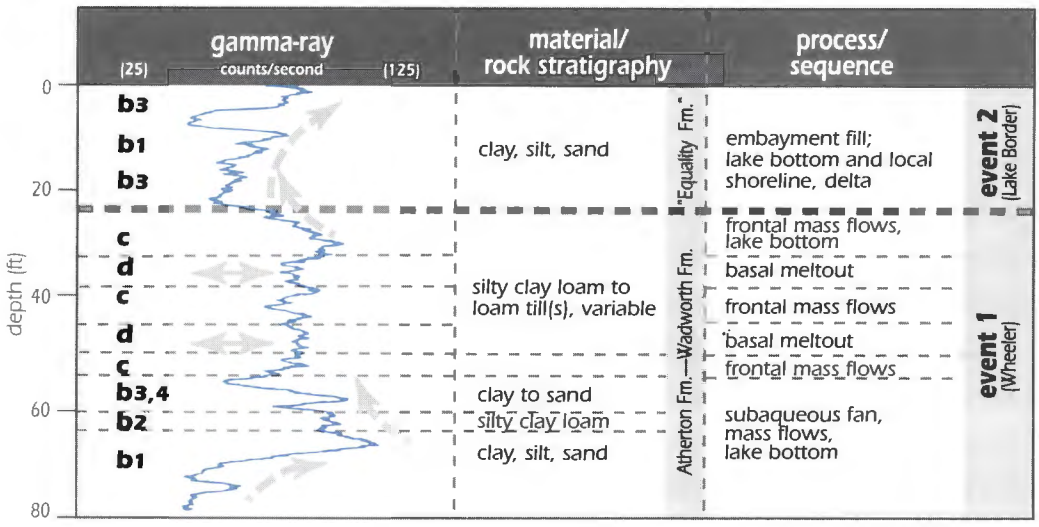


Figure 11. *Log illustrating a sequence of lake and moraine-bank deposition fronting ice in ancestral Lake Michigan, Porter County, northwestern Indiana. Compare with similarly positioned "dunes" log, Figure 12. Note encapsulation of "basal" till units within frontal flow/lake clay packages. Note offlap aspect, coarsening-upward ("proximalling") nature of lower whole megasequence. (Refer to Figure 5 for log-form designations.)*

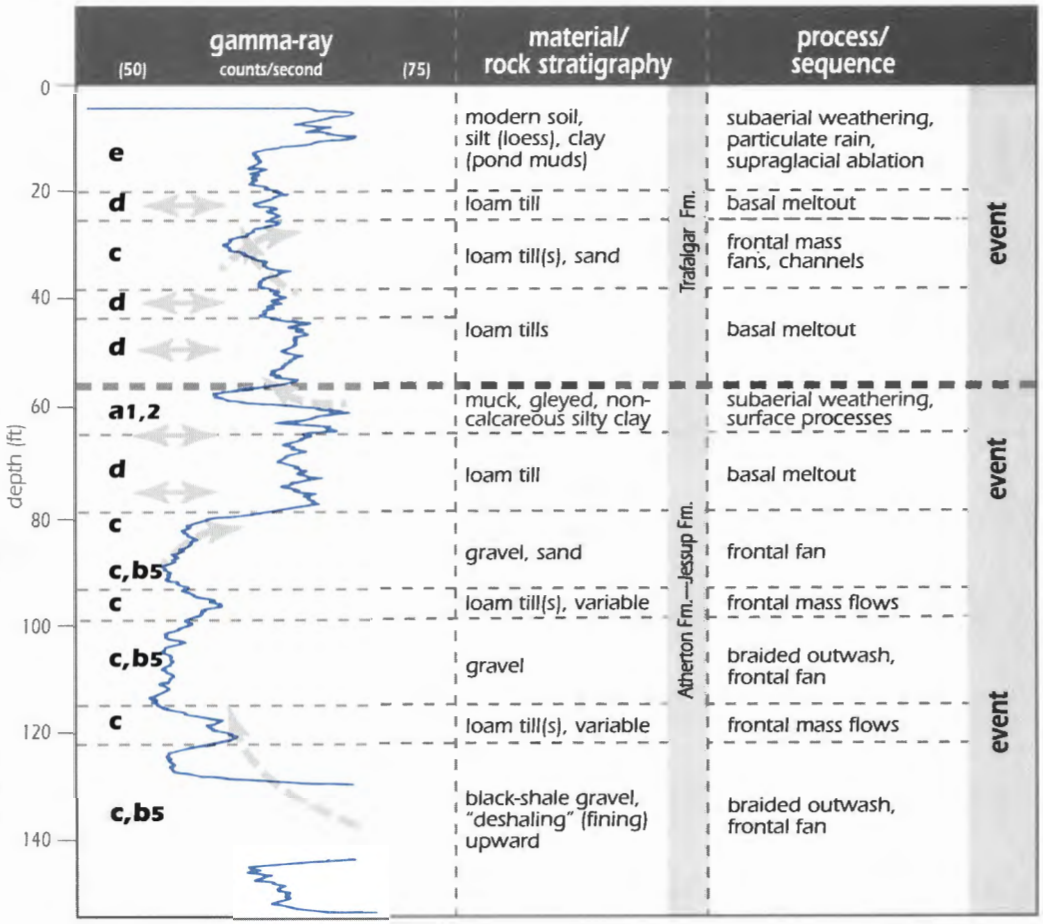


Figure 12. *Log illustrating stacked advance sequences, including multiple Wisconsin tills and interglacial (Sangamon) weathering profile of the central till plain, Howard County (USGS test hole D-7). Note the highly variable, stratified nature of the upper ablation unit, multiple loam tills (blocky form), and the clayey paleosol (high count-rate peaks) capped by silty muck (low count-rate valley). Count rates for tills generally parallel silt+clay content except in lowest unit; in that unit till mineralogy (probably higher shale content) is assumed to be of relatively greater importance. (Refer to Figure 5 for motif designations.)*

included materials of various textures. Where occupying positions that were subjected to surficial weathering or desiccation, they may contain a variety of joints or healed joints; more generally this is not the case, as evidenced in virtually all deep artificial exposures.

The gamma-ray log motif of such a unit is at its simplest a single, blocky, crew-cut-shaped form (log form **d**, fig. 5). Its consistent statistical chatter contrasts with smoother, deeply serrate patterns representative of stratified fine-grained sediments. The units are most obvious where embedded within other sequence patterns; they may be distinguished in some totally "clay" sections (for example, multiple **d** blocks, fig. 12) where gamma-ray responses mimic minor grain-size or mineralogic differences between till units, or both.

Supraglacial ablation sequence

The widespread existence of surface, supraglacial ablation deposits has been surmised on the basis of aerial photography, satellite imagery, and surface exposures (fig. 13) (Harrison, 1963; Bleuer, 1974, 1975). Downhole logging of hundreds of holes across the central plain has shown how nearly ubiquitous such deposits are, even without obvious landform evidence.

These near-surface deposits of the central till plain consist of interlayered tills, sands, and silts, products of the latest glacial-ice disintegration. Materials are likely to vary greatly in detail over small distances. Till components are commonly less dense than basal tills. They may be homogeneous, or grain-size characteristics may grade finer or coarser vertically and laterally; soft-sediment deformation may exist. A poorly stratified silt or pebbly

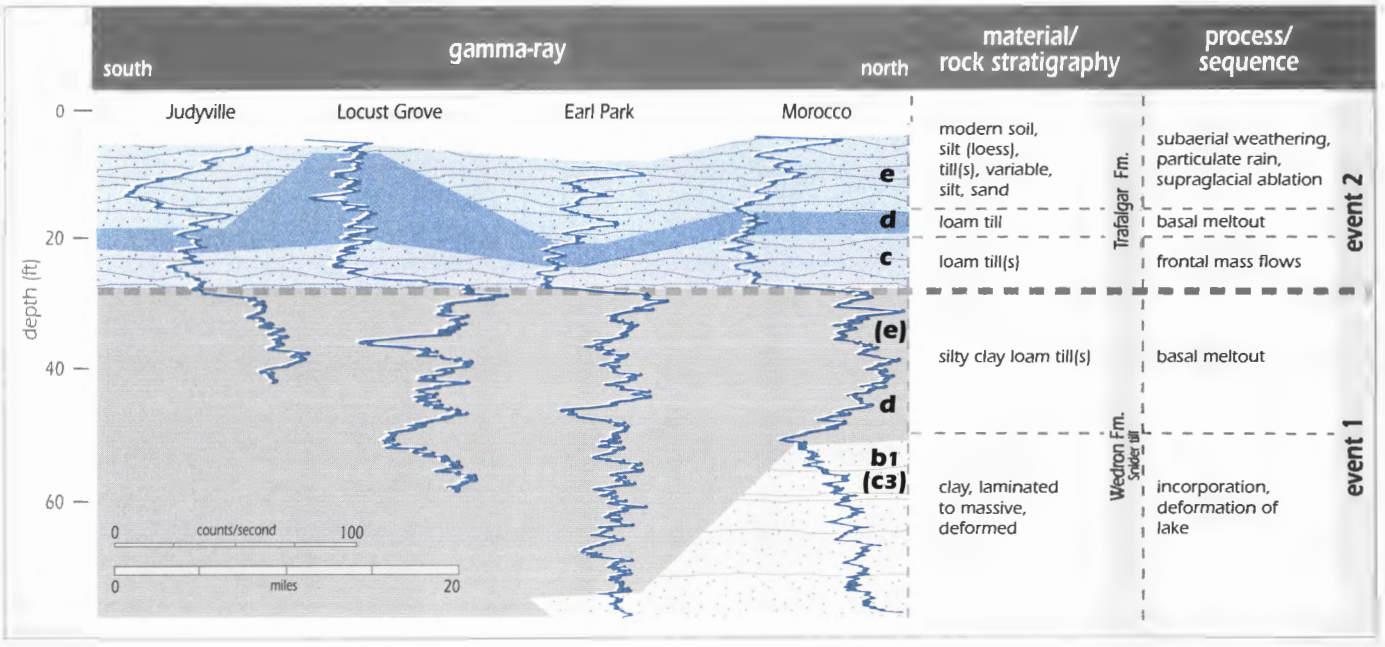
13a

Figure 13. *Surface form and log character of a disintegration-moraine landscape.*

a. *Aerial photograph of the Earl Park area, Benton County, west-central Indiana (from high-altitude infrared photograph, expansion of Figure 2b in Bleuer, 1974). The "x" indicates drill-hole location.*

b. *Log cross section of test holes, including that at Earl Park, illustrating the position, variable thickness, and nature of uppermost ablation materials that comprise a disintegration landscape. (Logs are aligned on the top of the Snider till; logged through 2-inch PVC pipe in 4-inch augered holes.) Note the highly variable ridge-and-valley log profile indicative of extreme grain-size variation within the ablation unit. (Refer to Figure 5 for log-form designations.)*

13b



silt commonly caps the sequence; thin sand or silt laminae may mark the base. Surface oxidation commonly extends through these materials, reaching a sharp base at a granular lamellae at the contact with more dense till below—an indication of the profound influence of this package upon local ground-water flow systems. The unit's thickness, about the same as local relief, and its common association with obvious disintegration landforms suggests that virtually any uppermost zone of distinctly high variability might be considered to be stacked materials of ablation origin.

The overall gamma-ray log motif of the ablation sequence (log form **d**, figs. 5, 7a, 13b) is commonly a funnel-shaped curve representing upward-fining with increasing interstratification of fine-grained sediment and a gradation upward into the loessal soils of the poorly drained till-plain surface. The base of the sequence is commonly marked by a subtle, low count-rate trough representative of a granular zone.

Combined with the capping postglacial materials, including loess, surface wash, and modern soil, this is a fining-upward marker sequence representing the ultimate culmination of a largest-scale glacial event. The sequence is the ongoing, postglacial onlap record of the "atmospheric sea," the terrestrial equivalent of a simultaneous marine onlap. Uppermost deposits are equivalent in concept and age to Galloway's (1989) "marine flooding unit" of the genetic stratigraphic sequence (Bleuer and Brown, 1999).

RELATED SEQUENCES

Glacial-fluvial sequences

Glacial-fluvial deposits are primarily granular materials representative of a variety of fan, braided-stream, and large-channel environments (Gruver, 1984; Ballard, 1985; Fraser, 1993, Fraser and Bleuer, 1991a, b). These deposits reflect high debris load and highly cyclic deposition owing to variable discharge and channel geometry. In general, areally extensive deposits may appear sheet-like; they should contain evidence of cyclic deposition, whether in the form of coarse-to-fine waning flow cycles in channels or as stacked longitudinal bars. They may contain fine-grained channel-fill plugs with sharp erosion surfaces above and below (for example, Selley, 1978a, 1978b).

Some of these deposits are continuous over large areas, such as those of the St. Joseph-Kankakee valleys and tributaries. These are essentially the medial to distal extensions of the frontal sequence described above. Some deposits are downvalley threads of so-called "valley train." Some deposits are discontinuous, lenticular, or intertongued with till bodies as part of the frontal sequence in examples above. And some are associated with ice-contact valleys and with collapsed tunnel systems (including elements of the upper White, Wabash, and Whitewater River valleys). These contain a variety of sediment-gravity-flow deposits derived from melting ice or valley sides (for example, Paul, 1983).

