Terrigenous Clastic Depositional Systems

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Applications to Petroleum, Coal, and Uranium Exploration

With 237 Figures

Springer-Verlag
New York Berlin Heidelberg Tokyo

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Library of Congress Cataloging in Publication Data
Galloway, W. E.
Terrigenous clastic depositional systems.
Bibliography: p.
1. Sedimentation and deposition. I. Hobday, David K.
II. Title.
QE571.G27 1983 553.2 83-668

Softcover reprint of the hardcover 1st edition 1983

Typeset by Ampersand Inc., Rutland, Vermont.

9 8 7 6 5 4 3 2 1

ISBN-13: 978-1-4684-0172-1 e-ISBN-13: 978-1-4684-0170-7
DOI: 10.1007/978-1-4684-0170-7

We dedicate this book to our teachers and friends,
Frank Brown
John Ferm
Bill Fisher

Preface

The reserves, or extractable fraction, of the fuel–mineral endowment are sufficient to supply the bulk of the world's energy requirements for the immediately forseeable future—well into the next century according to even the most pessimistic predictions. But increasingly sophisticated exploration concepts and technology must be employed to maintain and, if possible, add to the reserve base. Most of the world's fuel-mineral resources are in sedimentary rocks. Any procedure or concept that helps describe, understand, and predict the external geometry and internal attributes of major sedimentary units can therefore contribute to discovery and recovery of coal, uranium, and petroleum.

While conceding the desirability of renewable and nonpolluting energy supply from gravitational, wind, or solar sources, the widespread deployment of these systems lies far in the future—thus the continued commercial emphasis on conventional nonrenewable fuel mineral resources, even though their relative significance will fluctuate with time. For example, a decade ago the prognostications for uranium were uniformly optimistic. But in the early 1980s the uranium picture is quite sombre, although unlikely to remain permanently depressed. Whether uranium soars to the heights of early expectations remains to be seen. Problems of waste disposal and public acceptance persist. Fusion reactors may ultimately eliminate the need for uranium in power generation, but for the next few decades there will be continued demand for uranium to fuel existing power plants and those that come on stream.

This book is, to some extent, a hybrid. It is directed toward the practicing exploration and development geologist who is, of necessity, something of a generalist. However, the stress on process and principle may also make this a suitable text for courses in resource geology.

Our grouping of coal, uranium, and petroleum may appear to be incongruous and artificial. However, our basic premise is that there are common genetic attributes shared by all three, and that the sedimentological principles governing their distribution are fundamentally similar. We have both had geologic careers divided among all three of the fuel minerals. Factors that we have found to be important include depositional processes and environments and their resultant genetic facies, interrelationships of genetic facies within depositional systems, early postdepositional modifications by circulating ground water, and, finally, the changes that take place at depth as sedimentary basins evolve in response to tectonic and regional hydrologic controls.

In many instances the paleoenvironmental factor is preeminent in controlling the distribution of fuel minerals. The origins of peat and both syngenetic and placer uranium are directly related to depositional environment. Peat is subsequently modified to coal by burial and heating during the normal sequence of basin evolution.

However, many attempts to relate fuel-mineral deposits to genetic facies associations alone have met with mixed success. Sedimentary facies with apparently all of the necessary attributes for hosting fuel minerals commonly prove to be singularly barren, whereas some rich deposits in ostensibly unfavorable host facies defy conventional explanation. These exceptions indicate the need to consider additional factors, some of which may not be reflected in static facies elements. For example, it was recognized 30 years ago that the role of postdepositional ground-water flow is crucial in sandstone-type uranium mineralization. Hydrologic setting is important in peat genesis, and critical to its preservation as coal; it may even have influenced the distribution of placer uranium in early Precambrian Witwatersrand-type algal mats. Thus, differences in ground-water circulation arising from topographic, structural, or climatic controls explain differences in uranium mineralization in sandstones of similar origin. They may also explain mutually exclusive distributions of coal and epigenetic uranium in identical, coeval facies in different parts of a sedimentary basin. For these reasons, we summarize principles of ground-water flow in large sedimentary basins and explore implications for fuel-mineral genesis.

Numerous excellent textbooks and other compilations are devoted to sedimentary facies, environments, and processes, reflecting the burgeoning interest and involvement of geologists in these fields. There has been a corresponding recent proliferation of literature on fuel minerals from the standpoint of their geographic distribution, regional geologic setting, host rock associations, and economic and engineering aspects of their exploitation. This book attempts to bridge the gap between process-related studies of sedimentary rocks and the more traditional economic geology of commercial deposits of coal, uranium, and petroleum. Due attention is paid to subsurface techniques which, integrated with outcrop data, enable the most realistic reconstructions of genetic stratigraphy, and offer the greatest application in exploration. After reviewing depositional systems and their component genetic facies with emphasis on field and subsurface recognition, we examine ground-water flow systems—how they evolve in relation to changing structural configuration, consolidation, climatic regime, and topography in the recharge area. This sets the stage for an account of the associated fuel minerals in terms of their paleoenvironmental setting, emplacement, and subsequent transformations.

