

Chapter 2

Facies Analysis and Sequence Stratigraphy

The three-dimensional distribution of bodies of rock and sediments with different sedimentological properties and associated hydraulic properties is controlled to varying degrees by the depositional history of the strata of interest. Primary (depositional) variations in sediment textures and fabrics are modified by diagenetic processes, such as compaction, dissolution, and cement precipitation. A facies is a body of sedimentary rock with specified characteristics, which may include lithology (lithofacies), fossils (biofacies), and hydraulic properties (hydrofacies). Sedimentary facies analysis is based on the concept that facies transitions occur more commonly than would be expected if sedimentation processes were random. A facies model (or type model) is an idealized sequence of facies defined as a general summary of a specific sedimentary environment. Sequence stratigraphy is based on the concept that the sedimentary rock record can be divided into unconformity-bounded sequences, which reflect the sedimentological response to sea level changes, subsidence, and sediment supply. The value of facies analysis and sequence stratigraphy is that they can provide some predictability to the facies distribution between data points (i.e., wells). Where there is an underlying sedimentological control on the distribution of the hydraulic properties in aquifer systems, facies analysis can be used to better incorporate the underlying sedimentological fabric into groundwater models.

2.1 Introduction

A fundamental concept in the characterization of sedimentary rock aquifers is that the geometry and hydraulic properties of aquifers and confining units are related to sediment and rock types, which are, in turn, related to their depositional and diagenetic history. Geological heterogeneity is the product of complex yet discernable geological processes. Sedimentological studies can, therefore, provide valuable information towards quantifying the spatial structure of aquifers and reservoirs

(Davis et al. 1993). In particular, connectivity of bodies of sediment with high and low-hydraulic conductivity is a key feature in controlling groundwater flow and solute transport. Connected high-hydraulic conductivity zones act as flow conduits and connected low-hydraulic conductivity strata act as confining strata.

The spatial variability of textural and hydraulic parameters within sedimentary deposits has an element of predictability based on an understanding of depositional processes and environments. It has long been appreciated in the oil and gas industry that the vast data on modern and ancient sediments and sedimentary rocks from the sedimentology discipline can be invaluable for reservoir and aquifer characterization. Knowledge of the geometrical, compositional, and textural characteristics of sediment and rock types from different depositional environments, obtained from the vast sedimentological literature, can provide a valuable framework for determining the architecture of aquifers and groundwater basins. Indeed, the need for information on the geology of oil and gas reservoirs has been the ultimate primary driver for sedimentological research over the past 50 years. In terms of applied hydrogeology, the principal value of sedimentological data is that it can allow for more accurate interpolation and extrapolation of limited point data.

Tools such as facies analysis, sequence stratigraphy, and geostatistical analysis are used to evaluate the three-dimensional relationships among sedimentary strata and their relationships to aquifer hydraulic properties. An underlying assumption in characterizing reservoir or aquifer strata from outcrop studies is that the original framework of the sediments (i.e., grain-size distribution, texture, and fabric) determined by depositional processes still predominantly controls the permeability structure of the rock, although not necessarily the magnitude or even degree of contrast (Stalkup 1986).

Hydrogeologists would like to be able to use generic facies models to extrapolate limited field data and thereby avoid the expense and time involved in collecting more detailed site-specific information (Anderson 1989). Information on the depositional environment of aquifer and confining strata may allow hydrogeologists to better predict the expected spatial trends in hydraulic conductivity from limited site-specific information. Facies analysis is used in groundwater investigations in three main manners (Neton et al. 1994):

- (1) deterministic prediction of trends in hydraulic conductivity from a limited number of point measurements
- (2) assessment of the validity of stochastically determined distributions of hydraulic conductivity
- (3) as a guide in well placement and the interpretation of aquifer test data.

It must be recognized that the hydraulic properties of sedimentary rocks can never be fully predictable. Every sedimentary formation has its unique features that cannot be predicted from general geological models. Additionally, primary textural differences may be overprinted by diagenesis, which, as a broad generalization, becomes more important with the burial history of the sediments. The interaction of diagenesis and depositional texture may be either a positive or negative feedback.

A positive feedback occurs when, for example, low-permeability clay-rich beds are preferentially compacted, further increasing the permeability contrast with clay-poor sands. In karstic carbonate systems, high permeability strata and fractured horizons are preferential loci for fluid flow and associated dissolution and permeability increase. A negative feedback would occur if high permeability sands are the preferential site of cementation due to enhanced solute transport associated with greater fluid flow rates.

2.2 Facies, Facies Sequences, and Facies Models

The sedimentary facies concept was reviewed by Middleton (1978), Walker (1984), Reading (1986a), Selley (1985; 2000), and many others. The most basic definition of a facies is a “body of rock with specified characteristics” (Reading 1986b, p. 4). Sedimentary facies are defined as areally restricted, three-dimensional bodies of rock or sediment that are distinguished from other bodies by their lithology, sedimentary structures, geometry, fossil content, and other attributes. Lithofacies are defined solely on the basis of their lithology. Similarly, biofacies are defined based on their fossil content. Ichnofacies are categorized based on their trace fossil assemblage.

The facies concept has been extended in some definitions to also reflect a particular depositional process or environment. For example, a purely descriptive lithofacies is a well-sorted, unfossiliferous, medium-grain quartz sand, whereas a corresponding genetic description might be a medium-grained quartz *dune* sand. Some have objected to the genetic definition of facies, in preference to retaining the original purely descriptive definition (e.g., Middleton 1978; Walker 1984; Selley 1985, 2000).

Anderton (1985) defined an interpretative (genetic) facies as a label summarizing the interpretation of the processes and environment of deposition of a certain unit of rock. Interpretative or genetic facies descriptions are commonly used. Anderton (1985) observed that there should be no objection to the use of interpretative facies so long as the distinction between descriptive and interpretative facies is clear from the context. It is normally obvious from the context whether the term facies is used in a descriptive or interpretative sense (Walker 2006).

Facies can be defined on a variety of scales depending upon (Walker 2006)

- the purpose of the study
- the time available to make the measurements
- the abundance of descriptive features in the studied strata.

For example, a ripple cross-laminated sand can be defined as a single facies, or constituent individual ripples or cross-laminated beds can be defined as a facies. Typically, in groundwater investigations, scales on the coarse end (decimeter to meter scale) of the spectrum are appropriate as the data will eventually have to be

upscaled to be incorporated into a large-scale (often kilometer or greater) groundwater model.

The principle value of facies analysis lies in that only a finite number of facies occurs repeatedly in rocks of different ages all over the world (Selley 1985). This provides important order in the analysis of sedimentary rock, which would not occur if each bed of rock were treated as a unique entity. However, facies have limited value when taken in isolation. A knowledge of the context and associations of facies is critical for environmental interpretations (Reading 1986b) and, in turn, realizing the predictive value of facies analysis.

