A Review of Hydrocarbon Bearing Formations, Their Economic Significance and Their Potential for Object-based Modeling

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This review of hydrocarbon bearing formations is intended to motivate the development of facies modeling in settings that have not been thoroughly considered.

Introduction

Most of the major oilfields in the world have come into high water-cut development stage, so reservoir research has been focusing on fine-scaled geological bodies, such as turbidite lobe events. Because of their scale, the correlation between wells of these objects has great uncertainty and is very hard to be assessed by conventional approaches. What should CCG focus on next to meet this needs? Are object-based modeling approaches suitable for describing them? In this report, an investigation on world hydrocarbon bearing formations and their economic significance will be conducted to find the most important hydrocarbon bearing formations, and a brief review of major depositional systems will also be performed for their potential for object-based modeling. The scope of the work includes: 1) a brief review on hydrocarbon bearing depositional systems; 2) a brief discussions on their potential for object based modeling; and 3) the economical significance of these depositional systems.

Hydrocarbon bearing depositional systems

The whole depositional system can be classified as four subsystems in basin scale based on their global tectonic positions: 1) continental depositional systems, 2) coastal and nearshore depositional systems, 3) continental shelf depositional systems, and 4) deep-sea depositional systems (DSD); see Figure 1. Each subsystem can be further classified according to its petrophysical characteristic, clastic rock or carbonatite. In this report, the fine-scaled classification is used for depositional system review; and large-scaled classification is used for world hydrocarbon reserves review for statistical convenience and practicality.

Continental depositional systems

Fluvial and lacustrine systems (FL)

(1) Alluvial fans

Alluvial fans are depositions with gross shape approximating a segment of a cone and exhibiting a convex-up transverse profile. Many have fairly steep depositional slopes. Sediments on alluvial fans are typically poorly sorted and include abundant gravel-size detritus. Stanistreet and McCarthy (1993) suggest that fans can be classified into three principal types: those formed dominantly by debris-flow processes (debris-flow-dominated fans), those formed dominantly by braided-stream processes (braided fluvial fans), and those formed by processes associated with low sinuosity / meandering streams (low-sinuosity/ meandering fluvial fans); see Figure 2 [1].

In radial cross profile, alluvial fans can be divided into three parts; see Figure 3. The upper fan, also called the proximal fan or fanhead, has the steepest slope and coarsest sediment. The coarse deposits in the upper fan are often referred to as fanglomerates. Stream-flow in the upper fan tends to be confined by a single channel, which may be entrenched as much as 20-30 m below the fan surface. Shifting of this channel can occur owing to clogging of the channel with stream-flow or debris-flow deposits. The midfan is characterized by a gentler slope and sediment of intermediate size. A branching network of shallower channels typically feeds different parts of the midfan. The distal fan, or fanbase, makes up the toe of the fan and is distinguished by the gentlest slopes, finest sediment, and lack of well-defined channels; see Figure 3. The above description applies particularly to debris-flow-dominated fans [1].

Stream-flow process takes place on all types of alluvial fans and is the dominant processes on braided fluvial fans and low-sinuosity/meandering fluvial fans. Stream-flow leads to deposition of three main types of fan deposits: stream-channel sediments, sheetflood deposits, and sieve deposits.

Discussion: Most alluvial fans have clear geometries in large scale, so object based modeling approach can be used on large-scaled alluvial fan modeling. For fine scale, the geometry is usually not clear for coarse grain-sized alluvial fans, but it is usually clear for fine grain-sized ones. Therefore, the suitability of object-based modeling approaches on alluvial fans is problem-related.

(2) River

River systems through time have been more important as sediment transport conduits to lakes and oceans than as sites of deposition. Nonetheless, rivers do deposit sediment and some of this sediment is preserved under certain conditions to become part of the ancient sedimentary record. On the basis of channel morphology, a wide spectrum of rivers are known in modern environments, ranging from those with low sinuosity to those with high sinuosity, and from those that transport dominantly sand or mud to those that transport dominantly gravel; see Figures 4 through 7 [1].

The basic channel styles described above are often difficult to recognize in geological records. The grain size of the fluvial system has been suggested as a parameter to subdivide fluvial systems because it can be measured for both ancient and modern ones, at outcrop and in the subsurface. On this basis, river systems can be broadly subdivided into four principal types: very high-bedload, bed-load, mixed-load and suspended-load dominated rivers. Each of the four system-types displays characteristic channel fill geometries, facies assemblages and vertical succession; see Table 1 and Figure 8 [2].

Discussion: All kinds of river systems have been well studied, so there are a lot of mature river depositional models. Because of its one-directional flow mechanism and clear geometry, river system is very suitable for object-based modeling. Many object-based approaches have been developed for describing alluvial-type reservoirs. Because of the diversity of river systems, no versatile program can be developed.

Coastal and nearshore depositional systems

Siliciclastic shoreline systems (SSL)

(1) Deltaic

Two basic types of deltas include alluvial deltas and nonalluvial deltas; see Figure 9. On the basis of delta-front regime, deltas are classified as (1) fluvial-dominated, (2) tide-dominated, and (3) wave-dominated deltas; see Figure 10. Variations in sediment input, outflow velocity, wave and current energy, and other factors cause the depositional features of deltas to exhibit a high degree of variability from one delta to another. Nevertheless, all deltas can be divided into subaerial and subaqueous components, each of which can be further subdivided; see Figure 11. The subaerial component of deltas is generally larger than the subaqueous component and is divided into upper delta plain and lower delta plain. The subaqueous delta plain lies seaward of the lower deltaic plain below low-tide water level and is characterized by relatively open marine faunas. Figure 12 gives an example of fluvial-dominated delta. The deposits are distributary-mouth bar sandstones that grade laterally into bay-fill muds, which resemble meandering river deposition [1].

Discussion: River-dominated delta is suitable for object-based modeling. Wave-dominated and tide-dominated deltas are more sophisticated because of the influence of wave/tide. For reservoirs with strong wave/tide influence which makes the reservoir too sophisticated, pixel-based modeling methods can be used. Two-step modeling approach can be used: (1) object-based sequence stratigraphy modeling for deltaic distribution; (2) corresponding facies modeling in small-scaled framework.

(2) Beach and Barrier Island

Mainland beaches are long, narrow accumulations of sand aligned parallel to the shoreline and attached to land. Bodies of beach sand are typically cut across here and there by headlands and sea cliffs, estuaries, river deltas, tidal inlets, bays, and lagoons. Barrier-island beaches are similar to mainland beaches, but are separated from land shallow lagoon, estuary or marsh. Also they are commonly dissected by tidal channels or inlets; see Figure 13 [1].

Discussion: The shape and structure of this environment are very simple, so pixel-based modeling is good enough for its modeling.

(3) Tidal-flat

Tidal flats form primarily on mesotidal and macrotidal coasts where strong wave activity is absent. They are developed either along open coasts of low relief and relatively low wave energy or behind barriers on high-energy coasts where protection is afforded from waves by barrier islands, spits, reefs, and other structures. Thus, they are occurred within estuaries, bays, the backshores of barrier-island complexes, and deltas, as well as along open coasts. In areas with a large tidal range, tidal flats typically rimmed the margins of back-barrier lagoons, estuaries and the open coast. They may be up to several kilometers wide, and formed flat to gently sloping areas (typically <1˚) that extend from the supratidal zone, through the intertidal zone, and into the shallow portion of the subtidal zone; see Figure 14 [3].

Discussion: Tide flows in two-directions, so it is very sophisticated to express it with mathematical model. And its geometry is not clear. Pixel-based modeling method is a good choice at present.