Our views are necessarily prejudiced by our own experience, but we attempt to do justice to the prevailing state of the art in basin analysis. Prodigious volumes have been published on the relationship of petroleum to clastic depositional systems, so only an overview is possible here. However, we document important studies in mature hydrocarbon provinces that provide excellent models for exploration in less-explored basins. In contrast, with a few conspicuous exceptions, coal and sedimentary uranium have only recently attracted the same level of detailed attention from sedimentologists. This stems in part from the early dominance of petroleum as a fuel, the temporary eclipse of coal, and the relatively recent emergence of uranium; and probably also from an overemphasis on descriptive stratigraphy, particularly in coal basins. The burgeoning studies of sedimentary uranium have presently reached a plateau, which permits a fairly comprehensive synthesis. Although general environments of coal formation have been known since the last century, it was only with detailed studies of modern fluvial and deltaic environments, starting with the Mississippi, that predictive models were developed. These coal models are currently undergoing considerable refinement. Those that we describe have all shown economic application in exploration and mine development.

The importance of sedimentary facies in affecting the quality and extraction of fuel minerals is also being more widely appreciated. For example, the roof and floor properties of coal mines are largely determined by subfacies characteristics. Knowledge of the depositional framework and associated fluid flow and engineering properties has long been important in hydrocarbon production. Progressively more sophisticated geological input is used in genetic-predictive modeling, and this trend is likely to increase as reserves become depleted.

Compilation of a book which focuses on the geology and mineral deposits of many parts of the world brings one face to face with the problem of units of measurement. There is no ready solution to the complexity of English and metric units applied in different countries, or in the same country at different times, or for different commodities. We have attempted to cite measurements in their original units and to provide equivalencies in parentheses. Where original figures are rounded off, conversions are similarly rounded. In reality, the resource geologist must remain, for some time to come, conversant in both English and metric.

Acknowledgments

A book of this scope inherently transcends the personal experience of two authors. We have each been blessed with stimulating environments and co-workers who have contributed not only to the evolution to our ideas, but more directly, to the completion of this manuscript.

Friends and associates who suggested ideas, provided figures and data, and most importantly, served as sounding boards and reviewers for particular topics, include Sam Adams, John Barwis, Knut Bjørlykke, Pat Eriksson, Frank Ethridge, John Hunt, Brian Jones, Rufus LeBlanc, Evan Leitch, Robert Morton, Marjorie Muir, Jonathon Price, Ray Rahmani, Stan Schumm, Greg Skilbeck, Michelle Smyth, Ron Steel, Tony Tankard, Bruce Thom, Jŏzsef Tóth, Bill van Rensburg, Vic Von Brunn, Roger Walker, and John Ward. To each of these we extend our gratitude.

Additional associates who contributed to the preparation of the manuscript include Sheila Binns, Dawn Garbler, Marjorie Starr, Avril Troth, and Doris Tyler (typing); Micheline Davis, Len Hay, and John Roberts (drafting); and Lucille Harrell, Jim Morgan, and Dan Scranton.The index was compiled by Amanda Masterson.

The Department of Geology and Geophysics, University of Oklahoma, provided the much needed time and research support for one of us (WEG) during a tenure as Visiting Professor. Additional time and support was made available by our employers, the Bureau of Economic Geology, University of Texas at Austin, and the Department of Geology and Geophysics, University of Sydney. To each of these organizations we express our thanks.

Finally, we wish to acknowledge the many hours of time and effort spent by Martin Jackson in reviewing the entire manuscript. His thoughtful suggestions and comments have undoubtedly rounded off many of the rough edges endemic to joint authorship and aided clarity of the text.

To our wives, who seem always to welcome us back from our philanderings with mistress geology, we can only repeat "thanks again."

Contents

Chapter 1

The Fuel-Mineral Resource Base

Introduction

Nonrenewable energy resources available in very large quantities are limited to heavy hydrogen and dry geothermal energy. Large-scale renewable resources are solar and atmospheric electricity (Moody, 1978). These four may be regarded as the ultimate energy sources, but they are unlikely to contribute significantly to the total energy budget for at least the next few decades. Synthetic fuels are already in production, but widespread conversion is being held back by economic and environmental considerations. Wind, water, and biomass conversion will play an enlarged, but still relatively minor, role. This leaves coal, uranium, and petroleum to provide the bulk of the immediately foreseeable energy requirements.

The use of coal goes back thousands of years to its combustion in Bronze Age funeral pyres. It was used by the ancient Greeks and Romans, and subsequently by the American Indians, Chinese, and European nations, where it gradually supplanted animals, wind, water, and wood as the main energy source, fueling the Industrial Revolution. Although superseded this century by petroleum, coal has made a strong comeback since the early 1970s and is on the ascent. Petroleum, too, has a long history of human utilization, being employed in warfare and embalming prior to 500 BC, and, subsequently, in medicines and street lamps. A petroleum field was established as early as 211 BC in Szechwan, China (Halbouty, 1980), but only with the 1859 Titusville discovery was the modern petroleum industry presaged. The degree to which Western nations became reliant on petroleum in motive and stationary power sources was made apparent by the 1973 OPEC oil embargo. Uranium, in contrast, has been used for less than 50 years, with consumption accelerated by World War II weapons research and, from 1968 to 1973, by fuel-mineral demand.

