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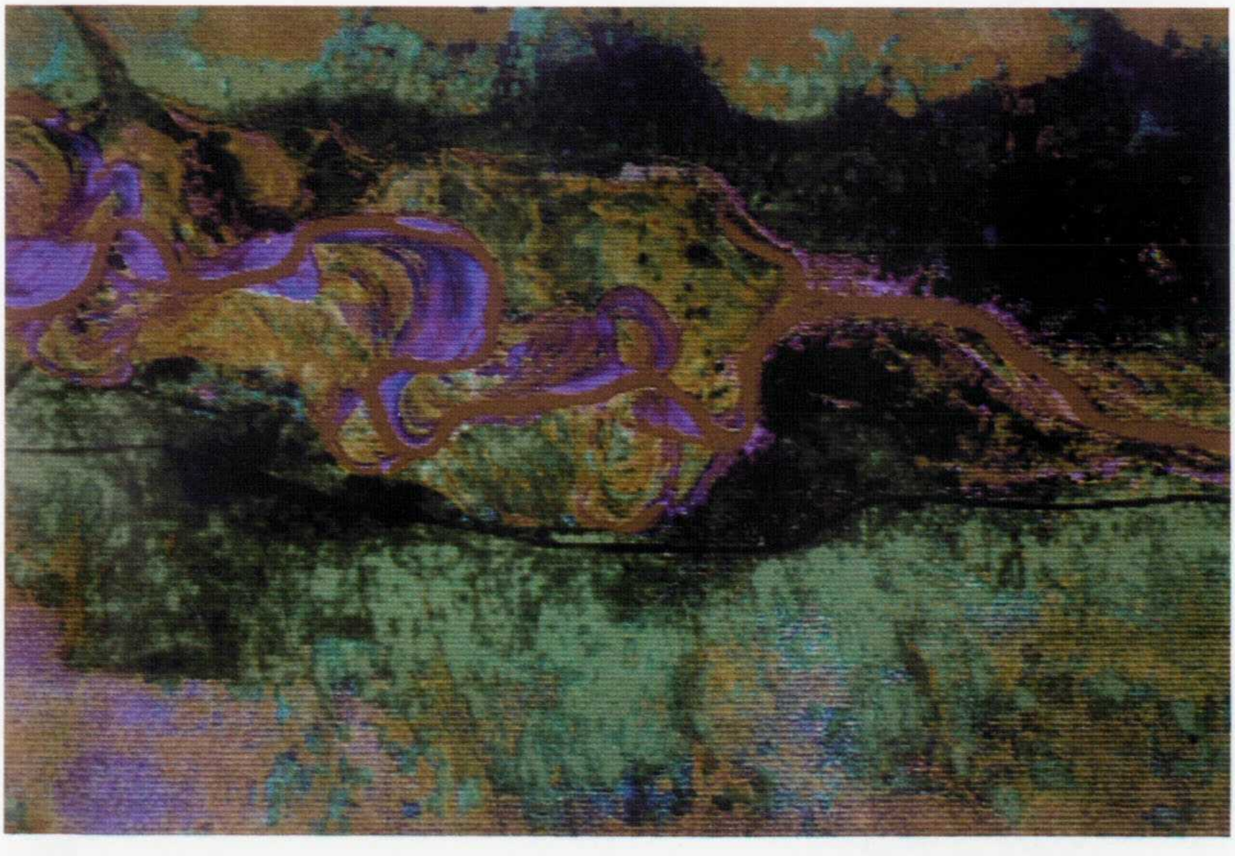
ODA

A GUIDE TO THE SEDIMENTOLOGY OF UNCONSOLIDATED SEDIMENTARY AQUIFERS (UNSAs)

Steve Mathers and Jan Zalasiewicz
with contributions by Jeffrey Davies



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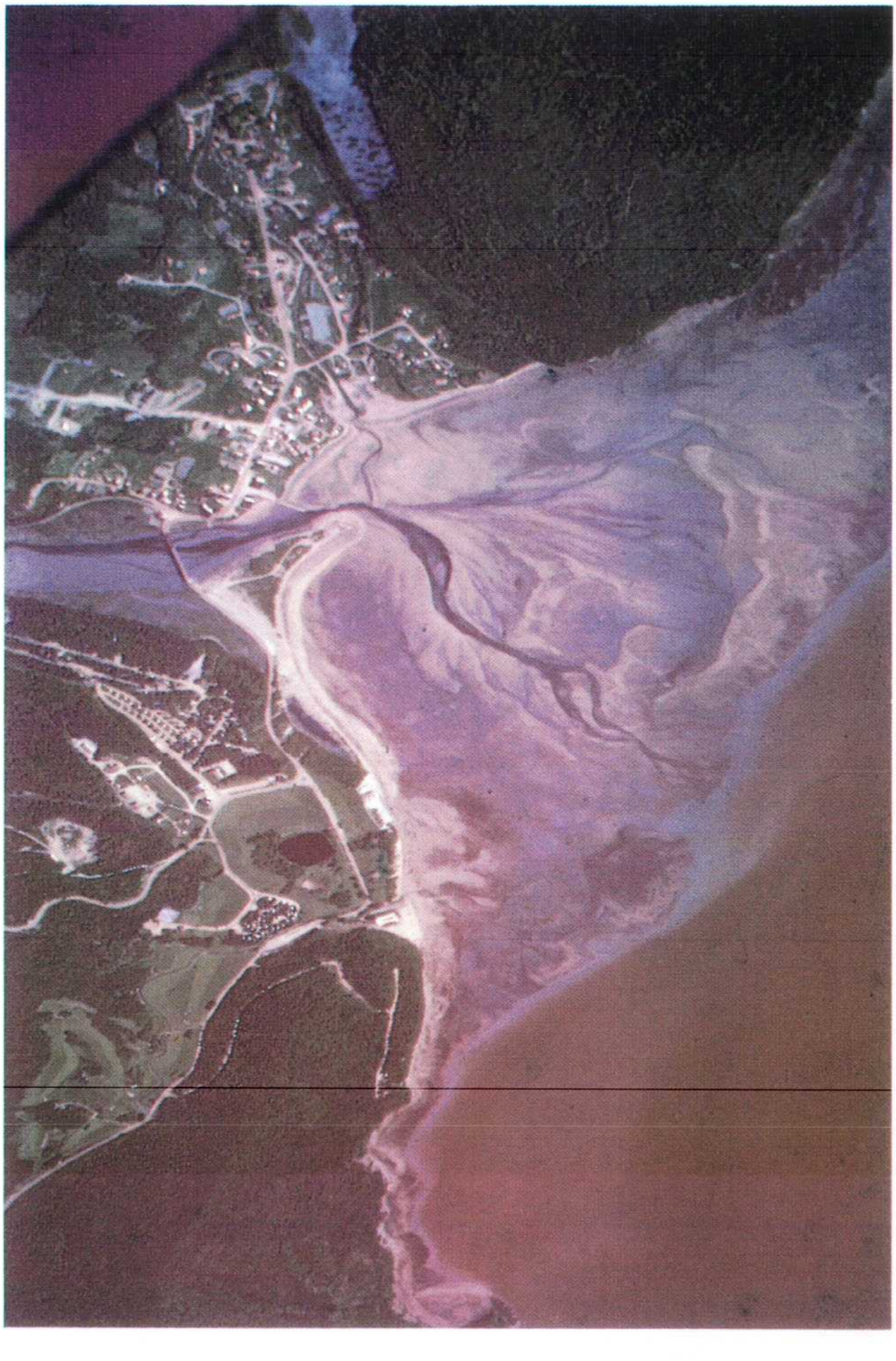

Aerial view of the macrotidal delta at Alma, Bay of Fundy, Canada, at low water. This wedge of coarse-grained permeable sediment is sculpted by powerful tidal currents, and modified into beach ridges at its seaward edge by wind-forced waves. Finer-grained, less permeable sediment accumulates in troughs behind the beach ridges and in abandoned tidal channels. (Photo courtesy D.J.C. Laming).

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PREFACE

The initial aim of the ODA/BGS R&D project on UNSAs is to prepare a series of reviews to assist overseas hydrogeologists at all stages in the evaluation and development of groundwater resources in UNSAs. Each review comprises a detailed state-of-the-art synthesis of a particular aspect of the hydrogeology of UNSAs. An overall Handbook will also be produced, in order to summarise these detailed reviews and draw together the results of the project.

This particular review deals with the sedimentology of unconsolidated deposits likely to contain extractable groundwater resources. Specifically, it aims to help the hydrogeologist to define the geometry and lithology of the sedimentological units, and therefore the hydrogeological units, present within a typical UNSA system. The environments in which these deposits form are each described through the use of conceptual models and examples. Key references are given to allow the specialist to obtain further information. This review, together with the Handbook, are designed to allow both specialist and non-specialist to jointly discuss groundwater development issues.

Many examples presented here have been taken from work carried out in the developed world. There are numerous and important UNSAs present in the developing world. But, few of these have been investigated in sufficient detail to allow three-dimensional, predictive sedimentological models to be constructed of them. It is hoped that this review will highlight the need for a fuller understanding of UNSAs, for such understanding is crucial to the efficient development and management of groundwater.

This review is a compilation of existing knowledge. It is intended to be updated, as appropriate, following the results of research which will be carried out during the lifetime of the project, which is scheduled to run until 1996.

The project is funded by the ODA as part of their research and development programme designed to improve living standards and conditions in the world's developing countries.

Project Manager : Dr. R. Herbert
Hydrogeological Adviser to ODA
British Geological Survey

A Guide to the sedimentology of unconsolidated sedimentary aquifers (UNSAs)

INTRODUCTION

WHAT ARE UNSAs AND WHY IS IT IMPORTANT TO UNDERSTAND THEM?