Carbonate and evaporate shoreline systems (CES)

(1) Evaporite

Evaporite deposits are composed dominantly of halite (NaCl) and the sulfate minerals gypsum (CaSO4·2H2O) and anhydrite (CaSO4). Evaporites are deposited under climatic conditions where evaporation losses exceed precipitation (rain and snow). They are forming today in both nonmarine and marine environments [1].

Modern marine evaporites are forming in two principal kinds of settings: coastal sabkhas and Salinas. Marine sabkhas are coastal supratidal mud flats. Evaporite minerals do not precipitate from standing water but instead form displacively within sabkhas sediments, consisting of carbonates and/or siliciclastic deposits, in a capillary zone above a saline water table. Water lost by evaporation is replaced by downward seepage of storm-driven seawater or by interflow of groundwater from continental sources [3].

Continental evaporites: the basic facies model for continental evaporites is a closed basin with a shallow groundwater table and a more-or-less centrally located Playa Lake. Where the groundwater table intersects the surface at the deepest parts of the basin, a saline lake or a salt pan forms and is concentrically surrounded by saline and dry mud flats; see Figure 15. The latter may grade into sand flats, with or without alluvial fans.

Discussion: Evaporite environment is a mixed chemical-siliciclastic systems. Its mechanism is very sophisticated and it can be in any shape, so it is suitable for pixel-based modeling.

Continental shelf depositional systems

Siliciclastic shelf systems (SSF)

(1) Neritic (shelf)

The neritic zone encompasses the shallow-water areas of the ocean lying shore-ward of the shelf break. The idealized distribution of bedforms along the sediment transport path on tide-dominated shelves is illustrated in Figure 16. At high tidal velocities, of about 150 cm/sec, the seafloor may be eroded, leaving furrows and gravel waves. With progressively diminishing velocity farther down the transport path, eroded sediments are deposited to form flow-parallel sand ribbons, large dunes, small dunes, a rippled sand sheet, and finally sand patches. Sand ridges may form in the dune belt if enough sand is present [1].

Discussion: A complex spectrum of transport processes operate on wave-/storm-dominated shelves, including fair-weather waves and swells, storm waves, wind-driven surface currents, river-generated plumes, and density currents. It is so sophisticated that it is suitable for pixel-based modeling.

Carbonate shelf systems and reefs (CSR)

(1) Carbonate shelf (nonreef)

Carbonate environment may be present in some parts of marginal-marine environment such as beaches, lagoons, and tidal flats. With respect to the nature of the platform edge, four basic types of carbonate platforms or shelves are recognized in the modern ocean: (1) rimmed carbonate platforms, (2) unrimmed (open shelf) carbonate platforms, (3) carbonate ramps, and (4) isolated carbonate platforms; see Figure 17 [1].

Discussion: The carbonate in carbonate shelf (nonreef) environment has simple shape and sophisticated mechanism. It is suitable for pixel-based modeling.

(2) Slope/basin carbonates

Three fundamental kinds of carbonate slopes are recognized: erosional, by-pass, and accretionary; see Figure 18. Erosional slope has a steep face (>25˚) that retreats with time owing to scouring by sediment gravity flows or contour currents. Little or no sediment was deposited on these slopes, although turbidites or other sediment-gravity-flow deposits might be present on the basin floor seaward of the slope. By-pass slopes are subjected to less erosion and have a more gentle dip (>10-12˚). Some sand-size and coarser sediment accumulated in gullies and minor amounts of pelagic/hemipelagic muds may be deposited on the slopes; however, sedimentation rates on such slopes are very low. Most sediment derived from the shallow-water platform edge bypassed the slope and was carried into deeper water (e.g., by turbidity currents). Accretionary slopes have low dip angles (2-3˚) that are built and maintained by sedimentation processes. These are the only kinds of slopes on which significant deposits of carbonate sediments accumulated [1].

Two basic models for accretionary (depositional) carbonate slopes have been proposed: slope aprons and submarine fans; see Figure 19. Carbonate aprons were distinguished by having a line source or multiple sources that feed sediment seaward through closely-spaced gullies, generating wedge-shaped aprons of sediment [1].

Discussion: The mechanism and shape of carbonate slope is more like fluvial fan, although the sediment may be not only clastic. They are suitable for object-based modeling.

(3) Organic Reef

The outer shelves of many rimmed platforms are characterized by the presence of nearly continuous carbonate reefs that constitute an effective barrier to wave movement across the shelf. Reefs could be developed also as fringing masses along the shoreline or as isolated patches within the inner shelf. Reefs constituted a unique depositional environment that differed greatly from other parts of the shelf environments; see Figure 20 [1].

Discussion: The mechanism of organic reef is very special. These creatures are only living in some specific environment, such as in the area where water is clear and warm. So it can only be found in some specific position. It is suitable for pixel-based modeling.

Deep-sea depositional systems (DSD)

(1) Oceanic (deep-water)

No entirely satisfactory scheme for oceanic system was given due to both genesis and descriptive properties of all kinds of deep-sea sediments which has yet been devised. Two broad classes of deep-sea sediment, terrigenous and pelagic are often mentioned; see Table 2. However, these two terms are difficult to define precisely. Terrigenous deposits include gravel, sand, and mud derived from land and transported within the more proximate parts of the deep ocean by a variety of processes (e.g., turbidity currents, contour currents, ice rafting). Some pelagic deposits (clays) were also derived from land but were deposited by slow settling in the more distal parts of the ocean; others consisted of pelagic biogenic remains that rained down from near-surface waters. A third minor category of deeper-water sediments are shallow-water carbonate sediments that have been retransported from the shelf into deeper water (allochthonous deep-water carbonates) [1].

Discussion: Submarine fan formed in deep-water, but its mechanism is more like fluvial system.

Object-based modeling approach can be used on this depositional system.

Global hydrocarbon reserves overview

Are we running out of oil? Wrong question! The question is "When is *the big rollover*?" What's *the big rollover*? It's when the demand for oil outstrips the capacity to produce it [5]. According to a report of AGT Energy, total world oil reserves is 9 to 13 Trillion bbls; see Figures 21, 22 [6]. Besides the hydrocarbon resources mentioned in Figure 21, there are some unconventional gas resources which have become more and more important as a significant contributor to the production gap left by conventional gas, including: 1) shallow biogenic gas; 2) 'tight' gas and basin-centered gas; 3) coalbed methane (CBM); 4) shale gas; 5) gas hydrates; and 6) continuous generation gases [7].

Unconventional hydrocarbon resources

(1) Heavy oil

Heavy oil is a type of crude oil which is very viscous and does not flow easily. The common characteristic properties are high specific gravity, low hydrogen to carbon ratios, high carbon residues, and the contents include asphaltenes, heavy metal, sulphur and nitrogen [4]. The major heavy oil production countries are Venezuela and CIS (Figure 2) [2].

(2) Bitumen

There are a lot of bitumen resources in the world, including oil sands resources; see Figure 21 [6]. Oil sands are a mixture of sand, bitumen and water [10]. Oil sands in Canada are thought to be the world's largest known hydrocarbon resource. With 300 billion barrels of recoverable reserves, Canada's oil sands exceed Saudi Arabian reserves of 262 billion barrels. Most of Canada's oil sands are found in Alberta, and the highest quality oil sands are the Athabasca deposits found in northern Alberta [10]. Alberta's oil sands deposits were described by Time Magazine as "Canada's greatest buried energy treasure," and "could satisfy the world's demand for petroleum for the next century" [9].

(3) Unconventional gas

With continuous high oil and gas price, many marginal hydrocarbon resources, such as heavy oil resources and unconventional gas resources, have been developed as supplement to the conventional gas production gap. Among these resources, CBM has made an increasingly important contribution to gas supply, especially in North America [11], and many countries have started its development, such as China, USA, and Canada. As a new and promising gas resource, research on the distribution and development techniques of CBM becomes a hot spot with the assignment of Kyoto Protocol. Many countries, such as India, have begun CBM resources assessment and experimental research, but large-scaled production has not begun yet. Global coal reserves data can be used to have a glance estimation of possible global CBM distribution for coal is the source rock of CBM. Among coal-bearing countries, Canada has abundant of unconventional gas including CBM, and has started its production since 2002; see Table 3 [7].