Facies sequences are a series of facies whose transitions and relationships are geologically significant with respect to depositional environment (Walker 1984; Reading 1986b). The term ‘sequence’ had been co-opted in the sequence stratigraphy literature (Sect. 2.4) to have a more specific meaning. Hence, perhaps ‘facies sequences’ should now be referred to as ‘facies successions’. Nevertheless, for the purpose of consistency with the historic literature, the original terminology is retained. A critical point is that where an individual facies may be ambiguous as to depositional environment, the sequence in which facies occur may contain much more information and be more diagnostic of depositional environment.

Depositional elements are facies sequences or associations that are easily defined and understood, and are characteristic of a specific depositional environment (Walker 2006). A depositional element (e.g., shoreface) may occur in several geographic settings. A similar concept is the architectural element of Miall (1985), which are defined in terms of geometry, scale, and lithofacies assemblages. Depositional or architectural elements are the recommended unit for sedimentological analysis for groundwater investigations because they are mappable units on a scale appropriate for groundwater models (Phillips et al. 1989; Davis et al. 1993; Hornung and Aigner 1999).

A facies model (or type model) is an idealized sequence of facies defined as a general summary of a specific sedimentary environment based on studies of both ancient rock and recent sediments (Walker 1984). Available information on a depositional environment is distilled to extract general information and generate an idealized environmental summary or sequence of facies. In addition to being a summary of the environment, a facies model should act as (Walker 1984)

- a norm for the purpose of comparison
- a framework and guide for future observations
- a predictor in new geological situations
- an integrated basis for interpretation of the environment of the system that it represents.

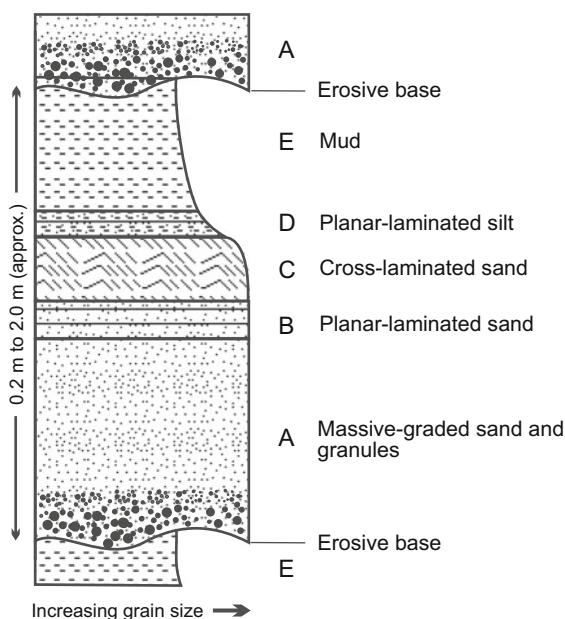
The fundamental assumption underlying facies models is that facies transitions occur more commonly than would be expected if the processes of deposition were random. Where the facies concept is particularly valuable is in sedimentary sequences where apparently similar facies are repeated many times over (Walker 1984).

A classic example of a facies model is the ‘Bouma sequence’ for the deposits of low-density turbidity currents (i.e., turbidites), which was described by Arnold Bouma (1962). A turbidity current is a rapid bottom-flowing sediment gravity (density) flow that is laden with suspended sediment. The Bouma sequence consists of five facies, designated A through E, from the base upwards (Fig. 2.1). The base of the classic Bouma sequence is an unconformity. Strata composed of turbidite deposits consist of stacked Bouma sequences. Not all of the five facies may be present in a given turbidite, but the general sequence pattern is usually retained. Turbidite strata thus can be described by a single facies model that contains five facies.

A limited amount of local information plus the guidance of a well-understood facies model allow for potentially important predictions about local depositional environments (Walker 1984). Given one or a limited number of pieces of information, it may be possible to assign the information to a particular model and, therefore, use the model to predict the rest of the system (Walker 2006). The basic procedure for building sedimentological models include (Walker 2006):

- recognition and definition of facies associations and depositional or architectural elements
- careful fitting of the elements into their three-dimensional framework, which involves determining both the elements that occur together and those that never occur together
- definition of the surfaces that separate elements
- interpretation of the elements as much as possible
- inferring a representative facies model (used as a norm).

Fig. 2.1 Conceptual diagram of the classic Bouma (1962) facies model of a turbidite sequence. All of the facies (A through E) may not be present in a given actual turbidite sequence



- evaluation of how the distribution of deposition or architectural elements in the studied strata conform to the model.

Genetic definitions have the advantage of potentially adding some predictability to the facies analysis because of sedimentological controls over the geometry of facies and genetic associations with other facies. For example, a meandering stream channel sand facies would be expected to be elongated in the direction of the paleo-stream gradient and be laterally and vertically associated with muddy floodplain deposits. Facies models can provide some insights into the likely geometry of individual elements.

Facies models were developed largely based on data from modern environments. However, the preservation potential of recent sediments is a critical issue when developing facies models from modern sediments. Most sediments are removed by erosion after deposition, and in many environments most sediment deposits have little chance for preservation (Reading 1986b). Sediment preservation potential is particularly low in depositional settings with limited accommodation space, such as shallow water and subaerial environments.

2.3 Limitation of Facies Models

The primary limitation of facies models is that facies characteristics and distributions are a complex function of the interaction of numerous variables within a depositional environment. Geological deposits have both apparently random and regular or predictable elements. With respect to fluvial deposits, Miall (1985) noted that numerous facies models have been proposed, which, in reality, reflect fixed points on a multidimensional continuum of variables. Sedimentary deposits, in general, are a continuum rather than consisting of a fixed number of discrete facies models (Anderton 1985). Walker (2006) countered that facies modeling is based on the recognition that there is system and order in nature, and geologists can identify and agree upon a limited number of depositional environments and systems. Indeed, facies models are general summaries of basic characteristics for which there is considerable variation in the details. Owing to the complexity of the heterogeneity and the subjective nature of geologic interpretation, estimated facies patterns are inherently characterized by a high degree of uncertainty (Fogg 1989).

Siliciclastic and carbonate facies models summarized in Chaps. 3 and 4 are conceptual-type models that illustrate characteristic features and patterns of sediments deposited in different depositional environments, which may be developed to varying degrees in actual deposits or may have been partially removed by subsequent erosional events. For siliciclastic sediments, the textures of a sediment are a function of not just the depositional environment, but also of its previous history (e.g., source of the sediment being transported into an environment) and subsequent diagenesis.