UNSAs are unconsolidated sedimentary aquifers. These are the water-bearing strata within the swathes of unconsolidated sediment that mantle much of the earth's surface. There is no clear dividing line between UNSAs and aquifers in consolidated rocks, as lithification is a gradational process: deposits a hundred years old can be lithified, while some deposits 500 million years old are still essentially unlithified. However, for most purposes, UNSAs can be understood as deposits which have accumulated over the past few million years, that is during Quaternary and Neogene (late Tertiary) time. They are important sources of water in many parts of the world, and in particular constitute the only major sources of groundwater for vast areas throughout the developing world. In the influential text-book *Hydrogeology* by Davies and De Weist it says:

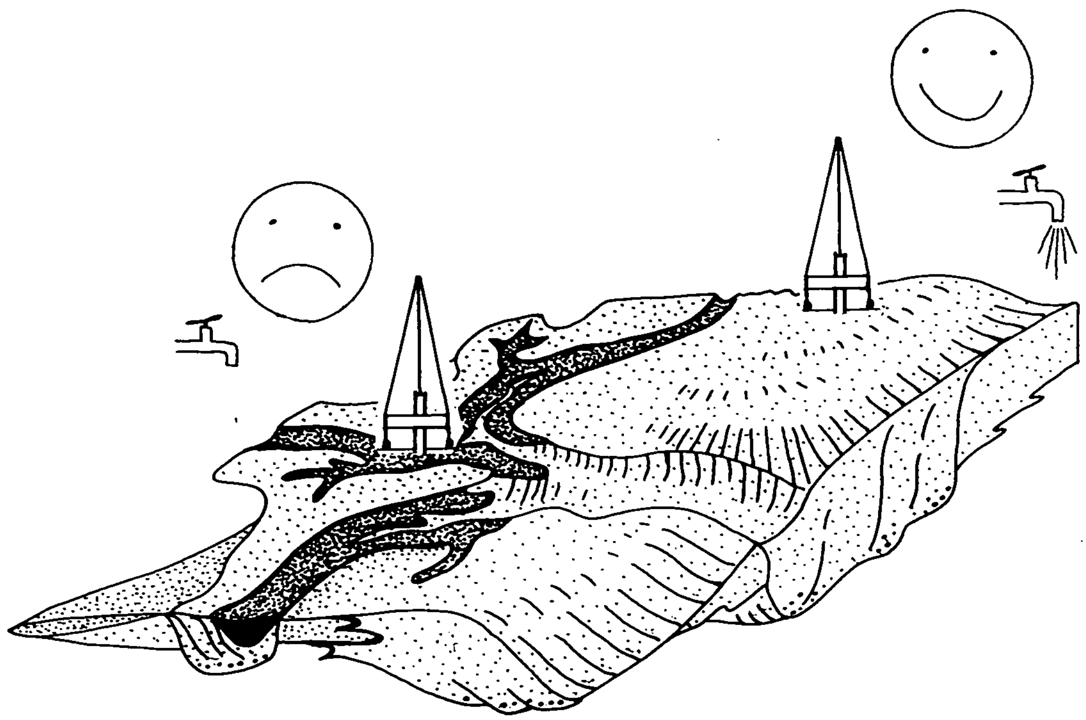
"The search for ground water most commonly starts with an investigation of nonindurated sediments. There are sound reasons for this preference. First, the deposits are easy to drill or dig so that exploration is rapid and inexpensive. Second, the deposits are most likely to be found in valleys where ground-water levels are close to the surface and where, as a consequence, pumping lifts are small. Third, the deposits are commonly in a favourable location with respect to recharge from lakes and rivers. Fourth, nonindurated sediments have generally higher specific yields than other material. Fifth, and perhaps most important, permeabilities are much higher than other natural materials with the exception of some recent volcanic rocks and cavernous limestones."

To date, though, few attempts have been made to understand the detailed internal structure of unconsolidated aquifers even though such knowledge may be crucial to the long term success of any water development project. This shortcoming is probably the reason why the operational lives of many water boreholes are frequently much shorter than expected.

The meandering Sigatoka River, Fiji. This type of sedimentary system typically consists of a mixture of aquifers (the sand deposited as point bars inside meander bends) and aquicludes (the overbank muds deposited on the flood plain).

These strand lines of pumice on a beach of black volcanic ash demonstrate the ability of sedimentary processes to sort sediment. Santorini Island.

Understanding of the internal structure or 'architecture' of many types of sedimentary deposit has, however, advanced greatly over the past couple of decades. Part of this research has been academic, but much has been sponsored by the oil industry, so as to better predict the possible location of oil within sedimentary traps. Oil, like water, is most profitably located within bodies of relatively coarse-grained and porous sediment. Thus, there is obvious scope for applying this recently gained understanding to hydrogeological problems. Advances have also been made in the understanding of the geometry of complex 'soft-rock' deposits by the application of appropriate combinations of investigative techniques, including remote sensing, rapid geophysical methods and new drilling techniques. The combination of these bodies of knowledge can provide a framework for locating and assessing UNSAs.



Sedimentary bodies are characterised by variably complex geometry and internal structure. These properties exert a strong internal control on the location, quantity and quality of groundwater. Diagram adapted from Galloway and Hobday (1983).

MAJOR AREAS OF UNCONSOLIDATED SEDIMENTARY AQUIFERS WORLDWIDE

- The map shows the distribution of the thickest and most extensive Quaternary deposits in the world. The great majority of these are unconsolidated, and many include water-bearing deposits (UNSAs).

- A generalised world map such as this, though, severely under-estimates the true extent of UNSAs worldwide. This is because:

  - unconsolidated pre-Quaternary deposits are omitted; these too have a wide distribution, though are difficult to delineate (as they grade into consolidated deposits); they too can include significant UNSAs.

  - the simplification of linework necessary at this scale means that a large proportion of unconsolidated deposits have had to be omitted. The inset map shows the example of Uganda, which seems to have no unconsolidated sediments at the global scale, while significant and extensive deposits 'appear' once the the country is looked at more closely. At a yet larger scale the unconsolidated sediments appear yet more widespread. The message is clear. *Unconsolidated sediments, and therefore UNSAs, are ubiquitous.*

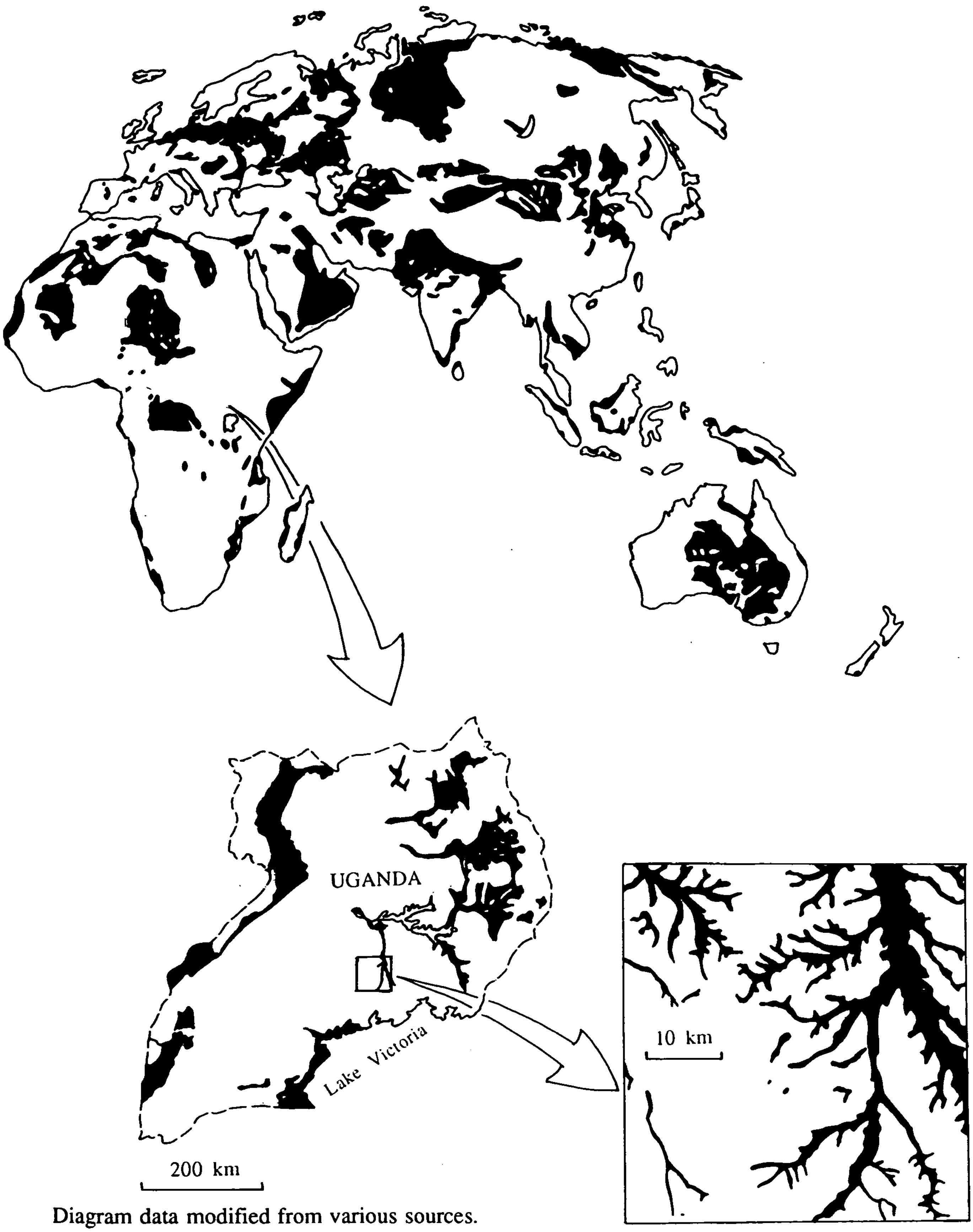


Diagram data modified from various sources.