Conventional oil and gas resources

Although the oil industry seeks to increase production of unconventional oil and gas supplies, the most oil and gas production today still comes from conventional oil and gas reserves. Conventional oil and gas still is the most important hydrocarbon resources nowadays. The major statistics data used in this report comes from Energy Information Administration (EIA), the official energy statistics of the American Government and most reserves were estimated on January of 2006 [12-115].

The statistics data is sorted by countries; see Table 4, Figure 23. Then it is summarized by districts; see Table 5.

Conventional hydrocarbon distribution has following characteristics:

- Middle East and North America are the major oil bearing and production districts; see Figures 24, 25). Saudi Arabia, Canada and Iran are the first 3 major oil bearing countries; Saudi Arabia, Russia and USA are the first 3 major oil production countries today.
- Middle East and CIS are the most important gas bearing districts in the world; see Figures 26, 27. Russia, Iran and Qatar are the first 3 major gas bearing countries; Russia, USA and Canada are the first 3 major gas production countries at present.
- USA, Russia and China are the first 3 major coal bearing countries; China, USA and India are the first 3 major coal production countries nowadays. India, Australia and South Africa also have abundant coal reserves; see Figures 28, 29. From world coal reserves distribution, we can deduce that CBM reserves should be abundant in these 6 countries under appropriate geological conditions.

Some comments

Features of recent sediments and ancient sedimentary rocks can be combined and condensed into models that characterize particular sedimentary environments. This combination of features from modern and ancient situations has been emphasized from the earliest days; in 1893 Johannes Walther "explained that the most satisfying genetic explanations of ancient phenomena were by analogy with modern geological processes" [116].

Depositional systems are sets of depositional environments linked by the process of sediment routing. They are responsible for large stratigraphic thickness and environmental changes in one part of the system which can generally be recognized in the stratigraphy of another part of the system. Depositional systems and their sedimentary products reflect the integration of autogenic (internal) and allogenic (external) controls. Sedimentary basins with different driving mechanisms have distinctive assemblages of depositional systems and facies. There are many depositional systems classification methods which are suitable for specific research purposes. In this report, a combined hydrocarbon bearing related classification is used for research convenience; see Figure 1 [117, 118].

From depositional systems view, we can see that SSL and CSR are the important world hydrocarbon bearing depositional systems; see Figures 23, 30 and Table 6. 81% oil reserves and 69% oil production come from these two types of depositional systems; 73% gas reserves and 69% gas production come from these two types of depositional systems. That makes sense. SSL is located at the marginal position of sea basin and there are very good sand bodies such as delta front sand in this depositional system, and CSR is not only good source rock but also very good container rock itself.

From the global view,

- Fluvial and Lacustrine Systems (FL) is mainly located in China, South-East Asia, and Central Africa; USA and Brazil also have lots of FL-type reservoirs;

- Siliciclastic Shoreline Systems (SSL) is mainly located in North America, western South America, North Africa, Europe, Russia and Australia, and it is the most common hydrocarbon bearing depositional systems in the world;
- Carbonate and Evaporate Shoreline Systems (CES) is limited distributed in Brazil, Abu Dhabi and Yemen;
- Siliciclastic Shelf Systems (SSF) is only distributed in Oman, Central Africa, South Africa, and it is mainly a gas-bearing depositional system;
- Carbonate Shelf Systems and Reefs (CSR) is mainly distributed in Arabia, Venezuela and North America; they are the most important oil and gas production districts in the world;
- Deep-sea Depositional Systems (DSD) is a research hot spot in recent years, and many countries have dedicated to the study of DSD.

Conclusions

Base on above investigation and depositional systems overview, deltaic is the most important object-based modeling target. Deltaic sand is the major sand body of Siliciclastic Shoreline Systems (SSL), and SSL is one of the most important hydrocarbon bearing depositional systems in the world; see Figure 30. There are many giant oilfields with delta-type formations in the world, such as the giant Ganges-Brahmaputra delta which covers almost all of Bangladesh and parts of eastern India and West Bengal, the Mackenzie Delta of Canada which has recoverable natural gas reserves 9-10Tcf.

Deltaic is one of the well-studied depositional systems. There are many mature models for delta, e.g. the models defined in Figure 31; and the geometry of delta is kind of simple and clear which is suitable for object-based modeling. It is also a well-studied environment for sequence stratigraphy. Sequence stratigraphy boundary surface is also an important object modeling target. With these theoretical models, object models can be easily defined at each scale.

Many giant oilfields with deltaic reservoir in the world have come into high water-cut stage, so finer-scaled reservoir models are needed. The uncertainty at this scale is still huge. Object-based modeling approaches are very suitable for describing the sophisticated objects/depositional process of deltaic formations.

Deltaic is a type of fluvial depositional system; see Figure 32. Some existed object-based modeling approaches, say, *alluvsim* for channel modeling, *Turbsim*, *LE_model* and *surfsim* for time surface modeling, are good starting points. That is, we have enough technique preparation for deltaic modeling.

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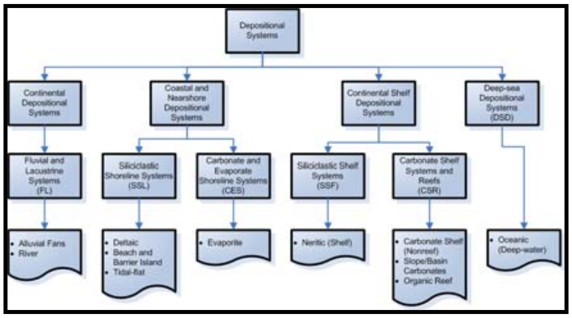


Figure 1: A flow chart showing the classification method used in this report

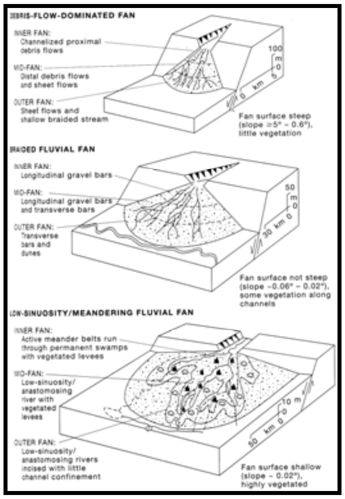


Figure 2: Principal kinds of alluvial fans (from Boggs, 2001)

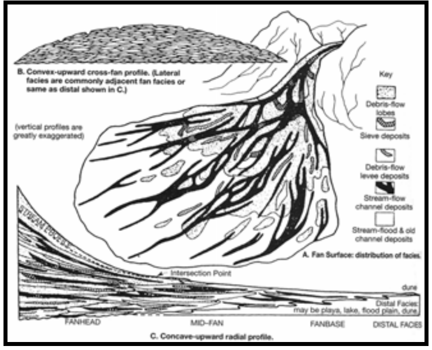


Figure 3: Typical surface features and profiles of alluvial fans (from Boggs, 2001)

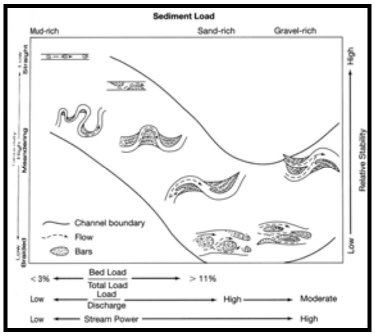


Figure 4: Channel patterns displayed by rivers of various sinuosity, bed load, and stream power (from Boggs, 2001)