Miall (2006) noted with respect to fluvial deposits that important limitations of facies models are fragmentary preservation and variability. There can be a great

difference in modern facies assemblages and facies distribution and what is actually preserved in the geologic record. Earlier deposited sediments are subject to later partial or complete erosion and redeposition. Multiple factors control sediment deposition, which can result in a great variation in the physical character of sedimentary aquifers. Considerable uncertainty exists about the appropriateness of the analogs used for each specific case (Miall 2006). Large-scale facies trends can be deduced from facies models. Facies models are less useful for delineating small-scale heterogeneity within facies because small-scale spatial trends are dependent of local site-specific conditions (Anderson 1989).

Although a number of workers have identified limitations of facies analysis, the message is not that facies analysis has no value or is not worth the effort. The advised caution is more to avoid overinterpretation of data. Despite its limitations, facies modeling has been demonstrated to be an invaluable tool for the analysis of sedimentary deposits and ultimately aquifer characterization.

2.4 Sequence Stratigraphy

2.4.1 Introduction

Facies migrate over time due to global (eustatic) sea level change, variations in sediment supply, and subsidence. A basic limitation of standard facies analysis is that the predictive capacity of facies models is limited by their static view of time and relative sea level changes (Handford and Loucks 1993). Relative sea level changes are the sum of the rates of subsidence (or uplift) and eustatic sea level change. Sediment deposition is controlled to a large degree by sediment supply and accommodation, which is the amount of space that is available for sediments to fill up to base level. Base level is defined as the dynamic surface between erosion and deposition and is the highest level to which sedimentary successions can be built (Catuneanu et al. 2009). Base level in marine environments is approximately sea level. In nearshore environments, changes in water depth (and thus types of sediments deposited) and the position of the shoreline reflect the balance between sediment supply, the direction and rate of changes in sea level, and the subsidence rate. Depending upon the accommodation space, sediment supply, and magnitude and direction of relative change in sea level, sedimentary deposits may, in a predictable manner, shallow or deepen upwards, and individual facies may migrate either seawards (prograde) or landwards (retreat). Sequence stratigraphy integrates time and relative sea level changes to predict the migration and distribution of facies.

Sequence stratigraphy has arguably revolutionized stratigraphic analysis in the oil and gas industry, but to date, has had limited application in the evaluation and management of groundwater resources. The basic concept that the sedimentary rock record can be divided into unconformity-bounded sequences was recognized by Sloss (1963), who subdivided the North American cratonic deposits (Late Precambrian to the present) into six sequences. The seminal publication on

sequence stratigraphy was the American Association of Petroleum Geologists Memoir 26, “*Seismic Stratigraphy—Application to Hydrocarbon Exploration*”, in which a depositional sequence was defined by Mitchum et al. (1977, p. 53) as a

stratigraphic unit composed of a relatively conformable succession of genetically related strata and bounded at its top and based by unconformities or their correlated conformities.

The basic sequence stratigraphic approach involves dividing intervals of sedimentary rock strata into genetically related units bounded by surfaces with chronostratigraphic significance (Van Wagoner et al. 1988). A huge number of papers on various aspects of sequence stratigraphy has been published since Memoir 26 including dedicated books and review papers (e.g., Van Wagoner et al. 1988, 1990; Posamentier et al. 1993; Posamentier and James 1993; Posamentier and Allen 1999; Catuneanu 2006; Emery and Myers 2009; Miall 2010).

Sequence stratigraphy has been widely adopted in the oil and gas industry because it provides a powerful methodology for the analysis of time and rock relationships in sedimentary strata and a framework to predict facies relationships (Van Wagoner et al. 1988). The principal value of sequence stratigraphy is that it provides more predictability, particular where local or global sea level curves can be used to predict stratigraphic relationships in areas with minimal data (e.g., undrilled areas). What follows is a brief introduction into basic sequence stratigraphy concepts.

Depositional sequences are chronostratigraphically significant because they were deposited during an interval of geological time bounded by the ages of the sequence boundaries (Mitchum et al. 1977). Unconformities are surfaces of erosion or non-deposition that separate younger strata from older rocks and represent a significant hiatus. A hiatus is the total interval of geological time that is not represented by strata at a specific position along a stratigraphic surface (Mitchum et al. 1977). Conformities, on the contrary, have no evidence of erosion and nondeposition, and no significant hiatus is indicated. It is important to appreciate that sequences are chronostratigraphic units and that lithostratigraphic units may not coincide with chronostratigraphy as lithologic units may be time transgressive (Vail et al. 1977b). Inasmuch as hydrogeologic units often coincide with lithologic units, preferential flow (aquifer) and confining units may also not correspond to sequence stratigraphic units.

The definition of depositional sequence requires that the strata be ‘genetically related’. A genetically related unit is deposited during a single episodic event, as opposed to being an arbitrary unit bounded by arbitrarily chosen unconformities (Mitchum et al. 1977). The key value of sequence stratigraphy lies in that sequence boundaries and depositional sequences can be related to local changes in relative sea level (i.e., changes in sea level relative to land surface) and global changes in absolute sea level (Vail et al. 1977a). Sequence stratigraphy is thus particularly useful for shallow-marine facies, whose deposition is partially controlled by sea level. Deep-marine facies are not directly controlled by sea level, and hinterland sequences are deposited independently of marine sequences (Vail et al. 1977a). However, sequence boundaries may also have non-eustatic (e.g., tectonic origins)

and may form gradually over finite intervals of geological time, rather than more or less instantaneously (Christie-Blick and Driscoll 1995).

The initial activity in sequence stratigraphic analysis is the identification and correlation of sequence boundaries and depositional sequences. Sequence boundaries are most readily identified by discordant (i.e., lapout) relationships in which strata terminate against a surface, as opposed to concordant relationships where strata parallel a surface (Mitchum et al. 1977). Basic discordant (lapout) relationships are illustrated in Fig. 2.2. The relationships between relative sea level change, sediment supply, and the transgression and regression of marine sediments were summarized by Vail et al. (1977a).

Sequence stratigraphy was originally based upon the interpretation of seismic reflection data. Lapout relationships, which are best observed on seismic profiles, are a key to the physical recognition of sequence stratigraphic surfaces (Catuneanu et al. 2009). However, sequence stratigraphy is also applied to the interpretation of field (outcrop) data and borehole data, when there is a sufficient density of wells. The relative low resolution of seismic reflection data relative to field and well data needs to be considered when comparing different data sources. As has been noted by a number of workers (e.g., Schlager 2005), features that appear as a surface in seismic reflection profiles may correspond to an actual transitional lithological boundary of some thickness.