Exploitation of these three fuel minerals is subject to obstacles of different kinds (Clarke, 1978). In the case of petroleum, the bottleneck is in conceptual and technological considerations at the exploration stage, and in efficient extraction from the reservoir; in the case of uranium it is environmental apprehension at the energy-conversion stage; and in coal it is at the recovery stage.

Coal reserves are generally regarded as sufficient for at least the next 300 years at present rates of consumption, but current use is likely to increase severalfold. There is remarkably little consensus regarding the volume of coal resources

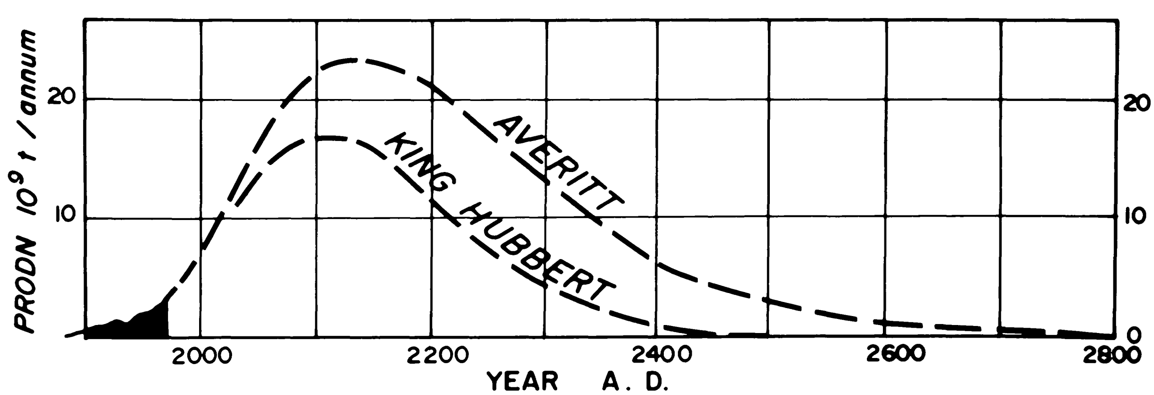

Figure 1-1. Projections of global coal production based on estimates by Averitt (1969) and King Hubbert (1969). (After Fettweis, 1979.)

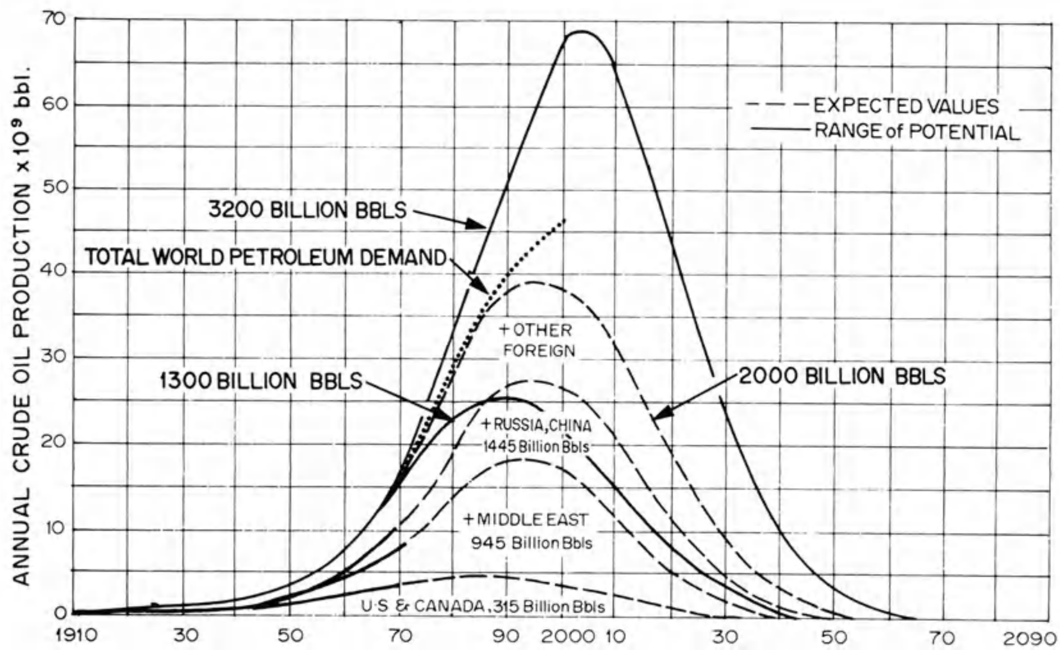

Figure 1-2. Projected crude oil production based on an estimated reserve of 2000 billion barrels. (After Moody, 1978.)

or reserves, with different countries frequently employing different criteria in their estimates. Based on King Hubbert's (1969) curve (Fig. 1-1), coal should represent a major energy source for the next 500 years. Averitt's (1969) figures are even more optimistic. Coal use is expected to peak between the years 2100 and 2200 at between six and nine times current annual production, declining to an insignificant level around the year 2800. The 1974 World Energy Conference estimated the world's coal resources at 11×10^{12}t. However, only 0.6×10^{12}t were known in detail and regarded as extractable under then-existing economic and technological constraints, thus constituting reserves (Fettweis, 1979, p. 19). The 1977 estimate was 12.9 $\times 10^{12}$t, of which 6 percent was regarded as reserves. Clarke's (1978) prediction of an increase in the world's coal reserves to $5\text{–}6 \times 10^{12}$t was based on expectations of increased demand, coupled with increased prices as other bulk energy supplies dwindle, leading to increased recovery.