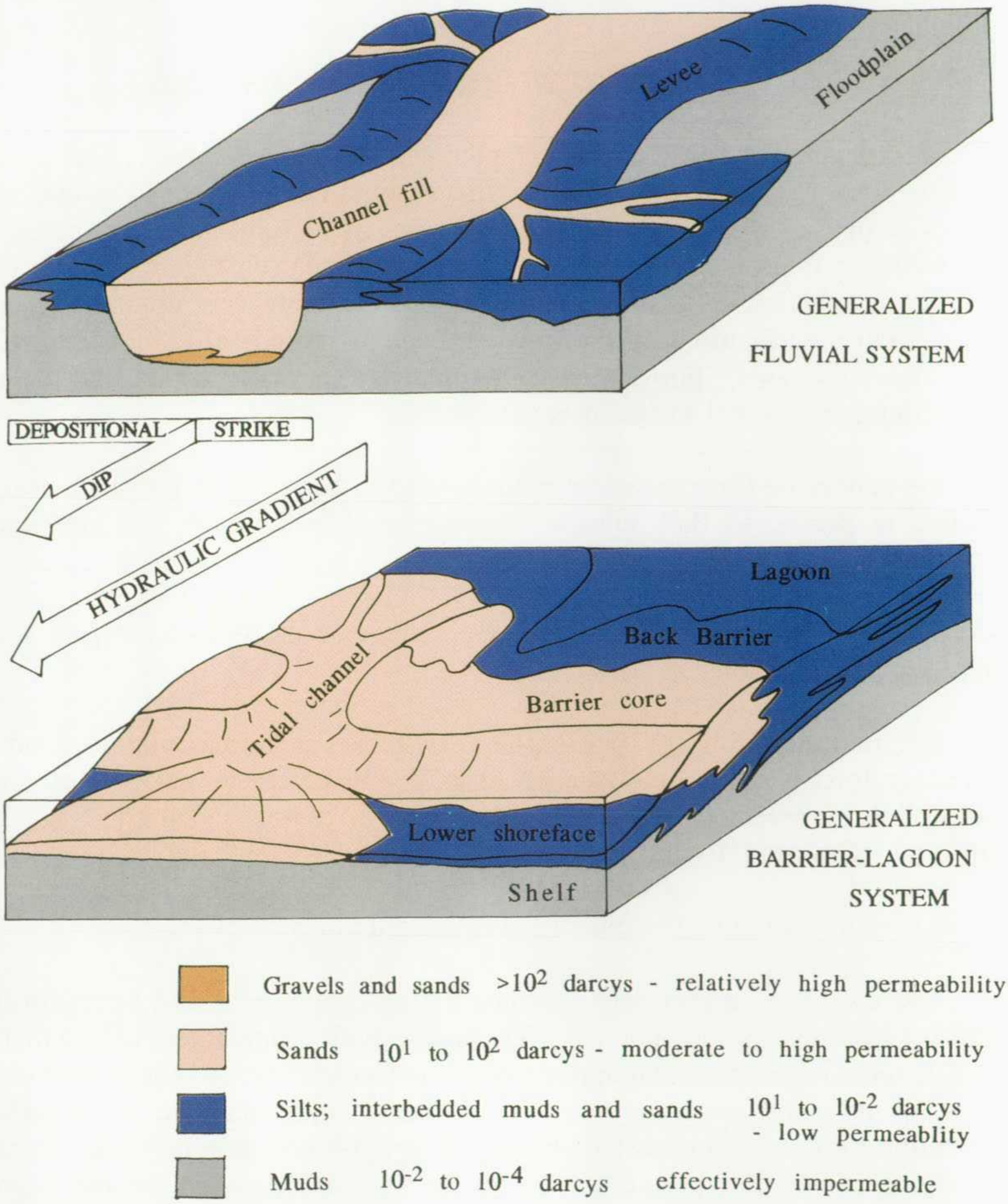
GENERAL SEDIMENTOLOGICAL MODELS

The structure of sedimentary deposits reflects the changing geography of the original depositional environment. The deposits show, in effect, a succession of landscapes stacked one on top of another. These landscapes may be terrestrial or subaqueous. They do not represent a complete record. When these landscapes were undergoing erosion, or were not accumulating sediment, then, for that part of their history, they will not leave any direct physical traces of their existence. (They may, though, leave indirect evidence, in the form of sediment that is transported and deposited elsewhere).

The processes shaping these buried landscapes are predominantly water and wind (and locally ice), which in turn derive their energy from gravity, energy transfers within climatic systems, and tides. These processes are remarkably efficient at sorting sediment into bodies of different grain size and sorting characteristics - and hence aquifer properties. The three-dimensional geometry (or "architecture") of these sediment bodies is not random, but forms ordered sequences which reflect the interplay of controlling forces. The implications of this relationship for prospecting for water (or other minerals) are profound. An understanding of the internal dynamics of the sedimentary systems, and the changing patterns of external forces, can reconstruct the sequence of buried landscapes, and so help predict the likely arrangement of aquifers and aquicludes in the ground beneath our feet.

For simplicity, the diversity of terrestrial and nearshore environments in which potentially water-bearing sediment accumulates may be divided into a number of broad types or *sedimentary environments*, which form the basis for this classification of UNSAs. The manual describes typical characteristics of the most important of these sedimentary environments, presenting them as idealised cartoons or *general sedimentological models*. The manual concentrates on the factors of most practical relevance to hydrogeology, such as porosity, permeability, and the geometry and interconnectedness of sediment bodies.

The purpose of such sedimentological models is to help provide a realistic basis for the quantitative modelling of groundwater volume and movement. In short, they are directed to 'converting the apparent chaos in nature into an orderly system that can be tested scientifically and modelled mathematically' (Anderson 1989).



General sedimentological models for fluvial and barrier-lagoon systems showing the close relationship between non-indurated sediments of varied grain size and hydrological properties. Typical permeability values are given in darcys (1 darcy = 0.64 m/day). Modified after Galloway (1979).

THIS SCHEME OF COLOUR CODING IS USED THROUGHOUT THIS MANUAL (see also page 16).

SPECIFIC WORKING MODELS

Our understanding of landscape development is always imperfect. The cartoons of sedimentary environments shown in this manual can only act as guides to the *kinds* of structures that *might* be expected, mental pictures that may be of help when trying to interpret the recent geology of particular areas. In any one place, local factors of climate, tectonics and available sediment type combine to create unique, local modifications of these general sedimentological models depicted in the idealised cartoons. Furthermore, the cartoons generally depict end members only, of intergradational series of environments.

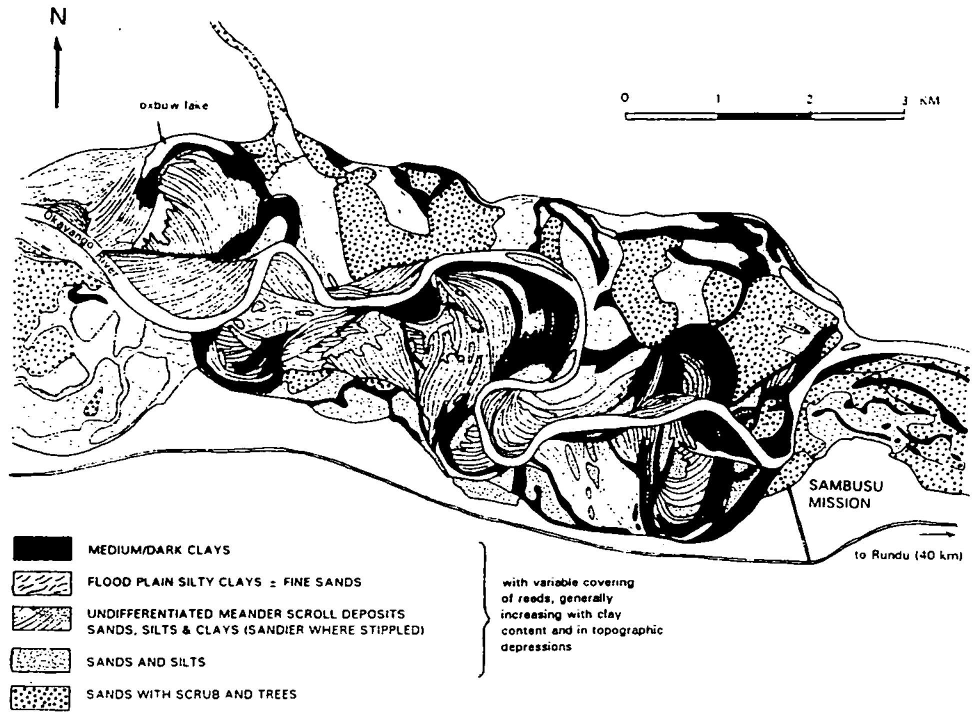
Thus, the general sedimentological models need to be tested in the field, using all available evidence, so that *specific working models* for each test area can be arrived at.

The kinds of evidence needed to test and refine the models come from several different sources, among them:

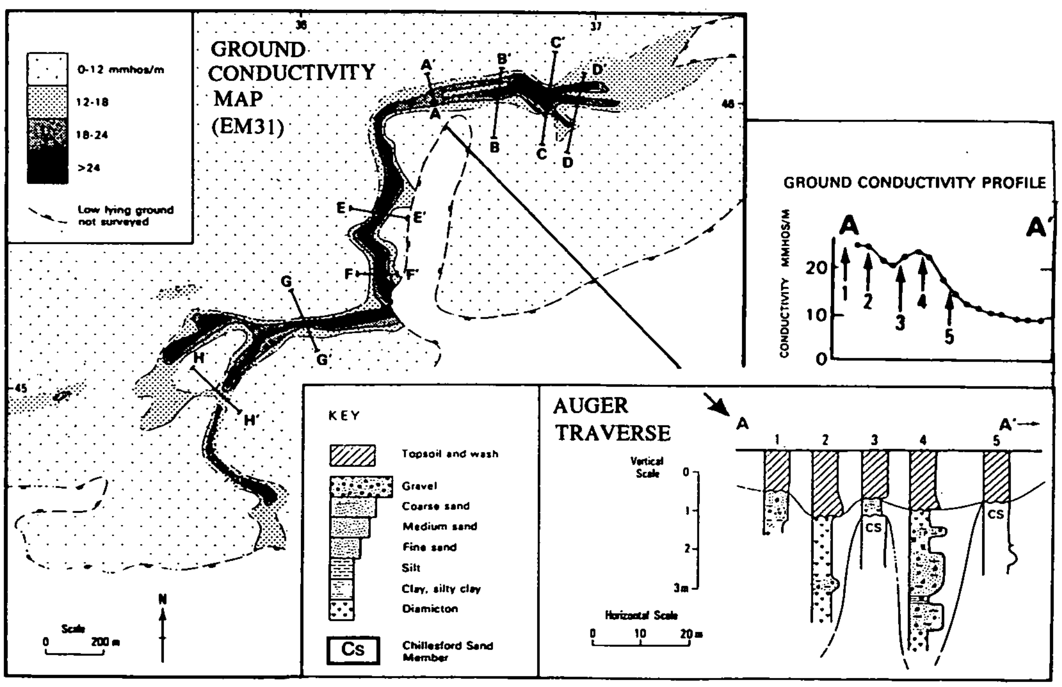
- An understanding of present-day patterns of sedimentation, and the controlling forces. This may be arrived at, for instance, by analysis of surface geomorphology revealed by aerial photographs or remotely sensed images, and knowledge of rainfall/discharge patterns.

- An appreciation of the climatic and tectonic history of the area.