Multiple orders of global sea level change were documented by Vail et al. (1977b) and subsequently refined and expanded upon in numerous subsequent studies. Vail et al. (1977b) documented three orders of cycles (Table 2.1). Kerans and Tinker (1997) presented a five-order sequence classification (Table 2.2).

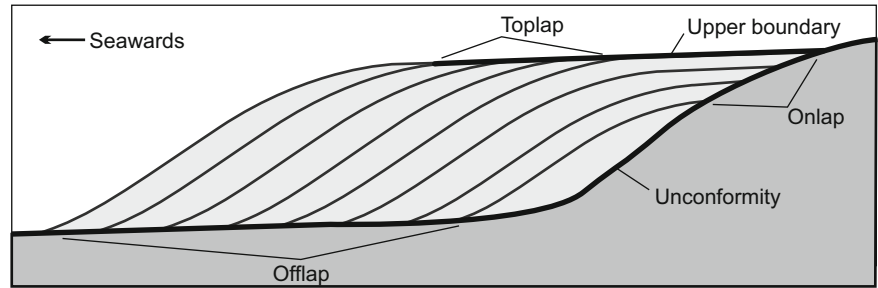


Fig. 2.2 Conceptual diagram of basic lapout relationships relevant to sequence stratigraphy

Table 2.1 Global sea level cycles of Vail et al. (1977b)

Order	Duration (million years)	Cycle type
1	225–300	Multiple period
2	10–80	Supercycles (1 or 2 per period)
3	1–10	Cycle (1 or more per epoch)

Table 2.2 Sequence classification system of Kerans and Tinker (1997)

Tectono-Eustatic cycle order	Sequence stratigraphic unit	Duration (million years)	Relative sea level amplitude (m)	Relative sea level change rate (cm/1000 yr)
First		>100		<1
Second	Supersequence	10–100	50–100	1–3
Third	Depositional sequence	1–10	50–100	1–10
Fourth	Parasequence and cycle set	0.1–1	1–150	40–500
Fifth	Parasequence, high-frequency cycle	0.01–0.1	1–150	60–700

There is inconsistency in the literature regarding the deposition significance of higher order sequences, the order assigned to a given type of unit, and the durations of unit types. Schlager (2005), for example, observed that although the principle of defining orders by duration has been almost universally followed, the actual values used in the definitions vary widely.

2.4.2 Sequence Stratigraphic Concepts and Definitions

The basic sequence stratigraphic concepts and key definitions with respect to siliciclastic sediments were overviewed by Van Wagoner et al. (1988) and are illustrated in Fig. 2.3 and summarized below. Parasequences and parasequence sets are the fundamental building blocks of sequences. A parasequence is a relatively conformable succession of genetically related beds or bedsets bounded by marine flooding surfaces. A marine flooding surface is a surface that separates younger from older strata, across which there is evidence for an abrupt increase in water depth. A parasequence set is a succession of genetically related parasequences, which form a distinctive stacking pattern that, in many cases, is bounded by major marine flooding surfaces. Depending upon the relationship between the rates of deposition and accommodation, parasequence sets may be either progradation (shallow upwards), retrogradation (deepening upwards), or aggradation (rate of deposition equals rate of accommodation). Systems tracts link contemporaneous depositional environments together. The three most important system tracts are the lowland systems tract (LST), transgressive systems tract (TST), and highstand systems tract (HST).

Lowstand systems tracts are prograding packages deposited at the early stage of base level rise when the sediment supply outpaces the base level rise. Strata downlap on the sequence boundary in a basinwards direction. LSTs are bounded above by the maximum regressive surface (MRS; maximum shoreline progradation), which is,

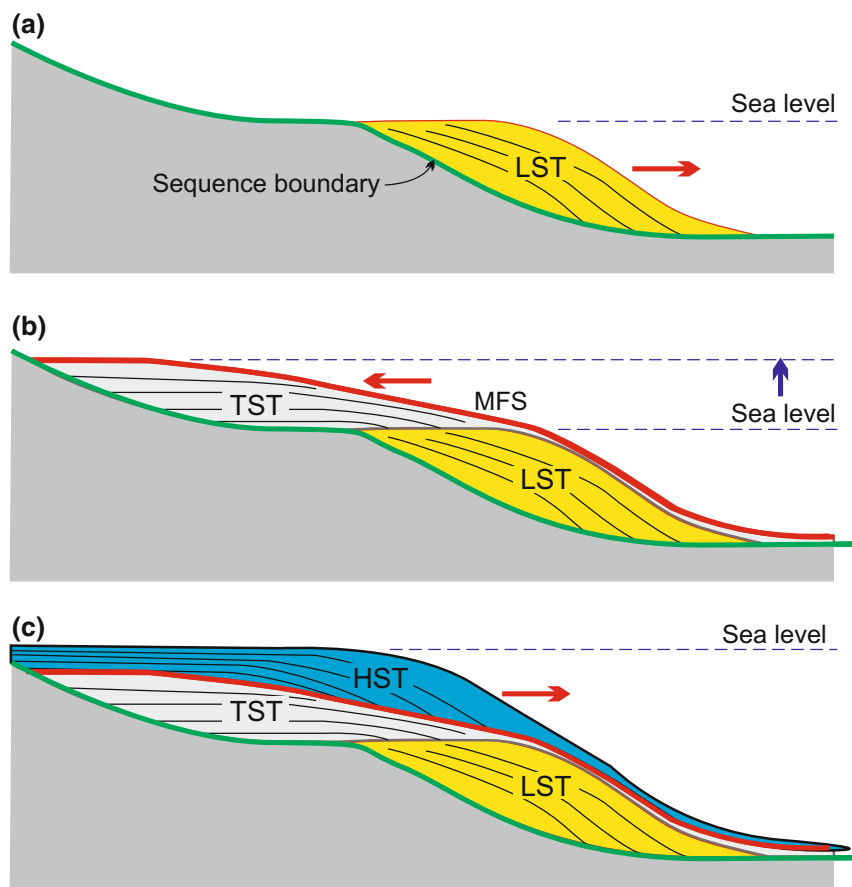


Fig. 2.3 Basic sequence stratigraphy diagram. **a** Lowstand system tract (*LST*) offlaps on the sequence boundary. **b** Transgressive system tract (*TST*) onlaps the sequence boundary. Its upper boundary is the maximum flooding surface (*MFS*), which is the surface of deposition at its maximum landward position (i.e., time of maximum transgression). **c** Highstand systems tract (*HST*) marks return of progradation with the offlap of strata on the *MFS*

subsequently, a transgressive surface. The MRS marks the initiation of transgression and is the first significant flooding surface across the shelf.