Crude oil reserves from conventional sources are estimated at around 2000×10^9 bbl (Fig. 1-2). Of this, some 375×10^9 bbl have already been extracted, leaving about 725×10^9 bbl of proved reserves and some 900×10^9 bbl total undiscovered recoverable reserves, or potential reserves. World production is expected to peak during the next decade, but some additional 24×10^9 bbl need to be discovered each year in order to replace depleted reserves (Grivetti, 1981).

Natural gas resource estimates are in the range of $5\text{–}12 \times 10^{12}$ ft^3 ($0.14\text{–}0.37 \times 10^{12}$ m^3), of which a large proportion is in Middle Eastern and Eastern Bloc countries. Even in the United States, however, very large volumes of gas remain, and exploration for gas has accelerated since 1978. The price factor is critical in hydrocarbon reserve determinations. For example, price increases over the past few years instantly increased the reserves in some mature fields. Over a slightly longer term, price incentives add to reserves by increasing exploration activity.

Uranium reserve figures fluctuate even more markedly in response to price fluctuations. The size of uranium resources is limited only by cost factors because the element is widely distributed at low concentrations. Even so, and in spite of predictions for reduced nuclear generating capacity, temporary shortfalls in uranium supply are likely to result from the existing decline in exploration.

Table 1-1. Rounded Estimates of the Present World Distribution of Mineral Energy Resources[a]

	Oil and NGL	Gas	Tar	Oil Shale	Coal	Uranium	Total
Russia, China, etc.	1	—	1	—	26	NA	29
United States	—	—	—	2	18	15	35
Canada	—	—	1	—	—	9	10
Middle East	1	—	NA	—	—	—	1
Other	1	—	—	1	4	18	24
World	4	1	2	3	49	41	100

[a]After Moody (1978).

World energy resource distributions, as summarized in Table 1-1, show some surprises. The oil fields of the Middle East have about one percent of the world energy resources, with the total for oil amounting to a mere 4 percent. Gas, tar, and oil shale similarly represent only a few percent. The lion's share is coal and uranium, which together constitute 90 percent. Total energy resources of the United States amount to over one-third of the world figure.

Chapter 2

Approaches to Genetic Stratigraphic Analysis

The real world is immensely complex [and] continuous. Isolated structures are therefore subjective and artificial portions of reality, and the biggest initial problem is the identification and separation of meaningful sections of the real world. On the one hand, every section or structure must be sufficiently complex . . . so that its study will yield significant and useful results; on the other, every section must be simple enough for comprehension and investigation.

Chorley and Kennedy (1971, p. 1)

Introduction

One of the most difficult tasks in the application of genetic facies interpretation in resourc exploration, appraisal, and development is thı delineation of depositional units of sufficient extent and appropriate scale for analysis. The depositional basin defines the boundaries and general conditions of the accumulation of a sediment pile. Depositional systems, as described in subsequent chapters, provide "meaningful sections" of the basin fill. Their recognition and delineation establish a framework for facies differentiation and mapping, using appropriate process–response models. It is commonly at the facies level that source units, fluid-migration pathways (the basin plumbing), potential hosts or reservoirs, and trapping configurations are sought and dissected.

In most sedimentary basins, exploration and development of energy minerals relies increasingly on generation and analysis of subsurface data. Detailed description of sedimentologic attributes requiring outcrop exposure as a basis for genetic stratigraphic interpretation becomes, at best, of limited use. Similarly, whole diamond core is a rare luxury that is typically available only in areally and stratigraphically restricted portions of the basin fill. However, the concept of a depositional system implies that component facies are spatially related, three-dimensional units, which may be readily described by commonly available types of subsurface data, augmented where possible with descriptions of core or outcrop sections. This approach to facies analysis relies heavily on reconstruction of basin morphology and bedding architecture, determination of gross lithology, quantitative delineation of the geometry of framework sandstones, and recognition of vertical and lateral successions and common facies associations. The following sections discuss approaches to three-dimensional facies analysis, with emphasis on subsurface data, and review basic sedimentologic concepts that are fundamental to development of flexible process–response facies models.

Depositional Architecture

Bedding geometry and spatial relationships within and among lithologic units is a fundamental property of genetic stratigraphic sequences constituting a basin fill. Delineation of "bedding style" or "depositional architecture" on both regional and local scales provides much information on depositional processes and probable depositional systems or environments.