The gamma-ray motif of granular outwash deposits is most commonly a simple, consistent low count rate throughout the section, reflecting the dominant mineralogy of quartz-sand and carbonate-gravel clasts. In a few examples, minor funnel-shaped cycles of gradually increasing count rate upward suggest fining-upward cycles that may be related to fine-grained slackwater deposits or void infillings of bar-top materials; in other examples, minor bell-shaped cycles suggest the possibility of microdeltaic infill of channel plugs. In contrast, minor bell-shaped forms in wholly granular sequences may indicate fining-upward, waning flow sequences defined by subtly higher logging materials at the base rather than at the top. The base of these may represent coarser basal channels or longitudinal bar features composed of coarse Precambrian crystalline rocks (feldspathic/micaceous) and Pennsylvanian sandstones (micaceous) (Bleuer and Melhorn, 1989). However, these examples do not approach the extreme log response characteristic of the head-of-fan, black-shale-rich materials noted above (fig. 10).

The gamma-ray log motif characteristic of channelized outwash deposition ice-contact settings (fig. 14) is similar to that described for ice-frontal settings, except here the section is not necessarily a gradational sequence; rather it is thick and repetitious. The log signature is similar but inverse (overall) with respect to that termed "nervous" in

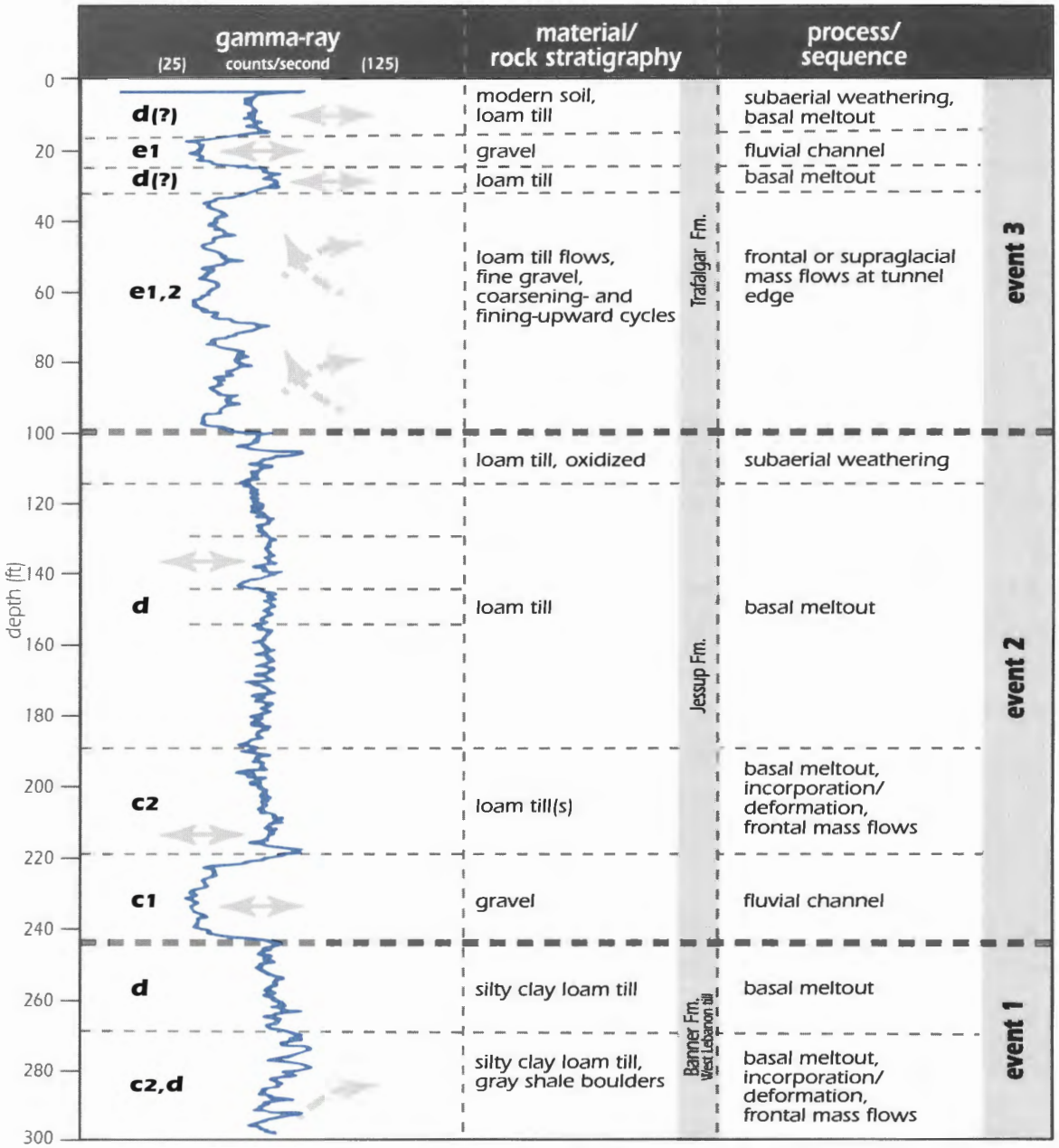


Figure 14. *Log illustrating a thick outwash body containing repetitive till flows, an apparent single event sequence, overlying older sequences of wholly differing character. Located at Kendallville, northeastern Indiana, on upland adjacent to a linear, ice-crevasse drainageway. (Refer to Figure 5 for log-form designations.)*

descriptions of submarine turbidites (as "proximal fan turbidite-infilled channels" of Selly (1987b, fig. 4) (fig. 6d). That is, the log form is highly variable with numerous broad peaks and troughs, with peak count rates of various flow units differing greatly. Block-, funnel-, and bell-shaped curves are common, reflecting a range from fining- to coarsening-upward trends within flow units. In general, these log properties indicate subtly differing modes of origin of flow units, as reflected

in highly varying grain-size, variable sharp erosional to gradational basal contacts, and multiplicity of units.

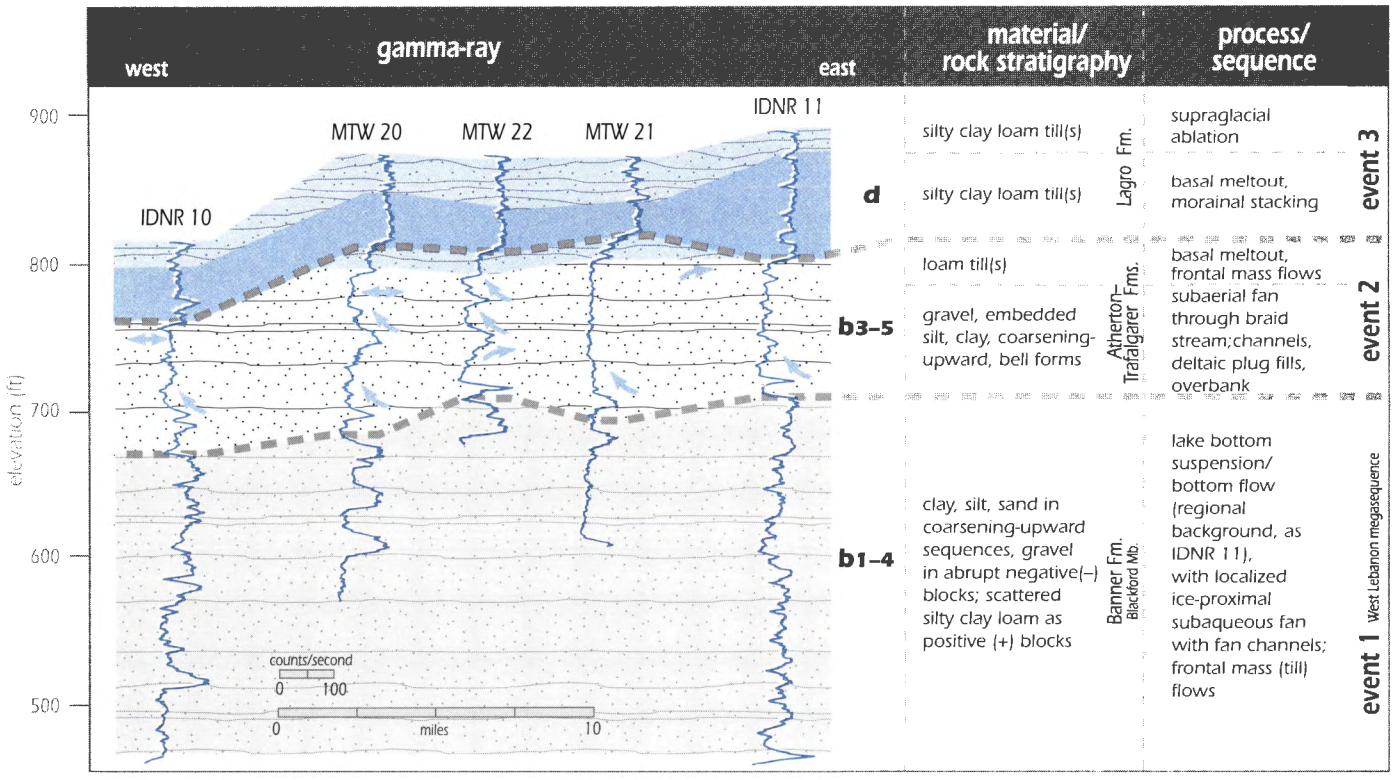
Glacial lake sequences

Glacial lake sequences were formed in ice-contact through distal lake environments. More ice-proximal settings, subaqueous fan, mudflow (morainal bank), and a mixed fan-mudflow fringe were sites of dense interflow, underflow, and bergdrop deposition (Bleuer and Woodfield, 1993). Medial and distal lake-bottom settings were sites of suspension fallout and dense bottomflow deposition.

Examples are found in the deposits of the early-glacial, ice-dammed Marion Valley Section of the Lafayette Bedrock Valley in central Indiana (the Teays valley; terminology of Bleuer, 1989) (fig. 15) and in the deposits of ancestral Lake Michigan in northwestern Indiana (figs. 16 and 17). In the Marion valley, advancing ice blocked a long, narrow, and deep preglacial valley. Water rose to levels determined by sags in the south wall, forming a particularly narrow depositional basin into which a glaciar front progressed obliquely and in isolated nodes. Valley fill is a single megasequence, dominantly coarse, granular fan material in the west and fine-grained lake-bottom material in the east. Embedded in the latter are local granular fans, apparently derived from the point sources of northern tributaries.

In an early Lake Michigan basin, ice fronted a large crescentic lake that occupied a basin formed north of the southward-rising basin rim. The lake basin was a regional hole left by collapsing earlier ice masses. Basin fill over the greater Lake Michigan rim region (extending as far south as Kentland),

Figure 15. *Log cross section illustrating the thick lake-sediment fill sequences in the Marion valley (Lafayette or Teays bedrock valley) of east-central Indiana. Note the regional background of fine-grained sediments with localized gradational coarsening-upward (bell log form) and abrupt coarsening (inverse block log form) sequences, which represent local influxes of subaqueous fans and channels derived from an advancing glacial source. Spiked inflections at 20-foot intervals in Indiana Department of Natural Resources (IDNR) test holes reflect drill-pipe joints. No horizontal scale. Modified from Bleuer and others (1991, fig. 2). (Refer to Figure 5 for log-form designations.)*



although representative of several discrete megasequences areally, is a surprisingly ubiquitous coarsening-upward sequence. At any one place it is a single advance sequence. The progression consists of lake-bottom, delta, and ice-proximal fan materials, capped to the north by morainal bank and subglacial materials of the latest advances.

These proximalling-upward, glacial-advance sequences are equivalent to the facies and progressions of prograding glaciodeltaic offlap illustrated for Permian-Carboniferous sequences (Levell and others, 1988). Parts of these progressions have already been discussed individually, and only dominantly lake basin and fan aspects are discussed further below.

Gamma-ray log motifs of distal lake sequences within the Marion valley include dominantly high-logging masses of blocks to highly serrate blocks (fig. 15, West Lebanon megasequence, IDNR 11). In most of these instances, the clayey beds, even where represented by a blocky overall log form, contain high-amplitude variation (in contrast to low-amplitude statistical chatter of till block patterns), owing to the trace's lengthy transit time from high-count clays to lower count-rate silts and back again.

The sequence commonly includes serrate bell and funnel forms indicative of coarsening-upward vertical sequences that represent embedded fan deposition and fan avulsion (fig. 15, IDNR 10). Sequences may also include inverse block forms indicative of subaqueous channel forms, extensions of fan channels across and through muddy substrate (fig. 15, MTW 20). These patterns of sandy and coarse granular zones interfingered with the fine lake sediments are similar to "cylindrical" or "nervous" patterns (Selley, 1978a,b; Serra, 1985) or "glaciolacustrine turbidites" (facies 4/5 of Levell and others, 1988, fig. 17E). All are considered representative of abrupt introductions of coarse materials into a lake environment, that is, as subaqueous channel and supra-fan lobe deposits, including turbidites and mass flows.