Transgressive systems tracts are deposited when base level rise outpaces sediment supply and, as a result, the shoreline and associated facies shifts landwards. Laterally extensive bodies of nearshore sediment (e.g., beach and deltaic sands and shallow water carbonates) are deposited as the loci of sediment deposition retreats with shoreline. Siliciclastic TSTs are characterized by one or more retrogradational parasequence sets and are bounded at the top by the maximum marine flood surface (MFS). The MFS marks the maximum transgression of sea level. It is the surface that marks the turn-around from landward-stepping to seaward-stepping strata.

Highstand systems tracts are deposited during the later stage of the progradation phase in which sediment supply once again outpaces base level rise and the shore starts to prograde again. HSTs are characterized by one or more aggradation parasequences that are succeeded by one or more progradational parasequence sets. HSTs are deposited during the latter part of a eustatic sea level rise, a eustatic standstill, or the early part of a eustatic fall. Some schemes subdivide the HST as also including a falling-stage systems tract (FSST), which consists of sediments that accumulated during a period of fall of relative sea. FSSTs are characterized by the seaward progradation of coastal deposits.

Classical sequence stratigraphy (Fig. 2.3) is best suited to the study of siliciclastic sedimentation at a differentially subsiding, passive continental margin with a well-defined shelf-slope break, and under conditions of fluctuating sea levels (Christie-Blick and Driscoll 1995). As is the case for facies models, sequence stratigraphic models represent general conditions, and it is important to appreciate the variability inherent in natural systems. Indeed, focusing on assigning strata to particular sequence types and subtypes tends to obscure that natural variability in sedimentary systems.

Catuneanu et al. (2009) noted that despite its widespread use, there is no standard code or guide for the application of sequence stratigraphy, particularly with respect to the classification of surfaces and nomenclature for sequence boundaries and system tracts. A basic sequence stratigraphic workflow was proposed, which includes four main elements (Catuneanu et al. 2009):

- observation of stacking trends and strata terminations
- delineation of sequence stratigraphic surfaces from stacking patterns and strata termination patterns
- identification of system tracts using surfaces, stacking patterns, and strata geometries
- definition of stratigraphic sequences using surfaces and system tracts.

2.4.3 Applications of Sequence Stratigraphy

Sequence stratigraphy is very widely used tool in the oil and gas industry for predicting the spatial distribution of lithofacies. It has proven to offer great value as a ‘unifying framework’ for analyzing and interpreting sedimentological (facies), lithostratigraphic, and chronostratigraphic data (Christie-Blick and Driscoll 1995). Sequence stratigraphy has been applied to a much lesser degree in groundwater projects, in which it is used mainly as an interpretative tool. The greatest potential value of high-resolution sequence stratigraphy in groundwater studies lies in improved interpolation between wells and extrapolation from wells. Proper correlation of lithofacies is critical for evaluating the connectivity of both aquifer and confining strata (Scharling et al. 2009). The true potential of sequence stratigraphy for predicting lithofacies and hydrofacies has yet to be realized.

It is important to emphasize that sequence stratigraphic analysis may be largely an academic exercise where the analysis either does not provide any new information or does not provide an improved understanding of the strata of interest. Stratigraphic correlations may still be made in groundwater studies without consideration of sequence stratigraphy. That an unconformity is a major sequence boundary may not have hydrogeologic significance if it does not impact groundwater flow. Sequence stratigraphy has greatest applications in studies involving large geographic areas in which there are significant lateral facies changes and in which the strata of interest contains multiple sequences. Sequence stratigraphy has limited value for local, small-scale groundwater investigations.

Sequence stratigraphy was used to evaluate the stratigraphic relationship of Pliocene to Holocene siliciclastic strata in the Dominguez Gap of Los Angeles County, California (Ponti et al. 2007; Edwards et al. 2009; Nishikawa et al. 2009). The Dominguez Gap is the location of saline-water intrusion into the Los Angeles Groundwater Basin. The sequence stratigraphic analysis (Fig. 2.4) provided insights into the relationships between transmissive sand strata that are avenues for saline-water flow and, in turn, can lead to more accurate solute-transport models.

A combination of sequence stratigraphy and facies analysis was used in a study of Miocene to Cretaceous aquifers of the Coastal Plain of New Jersey (Sugarman and Miller 1997; Sugarman et al. 2005). Well logs were used to trace sequence boundaries to core-hole control throughout the study region. The aquifer system consists of sand aquifers separated by semiconfining and confining clays and sands. The depositional environments include offshore marine, beach, deltaic and fluvial,

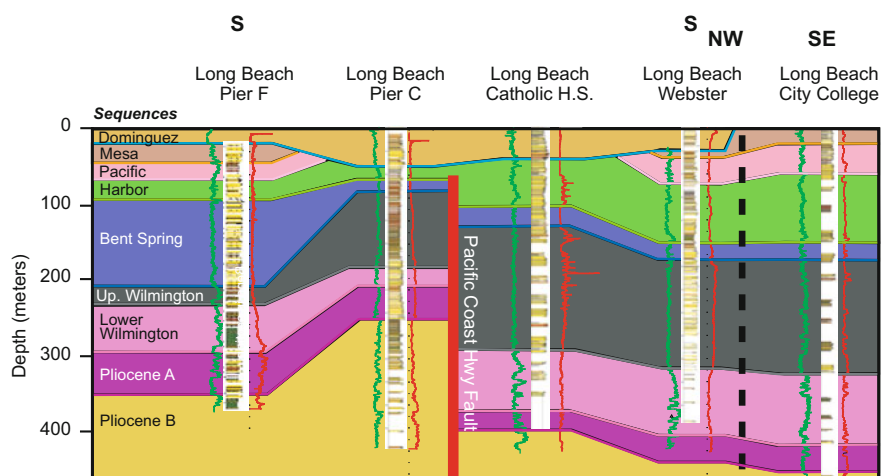


Fig. 2.4 Sequence stratigraphic interpretation of the Dominguez Gap at Long Beach, California by Ponti et al. (2007). The sequences in the approximately 8.3 km long cross-section are colored and resistivity (red) and natural gamma ray (green) logs are provided. Sequence stratigraphy has greatest potential values for large-scale investigations of geological complex sites such as the Dominguez Gap area

which result in the overall facies distribution being representative of historical sea level changes. Mapped sequences were found to be tied to global sea level changes. The principal value of utilizing sequence stratigraphy was that it allowed for more refined hydrostratigraphic correlations and predictions of the continuity of aquifers and confining units.