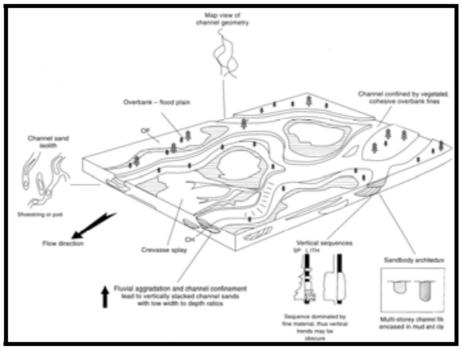


Figure 5: Block diagram of an anastomosing fluvial system illustrating the facies associations, channel belt and flood-plain subenvironments (from Emery and Myers, 1996)

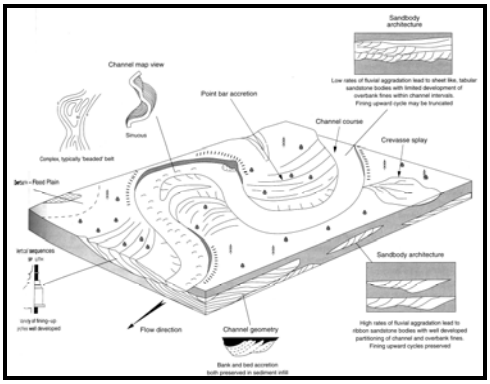


Figure 6: Block diagram of a high-sinuosity fluvial system illustrating the facies associations, channel belts and flood-plain sub-environments (from Emery and Myers, 1996)

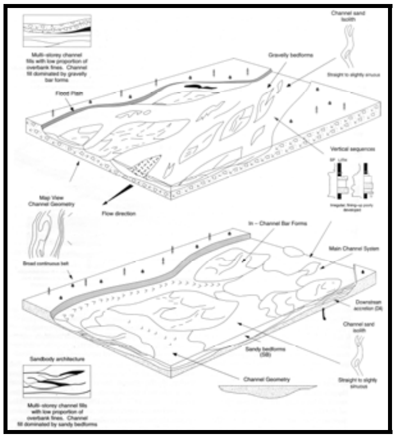


Figure 7: Block diagram of a low sinuosity (upper) gravelly and (lower) sand fluvial system illustrating the facies associations, channel belts and flood-plain sub-environments (from Emery and Myers, 1996)

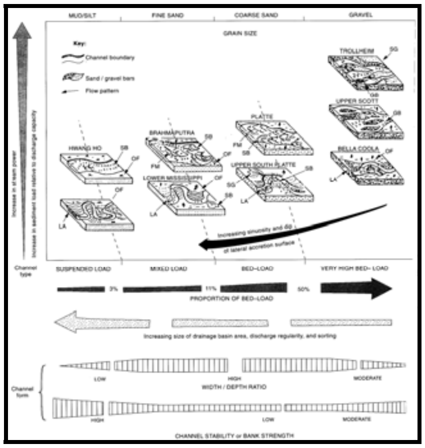


Figure 8: Relationship between grain size and channel pattern (from Emery and Myers, 1996)

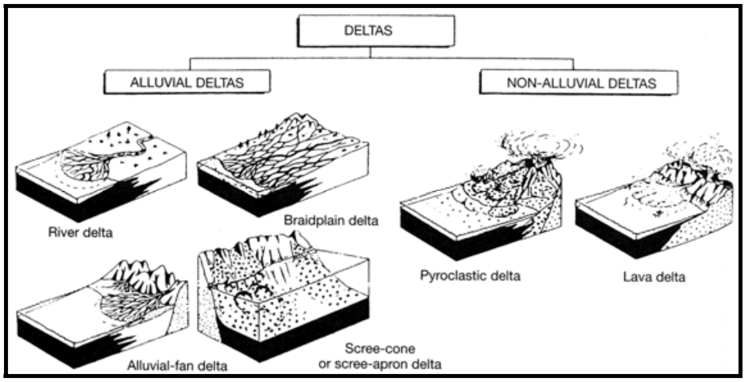


Figure 9: Subdivision of deltas into alluvial and nonalluvial varieties, with specific examples of both delta types (from Boggs, 2001)

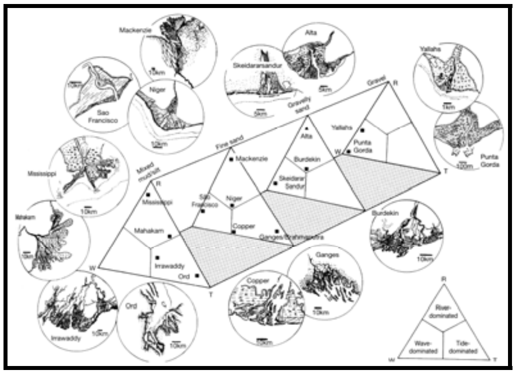


Figure 10: Classification of deltas on the basis of dominant process of sediment dispersal at the delta front and the prevailing grain size of sediment delivered to the front. Dispersal processes: R, river; W, wave; T, tidal (from Boggs, 2001)

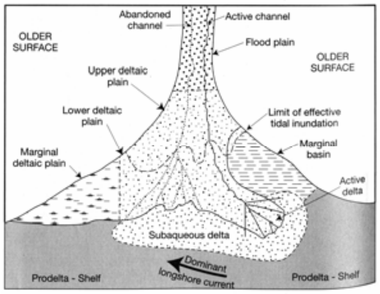


Figure 11: Principal components of a delta system (from Boggs, 2001)

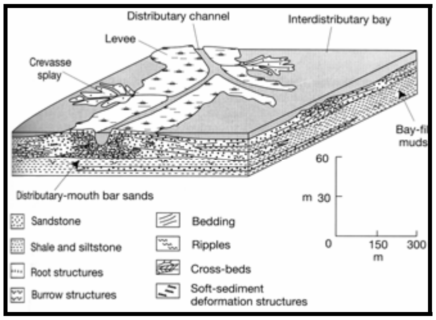


Figure 12: Three-dimensional model of fluvial– dominated delta deposits from Eastern Kentucky (from Boggs, 2001)

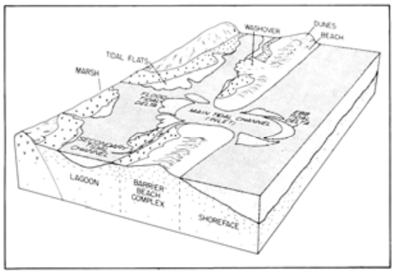


Figure 13: Block diagram illustrating the various sub-environments in a barrier-island system (from Walker, 1984)

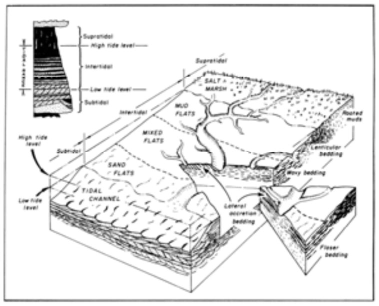


Figure 14: Block diagram of a typical Siliciclastic tidal flat (from Walker and James, 1992)

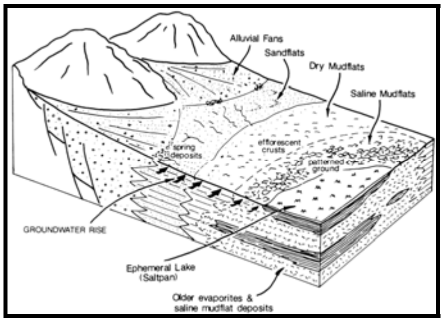


Figure 15: Depositional framework for continental evaporite (playa complex) model (from Walker and James, 1992)