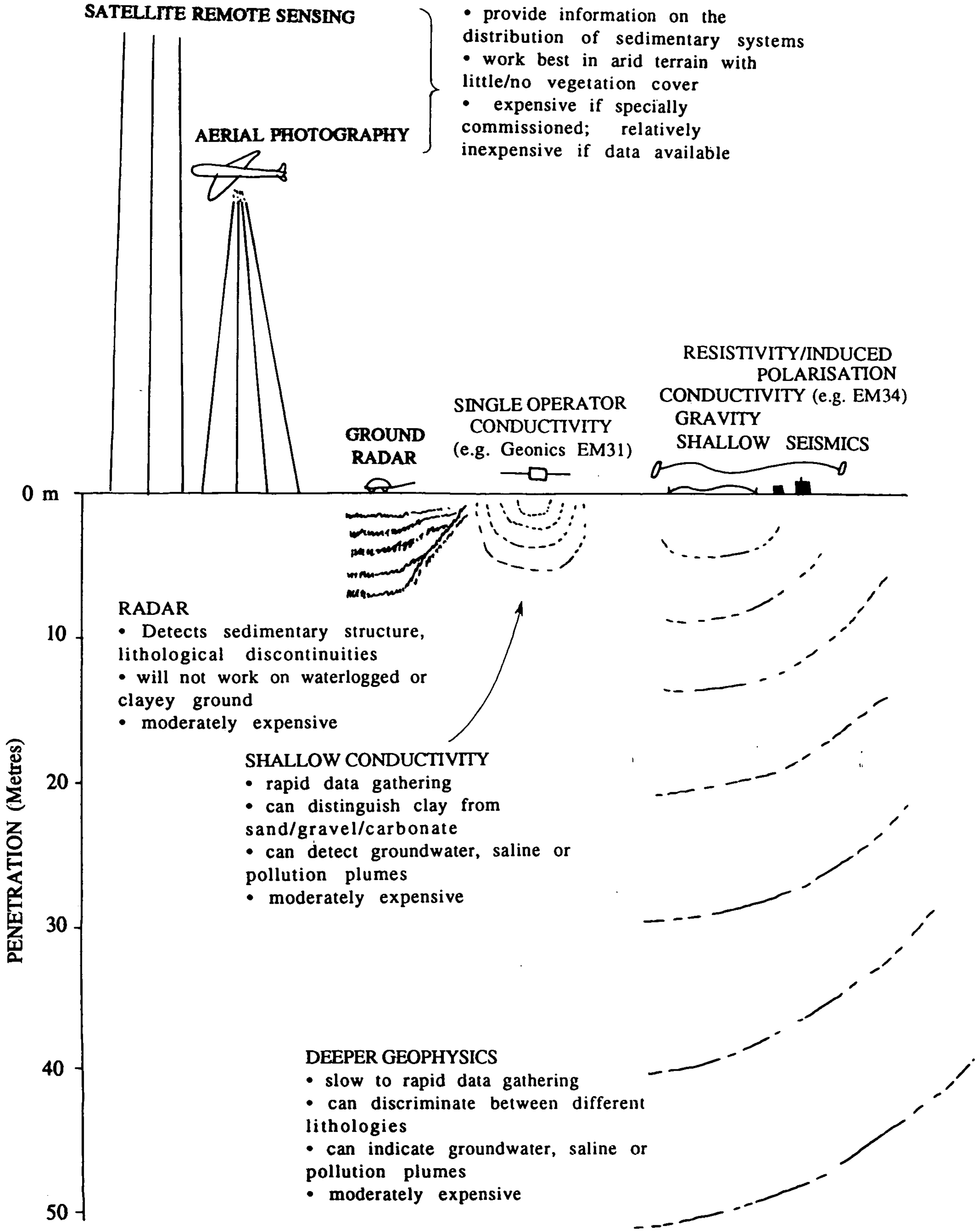
- The use of an appropriate combination of geophysical and direct (drilling, augering) investigative techniques. The shape and composition of sedimentary bodies is reflected in measurable properties such as gravity, electrical conductivity (or resistivity) and acoustic velocity. Thus geophysics can be a primary prospecting tool for groundwater. However, geophysical data by itself can rarely be unambiguously interpreted. It needs to be calibrated by the use of other techniques, such as drilling, augering or geological mapping. For each type of terrain, an appropriate 'mix' of investigative techniques needs to be assembled, by a mixture of past experience and trial and error.



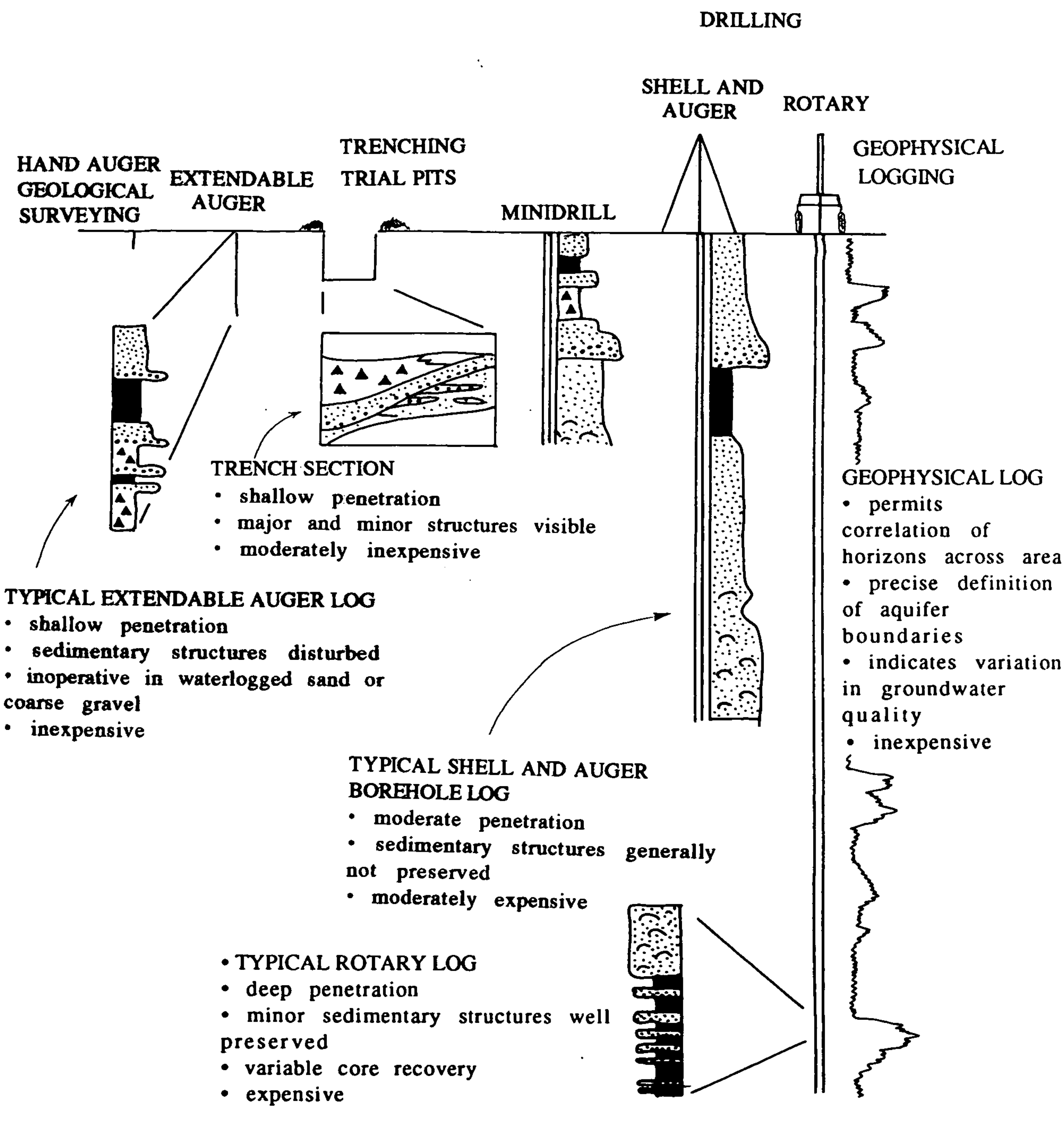
Analysis of mixed load (meandering) river deposits using remote sensing data. The Okavango river. Unpublished data provided by D Tragheim (BGS).



Analysis of complex unconsolidated deposits. Conductivity mapping picked out linear high-conductivity anomalies on a low-conductivity sand deposit. These anomalies, investigated by auger traverses, proved to be glacial channels filled largely with impermeable clay deposits. Example from eastern England from Mathers et al. (1991.)


SATELLITE REMOTE SENSING
AERIAL PHOTOGRAPHY
• provide information on the distribution of sedimentary systems
• work best in arid terrain with little/no vegetation cover
• expensive if specially commissioned; relatively inexpensive if data available
GROUND RADAR
SINGLE OPERATOR CONDUCTIVITY (e.g. Geonics EM31)
RESISTIVITY/INDUCED POLARISATION
CONDUCTIVITY (e.g. EM34)
GRAVITY
SHALLOW SEISMICS
0 m
10
20
30
40
50
PENETRATION (Metres)
RADAR
• Detects sedimentary structure, lithological discontinuities
• will not work on waterlogged or clayey ground
• moderately expensive
SHALLOW CONDUCTIVITY
• rapid data gathering
• can distinguish clay from sand/gravel/carbonate
• can detect groundwater, saline or pollution plumes
• moderately expensive
DEEPER GEOPHYSICS
• slow to rapid data gathering
• can discriminate between different lithologies
• can indicate groundwater, saline or pollution plumes
• moderately expensive

Building specific working models : non-invasive and invasive techniques of investigating non-indurated sediments. Modified after Mathers & Zalasiewicz (1985).



CONTROLS ON SEDIMENTATION

CLIMATE

Most unconsolidated sediments were deposited during the Neogene and Quaternary, the last few million years of the earth's history. Over this period of time there have been numerous climatic oscillations, which have been become more marked during the last 0.75 m.y. 15 000 years ago, for instance, ice-caps covered much of north America and reached down into northern Europe. Global sea level was around 100 m lower than at present. The patterns of winds, rivers and ocean currents were quite different to today's.

The sedimentary systems in which UNSAs are found - fluvial, deltaic and shallow marine - are particularly susceptible to changes in climate. They record a complex sedimentary history, which in turn produces a complex internal sedimentary geometry.

Studies of the near-continuous deposits in the deep ocean reveal the detailed pattern of growth and shrinkage of the volume of global ice during the Quaternary. set against this standard, most terrestrial sequences preserve only intermittent snapshots of the earth's history.