Houston (2004) applied high-resolution sequence stratigraphy to an investigation of groundwater resources in the Calama and Turi Basins of the Atacama Desert, northern Chile. Deposition in studied basins was controlled by episodic uplift and subsidence, which provided periodic accommodation space. Borehole geophysical logs and field observations were used to identify and correlate unconformity and sequence-bounded paleosols. The sequence stratigraphic analysis allowed for the development of a three-dimensional model of the basins, which helped delineate aquifer facies, low-permeability confining strata, and preferential flow paths.

Scharling et al. (2009) documented the application of sequence stratigraphy to an analysis of groundwater resources in Miocene strata at Jutland, Denmark. A descriptive sequence stratigraphic model was developed using existing seismic reflection data, lithologic and borehole geophysical logs (gamma ray), and biostratigraphic data. The borehole data in the study area was limited (<100 wells). Most of the wells in the region are shallow and do not penetrate the strata of interest. The final model had 23 surfaces including 10 sequence stratigraphic surfaces and 11 prominent lithofacies contact surfaces. The major benefit of the sequence stratigraphic analysis was an enhanced understanding of the distribution and connectivity of aquifers. Improper correlation of sand units (the main aquifer strata) and their connectivity could affect the flow regimes of groundwater models as groundwater is mainly transported in these units.

McFarlane et al. (1994) applied sequence stratigraphy to the analysis of the Dakota Aquifer of Kansas. Three sequences defined in the Front Range of Colorado were correlated to the study area, but the sequence stratigraphy was not an integral element of the data analysis.

Sequence stratigraphy was used mainly as a tool for stratigraphic interpretation of Tertiary carbonate and siliciclastic sediments in South Florida by Missimer (2001), Cunningham et al. (2001a, 2001b, 2003) and Ward et al. (2003). Cunningham et al. (2006) performed a sequence stratigraphic/cyclostratigraphic analysis of the Pleistocene limestones of the Biscayne Aquifer of southeastern Florida (Fig. 2.5). The analysis demonstrates that the stratigraphic section can be divided into high-frequency cycles, which can be correlated between wells. The strata were also divided into three porosity types that correlate with relative permeability. The most permeable porosity type (Type I) contains touching vug porosity and thus conduit flow. The three porosity types occur in predictable vertical patterns in the cycles, which results in predictability in the presence of flow zones.

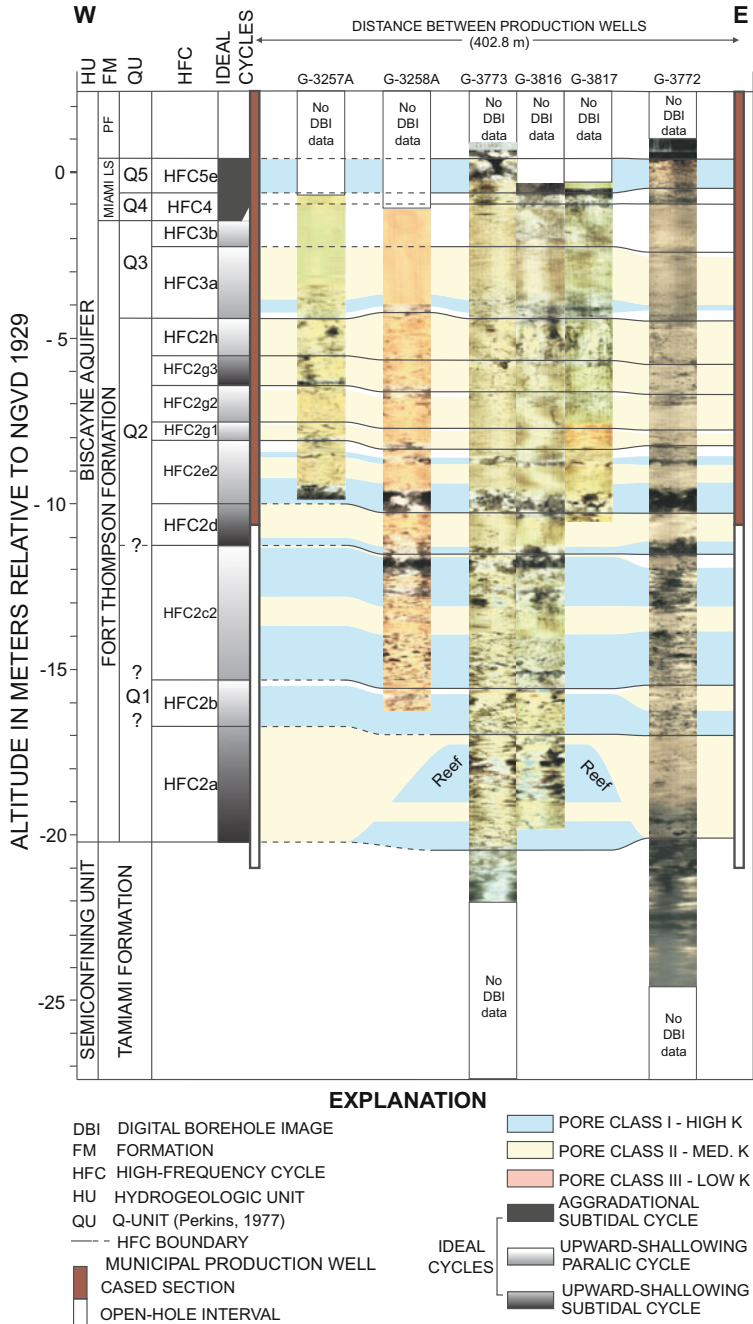


Fig. 2.5 Hydrostratigraphic correlation section from the Biscayne Aquifer (Miami-Dade County, Florida) including digital image logs by Cunningham et al. (2006). The stratigraphic section was divided into high-frequency cycles, which can be correlated between wells. A predictable vertical pattern of porosity and permeability was identified in the cycles. The highest permeabilities occur in porosity type I, which contains touching vug (conduit) porosity

2.5 Facies Modeling

The fundamental challenge in aquifer characterization is developing an acceptably accurate three-dimensional model of an aquifer system from scattered one-dimensional data from wells and boreholes. The term ‘acceptably’ recognizes that all models, by their nature, are imperfect (have inaccuracies), but still may be good enough to serve their intended purposes. A goal of aquifer characterization is to incrementally improve models through the collection of additional data and improved methods to process and interpret the data. It is useful to consider how facies data may be used to bridge the gaps between well data.

Facies analyses may be qualitatively used to develop conceptual models and to hydrogeologically interpret well data. Insights into the likely structure of an aquifer system may be derived from the knowledge of the depositional environment of the strata and the likely orientation, scale, and connectivity of aquifer and confining strata, which can be obtained from facies analysis and sequence stratigraphy.