Sedimentation within a basin of any size can occur at the margin or bottom. *Aggradation* is the process of vertical filling of the basin. Infilling from the margin is either by *progradation*, if sediment is washed into the basin, or by *lateral accretion*, if sediment moving within the basin preferentially accumulates against the margin (Fig. 2-1). Each of these three mechanisms produces a characteristic bedding architecture, and is typified by a general textural profile (Fig. 2-1). Aggradational bedding produces no inherent systematic textural trends; rather, each bed may display varying texture and composition. Progradation and lateral accretion both produce depositional units having a sigmoidal cross section. They are readily differentiated, however, by contrasting textural sequences: progradational sequences coarsen upward, whereas lateral accretion produces an upward-fining sequence. In

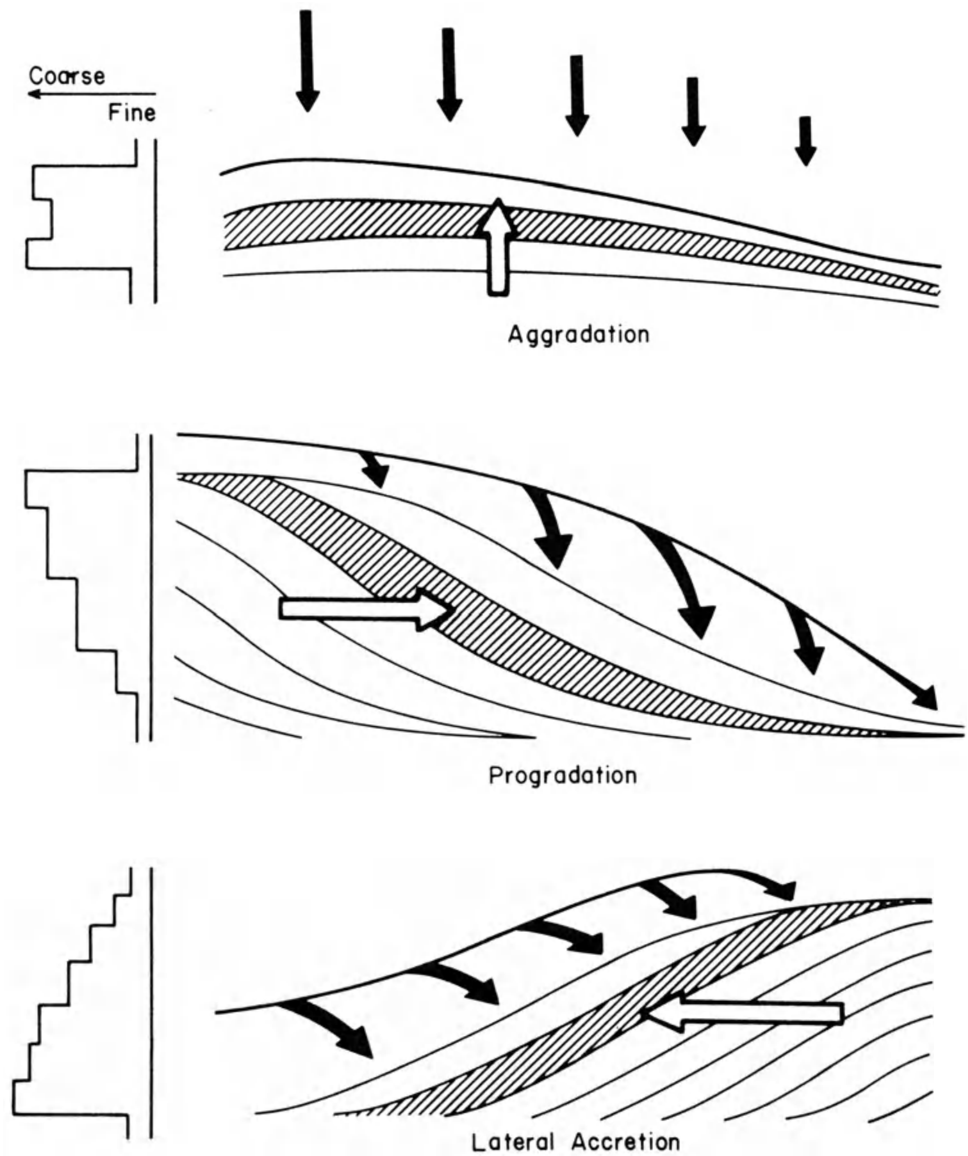

Figure 2-1. Three basic styles of basin-filling and their resultant bedding geometries and vertical textural sequences. (Modified from Galloway *et al.*, 1979.)

both, the sequence is reproduced laterally within a single genetic increment, and vertically as successive increments are stacked one on the other.

Accretionary, aggradational, and progradational depositional settings may exist side by side in the same depositional system. For example, an abandoned fluvial channel may fill by progradation along one side of sediment washed in during floods from an adjacent, active channel in which point bars are growing by lateral accretion. At the same time, overbank sediment deposited by flood waters causes the floodplain to aggrade, or build vertically. Whole depositional systems may be dominantly progradational (a delta system) or aggradational (an alluvial fan system); lateral accretion is more typical of local environments within larger systems.