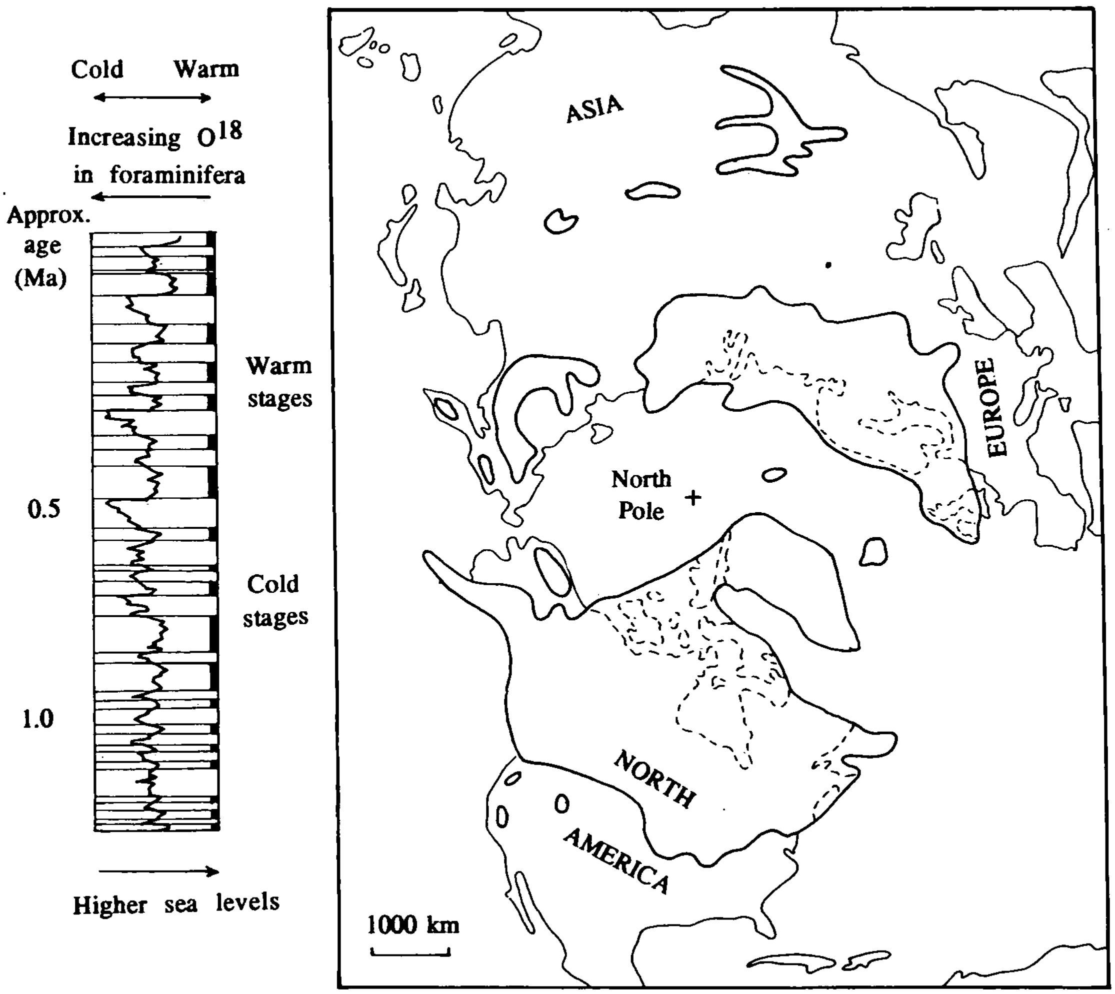
Climate changes lead to the growth and decay of major polar ice-sheets and the smaller ice-caps of mountainous areas outside high latitudes. There are two principal effects on sedimentary environments:

a) Changes in temperature, precipitation, prevailing wind direction, ocean circulation etc.

b) Sea level (base level): this changes the energy of gravity-controlled systems (e.g. rivers), the groundwater level and the factors influencing near-shore deposits.

The cyclic, repetitive nature of these changes distinguishes the Quaternary from most of the earth's history. The rapid migration of facies belts causes a complex juxtaposition of different sedimentary deposits. The composite sequences so formed differ greatly from those laid down over most of geological time, when climate and sea level were more stable, and when sedimentary environments could achieve and maintain an equilibrium, to produce widespread deposits of a uniform nature. Many present-day sedimentary environments are not yet in equilibrium with a sea level that has stabilised in what is, on a geological time-scale, the very recent past.

Thus many models of sedimentation which are based on ancient examples cannot be applied to UNSAs in a simple and straightforward fashion. The principles governing sedimentation remain constant, though, even if the external controls are less constant in their behaviour. So, while UNSAs include deposits which formed under widely different conditions, knowledge of the environmental history of any region can help predict the type of sedimentation that is likely to have taken place, and thus the kind of pattern of aquifers and aquicludes that might be present in deposits which formed in different climatic episodes of the Quaternary.



Climatic change through time; and maximum extent of Quaternary ice sheets in the northern hemisphere. Based on Bowen (1978).

TECTONICS

The regional geography of upland areas and depositional basins, and therefore overall patterns of erosion and deposition, are controlled by tectonic activity. Even within the short span of geological time in which the bulk of UNSAs were laid down, the tectonic history of a region can be significant. Thus, whether a coastline is emergent or undergoing subsidence will determine patterns of present-day sedimentation and the possibility of finding bodies of coastal sediment deposited in the recent past. The tilting of a landmass will affect the courses of rivers, and, within those courses, may cause different types of sediment to accumulate in different parts of the floodplain.

In tectonically active regions, there is likely to have been significant movement along active faults, which are often the controlling features of sedimentary basins. Many alluvial fans, for instance, develop along active fault zones separating upland areas from a depositional plain.

INTERNAL SEDIMENTARY DYNAMICS

The forces acting within particular sedimentary systems are powerful controls on the distribution of different types of sediment. The patterns of flow of water in a meandering river, for instance, govern the way in which sediment is eroded and deposited, and are reflected in the geometry of the resulting sedimentary accumulation.

Intrinsic checks and balances act as self-regulatory features in the evolution of sedimentary environments. Thus, river and delta channels switch direction (avulse) when so much sediment has built up in and around them that more direct and energetically efficient routes become available. On a larger scale, thick deposits of sediment accumulated in any one place will tend to depress the crust, and this subsidence makes room for further deposition.

PROVENANCE

The availability of sediment is a strong control on the make-up of sedimentary accumulations. Where there is a lack of available sand- or gravel-grade material, for instance, then the deposition of permeable bodies of sediment - aquifers - is unlikely, even if the 'right' sort of sedimentary environment is present.

The type of sediment coming into the basin, or being formed within the basin, depends on a number of factors, with climate and tectonic and geological setting being most important.

Hot tropical climates promote the breakdown of rocks, particularly by chemical and biological methods. Thus, minerals such as feldspars are broken down into clays, and sedimentary systems tend to contain a high proportion of fine-grained suspended load. In cold and/or dry regions, where vegetation tends to be sparser and chemical processes slower, then many primary minerals may survive to form sand-grade material. Climate also is important in controlling sediments such as evaporites, which are largely restricted to hot arid climates, whereas thick accumulations of organic material (peat) are generally more characteristic of warm than of cold climates.

The climatic history is also important. The effects of past glaciations in certain areas, for instance, may have been instrumental in providing an increased supply of coarse material to the basin in the 'recent' geological past, even though present-day sediment supply may be characterised by fine-grained material.

The tectonic setting and history of an area controls its topography and potential as a source of sediment supply. Mountain ranges erode rapidly, and can be a source of abundant coarse-grained material. Areas which have been stable for long periods of geological time - such as much of Africa - have already been eroded to a peneplain and thus are less prone to further mechanical erosion. The tectonic setting also controls the vulcanicity of a region, and thus the input of volcanic material into a sedimentary basin.

CLASSIFICATION OF SEDIMENTARY FACIES

GENERAL

This section of the manual sets out a subdivision of unconsolidated sediments geared towards the location and delineation of aquifers. The idealised cartoons of sedimentary systems are to be used as guides only, mental reference points that may be of value in helping to understand aquifer/aquiclude geometry in an area of exploration. *They should not be taken literally, as models that can be rigidly applied.* They are almost certainly oversimplifications, even with regard to the locations where they were originally devised.

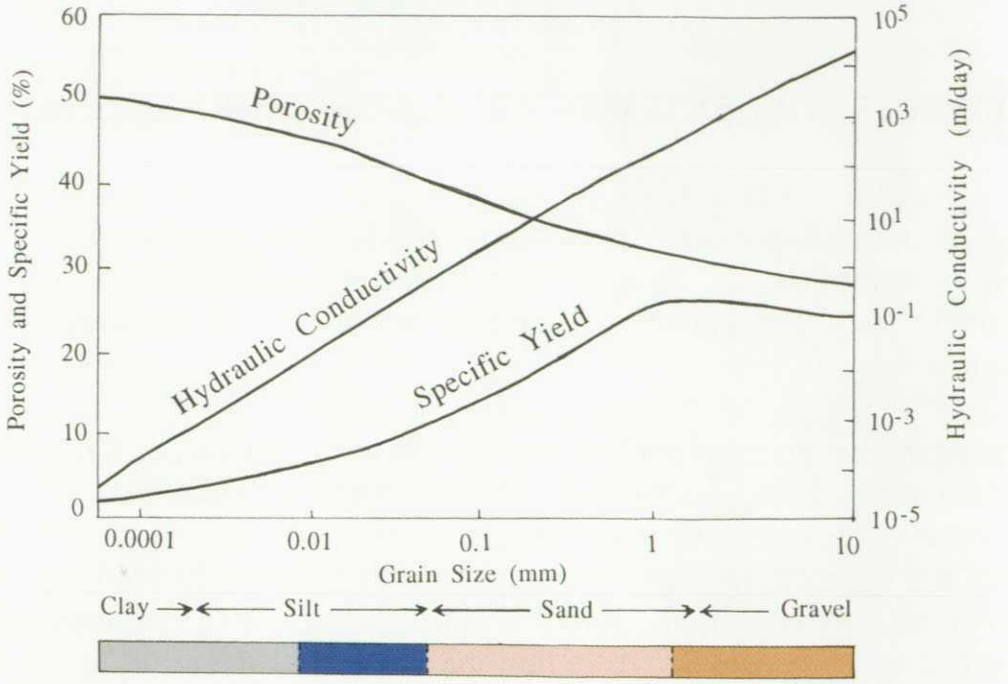
The cartoons are colour-coded as to lithology and so possible aquifer characteristics. The simplest are shaded **blue** for **potential aquifers** and **grey** for **potential aquicludes.** In more detailed cartoons the scheme is extended as follows:

Dark blue	-	dominantly sands and gravels (likely good aquifers)
Pale blue	-	dominantly sands (likely aquifers)
Brown	-	silts, or mixed sands and muds (poor aquifers)
Grey	-	dominantly muds (generally aquicludes)

These categories, again, are generalisations. In reality, there is a continuous gradation of aquifer characteristics. And, local peculiarities of, for instance, sediment supply, may often mean that a sedimentary facies that ideally should have 'good' aquifer properties may in fact be a poor aquifer - and vice versa.

Used cautiously, though, and modified to suit local conditions, they may offer a working framework for the classification of UNSAs.

For each sedimentary system discussed in this manual (e.g. deltas) the general characteristics of the environment are stated and where applicable a classification into individual types (e.g. wave-dominated deltas) is given. General sedimentological models are provided for each type. Thematic topics relevant to specific systems are then given (e.g. effects of welding on pyroclastic volcanic deposits). Finally, the effects of external control by climate and tectonics are discussed for those systems (e.g. fluvial systems) which are influenced by such factors.



Porosity, specific yield and hydraulic conductivity of unconsolidated sediments. Modified from Davies & De Wiest (1966). Colour scheme used in this manual also shown.