Till-stratigraphic sequences

Many till bodies within the drift of the lower Midwest are important stratigraphic entities, recognizable over large areas on the basis of mineralogic and grain-size characteristics (for example, Johnson, 1976; Kemmis, 1981; Wickham and Johnson, 1981; and Bleuer and others, 1983). As such, they are stratigraphic markers that can be the foundation of establishing regional or site-specific sequence geometries (fig. 18).

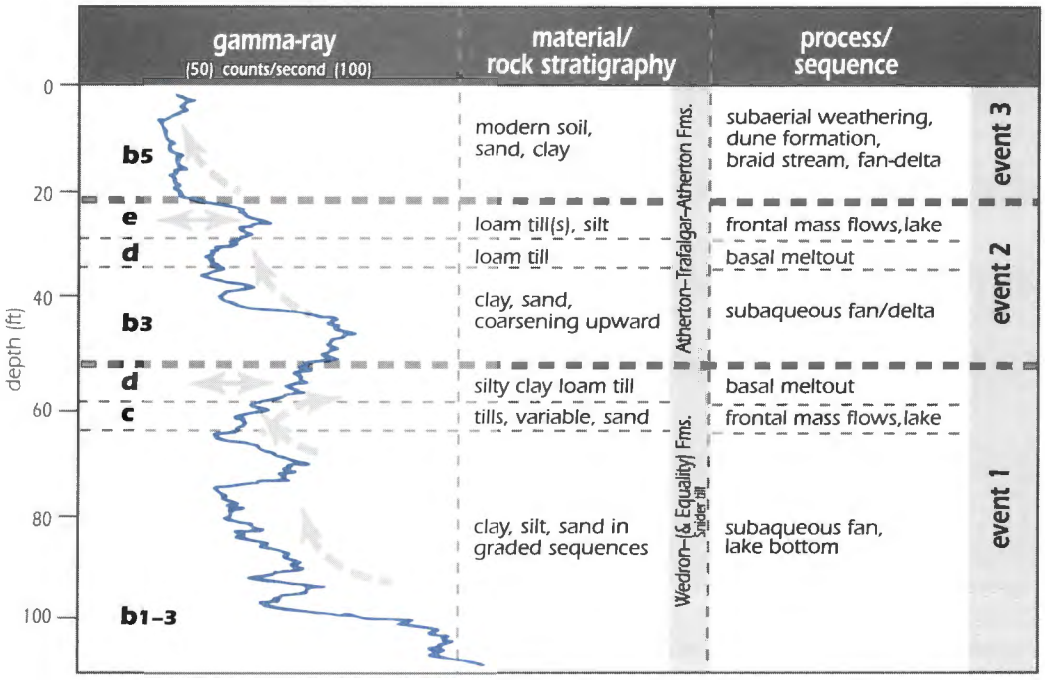


Figure 16. *Log illustrating lake, delta, and glacial sequences characteristic of the southern Kankakee Basin, near Fair Oaks, Newton County, northwestern Indiana. Note the log form of lake-bottom clays (serrate high count rate associated with silt-clay variations), deltaic silts and sands, and ice-derived clayey till flows (facies of the Snider till) associated with advance of the Lake Michigan lobe. Compare to Figure 6a, b, c; note position in Figure 17. (Refer to Figure 5 for log-form designations.)*

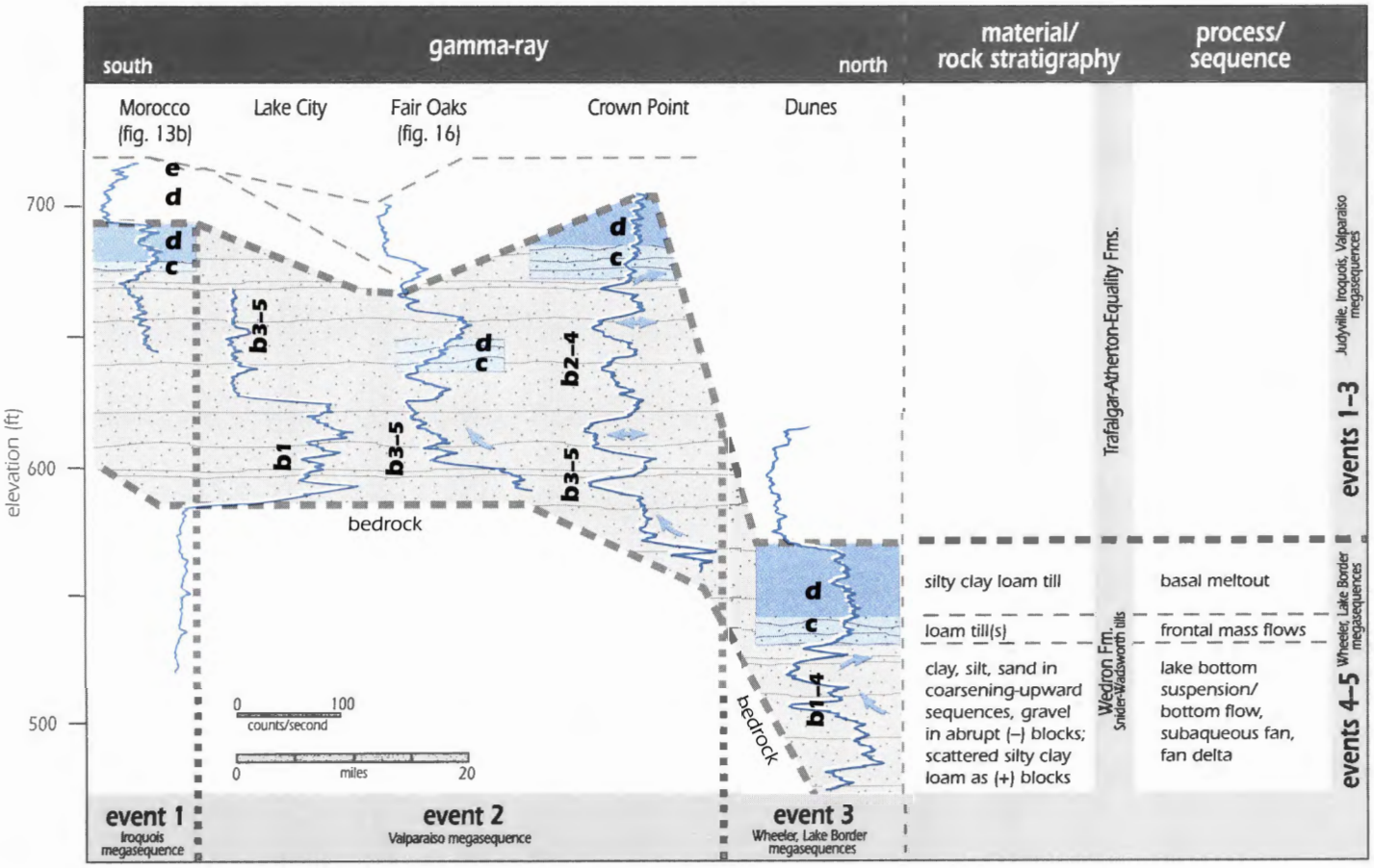


Figure 17. *Log cross section illustrating the wide distribution of till-capped lake, delta, and subaqueous fan deposits in the Kankakee Basin region of northwestern Indiana. What appears to be a single, basal coarsening-upward "offlap" sequence in most places probably represents at least three distinct advances of the Lake Michigan lobe over proglacial lake sediments. Compare with Figure 15. (Refer to Figure 5 for log-form designations.)*

The gamma-ray log motif of these units is the blocky pattern of a subglacial meltout unit. Many units may be distinguished simply by count-rate differences, the rate being an integrated measure of grain size and, possibly, elements of mineralogy of the units. Even subtle distinctions may differentiate till units, such as in multiple Trafalgar tills of the central till plain (multiple unit **d**, fig. 12), or a high-logging pre-Wisconsin unit of the Indianapolis area (Brown and others, 1993), or the Wakarusa till-Bourbon till distinction of north-central Indiana (Bleuer and Melhorn, 1989). In many local cases, overall blocky units may take on an internally recognizable pattern, such as a uniform block overlying a subtle, gradually fining- or coarsening-upward block.

The greatest stratigraphic distinctions are between the silty-clay-loam textured tills of the Lake Michigan and Erie lobes and the loam-textured tills of the central till plain. In western Indiana, the fine-grained tills include the Snider Till Member and an equivalent of the Wadsworth Till Member of Illinois, both of the Wedron Formation (figs. 13b, 16, and 17) (Bleuer, 1989, fig. 6A,B), and in eastern Indiana they are the tills of the Lagro Formation (fig. 15) (Bleuer, 1991, fig. 6C,D).

The Snider (or Yorkville) is a surface unit in Illinois, but it is abruptly buried by the upper tongue of the Trafalgar and its surficial ablation sequence in west-central Indiana (fig. 13b). Because of its relatively high clay content (>30 percent) and its shale clasts, the unit logs higher than any other in the region. For this reason, utilizing logs and sample cuttings, the Snider can be traced eastward in the subsurface nearly to the center of the state (fig. 18). A single radiocarbon date fixes the base of Wisconsin-aged loam till of the Trafalgar Formation in this same area. Logs allow the geometry of the entire Wisconsin package to be delimited, illustrating in this case the great contribution of Wisconsin-aged materials to the total landscape.

Classic aspects of glacial stratigraphy are weathering profiles, soils, and associated organic sediments and detritus of various sorts that have been used to mark the major divisions of the glacial record. Because of their common absence (owing to glacial erosion and nonglacial landscape processes), such units are not reliable stratigraphic entities in subsurface-based glacial geology. Drillers descriptions of probable weathered zones ("green clay") or granular beds or local aquifers may be adequate to define the position of such units, but these descriptions cannot be used for specific identification or correlation, given the many stratigraphic possibilities that must be admitted and the inherent limitations of water-well databases (see Figure 27 and following discussion). Nonetheless, such materials may be local marker beds that tag larger physical sequences or till-stratigraphic units whose log characteristics allow widespread tracing.

The clayey, smectitic, gleyed paleosol (Sangamon Soil; see Follmer, 1979) is locally preserved in its entirety, especially beneath much of the central till plain. Its complete profile and association is as follows: (top) basal Wisconsin till, with common organic or gleyed clay inclusions; thin clay rider; organic mat or thin muck atop organic silt with snails (Farmdale soil, Robein Silt); silt (Roxana Silt, a loess, the first glaciation-related materials to be deposited atop an old landscape); organic clay (uppermost mineral soil); gleyed (blue-green) clay (accretionary mineral soil); oxidized loam till; gray loam till (bottom).

The gamma-ray log form of this marker association (log form **a**, figs. 5, 7, 9, and 12) is a peak having two genetic parts represented by its upper bell (**a2**) and lower funnel (**a1**) halves. It represents the cumulic land-surface environment pre-

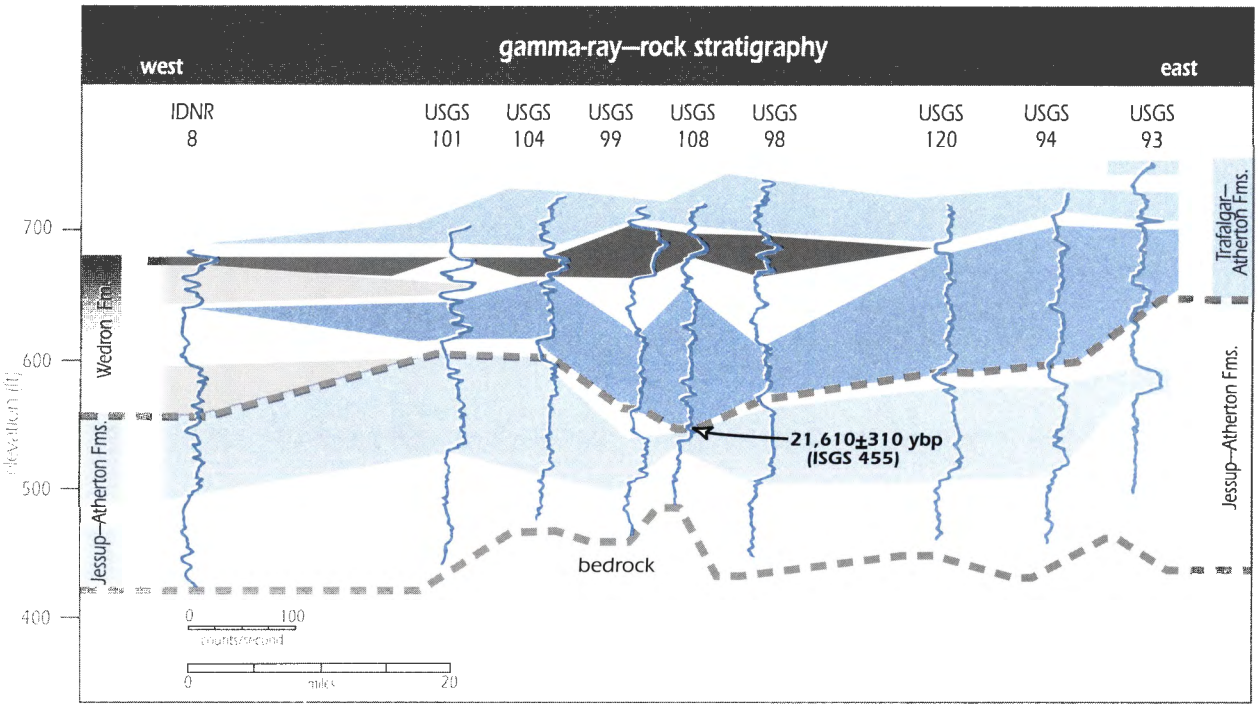


Figure 18. *Log cross section illustrating a regional distribution of glacial stratigraphic units, till units identifiable on the basis of position and log character in the Mahomet valley (Lafayette or Teays bedrock valley), north-central Indiana. Note the regional distribution of till units, especially the eastward pinchout of the clayey Snider till between loamy Trafalgar tills, and more generally, the highly visual record of the relationships between till units (in blue) and regional aquifers (white). Basal late Wisconsin data substantiates thickness of fill of an earlier Wabash drainage.*

served in a buried solum, commonly atop buried ablation materials. Log form **a1** is similar to log form **e3** of the surface ablation sequence, representing an upward fining of materials culminating in surface soil.