In addition to bedding styles, most clastic depositional systems are characterized by specific geometries and processes of sediment dispersal. Almost all bed-load transport processes leave a depositional record of the path of the sediment dispersal system. The principal exceptions to this rule are systems in which down-slope gravitational remobilization of coarse sediment produces significant zones of bed-load sediment bypass. Definition of the geometry of the bed-load (sand) framework, or depositional skeleton of the larger genetic units is basic to unraveling sediment dispersal pathways, and, in turn, provides much useful information about depositional processes and possible environments.

A primary distinction may be made between dip-fed and strike-fed sediment dispersal systems. A dip-fed system, such as a fluvial system, primarily transports sediment down-slope toward the depositional basin. In contrast, a strike-fed system, such as a barrier bar system, moves bed-load sediment parallel to the basin margin. Many depositional systems contain both dip- and strike-fed elements. Relative volume, vertical and areal distribution, and cross-sectional geometry of the dip-fed and strike-fed elements are some of the most powerful guides for genetic stratigraphic interpretation. Further, these parameters are readily determined from subsurface data.

Depositional Episodes

Frazier (1974) developed a conceptual model based on extensive three-dimensional stratigraphic studies of Quaternary depositional systems of the Gulf Coast Basin which integrated the principal components of the basin fill. This model, with due recognition of geometric variability introduced in basins of differing tectonic setting and bathymetric configuration, provides a basis for recognition of genetic stratigraphic units within large marine or lacustrine basin fills.

Several sedimentologic principles form the basis for the model (Frazier, 1974). (1) Terrigenous clastic sediments are allochthonous, and must therefore be transported to the basin margin, primarily by rivers. (2) Basins are filled by clastic sediment through a repetitive alternation of depositional and nondepositional intervals. At any one time, active deposition is concentrated in specific areas of the basin, although infinitesimal amounts of sediment accumulate elsewhere. Consequently, essential nondepositional interludes or hiatuses separate depositional units. (3) The time interval represented by a hiatus and its resultant stratigraphic surface varies from place to place; however, at least one time line extends throughout the entire extent of the surface. Thus, the hiatal surface upon which a progradational series of beds is deposited represents a progressively longer time interval in the basinward direction. Conversely, the subaerial surface that forms over the progradational interval represents increasing amounts of time in the landward direction. (4) A simple depositional event, which is a localized pulse of deposition separated by hiatal intervals from underlying and overlying strata, consists of three phases. Deposits of the *progradational phase* progressively fill the basin, forming a wedge of sediment that commonly thickens basinward. Contemporaneous *aggradational* phase deposits cap the progradational platform, commonly thickening in the landward direction. Termination or decrease in sediment output and ongoing basin subsidence results in deposition of a veneer of reworked, *transgressive phase* sediments across the basinward portion of the depositional unit. Thus each depositional event produces a facies sequence recording initial progradation, penecontemporaneous aggradation, and terminal transgression.

As shown in the schematic time–distance diagram in Figure 2-2, multiple depositional events combine to produce a major physical, genetic stratigraphic unit called a *depositional episode*. The depositional episode is a complex of facies sequences derived from common sources along the basin margin, and deposited in a period of relative base-level or tectonic stability (Frazier, 1974). Each depositional episode is bounded basinward by major transgressive events and hiatal intervals (and their resultant surfaces) that have regional or world-wide significance (Fig. 2-2). Further, the depositional episode contains an extensive subaerial hiatal surface, which increases in temporal significance landward. Bounding transgressions may be a product of tectonic or isotatic subsidence or of eustatic changes in base level. Boundaries between depositional episodes are ill-defined landward of the shoreline of maximum transgression. As pointed out by Frazier, conventional stratigraphic units and depositional episodes may coincide. However, the transgressive facies, which are genetic components of the stratigraphic sequence produced by a depositional episode, are commonly given individual formational status or are com-