The results of facies analyses can provide quantitative information on spatial correlation and can also be used as soft information or training images for geostatistical methods (Chap. 20). Geostatistics is a collection of numerical techniques used to characterize the spatial attributes of spatially dependent data. If data are random, then it is not possible to predict values between data points. Geostatistical techniques have multiple applications, but they are particularly useful for estimating or interpolating parameter values in spaces where sampling data are not available. The underlying concept is that, in general, things that are closer together tend to be more alike than things that are farther apart. For example, if a fluvial channel sand was identified at a given depth in a well, then there is a high probability that the sand will be located nearby at the same depth, particularly in the paleoflow direction. The degree of spatial correlation (i.e., probability that channel sand is present) decreases with increasing distance from the well. Data on spatial correlation of facies in the horizontal direction is sparse in most studies. Facies-specific general values may be used as default values in the absence of (or to supplement) site-specific data.

A more advanced technique is the development of models that can simulate the deposition of sedimentary rocks and thus facies distribution, which has been prompted to a large degree by the needs of oil and gas reservoir engineering. Synthetic depositional models have been developed based on factors (variables) such as sediment supply, rates of eustatic sea level change and subsidence, and hydraulic gradient (Allen 1978; Bridge and Leeder 1979; Leeder 1978; Flint and Bryant 1993; Webb 1994, 1995). There are two end-member modeling procedures (process and geometric methods), which were summarized by Webb and Anderson (1996).

Process-based models attempt to simulate the deposition of geological materials through the interaction of physical, chemical, and biological processes embodied in either theoretical or empirical relationships. Purely geometrical models attempt to produce spatial patterns similar to those observed in the field using empirically

derived geometric relationships. Most models incorporate aspects of both approaches (Webb and Anderson 1996).

Webb (1994, 1995), for example, developed the Braided Channel Simulator (BCS-3D), which can be used to simulate the three-dimensional internal geometry and relative distribution of facies of braided-stream deposits by simulating geomorphic surfaces associated with depositional processes. The simulations are performed on a scale appropriate for groundwater investigations; i.e., the architectural element scale of Miall (1985). The BCS-3D simulator can be used to model the three-dimensional shapes and spatial distribution of individual, recognizable sedimentary units. Webb (1994) noted it is relatively simple to adjust input parameters to match existing data in order to reproduce or simulate a well-described field setting. However, he also cautioned that it is rather difficult to determine these parameters *a priori*.

Webb and Anderson (1996) provide a good example of how facies simulations can be incorporated into groundwater models. The BCS-3D code was used to generate a three-dimensional realization of the internal structure (facies geometry) of the aquifer. The next step was to assign hydraulic conductivity values to each facies, which was performed using different methods:

- constant values were assigned to each facies unit.
- facies were combed into two groups (high and low-hydraulic conductivity), each of which was assigned a volumetrically weighted geometric mean value.
- each facies unit is assigned a value randomly sampled from a Gaussian hydraulic conductivity distribution assigned to that facies.

Sedimentological models have limited practical value because of the required level of calibration, the lack of resolution at scales relevant to many practical problems, and the impracticality of simulating the entire depositional history of an alluvial basin for a site investigation (Johnson 1995). Fluvial sedimentation, for example, is the product of simultaneous actions of various autogenic and allogenic sedimentary controls, and sufficient data would rarely be available to make computer modeling a practical tool (North 1996; Miall 2006). However sophisticated the statistical and numerical model used, ultimately these modeling efforts must resort to some means of determining the appropriate input data from the real world of actual fluvial systems (Miall 2006). Similar limitations occur in the modeling of other depositional systems.

2.6 Hydrofacies

The term ‘hydrofacies’ refers to hydrologically distinct lithofacies (Anderson 1989, Poeter and Gaylord 1990). The size, shape, and arrangement of lithofacies and erosional elements comprise the sedimentary architecture of a basin. Similarly, the arrangement of hydrofacies, consisting of both permeable and confining units,

determines the structure of the corresponding hydrogeological architecture of a groundwater basin. Aquifer characterization using the hydrofacies approach involves determination of the three-dimensional distribution of hydrofacies and their effective hydraulic properties.

The ultimate objective of hydrofacies analysis is to capture more of the three-dimensional hydrogeological structure or architecture of aquifer systems and create more realistic groundwater models that have a greater predictive capability. The fundamental challenge is interpolating and extrapolating spatially limited data to both develop conceptual models and populate numerical groundwater models. The facies approach recognizes that the distribution of sedimentary rock types is not random, but occurs in patterns that reflect processes within the depositional environment. Understanding facies and their internal variations and hydraulic properties of constituent elements is essential for characterizing the behavior of aquifer systems. Facies models thus provide some predictability in the distribution of sedimentary rock types and, in turn, hydrostratigraphic units.

Hydrofacies may correlate with lithofacies, facies associations, or architectural elements, where original sediment characteristics significantly influences current porosity and permeability. However, the correlation is often not one for one. A given hydrofacies may contain more than one sedimentological facies. The relationship between sedimentary facies and hydrofacies may be weak or nonexistent when porosity and permeability are largely controlled by diagenesis. Interconnectedness is the key to quantifying heterogeneity for the purpose of hydrogeological investigations (Anderson 1997).

Complete characterization of the subsurface would ideally yield a site-specific three-dimensional facies model that accurately incorporates the interconnectedness of both high- and low-connectivity zones (Anderson 1997). A basic approach to hydrofacies analysis is to perform a facies analysis in which the strata of the project area are assigned to depositional facies zones, based on knowledge of the basin depositional history, facies models, sequence stratigraphy, and available field and well data. The depositional facies are next assigned to hydrofacies. A given hydrofacies may include one or more depositional facies. Interpolation and extrapolation of facies or hydrofacies in areas without data can be performed by manual correlation or by using geostatistical methods in either a deterministic manner, in which a single realization is developed (e.g., using techniques such as kriging), or using a stochastic approach in which numerous realizations are generated (Chap. 20). Manual correlation should consider the overall depositional history of the basin such as the likely land surface or basin slope (and thus direction of sediment transport) and position of the paleo shoreline.

Hydraulic properties are then assigned to each hydrofacies based on available well and other data. Interfaces relationships (i.e., facies geometry) is discrete, while hydraulic conductivity distribution within facies may be described by a continuum (Anderson 1989). The hydrofacies data would next be upscaled (as needed) to populate the model grid. The values of hydraulic and solute-transported parameters in the hydrofacies-based model grid cells may be subsequently adjusted during the model calibration process.