The upper bell of the association—a delayed pull-off, a shallow slope from the paleosol peak (log form **a2**, figs. 5 and 7)—can be interpreted as representing that earliest glacial loess and organic silt rider, for example, the Roxana loess–Robein silt package at the base of Wisconsin deposits. Any thickness (over 6 inches) of overlying organic sediments, such as muck, would be the low-logging culmination of this sequence.

This marker association defines the ultimate genetic glacial megasequence. The lower part (log form **a1**, figs. 5 and 7) is the log representation of the *top* of a terrestrial glacial megasequence ("top" meaning the top of soil); it represents the *end* of a glacigenic cycle, the equivalent of the condensed section and marine flooding unit of marine sequences—the record of maximum transgression of the atmospheric sea. The upper part (log form **a2**, figs. 5 and 7) is the log representation of the *base* of a terrestrial glacial megasequence ("base" meaning the base of silt [loess]); it represents the *beginning* of a glacigenic cycle, the equivalent of distal (suspension fallout) of prograding offlap of marine sequences—the record of beginning recession of the atmospheric sea (Bleuer and Brown, 1999; paralleling Galloway, 1989).

NONGLACIAL SEQUENCES

Alluvial sequences

Postglacial alluvial deposition is associated mostly with meandering stream environments. Alluvial deposits are simple in gross form and represent last episodes of channel migration over a flood plain. Deposits exhibit varying vertical and lateral incision into earlier glacial outwash bodies or other substrate. Deposits fine upward from the granular channel point-bar deposits, through thin interlaminated sand and silt to silt loam floodplain deposits and local clayey plug fills. The deposits may contain a more complex stratigraphic sequence evidenced within the overbank materials (Munson and others, 1992), reflecting lengthy periods of channel migrations.

The gamma-ray log form of alluvial sequences is a sharp funnel-shaped form reflecting that fining-upward progression (log form **b4–5**, figs. 5 and 19). The overbank component, where thick enough, presumably would contain one or more internal coarsening- and fining-upward grain-size and pedogenic cycles (similar to loess cycles below) representing both gradational and abrupt change in position of the meandering channel in relation to the site.

The log pattern is an obvious one in the obvious surface fluvial settings—a thin funnel. However, in the subsurface the same pattern could be variously interpreted in the absence of detailed sample study. For example, it is commonly capped by lake-bottom clays created by ice- or hydraulic-damming of alluvial valleys, with the (alluvial) funnel top tucked into the base of the (lake-bottom) bell. (See hypothetical examples, uppermost part of log form **a1** vs. log forms **b4–5**, fig. 5; possibly upper **b**, figs. 5 and 7; see real examples, figs. 18 and 20.)

Lake sequences

Many midwestern lake sequences were created in water bodies not fronting in glacial ice. In southern Indiana, these are the outwash or hydraulically dammed lake beds (Gray, 1971), which include examples in mouths of tributaries to the lower Wabash, White, Ohio, and Whitewater River valleys. Present reversed-gradient surface profiles in such tributaries illustrate the general position of the outwash dam, a giant levee that sent splays upstream into the tributaries during large-scale flows in the main valleys. It is likely that these are not simple homogeneous or gradational sequences. Rather, they should be expected to contain a history of early alluviation, flood cycles, and finally, slackwater lakes.

The gamma-ray log motif of such a sequence in the Evansville area (fig. 19) includes an upper, high-logging, nearly blocky form with thin, embedded bell and funnel cycles (log form **b1**, figs. 5 and 7). This records fine-grained materials in thin coarsening- and fining-upward cycles that represent shallow, swampy, backwater environments associated with small (postglacial through recent) alluvial channels. This unit appears to blend into the upland loess of adjacent hillsides (fig. 19, logs 13 and 2). Underlying is a slightly

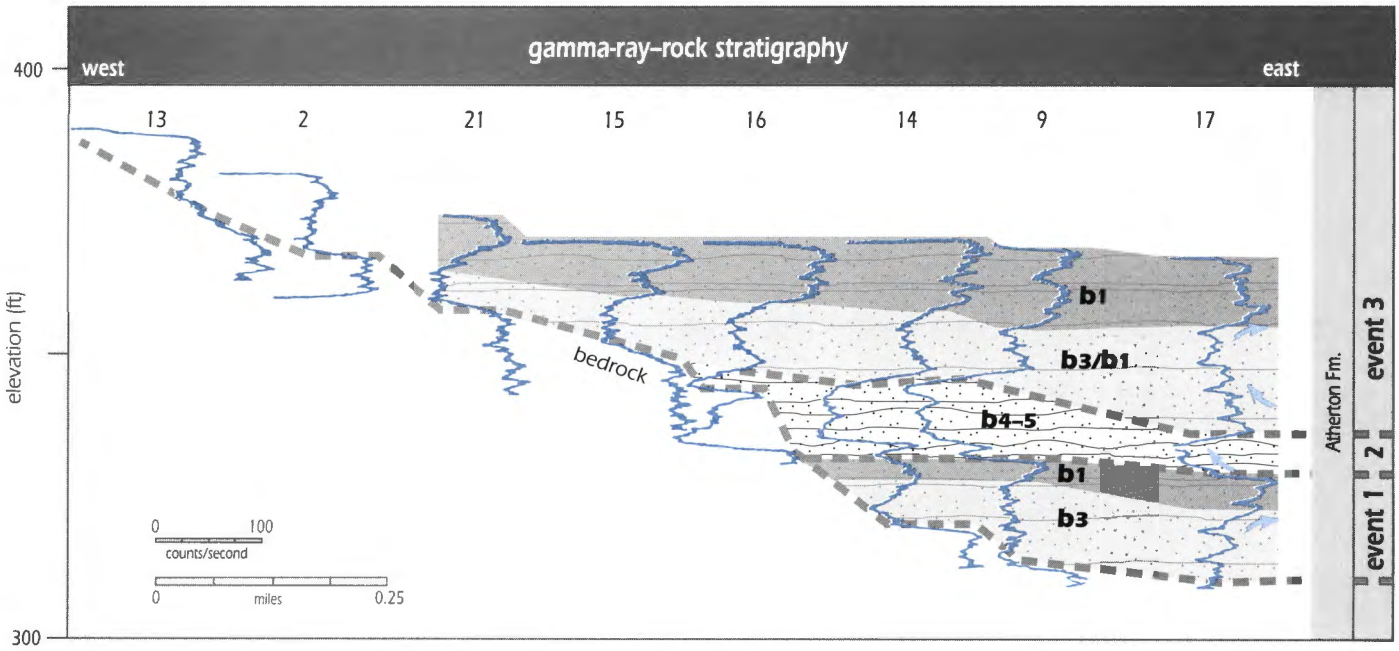


Figure 19. *Log cross section illustrating detailed relationships in the upland/lake plain transition, Bluegrass Creek valley near Evansville, southwestern Indiana. (Refer to Figure 5 for log-form designations.)*

lower-logging, bell-shaped form that is mostly characterized by its consistent, nearly linear rate decrease upward (log form **b3**, figs. 5 and 7). This coarsening-upward clay unit represents prograding bottomsets related to the growing dam to the south. Underlying that is a consistently lower-logging, funnel-capped, bell-shaped form (log form **b4–5**, figs. 5 and 7). This may record sand of an amalgamated, aggrading fluvial channel, point bar, and overbank of a through-flowing channel that appears graded to a level equivalent to that of the modern Ohio channel. The lowest log motif is largely a stack of thin funnel forms (log forms **b1**, **b3**, figs. 5 and 7) representing stacked alluvial sequences graded to an valley fill of an aggrading Ohio River.

Logs and detailed sample analysis allow soil and loess units of the upland to be traced through toeslope fan into the multiple lake and alluvial units of the valley. These data have served as a background for soil-period and liquefaction analysis within the area (Eggert and others, 1993; Samuelson and others, 1994).

Eolian and soil sequences

Windblown loess caps the landscape of central and southern Indiana, covering Wisconsin and older glacial materials and nonglaciated uplands. Surface soil development penetrates the silt loam parent loess 2 to 3 feet in depth, which in areas of thin loess penetrates much or all of the total loess thickness. A thin lower zone is known to be somewhat sandier than the main body in thin loess areas (so-called "gritty loess" of Ruhe, 1976). Outside the Wisconsin glacial limit, the base is defined by buried soil materials developed within various substrates on a complex landscape of many ages.

Detailed slow logging at expanded scales illustrates the subtle grain-size progressions of loess and soil sequences (fig. 20a, b, c). The gamma-ray log form of the soil/loess package is a subtle funnel shape (fig. 19, logs 13 and 2; fig. 20b, upper peak log B). The maximum clay bulge of the B2t horizon, the upper funnel peak, is evident even in these reduced examples. The underlying paleosol lies within the gradational pull-off from the shale peak in the Evansville examples.

Slow logging allows recognition of various subhorizons within the soil (Bleuer, *in* Hester and others, 1990) (fig. 19, log 21). In the Mt. Vernon example, increased intensity and thickness of the log's B-horizon peak in toeslope landscape positions (fig. 20b, section B), in contrast to

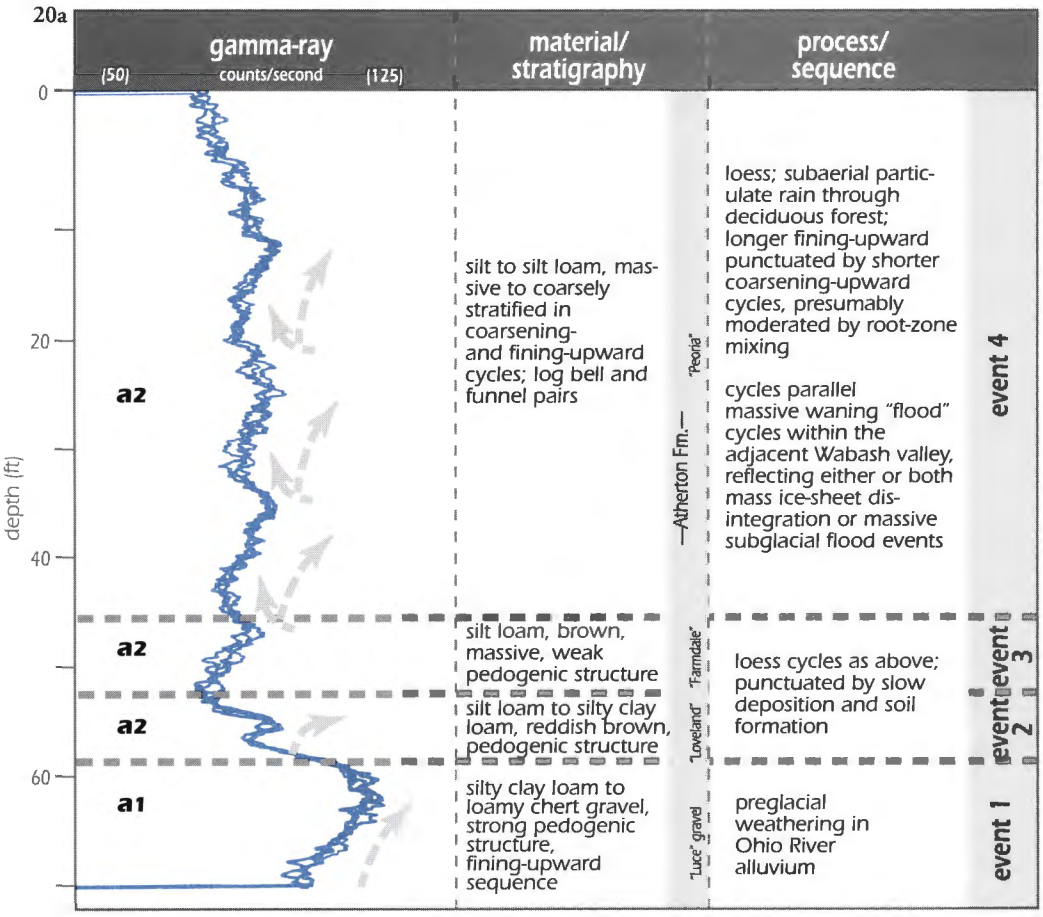
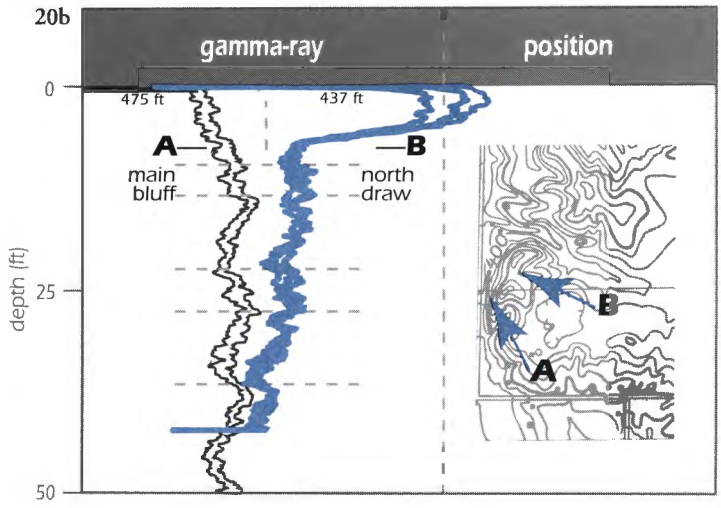