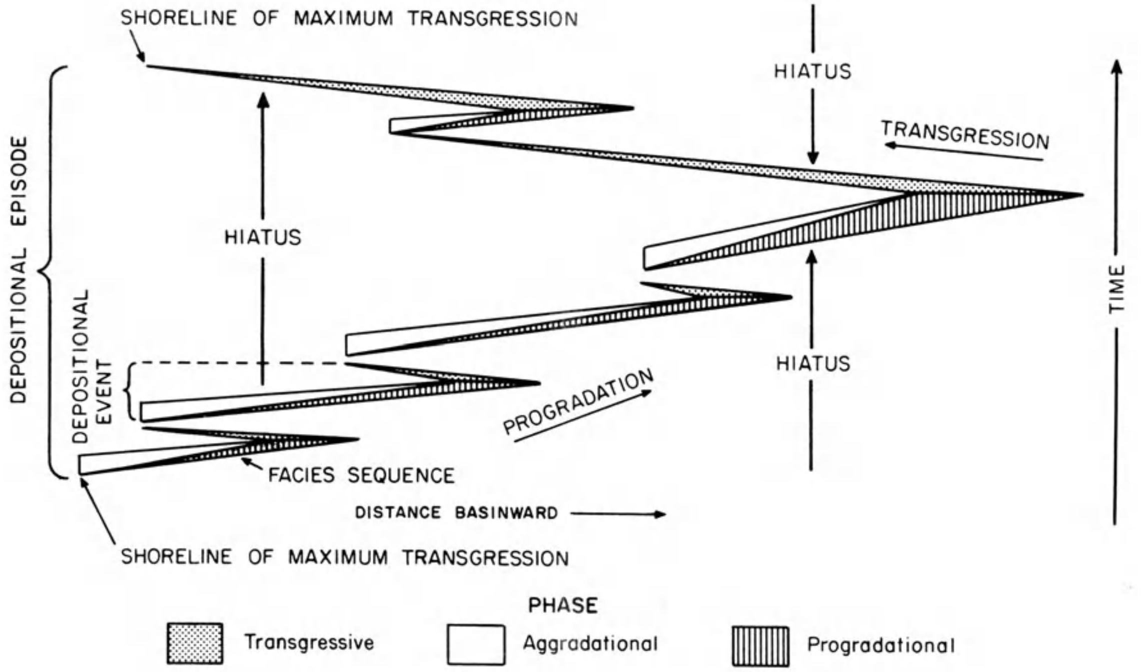

Figure 2-2. Schematic time–distance diagram illustrating the temporal and spatial relationships of a depositional episode and the phases of its component depositional events. Only patterned areas represent intervals of active terrigenous deposition in any one portion of the basin. The depositional episode is bounded by external hiatal surfaces and encompasses a single major internal hiatal surface. (Modified from Frazier, 1974.)

bined with the strata of the overlying depositional episode.

Recognition of depositional episodes and their component depositional events has two applications. First, these constitute both regional and local genetic units that must be recognized and correlated if quantitative facies mapping is to produce meaningful patterns. Secondly, the model relates the various bedding styles to preferred positions within the basin fill.

Both transgressive facies and hiatal surfaces provide physical stratigraphic correlation markers that can be used to define the boundaries of genetic units. Unlike hiatal surfaces, however, transgressive units do not necessarily incorporate a time line (Fig. 2-2). External hiatal surfaces, which represent long intervals of essentially no deposition of terrigenous clastic sediment, may be indicated by a variety of thin, laterally continuous beds or horizons, including: (1) marl and limestone beds, (2) richly glauconitic or phosphatic sand and mud, (3) fossiliferous or burrow-churned pelagic mud, and (4) veneers of marine-reworked, relict sand, silt, or mud. Presence of carbonate and other chemical constituents in these veneers reflects the long contact times between surficial sediments and the overlying water column. Chemical or biogenic materials may be indicated on subsurface well logs as thin zones of relatively dense, low-porosity, high-resistivity, and/or radioactive material. In contrast, nearly pure pelagic mud units are indicated by zones of minimum resistivity on electric logs. Thus, the most useful genetic boundary horizons are commonly distinguished by their log signature, as well as by their lateral continuity.

Alternatively, the hiatal surface may develop as a surface of marine erosion (Dietz, 1963). Resulting dissection, canyon cutting, and planation and concomitant aggradation of the basin floor are readily apparent in reflection seismic data (Brown and Fisher, 1980).

Internal hiatal horizons may be erosional or pedogenic surfaces, or may be recorded by deposition of peat. Though less useful for correlation or isolating genetic stratigraphic units, the chemical and physical attributes of such horizons may also produce distinctive log responses. However, lateral continuity is typically less well displayed than in their basinal counterparts, which form under more uniform subaqueous conditions.

In summary, interpretation of depositional architecture of the basin fill—determination of the major depositional episodes and the nature and extent of their bounding horizons, their contained bedding styles, and the overall geometry of framework sand facies—can be an adequate basis for early recognition of principal depositional systems and associated facies.

Quantitative Facies Mapping

Quantitative geologic mapping is standard procedure in energy resource geology. In addition to basic structure contour and interval isopach maps, isolith maps, such as a net sandstone or coal isopach, and proportion maps, including sandstone percentage and sand/shale ratio maps, define the areal extent and expected thickness of reservoirs or other economically important lithologies.

In terrigenous clastic depositional systems, a combination of genetic interval isopach map, net sand isopach map, and, if the interval thickness changes markedly, a sand percentage or ratio map is particularly useful for genetic stratigraphic interpretation. Such a map suite outlines principal depocenters for both total sediment and for the bed-load fraction, and displays the distribution, trends, and areal patterns of the framework sand facies. Further, the distribution of both framework and nonframework facies can be related to basement and intra-formational structure, and to basin morphology.

The detailed geometry of a specific sand body is typically obscured because the facies sequence of even a single depositional event consists of several partially superimposed sand units deposited in different environments. However, depositional grain of the framework sand facies dominates contour patterns. Even in thick sequences that incorporate many tens or hundreds of individual depositional cycles, vertical persistence of depositional environments characteristic of rapidly subsiding basins results in stacking of similar facies and preservation of framework trends. Although such stacking inherently decreases map resolution and causes loss of details of framework geometry, major attributes, such as positions of depocenters, relative abundance of dip- or strike-fed sand bodies, areal and stratigraphic distributions of framework sands within the genetic package, and impacts of contemporaneous structures on sand distribution, remain visible.