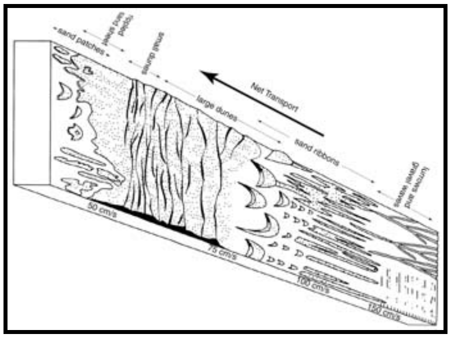


Figure 16: Idealized succession of bedforms along a sediment transport path on a tide-dominated shelf (from Boggs, 2001)

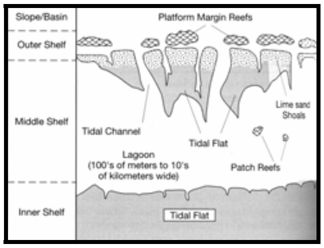


Figure 17: Schematic plan view of a modern, rimmed, tropical carbonate platform (from Boggs, 2001)

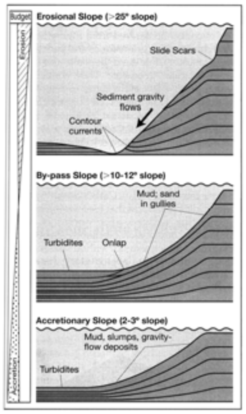


Figure 18: Principal kinds of carbonate slopes, based on examples from the Bahama platform (from Boggs, 2001)

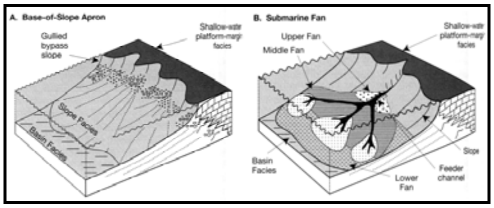


Figure 19: Mdels for carbonate slopes (from Boggs, 2001)

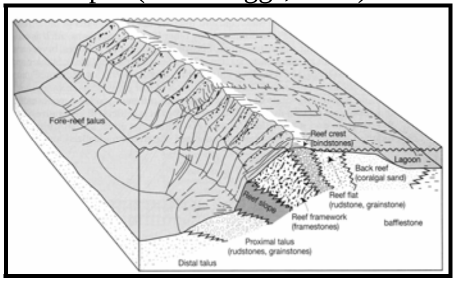


Figure 20: Idealized facies in a typical modern, mature coral reef (from Boggs, 2001)

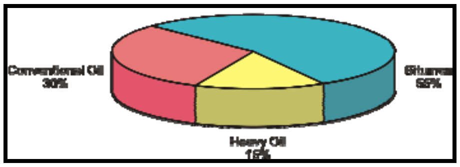


Figure 21: Total world oil reserves (from AGT Energy, 2006)

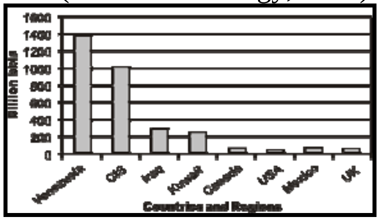


Figure 22: World heavy oil resources (from AGT Energy, 2006)

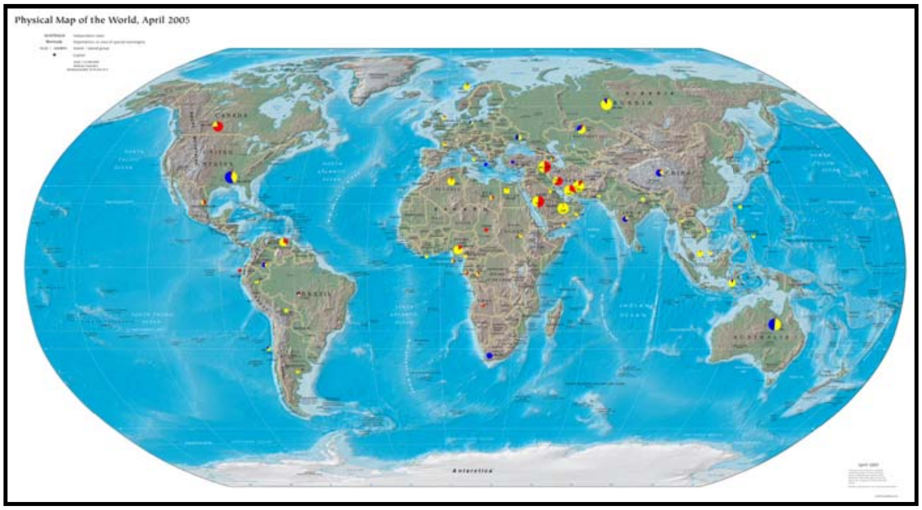


Figure 23: World hydrocarbon resources (red – oil, yellow –gas, blue- coal)

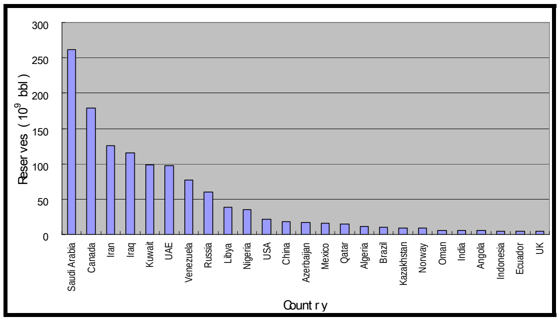


Figure 24: World oil reserves (Top 25)

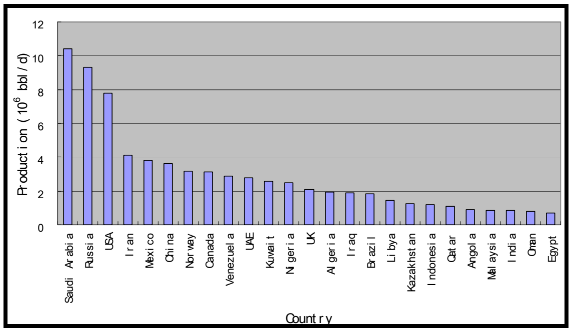


Figure 25: Major oil production countries (Top 25)

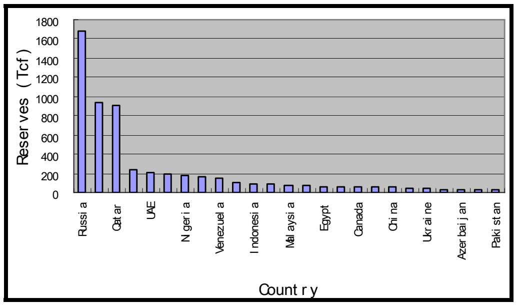


Figure 26: World gas reserves (Top 25)

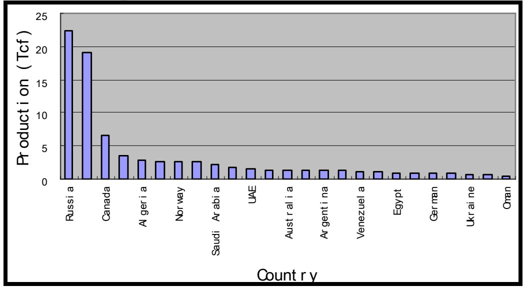


Figure 27: Major gas production countries (Top 25)

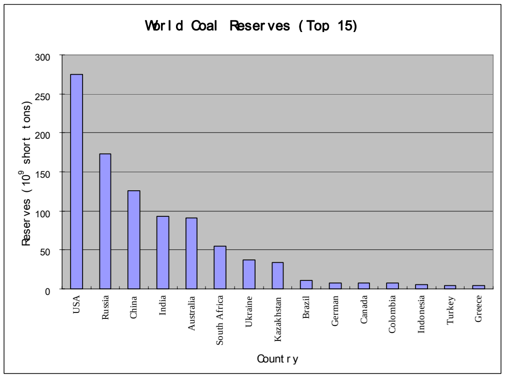


Figure 28: World coal reserves (Top 15)