Figure 20. *Slow logs of depositional cycles in thick loess and soils, illustrating three separate three log runs as an "envelope" of log response. Logs were created using slow logging speed (2.5 ft/min, TC= 10) and expanded scale, and logging through 2-inch PVC pipe in open, 4-inch augered hole. Site is the Mt. Vernon section (Hayward and Lowell, 1993) in the southwesternmost Indiana loess bluffs.*

a. (above) *Loess cycles and soils at the main bluff section (multiple runs illustrated here are expanded in Figure 20c).*



b. (left) *Loess cycles in the landscape—a comparison of main bluff and adjacent valley illustrating apparent equivalent cycles draping the landscape (different elevation positions) and B-horizon absence (bluff position, A) and colluvial (B-horizon) accumulation (toeslope/valley position, B).*

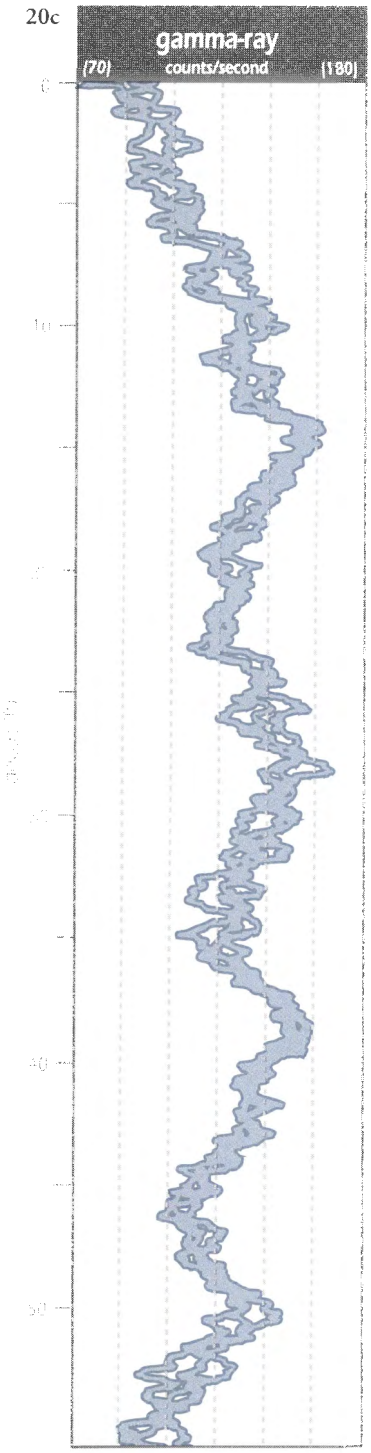


Figure 20 (continued).
c. *Comparisons of multiple slow runs, upper part of main bluff section (uppermost* **a2** *log forms of Figure 20a).*

its absence in the crest position, clearly records an over-thickening of the soil materials, indirectly illustrating the effects of Holocene (and probably post-settlement) soil erosion from the slopes above.

Large-scale elements of cyclic loess deposition, now studied primarily by the in vogue but tedious measurement of magnetic susceptibility of surface sections (Hayward and Lowell, 1993), could easily be discerned in gamma-ray logs (or probably magnetic susceptibility logs) run downhole at slow speeds and expanded scales (see Logging Methods section, pg. 4). Log profiles at the Mt. Vernon site (fig. 20) illustrate repeated sawtooth funnel cycles of linear ramps.

These profiles reflect gradations from stratified coarse silt through finer silty loam materials that are clearly visible in the adjacent surface section. The profiles suggest a relatively abrupt onset of coarse silt sedimentation followed by a gradation to finer silt. Thin, coarsening-upward legs might be inferred to be root-zone mixing superimposed on parent-material gradation.

In addition, loess sequence logs illustrate the nature of internal depositional profiles and marker units. The peak capping the "Loveland" loess at Mt. Vernon (fig. 20c) is the funnel-shaped cap to a lower sequence, a marker sequence itself defining the base of the primary, modern soil-capped loess sequence.

MAN-MADE SEQUENCES

Man-made deposits such as landfills, mine tailings, and earthen dams and embankments contain sedimentary sequences whose nature has been determined by engineering design or by on-site contingencies. Such sequences can be explored through downhole logging.

Mine-waste sequences

A form of man-made stratigraphy is seen in gob piles, the coal mine wastes of southwestern Indiana. Gob is a shaley, rocky, rubbly material that may be interlayered with coal slurry and other forms of fine washings. In a specific example (fig. 21), layers of gob, derived from a parting in the coal bed once mined at the site, contrast with the underlying coal slurry and a till substrate. Variations seen in the log reflect interlayered shaley and less shaley (higher and lower logging) zones.

Field description of these materials is obviously difficult and somewhat arbitrary. Here, materials described by the site geologists were various combinations of shale, underclay, coal, rash, sandstone, and pyrite. A log profile can provide an overall summary of such mixed conditions.

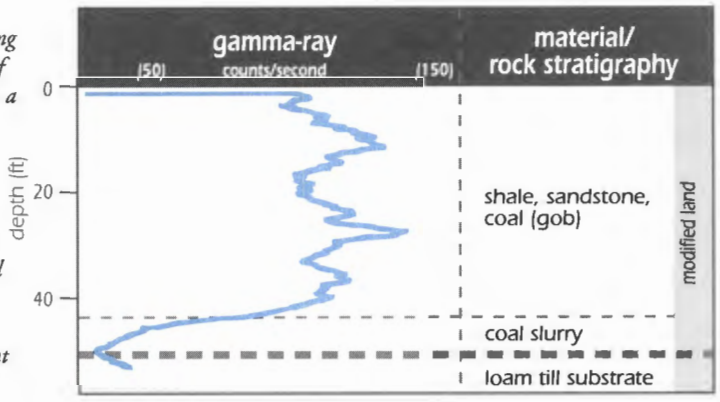


Figure 21. *Log illustrating man-made stratigraphy of coal mining waste within a gob pile at Green Valley Mine reclamation area, Vigo County, western Indiana. Materials are alternating lithologies of sandstone, coal, rash, and clinker (low count rates), shale (high count rate), and coal slurry (low count rate), atop till substrate.*

Landfill sequences

The stratigraphy of a municipal-waste landfill containing alternating layers of refuse and locally derived cover material (atop and within the confines of the local geology) can be readily illustrated through log profiles (Montgomery and others, 1985). In a central Indiana example (fig. 22), a site behind a levee on an alluvial flood plain overlying glacial outwash and thin dense tills, refuse (low-logging) and daily cover of recycled overbank silt (higher-logging) are clearly distinguishable from in situ silt below. Logs readily illustrate an area where the floodplain silt (log form **b4–5**) was excavated before landfilling, where direct hydrologic connection may exist between the fill and underlying gravel.

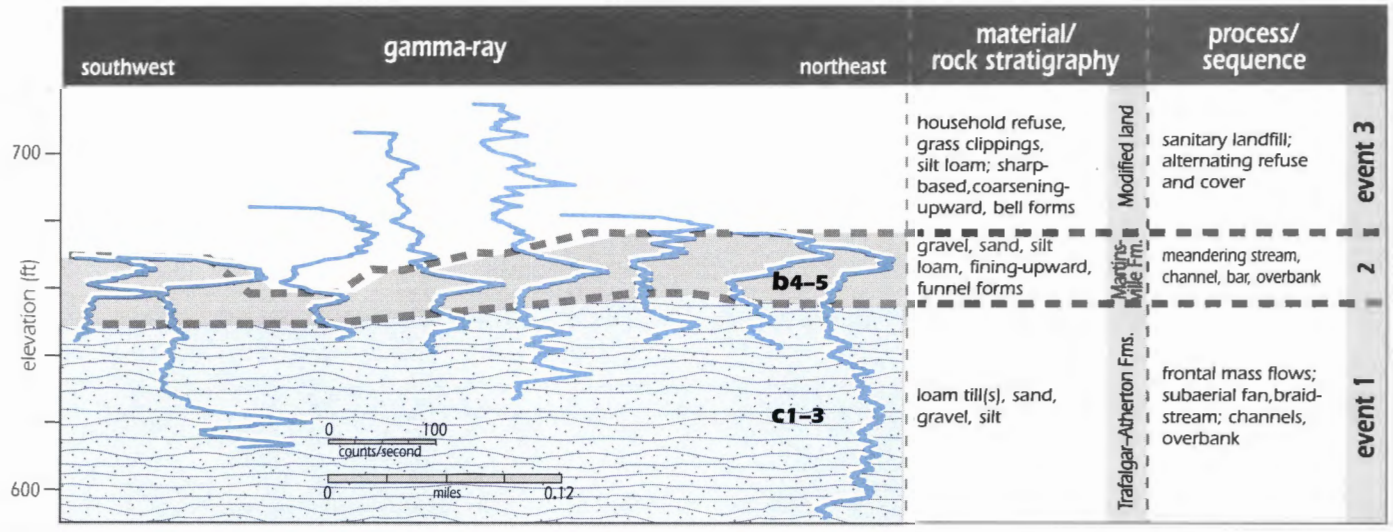


Figure 22. *Log cross section illustrating natural and man-made stratigraphy in and beside an area-method municipal landfill, Marion County, central Indiana. Note the log form of alternating layers of household municipal refuse (low count rates) and silty cover materials overlying alluvial overbank silt (immediate landfill base and the cover source; high count rate) with local man-made cutout. Underlying materials are glacial outwash and tills. No horizontal scale; total spacing is about ¾ mi. (Refer to Figure 5 for log-form designations.)*

Fill sequences

Engineering works such as earth-fill structures of highways and dams are stratified products that reflect an order dictated by available borrow material and engineering needs. An example is an interstate highway fill in southeastern Indiana (fig. 23), once the site of a major slide, where engineers continued to monitor compaction and slippage. Fill was derived from Ordovician shales and limestones of the region. Gamma-ray log response indicates zones of shale-rich, limestone-rich, and gradational lithologies of fill and is a record of the sequence of borrow within.