McCloskey and Finnemore (1996) provide an example of the application of the hydrofacies approach to a fault-bounded sedimentary basin in Santa Clara County, California. The basin fill sediments consist predominantly of alluvial fan, fluvial (braided stream), and lacustrine deposits. Using the basin sedimentary model and standard alluvial fan and fluvial facies models, the strata were categorized as having either high, medium, or low-hydraulic conductivity, and the distribution of each strata type was mapped (Fig. 2.6). The expected high-hydraulic conductivity strata are braided-stream fluvial deposits, which have the best sorting. Low-hydraulic conductivity strata include fine-grained proximal fan deposits. The facies model categorization of strata was supported by estimates of the sand to clay ratio obtained from borehole geophysical logs. Transmissivity data were subsequently obtained from pumping test and specific capacity data. A good match was observed between the distribution of hydraulic conductivity from the facies analysis and well transmissivity data. For groundwater model development, facies model and field hydraulic conductivity data would be combined to assign values to each facies zone and thus cells in the model grid.

Fish and Stewart (1991) performed a hydrofacies analysis of the Surficial Aquifer System in Miami-Dade County, Florida (USA). The studied strata included the Biscayne Aquifer, which is the primary water source for the Miami-Fort Lauderdale major metropolitan area. The hydrofacies approach involved categorizing the strata from 34 test wells into a series of lithofacies. The lithofacies were then each assigned to one of five hydraulic conductivity categories based on either hydraulic testing data, published values relating hydraulic conductivity to grain size and sorting, and hydrogeologic inferences based on inspection of samples. A series of cross-sections were then generated by manual correlation between the test well locations (Fig. 2.7)

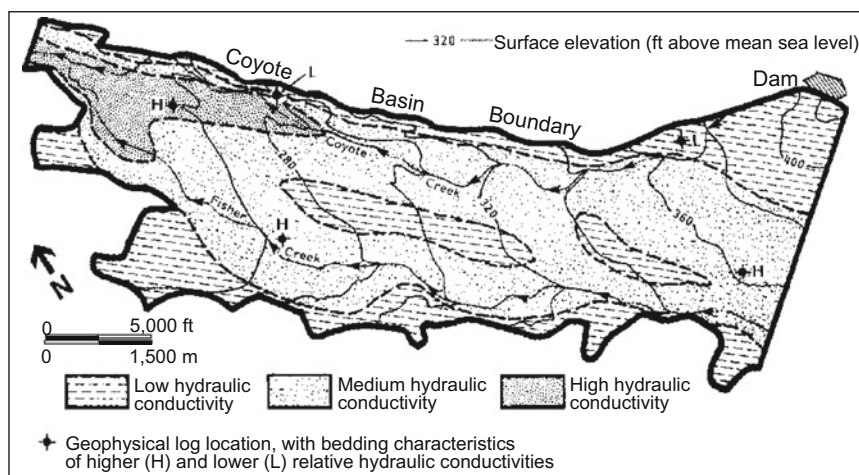


Fig. 2.6 Relative hydraulic conductivity map based on facies analysis for the Coyote Valley basin, Santa Clara County, California (modified from McCloskey and Finnemore 1996)

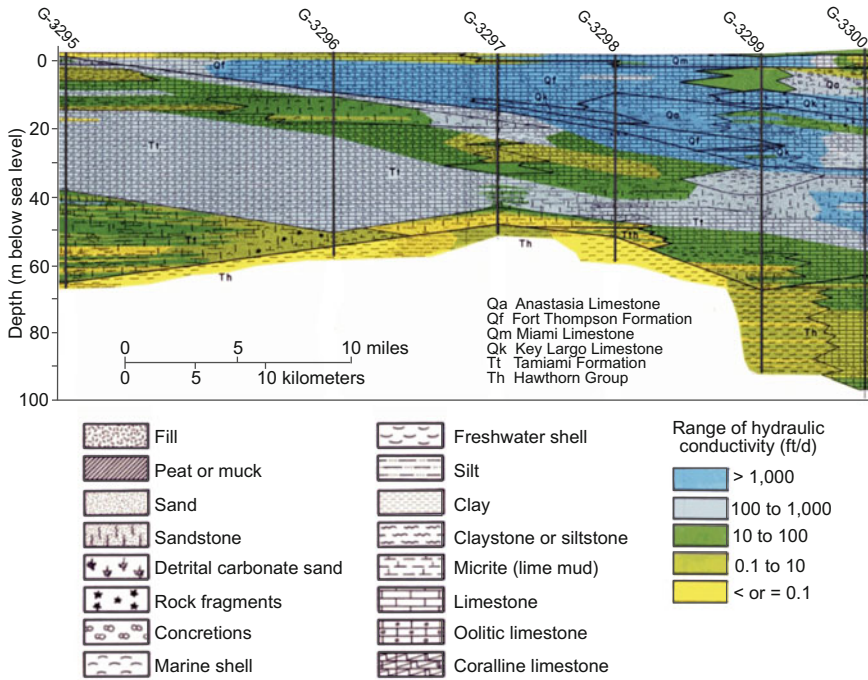


Fig. 2.7 Hydrofacies cross-section for the Surficial Aquifer System in Miami-Dade County, Florida (modified from Fish and Stewart 1991)

Surface geophysical data can be used to fill in the gaps between borehole data. In shallow aquifer systems, ground-penetrating radar (GPR) can be used to obtain data on aquifer structure, large-scale sedimentary features, and the position of the water table. Ezzy et al. (2006) implemented a high-resolution hydrofacies approach to a coastal plain alluvial aquifer located in the Bull Creek plain, north of Brisbane, Australia, which provides a good example of the application of surface geophysics in hydrofacies analysis. The study combined extensive well and core data with GPR surveys. GPR was particularly valuable for accurate definition of the boundary of narrow alluvial channels, which are significant conduits for shallow groundwater flow. Six hydrofacies were defined and the GPR data were used to develop a high-resolution map of alluvial aquifer thickness and interconnectivity and, in turn, hydrofacies distribution. Each of the hydrofacies were assigned values for hydraulic parameters based on testing results or commonly accepted literature values for the different materials. The values for the hydraulic parameters for the hydrofacies were refined through the model calibration process. Ezzy et al. (2006) noted that nonuniqueness in each hydrofacies zone remains an ill-posed problem and that the results of the model calibration is just one possible solution.

Facies and hydrofacies analyses are not a replacement for field data collection. Indeed, it requires the careful collection of higher-quality data. For example, well

cuttings need to be carefully described and analyzed along with borehole geophysical logs and available existing data on the strata of interest in order to extract information on facies distributions. Facies and hydrofacies analyses should be approached as methods to maximize the value obtained from collected data. Facies analyses can allow for better constraint of numerical models by improving the differentiation between geologically plausible and implausible solutions. Where there is an underlying sedimentological control on the distribution of the hydraulic properties in aquifer systems, facies analysis can be used to better incorporate the underlying sedimentological fabric into models.

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