CLASSIFICATION OF SEDIMENTARY ENVIRONMENTS
(In which UNSAs may occur)

ALLUVIAL	FANS	Wet Semi-arid
	FLUVIAL	Bedload rivers Mixed-load rivers Suspended-load rivers
DELTAIC	DELTAS	River-dominated Wave-dominated Tide-dominated
	FAN-DELTAS	(subdivided as deltas)
COASTLINES	SILICICLASTIC	Wave-dominated Mixed Tide-dominated
	CARBONATE-EVAPORITE	
LAKES	OPEN SYSTEMS CLOSED SYSTEMS	
VOLCANIC ENVIRONMENTS		
GLACIAL ENVIRONMENTS		
AEOLIAN ENVIRONMENTS	SAND DESERTS LOESS	

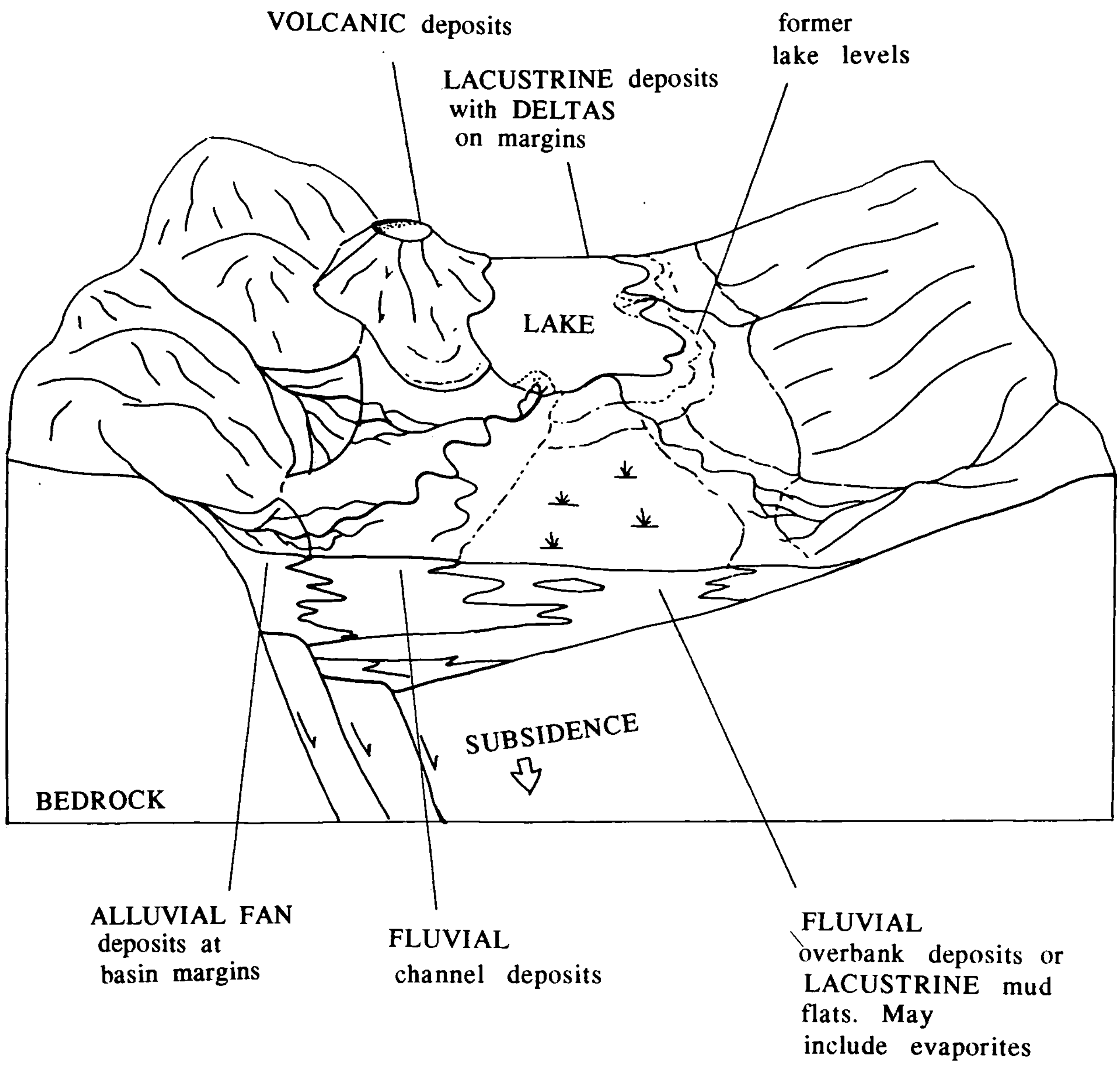
SEDIMENTARY SYSTEMS WITHIN GEOMORPHIC PROVINCES

This manual classifies UNSAs into different types of sedimentary system. Generally these do not occur in isolation, but as 'building blocks' which, arranged in various combinations, form different types of geomorphic province. A typical example of such a composite geomorphic province is an intramontane basin (see opposite).

Intramontane basins commonly occur as subsiding grabens or half-grabens within mountain ranges, and accumulate various types of sediment. The patterns of sedimentary infill depend upon the interaction of factors such as topography, climate and bedrock geology. No single model can be presented, but some typical associations may be noted. Alluvial fans, for example, commonly form at the margins of such basins. These in turn may be associated with fluvial or lacustrine systems. If the prevailing climate is arid, aeolian deposits or evaporites may form; if it is cold, glacial deposits may be present. Volcanic deposits may be associated with major bounding faults.

Other examples of geomorphic provinces include small islands (where coastal sedimentary systems may be associated with volcanic deposits) and coastal plains (where deltas and fluvial systems might be expected to accompany coastal sedimentary deposits).

It is important to try to subdivide geomorphic provinces into their constituent sedimentary systems. The patterns of aquifers and aquicludes will depend both upon the internal geometry of these sedimentary systems, and upon the way these 'building blocks' are arranged on and beneath the present-day landscape.



Some of the sedimentary systems that may be found in an intramontane basin.

DISTINGUISHING SEDIMENTARY ENVIRONMENTS

Much of this manual is concerned with showing the kind of aquifer/aquiclude geometries that tend to occur in different sedimentary environments. In practice, however, it is necessary to know, first of all, *which* of these sedimentary environments you are likely to be dealing with. In many cases, it can safely be assumed that the deposits being investigated relate to the geomorphological feature (an alluvial fan, for instance, or a meandering river) present at the surface.

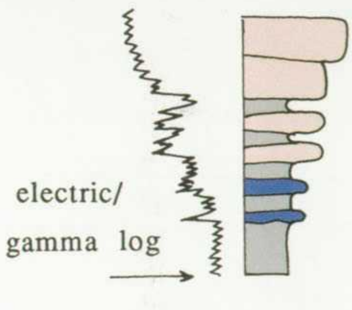
In other instances, it may be inferred that deposits at depth relate to an earlier phase of the evolution of a particular sedimentary system. A present-day meandering river, for instance, may be underlain by braided river deposits, formed when climatic and precipitation patterns were different to those of today.

There will be instances, though, when it will not be obvious which type of sedimentary system may be present in a particular area of investigation. At depth beneath a coastal plain, for instance, boreholes may reveal a succession of interbedded sands and clays.
These may have been laid down by rivers, by marine processes, or by both of these at different times. It is first necessary to make a primary distinction - terrestrial or marine? - before going on to test more specific models of sedimentary environment.
Here diagnostic evidence of environment (river/sea) and process (water/wind/ice/volcanism/gravity) must be sought. Such evidence is fully described in standard geology and sedimentology textbooks. In brief, though, typical evidence of this type includes:

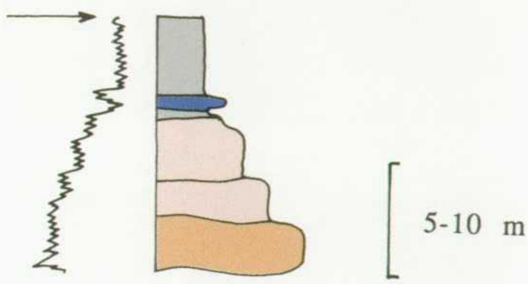
- <u>Fossils</u> - these are still the best way to distinguish marine sediments from terrestrial ones.
- <u>Minerals</u> - glauconite and phosphate, for instance, are typical of marine environments.
- <u>Texture</u> - e.g. glacial sediments tend to be poorly sorted, while aeolian and beach deposits are generally well sorted.
- <u>Trends</u> - in borehole sequences, coarsening- upwards patterns (as best identified by gamma logs) are typical of *prograding* environments (e.g. deltas) while laterally migrating channels (e.g. of rivers) commonly show fining-upwards patterns.
- <u>Sedimentary structures</u> - such as cross-bedding styles or grading patterns in individual beds are good indicators of palaeoenvironment, though are rarely discernable in borehole material of unconsolidated sediment.

These shells are of marine species, and so are an excellent guide to the general depositional environment of the sands in which they are enclosed. More sophisticated analysis of these fossils may yield information on salinity, water depth or current strength that may help to refine sedimentary models.

Unsorted deposits of this type are commonly produced by gravity flows (as debris flows) or glacial action. In this case, the over-consolidated (strongly compressed) nature of the deposit, together with some ice-scratched pebbles, indicates that deposition took place at the base of an ice sheet.



A coarsening-upwards sequence, typical of deposits which build outwards (prograde) into a basin, such as deltas.



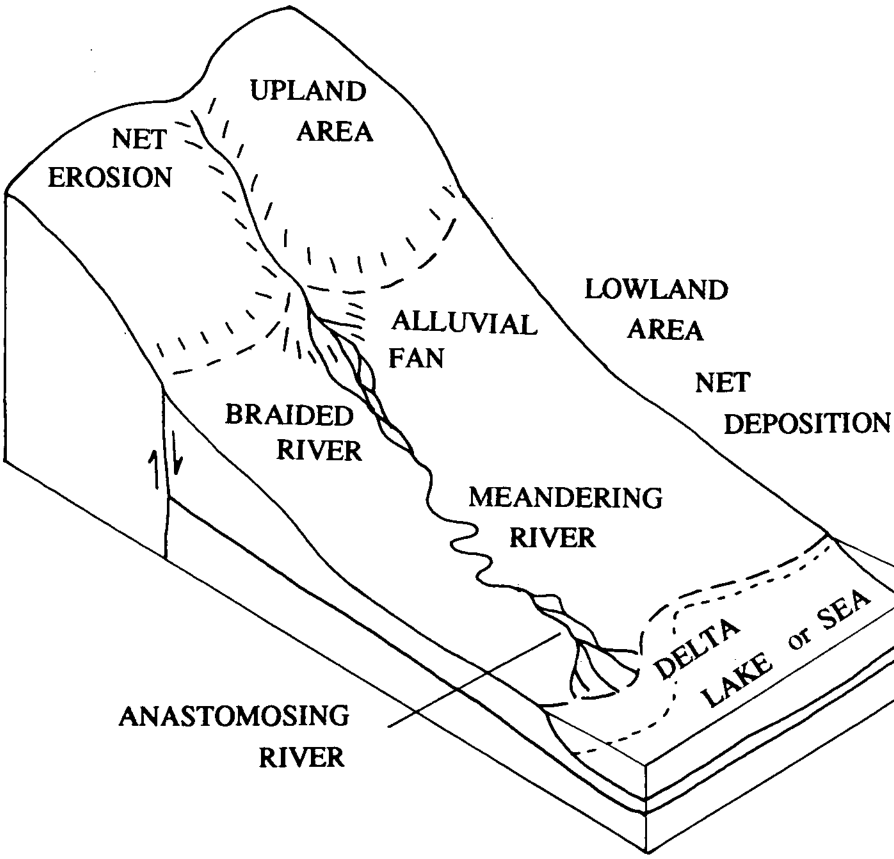
A fining-upwards sequence, commonly produced by laterally migrating river channels.