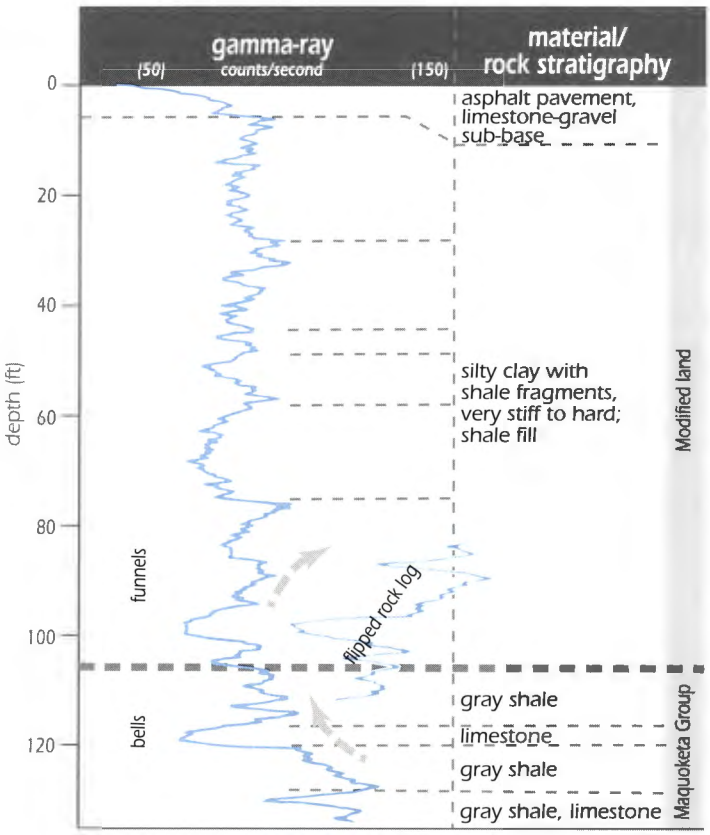


Figure 23. *Log illustrating man-made stratigraphy of highway fill at a site of a roadway subsidence from an aluminum-cased inclinometer hole, eastbound shoulder of Interstate Highway 74, Dearborn County, southeastern Indiana. Fill is an alternating mix of limestone- and shale-rich materials (low and high count rates, respectively) derived from the Ordovician rocks and derived soils. "Flipped rock log" suggests reversed stratigraphic order (of original rock sequence) reflected in fill.*

BENTONITE EFFECT

Thorium-rich bentonite grout or high-solids plugs produce effects that can be logged by gamma ray. Although uniformly mixed and emplaced grout does not greatly affect sequence appearance where sequences are well defined (fig. 24), subtle sequences could well be masked or altered by minor variances in grout composition. A bentonite-pellet hole plug creates a high-logging kick that allows the plug position to be identified, but that would be mistaken for exceptionally clayey strata if a plug was not otherwise expected.

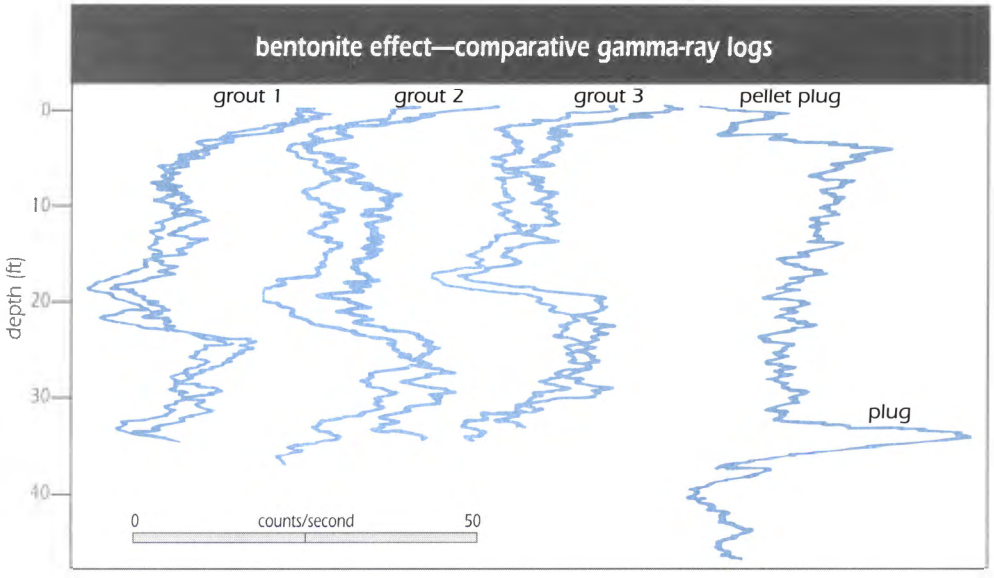


Figure 24. *Logs of demonstration holes grouted with a variety of bentonite-additive combinations and mixing-pumping combinations. Note the variation of bentonite-solids composition of the grout indicated by varying before (left-hand traces) and after (right-hand traces) logs and by vertical variation within the column (particularly grout 1) (logged through 2-inch PVC pipe in rotary-drilled, 6¾-inch holes). Location is near Brownsburg, central Indiana, with access provided courtesy of the Indiana Water Well Drilling Contractors Association. Materials represent the near-surface till/outwash sequence.*

ENVIRONMENTAL APPLICATIONS—THE OBJECTIVE RECORD

A broad range of environmental concerns involving water-resource protection, public health, engineering, and aesthetic issues relate directly to natural or man-made sequences of unconsolidated deposits. The most significant and recurring of these involve issues of ground-water occurrence, recharge, and protection.

Ground-water and gross stratigraphic issues can be considered mechanistically with great efficiency and possible adequacy using modern databases and plotting and analysis tools (fig. 25) (Bleuer and others, 2001; IGS Glacial Terrain Explorer, 2001). However, our primary working databases (such as Indiana's IDNR water-well database) record only the most glaring elements of vertical sequence because of inherent geologic variation *and* because of inherent "operator error," that is, human perception and reporting under varying drilling conditions (Bleuer and others, 2001). Their fundamental utility is in definition of the utilized aquifer at a place, and in regional-scale geostatistical analysis or machine mapping.

Figure 25. *Typical positions of granular materials (lighter-colored zones) within a till-plain stratigraphy dominated by "clay" (dark-colored zones). Plot is derived from the IGS iLITH working database version of the IDNR water-well database; example is from the Frankfort area of central Indiana (from Bleuer and others, 2001). Attempts to identify and correlate granular zones (aquifers) or stratigraphic packages amidst such variation, using water well data alone, are generally imprudent.*

Relatively few water research, engineering, or government permitted efforts use such methods routinely in exploration strategy. Yet such simple efforts can provide the most direct overall site view and a link to fundamental background understanding. And, they provide a permanent, objective record for clients and public (see Keys and Brown, 1973; Keys and others, 1979).

RELATIVE COSTS

For IGS endeavors, cost benefits of downhole logging are direct; the acquisition and interpretation process derived through "holes of opportunity" fills a vacuum, providing subsurface data where virtually none would otherwise exist. Most importantly, that data is in a usable and efficient form, one illustrating variation and vertical profiles of lithology directly and visually. In regional studies, logs are fundamental to a process; the logs are our primary basis of doing subsurface geology and, if forced to choose, logs alone have value, while sample sets alone do not. Thus, the benefits are enormous, whatever monetary scale factor may be applied.

In site-specific endeavors, benefits would not necessarily be so direct; the process would not replace standard methods of sampling and description where those are required. Rather, it could be part of a broader exploration strategy that provides an on-site, visual image of materials, contact positions, and variability that will be a guide in planning sampling strategies and in sample description. A major benefit is the encouragement of "smart" cornerstone tests that can quickly and inexpensively provide deep and laterally extensive coverage utilizing unsampled rotary or augered holes. The process can eliminate some need for an on-site professional presence. Further, it is a mechanism of using old, poorly documented wells within the exploration strategy. And, it could help tie site geology to regional geology.

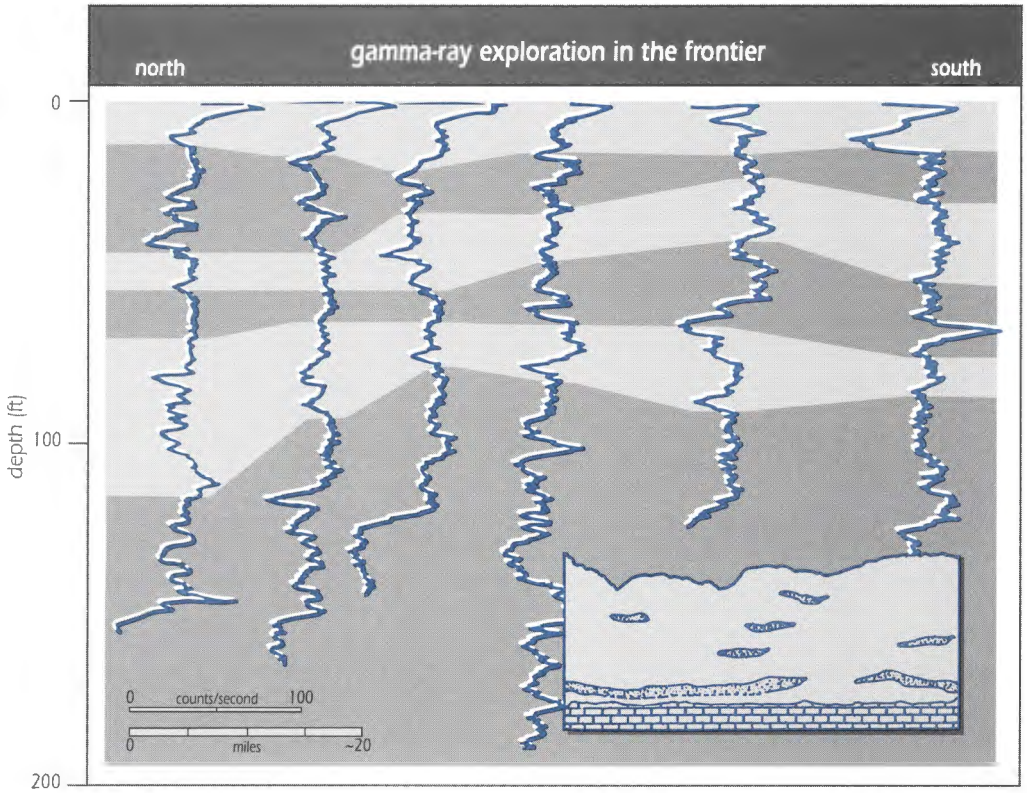


Figure 26. *Log cross section illustrating a suggested packaging of multiple, discrete units and sequences underlying the central till plain, and (inset) counting-down correlations developed from available lithologic logs (water-well logs) in the vicinity of a nearby hazardous-waste disposal site (after example of Mirsky, 1983, fig. 20). Gamma-ray log correlations are a preliminary working model, and possibly one that is largely wrong. Contrast this complexity of units (and corresponding complexity of hydrogeology) with the apparent simplicity of the lithologic section.*

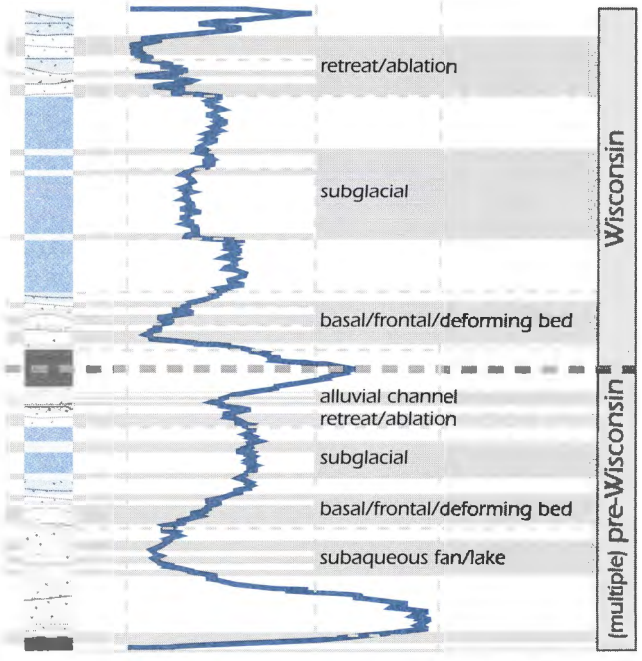


Figure 27. *The "stratigraphy of permeability." Typical positions of granular material (gray bands) within a log-defined till-plain stratigraphy (adapted from Figure 7a, a hypothetical log illustrating stacked megasequences of the central till plain). Compare with Figure 25.*

SUMMARY

The simple natural gamma-ray log—the fundamental lithologic log for use in glaciated terrain—can provide the basis for developing landscape and depositional-sequence models regionally. It can provide a basis for packaging and mapping units on-site.

Downhole geophysical logs alone may have greater basic value in environmentally oriented exploration in glacial and similar terrain than engineering logs and sample studies alone. But the methods combined can complete a total exploration strategy.

ACKNOWLEDGMENTS

The use of gamma-ray logs in Indiana glacial materials was enthusiastically promoted by Dr. George Otto during his periodic animated visits to the Survey. Dr. Otto had utilized "Widco" logs in soils engineering projects in northern and southwestern Indiana.

Our projects have involved the cooperation and encouragement of the Indiana Department of Natural Resources, Division of Water, particularly William Steen and Judith Beaty. Our studies have depended upon cooperation of water-well drilling contractors operating throughout the state, the U.S. Geological Survey Water Resources Division, private consultants, and property owners who have graciously made their work sites and completed wells available to us.

This report began as a presentation given to the 36th Annual Highway Geology Symposium (Bleuer, 1986). It has grown through various draft forms that have been distributed locally since 1985. As such, it includes illustrations from some of our earliest work combined with illustrations of concepts developed several years later. More complete use of logs in illustration of vertical sequences and depositional-sequence variation will be forthcoming as a fundamental background for regional atlas products.

REFERENCES

Aigner, T., Schauer, M., Junghans, W.-D., and Reinhardt, L., 1995, Outcrop gamma-ray logging and its applications—examples from the German Triassic: Sedimentary Geology, v. 100, p. 47–61.