Utility of maps is further increased if basic sedimentologic concepts and genetic models are incorporated in contouring style. For example, with the exception of gravitational remobilization in subaqueous slope settings, total bed-load sediment bypass is rare in terrigenous clastic systems. Consequently, elements of each portion of the sediment dispersal system are likely to be preserved as a series of interconnected sand bodies whose trends reflect directions of sediment transport. Thick, isolated pods or lobes of sand are rare.

Contouring more appropriately emphasizes continuity rather than isolation of sand deposits. Exceptions have strong implications for interpretation of depositional processes and depositional systems. Similarly, contouring should attempt to recognize and emphasize emerging patterns such as discrete belts, radiating distributary aprons, or subparallel pods. Systematic areal changes in pattern, dimensions, or trend of contours likely reflect significant facies changes.

In addition to the basic interval, isolith, and sand percentage maps, several derivative facies maps may also be useful in facies delineation and interpretation (Forgotson, 1960). Maps showing the thickness of the thickest sand body or the number of discrete sand bodies within the interval provide rapidly derived overviews of facies trends, as well as adding information about facies distribution. Three-component maps outline proportional content of multiple lithologies such as sand, mudstone, and limestone. Vertical position of sediments within a genetic sequence can be quantified and displayed using a center-of-gravity mapping technique (Forgotson, 1960). If data are computerized, a mathematically derived gradient or trend surface may be generated and used to remove regional gradients, so that details of framework geometry can be better resolved from the background trends (Wermund and Jenkins, 1970).

Wire-Line Logs

Various wire-line logs are the most common type of geologic data available for subsurface geologic analysis. Together with drill cuttings, such logs provide a basic suite of information about the lithology, petrophysical properties, and pore-fluid content of the strata penetrated.

No wire-line log determines lithology or grain size directly. Consequently, lithologic and textural interpretation are based on calibration of log response with core or other independent lithologic data, use of assumed correlations between lithology and the property actually measured, or comparison of several log types. Details of log interpretation lie beyond the objectives of this book. The mechanics of well logging, and the assumptions, techniques, and theories of log interpretation are discussed in numerous petroleum engineering texts and reference manuals. However, logs can be readily used for qualitative lithologic information, and provide a three-dimensional data base for facies recognition and mapping.

Log Types

Two types of logs are commonly utilized for lithofacies interpretation: the electric log and the natural gamma log. The electric log, which comes under many different names, including resistivity log, induction log, and laterlog, typically displays two basic traces, an S.P. (Spontaneous Potential) and a resistivity curve. The S.P. curve, which lies along the left side of the log, measures the relative electrical potential developed between the fluid within the bore hole and the formation, referenced to the fixed potential of an electrode at the surface. Indirectly, S.P. measures permeability, but the direction and magnitude of the electrical potential, and consequently of the deflection of the log trace, are also a function of the electrochemical contrast between bore-hole and formation fluids. In deep wells, where bore-hole fluids are typically less saline than formation waters, the S.P. curve deflects to the left from the base line (indicating negative current flux) within porous, permeable lithologies such as sand. S.P. response is less stable at shallower depths where freshwater aquifers are encountered.

The resistivity trace is a direct or calculated measurement of the resistivity of the rock matrix and its contained pore fluids. Several types of resistivity measurements are commonly recorded on the same log. Because resistivity of sediment or rock matrix is high compared to that of saline or even brackish water, measured resistivity is primarily a function of pore-fluid chemistry rather than of lithology. However, if porosity and permeability are low, as in a tightly cemented or highly compacted, texturally immature lithology, the resistivity curve may register the high matrix resistivity by a deflection to the right from the base line. The resistivity curve may thus be used to determine and measure thickness of sand bodies in fresh water zones or in facies sequences characterized by very low intergranular porosity.

The gamma log measures natural gamma radiation of the subsurface formations. Such radiation is primarily emitted by radiogenic potassium contained in clay minerals. In mixed siliciclastic sequences, the gamma curve can be readily used to distinguish between sand and shale. Further, the degree of the deflection is an index of "shaliness" of the interval. In addition, gamma logs may be particularly useful for recognition and correlation of highly organic marine shales. Such black shales commonly contain anomalous amounts of uranium, making them readily apparent on the highly sensitive oil well gamma log. Problems in use of the gamma log may occur if small amounts of other radioactive materials, such as uraniferous heavy minerals, phosphatic or glauconitic grains, or detrital mica, are present in the sands. Similarly, low gamma counts also characterize relatively pure carbonate units, which might be interbedded with sands and shales.

For quantitative lithologic techniques, such as summation of the net sand within a genetic unit, logs are internally calibrated by defining typical log responses of end-member lithologies within an interval known or assumed to contain thick, clean sand and mud units. Connecting deflections produced by the end-member lithologies define sand and shale baselines that bracket the log trace. Intermediate deflections indicate interbedded or texturally mixed lithologies. An operational definition of sand can be established by adopting a minimal proportion deflection (such as ½ or ⅔) from the shale base line as the cut off