ALLUVIAL SYSTEMS

GENERAL & CLASSIFICATION

Alluvial systems are essentially simple. They are the gravity-driven paths followed by water and entrained sediment from upland areas towards a regional base-level (e.g. a lake or the sea).

In detail each alluvial system is unique, the result of the interplay of many controlling factors, notably climate, topography, tectonics, base level changes and available sediment type. In general, though, alluvial tracts can be divided into a few distinct elements:



Most importantly from the hydrogeological point of view, each of these types of alluvial system has its own fashion of juxtaposing potential aquifers (sands, gravels) and aquicludes (muds) in characteristic internal geometries or *architectures*.

The principal elements of alluvial systems are:

- Alluvial fans (and fan-deltas)

● Bed load rivers (roughly corresponding to braided rivers).	}	
● Mixed load rivers (roughly corresponding to meandering rivers).	}	Fluvial systems
● Suspended load rivers (meandering to anastomosed rivers).	}	

These categories form a continuum, and so intermediate types are common.

The distribution of these elements of an alluvial system depends on a combination of factors which are largely related to the *energy* of the system.

The sensitivity of alluvial systems to changes in the controlling factors means that any part of the system is likely to have changed its character repeatedly in response to the pronounced environmental fluctuations of the last few million years.

ALLUVIAL FANS

General principles

- Alluvial fans form where a stream emerges from an upland area into an adjacent lowland basin. This results in an abrupt decrease in stream gradient and a lack of lateral confinement. The sudden decrease in stream energy leads to deposition of much of the sediment load over a fan-shaped area.

- Simple alluvial fans are conical, lobate or arcuate in plan view. In section they have a wedge-shaped profile, thinning downdip.

- Individual fan geometry depends mainly on climate, drainage basin size, discharge, relief and source-rock lithology.

- Fans pass downdip into either:

  a) fluvial belts (surface flow continues, at a lower gradient).
  b) standing water bodies, producing fan-deltas (surface flow arrested).
  c) dry basins (surface flow infiltrates and/or evaporates); these are terminal fans.

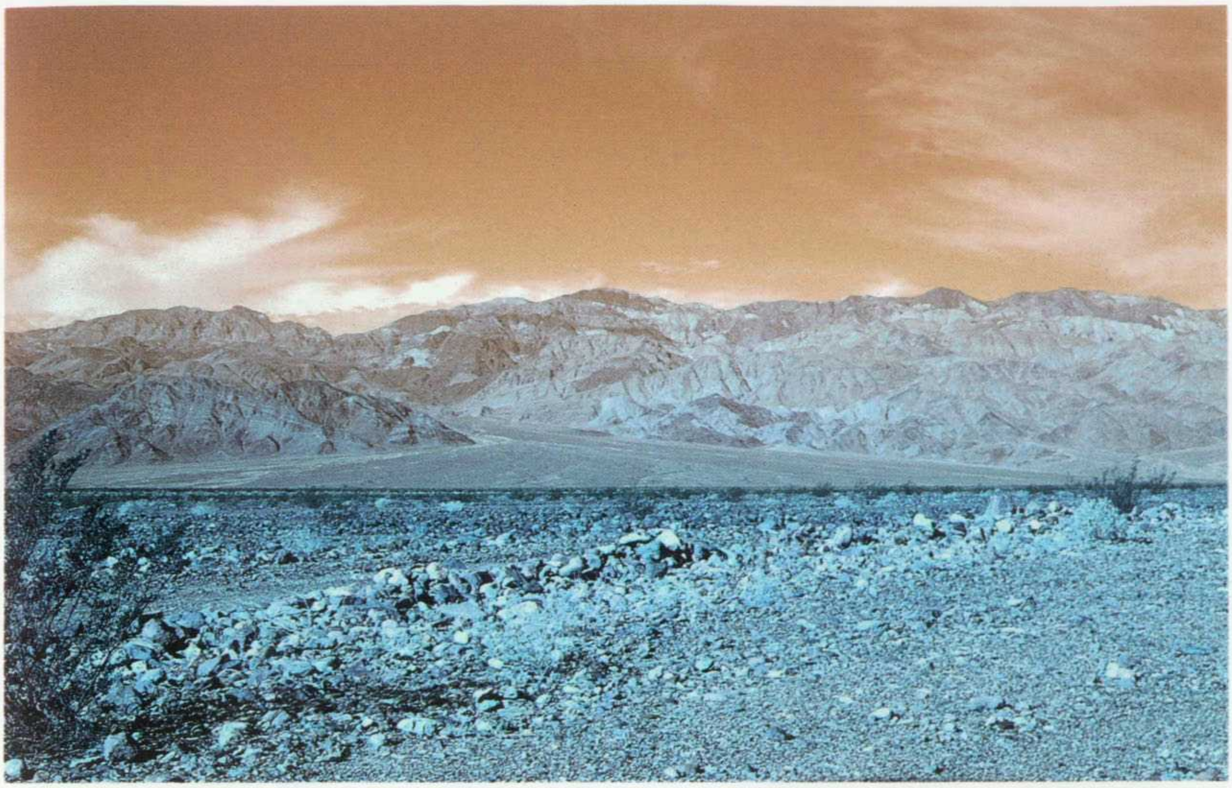
- Fans contain the most proximal, coarse and poorly sorted sediments of alluvial systems; master bedding parallels the fan surface; most fans are zoned with grain size decreasing downdip. Thus prograding fan sequences coarsen upwards. The coarse nature of the sediment of modern fans hinders investigation by drilling.

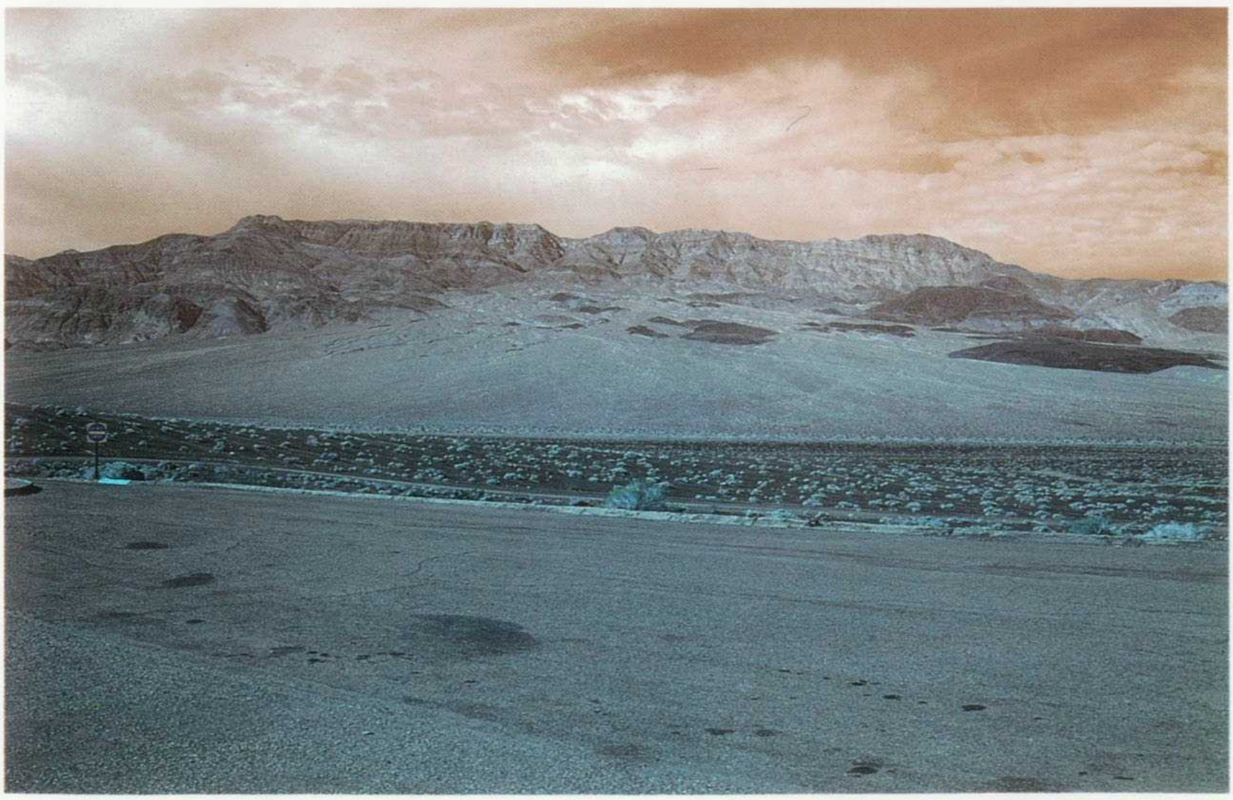
- Fans are commonly found fringing tectonically active upfaulted blocks and mountain ranges (e.g. in rifts, pull-apart basins); and also around glaciated upland areas.

- Two main types of fans are recognised:

  a) Wet fans (also known as stream-dominated or humid fans).
  b) Semi-arid fans.

Recent work (Blair & McPherson 1994) suggests that only the "semi-arid" types are real alluvial fans, and that wet fans would be better classified as simple fluvial systems.