Allen, D. R., 1975, Identification of sediments—their depositional environment and degree of compaction—from well logs, *in* Chilingorian, G. L., and Wolf, K. H., eds., Compaction of coarse-grained sediments: New York, Elsevier, Developments in sedimentology, v. 18a, p. 349–401.

Ballard, W. T., 1985, Sedimentology and controls on drainage development in the glaciofluvial White River system, northeast-central Indiana: Bloomington, Indiana University, M.S. thesis, 70 p.

Bleuer, N. K., 1974, Distribution and significance of some ice-disintegration features in west-central Indiana: Indiana Geological Survey Occasional Paper 8, 11 p.

———1975, The Stone Creek section, a historical key to the glacial stratigraphy of west-central Indiana: Indiana Geological Survey Occasional Paper 11, 9 p.

———1986, The nature of some glacial and manmade sedimentary sequences and their downhole logging by natural gamma ray, *in* West, T. R., Building on with sedimentary bedrock: Proceedings of the 26th Annual Highway Geology Symposium, p. 204–219.

———1989, Historical and geomorphic concepts of the Lafayette Bedrock Valley System (so-called Teays Valley) in Indiana: Indiana Geological Survey Special Report 46, 11 p.

———1991, The Lafayette Bedrock Valley System of Indiana—Concept, form, and till stratigraphy, *in* Melhorn, W. N., and Kempton, J. P., eds., Geology and hydrogeology of the Teays Mahomet Bedrock Valley System: Boulder, Colorado, Geological Society of America Special Paper 258, p. 51–77.

Bleuer, N. K., and Brown, S. E., 1999a, A "genetic-stratigraphic" basis for glacial-terrain characterization [abs.]: Geological Society of America Abstracts with Programs, North-Central Section, p. A-4–A-5.

Bleuer, N. K., and Brown, S. E., 1999b, Process, philosophy, and issues of glacial-terrain characterization at the Indiana Geological Survey [abs.]: Geological Society of America Abstracts with Programs, North-Central Section, p. A-5.

Bleuer, N. K., Brown, S. E., Dickson, M. L., Olejnik, J., O'Neal, M., and Rupp, R., 2001, Accelerated glacial terrain characterization and mapping: ARN 99-204m 319 project report, 45 p.

Bleuer, N. K., and Fraser, G. S., 1988, Mega-geometry of Wisconsinan glacial sequences [abs.]: Society of Economic Paleontologists and Mineralogists Midyear Meeting Abstracts, v. 5, p. 6.

Bleuer, N. K., and Fraser, G. S., 1989, Lithofacies interpretation of glacial sediments of the Kankakee River Basin from downhole gamma-ray logs [abs.]: Geological Society of America Abstracts with Programs, v. 21, p. 4.

Bleuer, N. K., and Melhorn, W. N., 1989, Glacial terrain models, north-central Indiana; the application of downhole logging to analysis of glacial vertical sequences, *in* Field Trip 2: Geological Society of America North-Central Section, p. 41–93.

Bleuer, N. K., Melhorn, W. N., and Pavey, R. R., 1983, Interlobate stratigraphy of the Wabash Valley, Indiana: Field Trip Guidebook, 30th Annual Field Conference, Midwest Friends of the Pleistocene, 135 p.

Bleuer, N. K., Melhorn, W. N., Steen, W. J., and Bruns, T. M., 1991, Aquifer systems of the buried Marion-Mahomet trunk valley (Lafayette Bedrock Valley System) of Indiana, *in* Melhorn, W. N., and Kempton, J. P., eds., Geology and hydrogeology of the Teays Mahomet Bedrock Valley System: Boulder, Colorado, Geological Society of America Special Paper 258, p. 79–89.

Bleuer, N. K., Olejnik, J., O'Neal, M., and Rupp, R., 2000, STATEMAP 2000 U.S. 31 Corridor North: Indiana Geological Survey STATEMAP project report.

Bleuer, N. K., and Woodfield, M. C., 1993, Glacial terrain, sequences, and aquifer sensitivity, Porter County, Indiana: Indiana Geological Survey Open-File Report 93-2, 61 p.

Bristow, O., and Bernius, G., 1984, Field evaluation of a magnetic susceptibility logging tool, *in* Current research: Geological Survey of Canada Paper 84-A, p. 453–462.

Brodzikowski, K., and van Loon, A. J., 1991, Glacigenic sediments: New York, Elsevier, Developments in Sedimentology 49, 674 p.

Brown, S. E., 1994, Geologic terrains of the Gary 7.5 minute quadrangle: Indiana Geological Survey Open-File Report 94-15, 2 plates.

Brown, S. E., 1996a, Geologic terrains of the Crown Point 7.5 minute quadrangle: Indiana Geological Survey Open-File Report 96-20, 3 plates, 9 p.

Brown, S. E., 1996b, Geologic terrains of the St. John and the Dyer 7.5 minute quadrangles in Indiana: Indiana Geological Survey Open-File Report 96-21, 3 plates, 8 p.

Brown, S. E., 2000, 1999 STATEMAP Michiana Corridor Glacial Geologic Terrain Map Set: Indiana Geological Survey STATEMAP project report.

Brown, S. E., and Bleuer, N. K., 1996, Geologic terrain map of the southern Lake Michigan rim, Part 1 of an atlas in three parts: Indiana Geological Survey Open-File Study, in preparation.

Brown, S. E., Bleuer, N. K., O'Neal, M., Olejnik, J., and Rupp, R., 2000, Glacial terrain EXPLORER: Indiana Geological Survey Open-File Study 00-08, 3 CDs.

Brown, S. E., Ferguson, V. R., and Fleming, A. H., 1993, Hydrogeologic framework of Marion County, Indiana: Indiana Geological Survey Open-File Report 93-5.

Brown, S. E., and Thompson, T. A., 1995a, Geologic terrains northwestern Lake County, Indiana: Indiana Geological Survey Open-File Report 95-05, 4 plates.

Brown, S. E., and Thompson, T. A., 1995b, Geologic terrains of the Chicago 30 X 60 minute quadrangle in Indiana: Indiana Geological Survey Open-File Report 95-09, 1 plate.

Cant, D. J., 1984, Subsurface sedimentology: Geoscience Canada, v. 11, p. 115–121.

Chamberlain, A. K., 1984, Surface gamma-ray logs–a correlation tool for frontier areas: Bulletin of the American Association of Petroleum Geologists, v. 68, p. 1040–1043.

Chamberlin, T. C., 1883, Preliminary paper on the terminal moraine of the Second Glacial Epoch: U.S. Geological Survey Annual Report 3, p. 291–402.

Christiansen, E. A., 1967, Geology and groundwater resources of the Saskatoon area (73-B), Saskatchewan: Saskatchewan Research Council Geology Division Map 7.

———ed., 1970, Physical environment of Saskatoon, Canada: National Research Council of Canada Publication 11378, 68 p.

Clayton, L., 1999, Diachronic diatribe [abs.]: Geological Society of America Abstracts with Programs, North-Central Section, p. A-10

Clayton, L., and Moran, S. L., 1974, A glacial process-form model, *in* Coates, D. R., Glacial geomorophology: SUNY Binghamton, p. 89–119.

Commission on Standardization of Laboratory and Field Tests, International Society for Rock Mechanics, 1981, Suggested methods for geophysical logging of boreholes [abs.]: International Journal of Rock Mechanics Mining Sciences and Geomechanics Abstracts, v. 18, p. 67–84.

Dyke, J. H., Keys, W. S., and Meneley, W. A., 1972, Application of geophysical logging to groundwater studies in southeastern Saskatchewan: Canadian Journal of Earth Science, v. 9, p. 78–94.

Eggert, D. L., Eckhoff, W. R., Bleuer, N. K., and Samuelson, A. C., 1993, Shear-wave velocities and soil periods of unconsolidated sediments (soils) that underlie Evansville, Indiana: 1993 National Earthquake Conference Proceedings, p. 317–326.

Ehlers, J., and Iwanoff, A., 1983, Geophysical well logging and its stratigraphic interpretation, *in* Ehlers, J., ed., Glacial deposits in northwest Europe: Rotterdam, Balkema, p. 263–265.

Elkington, P. A. S., Stouthamer, P., and Brown, J. R., 1982, Rock strength predictions from wireline logs [abs.]: International Journal of Rock Mechanics Mining Sciences and Geomechanics Abstracts, v. 19, p. 91–97.

Ettenson, F. R., Fulton, L. P., and Kepferle, R. C., 1979, Use of scintillometer and gamma-ray logs for correlation and stratigraphy in homogeneous black shales–summary: Geological Society of America Bulletin, v. 90, p. 421–423.

Eyles, N., 1983, Glacial geology–a landsystems approach, *in* Eyles, N., ed., Glacial geology–an introduction for engineers and earth scientists: New York, Pergamon, p. 1–18.

Eyles, N., and Clark, B. M., 1985, Geophysical well logging and the analysis of subsurface glacial depositional systems–an example from the Lake Ontario and Huron basins [abs.]: Geological Society of America Abstracts with Programs, North-Central Section, v. 17, p. 287.

Eyles, N., Clark, B. M., Kaye, B. G., Howard, K. W. F., and Eyles, C. H., 1985, The application of basin analysis techniques to glacial terrains–an example from the Lake Ontario Basin, Canada: Geoscience Canada, v. 12, p. 22–32.

Eyles, N., Eyles, C. H., and Miall, A. D., 1983, Lithofacies types and vertical profile models–an alternative approach to the description and environmental interpretation of glacial diamict and diamictite sequences: Sedimentology, v. 30, p. 393–410.

Eyles, N., and Menzies, J., 1983, The subglacial landsystem, *in* Eyles, N., ed., Glacial geology, an introduction for engineers and earth scientists: New York, Pergamon, p. 19–70.

Farvolden, R. N., Greenhouse, J. P., and Karrow, P. F., 1985, Grant 28 subsurface Quaternary stratigraphy using borehole geophysics, *in* Milne, V. G., ed., Geoscience research grant summary of research, 1984–1985: Ontario Geological Survey Miscellaneous Paper 127, p. 4–9.

Fertl, W. H., 1979, Gamma ray spectral data assists in complex formation evaluation: Transactions of the Society of Professional Well Log Analysis, Sixth Formation Evaluation Symposium, London [also Dresser Atlas Publication 3335, 62 p.].

Fleming, A. H., 1993, The hydrogeology of Allen County, Indiana–a geologic and ground-water atlas: Indiana Geological Survey Special Report 57, 111 p.

Follmer, L. R., 1978, The Sangamon soil in its type area–a review, *in* Mahaney, W. C., ed., Quaternary soils, Toronto, York University, p. 125–165.

Françá, A. B., and Potter, P. E., 1991, Stratigraphy and reservoir potential of glacial deposits of the Itararé Group (Carboniferous-Permian), Paraná Basin, Brazil: American Association of Petroleum Geologists Bulletin, v. 75, p. 62–85.

Fraser, G. S., 1993, Sedimentology of late Wisconsinan alluviation of the Wabash Valley: Indiana Geological Survey Special Report 56, 18 p.

Fraser, G. S., and Bleuer, N. K., 1991a, Geologic framework of the aquifers in the Valparaiso Moraine: Indiana Geological Survey Occasional Paper 59, 8 p.

Fraser, G. S., and Bleuer, N. K., 1991b, Geologic framework of the aquifers in the Kankakee River Lowland: Indiana Geological Survey Occasional Paper 60, 10 p.

Galloway, W. E., 1989, Genetic stratigraphic sequences in basin analysis I–architecture and genesis of flooding-surface bounded depositional units: American Association of Petroleum Geologists Bulletin, v. 73, p. 125–142.

Galloway, W. E., Ewing, T. E., Garrett, C. M., Tyler, N., and Beboit, D. G., 1983, Atlas of major Texas oil reservoirs: Austin, Texas Bureau of Economic Geology, 139 p.

Gray, H. H., 1971, Glacial lake deposits in southern Indiana–engineering problems and land use: Indiana Geological Survey Report of Progress 30, 15 p.

Gold, L. W., ed., 1981, Proceedings of the symposium on processes of glacier erosion and sedimentation: Annals of Glaciology, v. 2, p. 176–182.

Greenhouse, J. P., Karrow, P. F., and Farvolden, R. N., 1983, Grant 128 subsurface Quaternary stratigraphy using borehole geophysics, *in* Pye, E. G., Geoscience research grant program summary of research, 1982–1983: Ontario Geological Survey Miscellaneous Paper 113, p. 93–95.

Greenhouse, J. P., and Pehme, P. E., 1986, An approach to determining stratigraphic and physical properties of overburden using borehole geophysics, *in* Vileen, P. G., ed., Borehole geophysics for mining and geotechnical applications: Geological Survey of Canada Paper 85-27, p. 7–11.

Gruver, B. L., 1984, Pleistocene valley train deposition, Whitewater River, southeastern Indiana and southwestern Ohio: Bloomington, Indiana University, M.S. thesis, 145 p.

Guyod, H., 1966, Interpretation of electric and gamma ray logs in water wells: Log Analyst, v. 65, p. 30–44.

Harrison, W., 1963, Geology of Marion County, Indiana: Indiana Geological Survey Bulletin 28, 78 p.