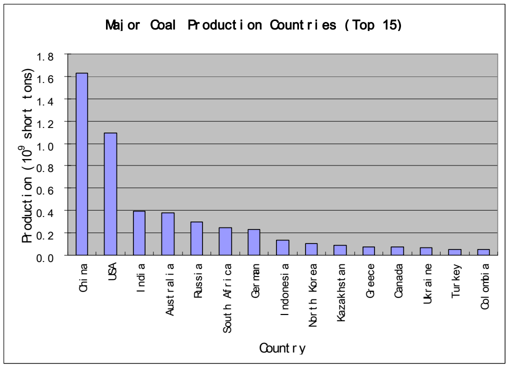


Figure 29: Major coal production countries (Top 15)

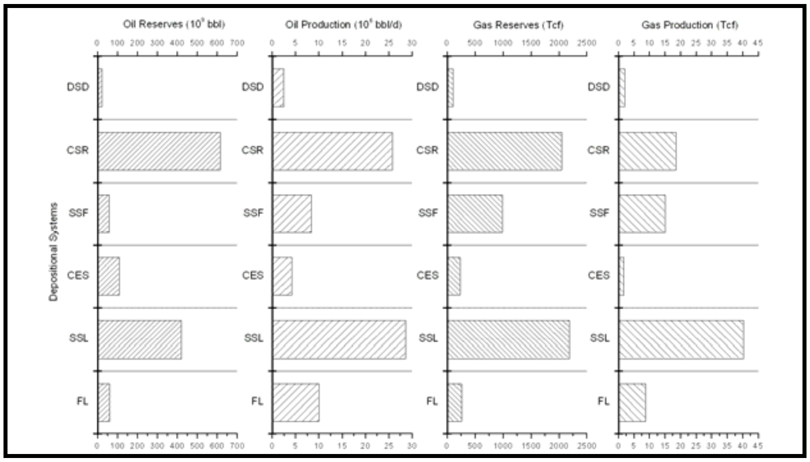


Figure 30: World petroleum resources (by depositional systems)

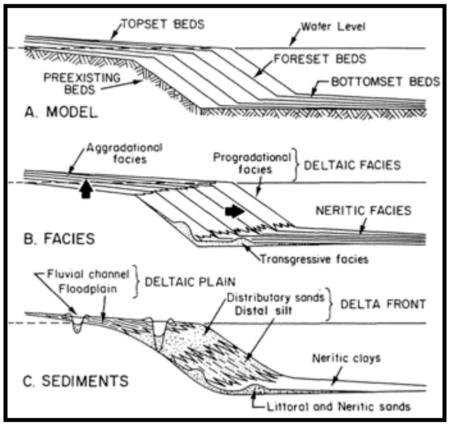


Figure 31: diagrammatic cross sections of depositional units within deltas: (A) the delta concept of Gilbert showing topset, foreset, and bottom set beds (from Gilbert, 1885); (B) deltaic and neritic facies from Frazier (from Frazier, 1967); (C) sediment types and depositional units of an idealized delta (from Berg, 1986)

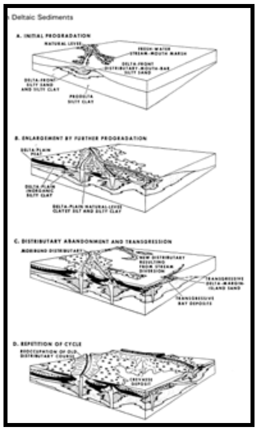
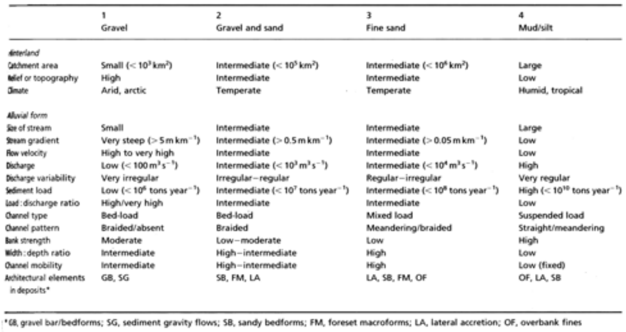


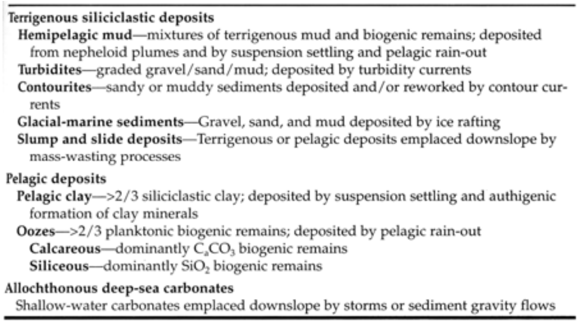
Figure 32: Diagrams showing the development of deltaic facies: (A) initial progradation; (B) enlargement by further progradation; (C) distributary abandonment and transgression; (D) repetition of cycle (from Frazier, 1967)



	1 Gravel	2 Gravel and sand	3 Fine sand	4 Mud/silt
Hinterland				
Catchment area	Small (< $10^3\,km^2$)	Intermediate (< $10^5\,km^2$)	Intermediate (< $10^6\,km^2$)	Large
Relief or topography	High	Intermediate	Intermediate	Low
Climate	Arid, arctic	Temperate	Temperate	Humid, tropical
Alluvial form				
Size of stream	Small	Intermediate	Intermediate	Large
Stream gradient	Very steep (> $5\,m\,km^{-1}$)	Intermediate (> $0.5\,m\,km^{-1}$)	Intermediate (> $0.05\,m\,km^{-1}$)	Low
Flow velocity	High to very high	Intermediate	Intermediate	Low
Discharge	Low (< $100\,m^3\,s^{-1}$)	Intermediate (< $10^3\,m^3\,s^{-1}$)	Intermediate (< $10^4\,m^3\,s^{-1}$)	High
Discharge variability	Very irregular	Irregular–regular	Regular–irregular	Very regular
Sediment load	Low (< 10^6 tons $year^{-1}$)	Intermediate (< 10^7 tons $year^{-1}$)	Intermediate (< 10^8 tons $year^{-1}$)	High (< 10^{10} tons $year^{-1}$)
Load : discharge ratio	High/very high	Intermediate	Intermediate	Low
Channel type	Bed-load	Bed-load	Mixed load	Suspended load
Channel pattern	Braided/absent	Braided	Meandering/braided	Straight/meandering
Bank strength	Moderate	Low–moderate	Low	High
Width : depth ratio	Intermediate	High–intermediate	High	Low
Channel mobility	Intermediate	High–intermediate	High	Low (fixed)
Architectural elements in deposits*	GB, SG	SB, FM, LA	LA, SB, FM, OF	OF, LA, SB

* GB, gravel bar/bedforms; SG, sediment gravity flows; SB, sandy bedforms; FM, foreset macroforms; LA, lateral accretion; OF, overbank fines

Table 1: Summary characteristics of fluvial depositional systems according to grain size (from Emery and Myers, 1996)



Terrigenous siliciclastic deposits

- **Hemipelagic mud**—mixtures of terrigenous mud and biogenic remains; deposited from nepheloid plumes and by suspension settling and pelagic rain-out
- **Turbidites**—graded gravel/sand/mud; deposited by turbidity currents
- **Contourites**—sandy or muddy sediments deposited and/or reworked by contour currents
- **Glacial-marine sediments**—Gravel, sand, and mud deposited by ice rafting
- **Slump and slide deposits**—Terrigenous or pelagic deposits emplaced downslope by mass-wasting processes

Pelagic deposits

- **Pelagic clay**—>2/3 siliciclastic clay; deposited by suspension settling and authigenic formation of clay minerals
- **Oozes**—>2/3 planktonic biogenic remains; deposited by pelagic rain-out
  - **Calcareous**—dominantly C_aCO_3 biogenic remains
  - **Siliceous**—dominantly SiO_2 biogenic remains

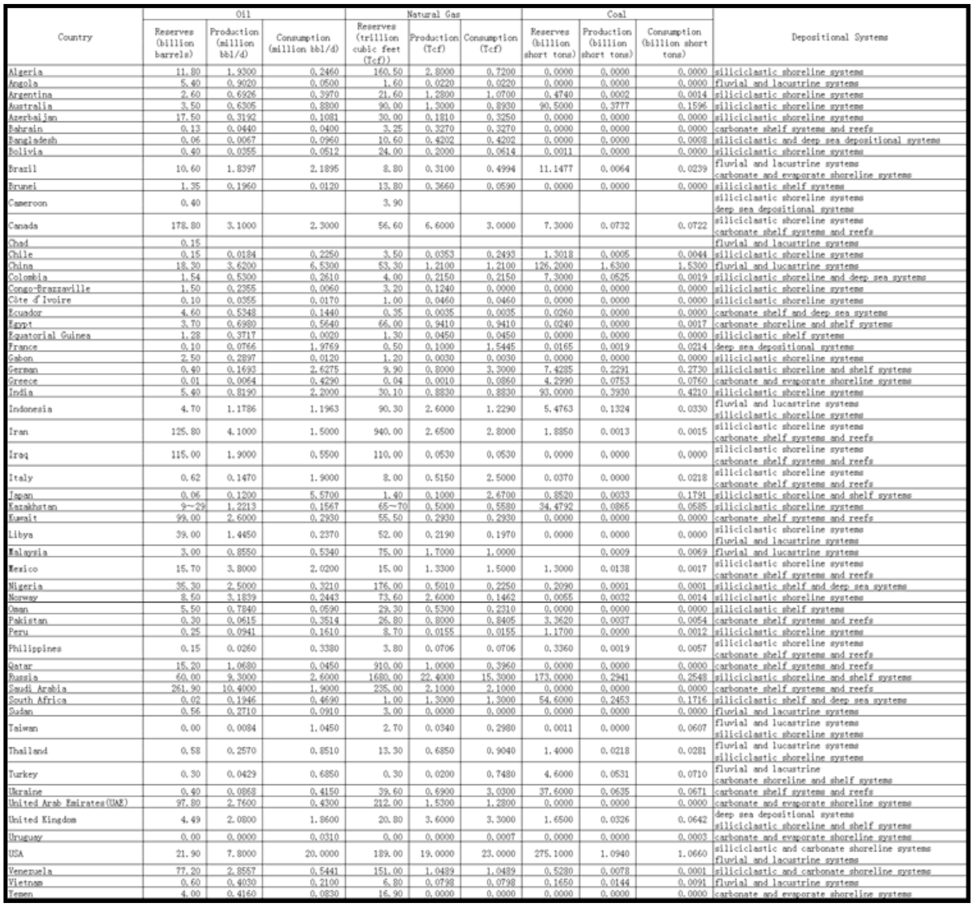
Allochthonous deep-sea carbonates

Shallow-water carbonates emplaced downslope by storms or sediment gravity flows

Table 2: Principal types of deep-sea sediments

	Status USA	Resource in Canada*	Status Canada
Shallow Biogenic Gas	On-going production	30Tcf	Production since 1905
Tight Gas	Growth Opportunity	600Tcf	Production since 1976
Coalbed Methane	On-going Production	400Tcf	Production since 2002
Shale Gas	On-going Production	100Tcf	Experimental activity
Gas Hydrates	Experimental Research	5,000Tcf	Experimental Research
Continuously Generated Methane	Pilot Projects	400Mmcf/d	Pilot Projects

Table 3: Unconventional Gas Resources in Canada– Status and Resources (from AJM Petroleum Consultants, 2006) *From various sources.