Hasenmueller, N. R., Bleuer, N. K., and Woodfield, M. C., 1994, Radon, methane, and trace elements in ground water from glacial aquifers, LaPorte County, Indiana: Indiana Geological Survey Open-File Report 94-5, 36 p.

Hasenmueller, N. R., Branam, T., and Bleuer, N., Olejnik, J., Cohen, D., and O'Neal, M., 2001, Evaluation of ground-water age and chemistry relations in aquifer systems in Lake, Porter, and LaPorte Counties of Indiana: Indiana Geological Survey Open-File Study 01-21, CD.

Hayward, R. K., and Lowell, T. V., 1993, Variations in loess accumulation rates in the Midcontinent, United States, as reflected by magnetic susceptibility: Geology, v. 21, p. 821–824.

Hearst, J. R., and Nelson, P. N., 1985, Well logging for physical properties: New York, McGraw-Hill, 571 p.

Hester, N. C., Bleuer, N. K., Eggert, D. E., and Hasenmueller, N. R., 1990, Geologic framework and physical properties of bedrock and lacustrine deposits in and around McCutchanville, Indiana: 1989–90 Midyear report, Office of Surface Mines Contract GR 993184.

Johnson, W. H., 1976, Quaternary stratigraphy in Illinois—status and current problems, *in* Mashaney, W. C., ed., Quaternary stratigraphy of North America: Stroudsburg, Pa., Dowden, Hutchison and Ross, p. 161–196.

Karrow, P. F., Greenhouse, J. P., and Ross, L. C., 1986, Subsurface Quaternary stratigraphy of the Kitchener-Waterloo area, Ontario [abs.]: Geological Society of America Abstracts with Programs, v. 18, p. 312.

Kemmis, T. J., 1981, Importance of regulation process to certain properties of basal tills deposited by the Laurentide ice sheet in Iowa and Illinois, U.S.A., *in* Gold, L. W., ed., Proceedings of the symposium on processes of glacier erosion and sedimentation: Annals of Glaciology, v. 2, p. 147–152.

Keys, W. S., 1989, Borehole geophysics applied to ground-water investigations: Dublin, Ohio, National Water Well Association, 313 p.

Keys, W. S., and Brown, R. F., 1973, Role of borehole geophysics in underground waste storage and artificial recharge, *in* Braunstein, Jules, ed., Second international symposium on underground waste management and artificial recharge, New Orleans: v. 1, p. 147–191.

Keys, W. S., Eggers, D. E., and Taylor, T. A., 1979, Borehole geophysics as applied to the management of radioactive waste-site selection and monitoring, *in* Carter, M. W., and others, eds., Management of low-level radioactive waste: New York, Pergamon, v. 2, p. 955–980.

Keys, W. S., and MacCary, L. M., 1971, Application of borehole geophysics to water-resources investigations: Techniques of Water-Resources Investigations of the U.S. Geological Survey, Book 2, chap. E1, 126 p.

Levell, B. K., Braakman, J. H., and Rutten, H. W., 1988, Oil-bearing sediments of Gondwana glaciation in Oman: American Association of Petroleum Geologists Bulletin 72, p. 775–796.

Locat, J., 1975, Une methode d'utilisation quantitative de la sonde neutron-neutron (porosite) pour l'etude des depots meubles: Geological Survey of Canada, Commission Geologique Etude 74-42, 43 p.

Lorch, S., 1985, Correction for the influences of the borehole on the measurement of natural gamma radiation in the borehole [text in German]: Geologisches Jahrbuch, ser. E, no. 32, p. 3–36.

Miall, A. D., 1990, Principles of sedimentary basin analysis, 2nd edition: New York, Springer-Verlag, 668 p.

Mirsky, Arthur, 1983, Urban and engineering geology of the Indianapolis area (Field Trip 8), *in* Shaver, R. H., and Sunderman, J. A., eds., Field trips in midwestern geology: Geological Society of America, Indiana Geological Survey, and Department of Geology, Indiana University, v. 2, p. 87–120.

Montgomery, R. J., Wierman, D. A., Taylor, R., and Kock, H. A., 1985, Use of downhole geophysical methods in determining the internal structures of a large landfill, *in* Surface and borehole geophysical methods in ground water investigations: Second National Conference, National Water Well Association, p. 377–386.

Moran, S. R., Clayton, L., Hooke, R. B., Fenton, M. M., and Andriashek, L., 1980, Glacier-bed landforms of the prairie region of North America: Journal of Glaciology, v. 25, p. 457–476.

Munson, P. J., Munson, C. A., Bleuer, N. K., and Labitzke, M. D., 1992, Distribution and dating of prehistoric earthquake liquefaction in the Wabash Valley of the central U.S.: Seismological Research Letters, v. 63, p. 337–342.

Norris, S. E., 1972, The use of gamma logs in determining the character of unconsolidated sediments and well construction features: Ground Water, v. 10, no. 6, p. 14–21.

North American Commission on Stratigraphic Nomenclature, 1983, North American Stratigraphic Code: American Association of Petroleum Geologists Bulletin, v. 67, p. 841–875.

Paul, M. A., 1983, The superglacial landsystem, *in* Eyles, N., ed., Glacial geology, an introduction for engineers and earth scientists: New York, Pergamon, p. 71–90.

Pirson, S. J., 1977, Geologic well log analysis: Houston, Gulf Publishing Co., 377 p.

Rasmussen, K. R., and Bai, W., 1987, Logging in deep water wells in central Jutland, Denmark: Boreas, v. 16, p. 313–404.

Reed, P. C., 1974, Data from controlled drilling program in Lee and Ogle Counties, Illinois: Illinois State Geological Survey Environmental Geology Notes 71, 40 p.

Reed, P. C., 1985, Comparative analyses of surface resistivity surveys and natural-gamma radiation borehole logs in Illinois, *in* Surface and borehole geophysical methods in ground water investigation: Second National Conference, National Water Well Association, p. 215–227.

Reed, P. C., Sargent, M. L., and Gross, D. L., 1983, Use of natural-gamma logging for characterization of bottom sediment in the Mississippi River [abs.]: Geological Society of America Abstracts with Programs, v. 15, p. 668.

Ruhe, R. V., 1976, Stratigraphy of mid-continent loess, U.S.A., *in* Mahaney, W. C., ed., Quaternary stratigraphy of North America: Stroudsburg, Pa., Dowden, Hutchinson and Ross, p. 197–211.

Rutter, N. W., and Wyder, J. E., 1969, Application of borehole stratigraphic techniques in areas of mountain glacial drift in Alberta, Canada: Canada Geological Survey Paper 69-35, 16 p.

Samuelson, A. C., Eggert, D. L., and Eckhoff, W. R., 1994, Downhole shearwave studies enhanced by gamma log lithologic interpretations: Environmental and Engineering Geophysical Society Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, p. 481–498.

Scholle, P. A., and Spearing, D., eds., 1982, Sandstone depositional environments: American Association of Petroleum Geologists Memoir 31, 410 p.

Selley, R. C., 1976, Subsurface environmental analysis of North Sea sediments: Bulletin of the American Association of Petroleum Geologists, v. 60, p. 184–195.

———1978a, Ancient sedimentary environments: Ithaca, N. Y., Cornell University Press, 287 p.

———1978b, Concepts and methods of subsurface facies analysis: American Association of Petroleum Geologists Education Course Note Series, no. 9, 86 p.

Senger, J. A., 1985, Defining glacial stratigraphy with the neutron log, *in* Surface and borehole geophysical methods in ground water investigations: Second National Conference, National Water Well Association, p. 355–368.

Serra, O., 1985, Sedimentary environments from wireline logs: Schlumberger, Inc., 211 p.

Shedlock, R. J., Cohen, D. A., Imbrigiotta, T. E., and Thompson, T. A., 1994, Hydrogeology and hydrochemistry of the dunes and wetlands along the southern shore of Lake Michigan, Indiana: U.S. Geological Survey Open-File Report 92-139, 85 p.

Slatt, R. M., Jordan, D. W., D'Agostino, A. E., and Gillespie, R. H., 1992, Outcrop gamma-ray logging to improve understanding of subsurface well log correlations, *in* Hurst, A., Griffiths, C. M., and Worthington, P. F., eds, Geological applications of wireline logs II: Geological Society of America Special Publication 65, p. 3–19.

Taylor, T. A., and Dey, J. A., 1985, Bibliography of borehole geophysics applied to ground-water hydrology: U.S. Geological Survey Circular 426, 62 p.

Timur, A., and Toksoz, M. N., 1985, Downhole geophysical logging: Annual Review of Earth and Planetary Science, v. 13, p. 313–344.

Whiteley, R. J., 1983, Recent developments in the applications of geophysics to geotechnical investigation in in situ testing for geotechnical investigations–Proceedings of an extension course for geotechnical investigations: Rotterdam, Balkema, 110 p.

Wickham, S. S., and Johnson, W. H., 1981, The Tiskilwa Till, a regional view of its origin and depositional processes, *in* Gold, L. W., ed., Proceedings of the symposium on processes of glacier erosion and sedimentation: Annals of Glaciology, v. 2, p. 176–182.

APPENDIX I

Distribution of potassium (K), uranium (U), and thorium (Th) in selected rocks and mineral (from Fertl, 1979)

mineralogy		element		
		K (%)	U (ppm)	Th (ppm)
clay minerals	illilte	4.5	1.5	———
	smectite	0.2	2–5	14–24
	bentonite	<0.5	1–20	6–50
carbonates		0–2.0	0.1–9.0	0.1–7.0
crystalline rocks	gabbro	0.5–0.6	0.9±	2.7–3.8
	granite	2.8–4.3	3.6–4.7	19–20
accessory minerals	epidote	———	20–50	50–500
	monazite	———	500–3,000	$2.5x10^4$
	zircon	———	300–3,000	100–250
feldspars	orthoclase	11.8–14.0	———	<0.01
	plagioclase	0.5	———	<0.01

Count rates for potassium, uranium, and thorium (from Fertl, 1979)

rate	element
11,200±400 cpm	potassium—15% by volume
7,300±300 cpm	uranium—125 ppm
4,400±150 cpm	potassium—465 ppm

APPENDIX 2

Log motifs common to north-central Indiana

(modified from Bleuer and Melhorn, 1989)

AP—(A-proximal)): defined initially from large-scale sequences in the central Kankakee Basin and beneath the Valparaiso Moraine and the LaPorte fan; a generally coarsening/thickening-upward sequence, a progressing from fine-grained lake sediments through coarser sub-aerial fan sediments, a proximal(ling) upward sequence; the same pattern could equally well represent delta and fan infill of small proglacial or supraglacial basins.

ADP—(A-distal blocky): defined from both large fan or fan-delta and small basin infill sequences; pattern refers to the equivalent of the lower (more distal) element of AP, with the addition of a positive block within its upper part; the block is commonly a diamict and occurs at the position of transition from silt to fine sand; it is interpreted as a delta-toe density-flow deposit.

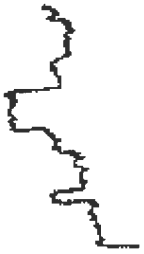
IAD—(inverse A-distal): defined from till-stratigraphic successions of north-central Indiana, commonly below the pre-Wisconsin paleosol or within the Wisconsin ablation sequence; an upside-down equivalent of the lower (distal) part of the A-proximal succession; a fining/thickening-upward sequence of diamictons and/or fine-stratified sediments; interpreted as fluvial and/or late-stage basin infill or, in larger sequences, as retrogradational fans.

BP—(B-proximal): defined from large fan sequences of the Lake Michigan Rim; a fining/thickening-upward pattern, fining related to introduction of diamicts; interpreted as the upward, ultimate consummation of the proximal(ling) of an A-proximal pattern, completing a fundamental glacial "offlap" sequence of main text.

BPB—(B-proximal blocky): common to stacked stratigraphies of till-plain settings; similar to B-proximal, but with blocky units appearing abruptly in the upper half; the blocks, mostly representing diamicts, are suggestive of high-viscosity plug flows, as opposed to thin, interbedded fluid flows below; common as a fining/thickening run up to a basal till block, the fundamental element of the glacial "offlap" sequence of main text.

IBP—(inverse B-proximal): an inverted BPB, also common to till-plain settings; occurs mostly atop blocky basal till units; grossly similar in form to A-proximal deltaic form, but representing diamicts with coarsening-thickening granular beds upward; interpreted as early-stage ice disintegration-sediment gravity flows in closed basins, grading to micro deltas and through-flowing fluvial bedload.

B—(blocky): common to till-plain settings and also as elements of most other overall log motifs; a uniform, straight-line, "crew-cut" form with sharp boundaries; interpreted as basal till or as plug-flow elements of IBP and BPB.



IB—(inverse blocky): inverse (log-logging) of B motif; granular material; sharp base suggests interpretation as channel cut-and-fill.


UNIVERSITATIS SIGILLUM
INDIANAENSIS
MDCCCXX
ET VERITAS


INDIANA GEOLOGICAL SURVEY 1837
INDIANA UNIVERSITY