Country	Oil			Natural Gas			Coal			Depositional Systems
	Reserves (billion barrels)	Production (million bbl/d)	Consumption (million bbl/d)	Reserves (trillion cubic feet (Tcf))	Production (Tcf)	Consumption (Tcf)	Reserves (billion short tons)	Production (billion short tons)	Consumption (billion short tons)	
Algeria	11.80	1.9300	0.2460	160.50	2.8000	0.7200	0.0000	0.0000	0.0000	siliciclastic shoreline systems
Angola	5.40	0.9020	0.0500	1.60	0.0220	0.0220	0.0000	0.0000	0.0000	fluvial and lacustrine systems
Argentina	2.60	0.6926	0.3970	21.60	1.2800	1.0700	0.4740	0.0002	0.0014	siliciclastic shoreline systems
Australia	3.50	0.6305	0.8800	90.00	1.3000	0.8930	90.5000	0.3777	0.1596	siliciclastic shoreline systems
Azerbaijan	17.50	0.3192	0.1081	30.00	0.1810	0.3250	0.0000	0.0000	0.0000	siliciclastic shoreline systems
Bahrain	0.13	0.0440	0.0400	3.25	0.3270	0.3270	0.0000	0.0000	0.0000	carbonate shelf systems and reefs
Bangladesh	0.06	0.0067	0.0960	10.60	0.4202	0.4202	0.0000	0.0000	0.0008	siliciclastic and deep sea depositional systems
Bolivia	0.40	0.0355	0.0512	24.00	0.2000	0.0614	0.0011	0.0000	0.0000	siliciclastic shoreline systems
Brazil	10.60	1.8397	2.1895	8.80	0.3100	0.4994	11.1477	0.0064	0.0239	fluvial and lacustrine systems carbonate and evaporate shoreline systems
Brunei	1.35	0.1960	0.0120	13.80	0.3660	0.0590	0.0000	0.0000	0.0000	siliciclastic shelf systems
Cameroon	0.40			3.90						siliciclastic shoreline systems deep sea depositional systems
Canada	178.80	3.1000	2.3000	56.60	6.6000	3.0000	7.3000	0.0732	0.0722	siliciclastic shoreline systems carbonate shelf systems and reefs
Chad	0.15									fluvial and lacustrine systems
Chile	0.15	0.0184	0.2250	3.50	0.0353	0.2493	1.3018	0.0005	0.0044	siliciclastic shoreline systems
China	18.30	3.6200	6.5300	53.30	1.2100	1.2100	126.2000	1.6300	1.5300	fluvial and lucastrine systems
Colombia	1.54	0.5300	0.2610	4.00	0.2150	0.2150	7.3000	0.0525	0.0019	siliciclastic shoreline and deep sea systems
Congo-Brazzaville	1.50	0.2355	0.0060	3.20	0.1240	0.0000	0.0000	0.0000	0.0000	siliciclastic shoreline systems
Côte d'Ivoire	0.10	0.0355	0.0170	1.00	0.0460	0.0460	0.0000	0.0000	0.0000	siliciclastic shoreline systems
Ecuador	4.60	0.5348	0.1440	0.35	0.0035	0.0035	0.0260	0.0000	0.0000	carbonate shelf and deep sea systems
Egypt	3.70	0.6980	0.5640	66.00	0.9410	0.9410	0.0240	0.0000	0.0017	carbonate shoreline and shelf systems
Equatorial Guinea	1.28	0.3717	0.0020	1.30	0.0450	0.0450	0.0000	0.0000	0.0000	siliciclastic shelf systems
France	0.10	0.0766	1.9769	0.50	0.1000	1.5445	0.0165	0.0019	0.0214	deep sea depositional systems
Gabon	2.50	0.2897	0.0120	1.20	0.0030	0.0030	0.0000	0.0000	0.0000	siliciclastic shoreline systems
German	0.40	0.1693	2.6275	9.90	0.8000	3.3000	7.4285	0.2291	0.2730	siliciclastic shoreline and shelf systems
Greece	0.01	0.0064	0.4290	0.04	0.0010	0.0860	4.2990	0.0753	0.0760	carbonate and evaporate shoreline systems
India	5.40	0.8190	2.2000	30.10	0.8830	0.8830	93.0000	0.3930	0.4210	siliciclastic shoreline systems
Indonesia	4.70	1.1786	1.1963	90.30	2.6000	1.2290	5.4763	0.1324	0.0330	fluvial and lucastrine systems siliciclastic shoreline systems
Iran	125.80	4.1000	1.5000	940.00	2.6500	2.8000	1.8850	0.0013	0.0015	siliciclastic shoreline systems carbonate shelf systems and reefs
Iraq	115.00	1.9000	0.5500	110.00	0.0530	0.0530	0.0000	0.0000	0.0000	siliciclastic shoreline systems carbonate shelf systems and reefs
Italy	0.62	0.1470	1.9000	8.00	0.5150	2.5000	0.0370	0.0000	0.0218	siliciclastic shoreline systems carbonate shelf systems and reefs
Japan	0.06	0.1200	5.5700	1.40	0.1000	2.6700	0.8520	0.0033	0.1791	siliciclastic shoreline and shelf systems
Kazakhstan	9~29	1.2213	0.1567	65~70	0.5000	0.5580	34.4792	0.0865	0.0585	siliciclastic shoreline systems
Kuwait	99.00	2.6000	0.2930	55.50	0.2930	0.2930	0.0000	0.0000	0.0000	carbonate shelf systems and reefs
Libya	39.00	1.4450	0.2370	52.00	0.2190	0.1970	0.0000	0.0000	0.0000	siliciclastic shoreline systems fluvial and lacustrine systems
Malaysia	3.00	0.8550	0.5340	75.00	1.7000	1.0000		0.0009	0.0069	fluvial and lucastrine systems
Mexico	15.70	3.8000	2.0200	15.00	1.3300	1.5000	1.3000	0.0138	0.0017	siliciclastic shoreline systems carbonate shelf systems and reefs
Nigeria	35.30	2.5000	0.3210	176.00	0.5010	0.2250	0.2090	0.0001	0.0001	siliciclastic shelf and deep sea systems
Norway	8.50	3.1839	0.2443	73.60	2.6000	0.1462	0.0055	0.0032	0.0014	siliciclastic shoreline systems
Oman	5.50	0.7840	0.0590	29.30	0.5300	0.2310	0.0000	0.0000	0.0000	siliciclastic shelf systems
Pakistan	0.30	0.0615	0.3514	26.80	0.8000	0.8405	3.3620	0.0037	0.0054	carbonate shelf systems and reefs
Peru	0.25	0.0941	0.1610	8.70	0.0155	0.0155	1.1700	0.0000	0.0012	siliciclastic shoreline systems
Philippines	0.15	0.0260	0.3380	3.80	0.0706	0.0706	0.3360	0.0019	0.0057	siliciclastic shoreline systems carbonate shelf systems and reefs
Qatar	15.20	1.0680	0.0450	910.00	1.0000	0.3960	0.0000	0.0000	0.0000	carbonate shelf systems and reefs
Russia	60.00	9.3000	2.6000	1680.00	22.4000	15.3000	173.0000	0.2941	0.2548	siliciclastic shoreline and shelf systems
Saudi Arabia	261.90	10.4000	1.9000	235.00	2.1000	2.1000	0.0000	0.0000	0.0000	carbonate shelf systems and reefs
South Africa	0.02	0.1946	0.4690	1.00	1.3000	1.3000	54.6000	0.2453	0.1716	siliciclastic shelf and deep sea systems
Sudan	0.56	0.2710	0.0910	3.00	0.0000	0.0000	0.0000	0.0000	0.0000	fluvial and lacustrine systems
Taiwan	0.00	0.0084	1.0450	2.70	0.0340	0.2980	0.0011	0.0000	0.0607	fluvial and lucastrine systems siliciclastic shoreline systems
Thailand	0.58	0.2570	0.8510	13.30	0.6850	0.9040	1.4000	0.0218	0.0281	fluvial and lucastrine systems siliciclastic shoreline systems
Turkey	0.30	0.0429	0.6850	0.30	0.0200	0.7480	4.6000	0.0531	0.0710	fluvial and lacustrine carbonate shoreline and shelf systems
Ukraine	0.40	0.0868	0.4150	39.60	0.6900	3.0300	37.6000	0.0635	0.0671	carbonate shelf systems and reefs
United Arab Emirates(UAE)	97.80	2.7600	0.4300	212.00	1.5300	1.2800	0.0000	0.0000	0.0000	carbonate and evaporate shoreline systems
United Kingdom	4.49	2.0800	1.8600	20.80	3.6000	3.3000	1.6500	0.0326	0.0642	deep sea depositional systems siliciclastic shoreline and shelf systems
Uruguay	0.00	0.0000	0.0310	0.00	0.0000	0.0007	0.0000	0.0000	0.0003	carbonate and evaporate shoreline systems
USA	21.90	7.8000	20.0000	189.00	19.0000	23.0000	275.1000	1.0940	1.0660	siliciclastic and carbonate shoreline systems fluvial and lacustrine systems
Venezuela	77.20	2.8557	0.5441	151.00	1.0489	1.0489	0.5280	0.0078	0.0001	siliciclastic and carbonate shoreline systems
Vietnam	0.60	0.4030	0.2100	6.80	0.0798	0.0798	0.1650	0.0144	0.0091	fluvial and lacustrine systems
Yemen	4.00	0.4160	0.0830	16.90	0.0000	0.0000	0.0000	0.0000	0.0000	carbonate and evaporate shoreline systems

Table 4: World hydrocarbon resources overview (by countries)

Continent/Distric	Oil			Natural Gas			Coal		
	Reserves (billion barrels)	Production (million bbl/d)	Consumption (million bbl/d)	Reserves (trillion cubic feet (Tcf))	Production (Tcf)	Consumption (Tcf)	Reserves (billion short tons)	Production (billion short tons)	Consumption (billion short tons)
Africa	101.71	8.87	2.02	470.70	6.00	3.50	54.83	0.25	0.17
Asia	34.5040	7.5512	21.8687	327.9000	8.9486	10.6681	231.5394	2.3104	2.4647
Australia	3.50	0.6305	0.8800	90.00	1.3000	0.8930	90.5000	0.3777	0.1596
CIS	77.90	10.93	3.28	1749.60	23.77	19.21	245.08	0.44	0.38
Europe	14.42	5.71	9.72	113.14	7.64	11.62	18.04	0.40	0.53
Middle East	724.33	24.07	4.90	2511.95	8.48	7.48	1.89	0.00	0.00
North America	216.40	14.70	24.32	260.60	26.93	27.50	283.70	1.18	1.14
South America	97.3430	6.6008	4.0288	221.9450	3.1082	3.1637	21.9486	0.0675	0.0332
Total	1270.0947	79.0610	71.0150	5745.8300	86.1778	84.0415	947.5217	5.0225	4.8814

Table 5: World hydrocarbon resources overview (by districts)

Facies	Oil		Gas	
	Reserves (10^9bbl)	Production (10^6bbl)	Reserves (Tcf)	Production (Tcf)
FL	59.89	9.984	261.11	8.7398
SSL	419.641	28.5664	2184.01	40.2062
CFS	107.11	4.1023	233.34	1.686
SSF	57.936	8.3429	986.99	14.9395
CSR	612.565	25.6901	2042.805	18.5666
DSD	21.958	2.3757	102.585	2.0399

Table 6: Petroleum resources in different depositional systems