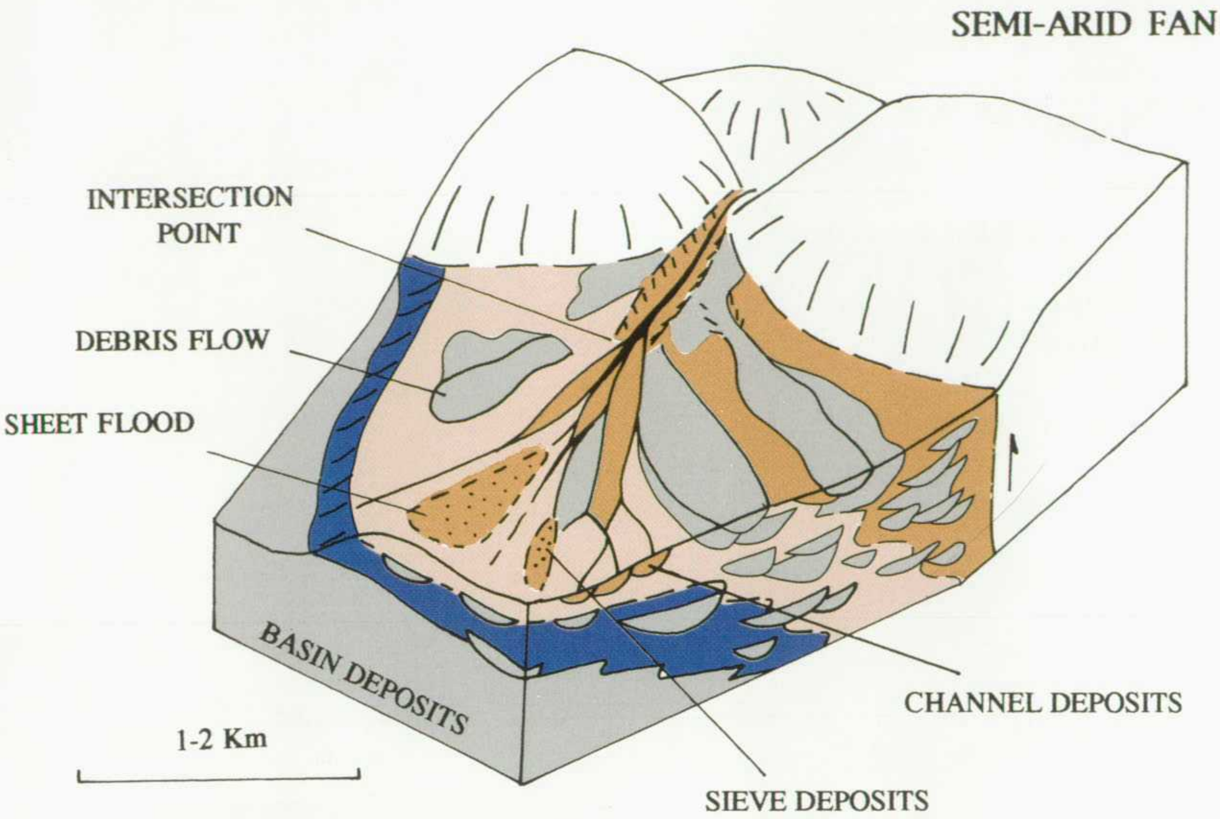
Semi-arid alluvial fans, Death Valley, USA. The lower photo shows mesquite grass on the lower fan surface, indicating the proximity of groundwater.

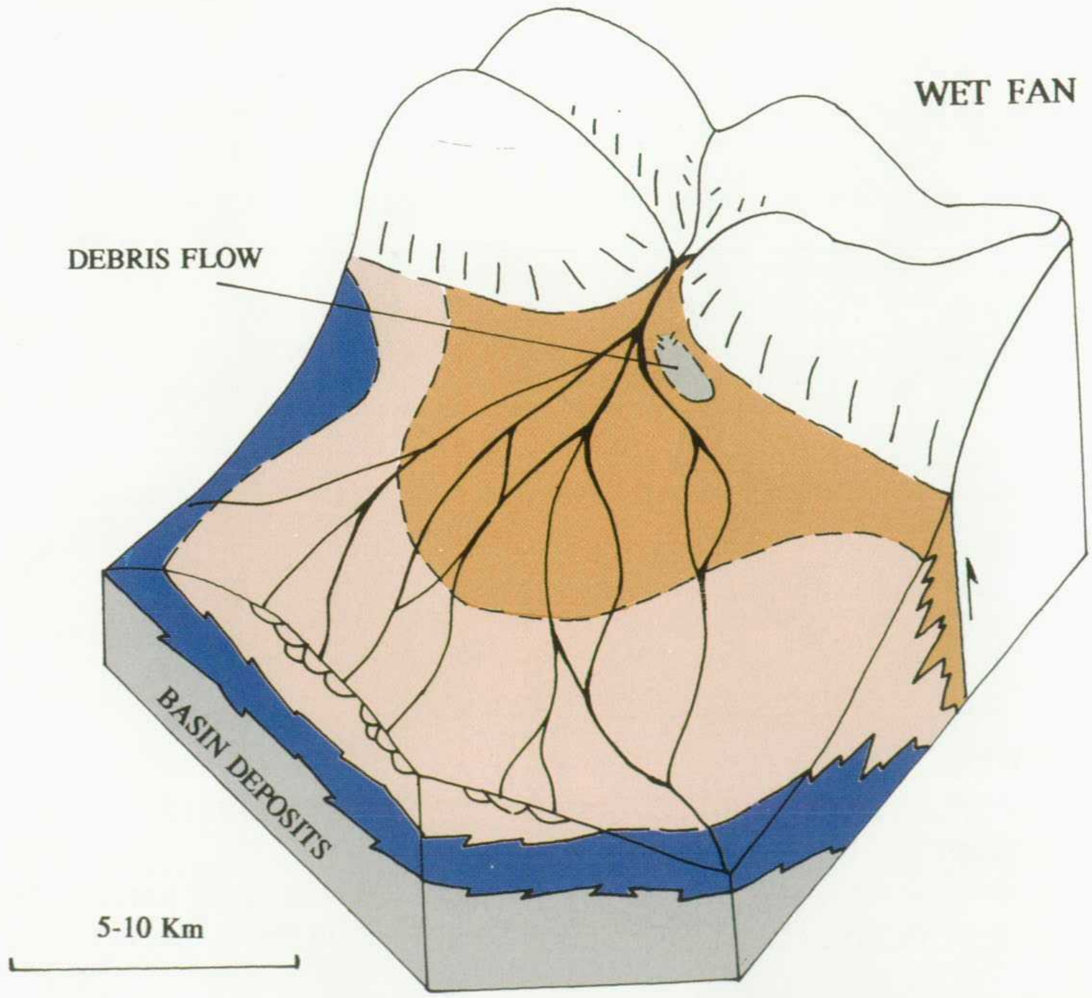
Semi-Arid Fans

Size	Small, up to 10 km^2
Gradient	Steep, up to 1:10
Climate	Semi-arid; infrequent, often heavy, rainfall; ephemeral stream flow; sparsely vegetated,.
Facies	Complex mixture of some/all of: a) Debris flows (often dominant) - diamicts b) Sheetflood deposits - sands, silts and clays c) Channel deposits - sands and gravels d) Sieve deposits? - sands and gravels
Sediment body geometry/ hydrogeology	Very variable diamicts - clays, silts, sands and gravels; generally fining distally but not well sorted. Aquifers and aquicludes interbedded - difficult to predict hydrogeology; deep ground water table where unconfined.
Examples	Marginal fans of Death Valley, USA; Iran (tapped by 'quanats'); Oman ('aflajs').

Wet Fans

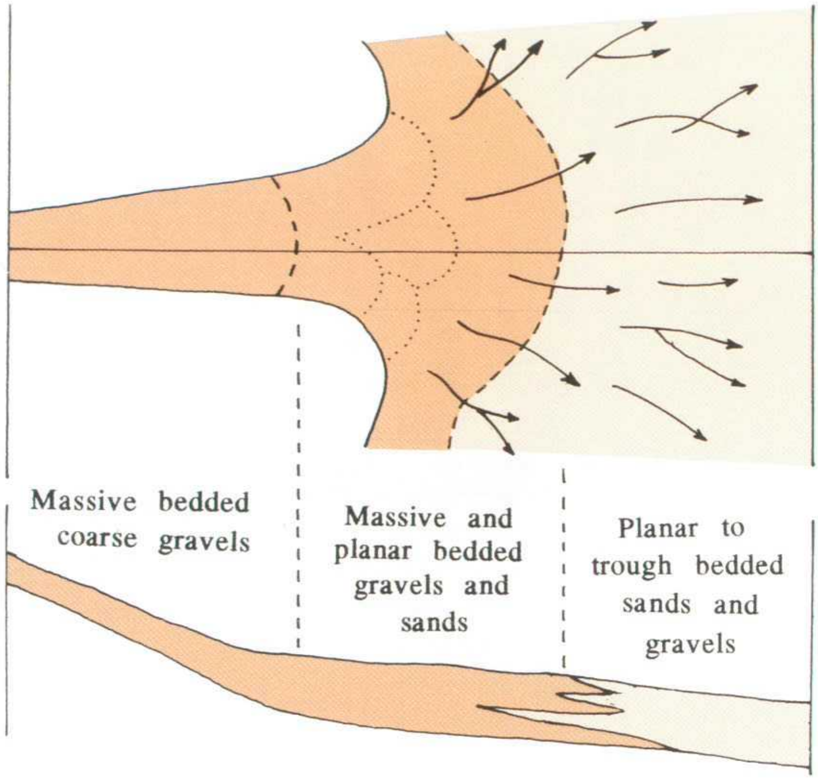
Size	Small to very large - up to 16 000 km^2
Gradient	Shallow, commonly 1:250 - 1:1000
Climate	High precipitation (often seasonal); perennial stream flow; commonly vegetated and stable fans.
Facies	Mainly channel facies; some proximal debris flows
Sediment body geometry and hydrogeology	Predominantly stacked channel sands and gravels fining distally into sands and silts; some lenticular debris flow deposits (_aquicludes) in proximal zones; shallow ground water table.
Examples	Kosi Fan, India/Nepal; Afghanistan; China.

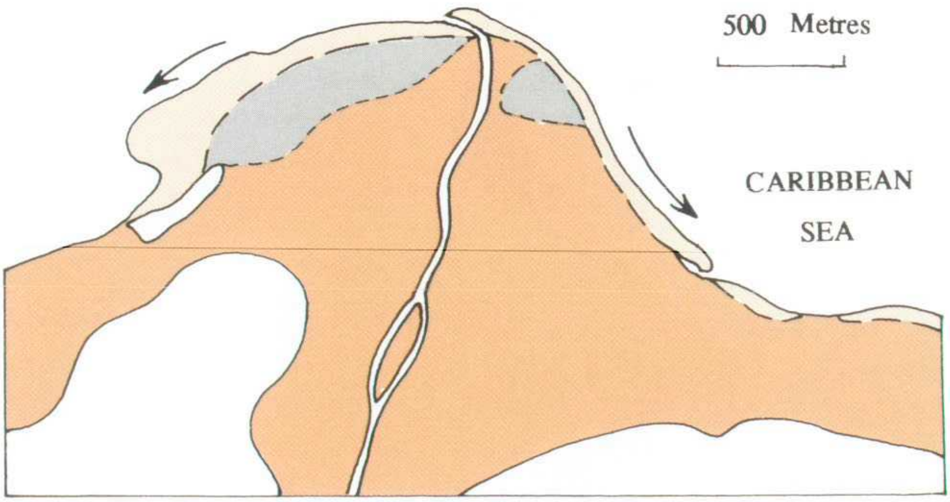

SEMI-ARID FAN
INTERSECTION POINT
DEBRIS FLOW
SHEET FLOOD
BASIN DEPOSITS
CHANNEL DEPOSITS
1-2 Km
SIEVE DEPOSITS


WET FAN
DEBRIS FLOW
BASIN DEPOSITS
5-10 Km

EXAMPLES OF DISTAL FINING

(a) Fan
An interpreted example - the Cambrian Van Horn Sandstone, a wet alluvial fan. Based on McGowen & Groat (1971).

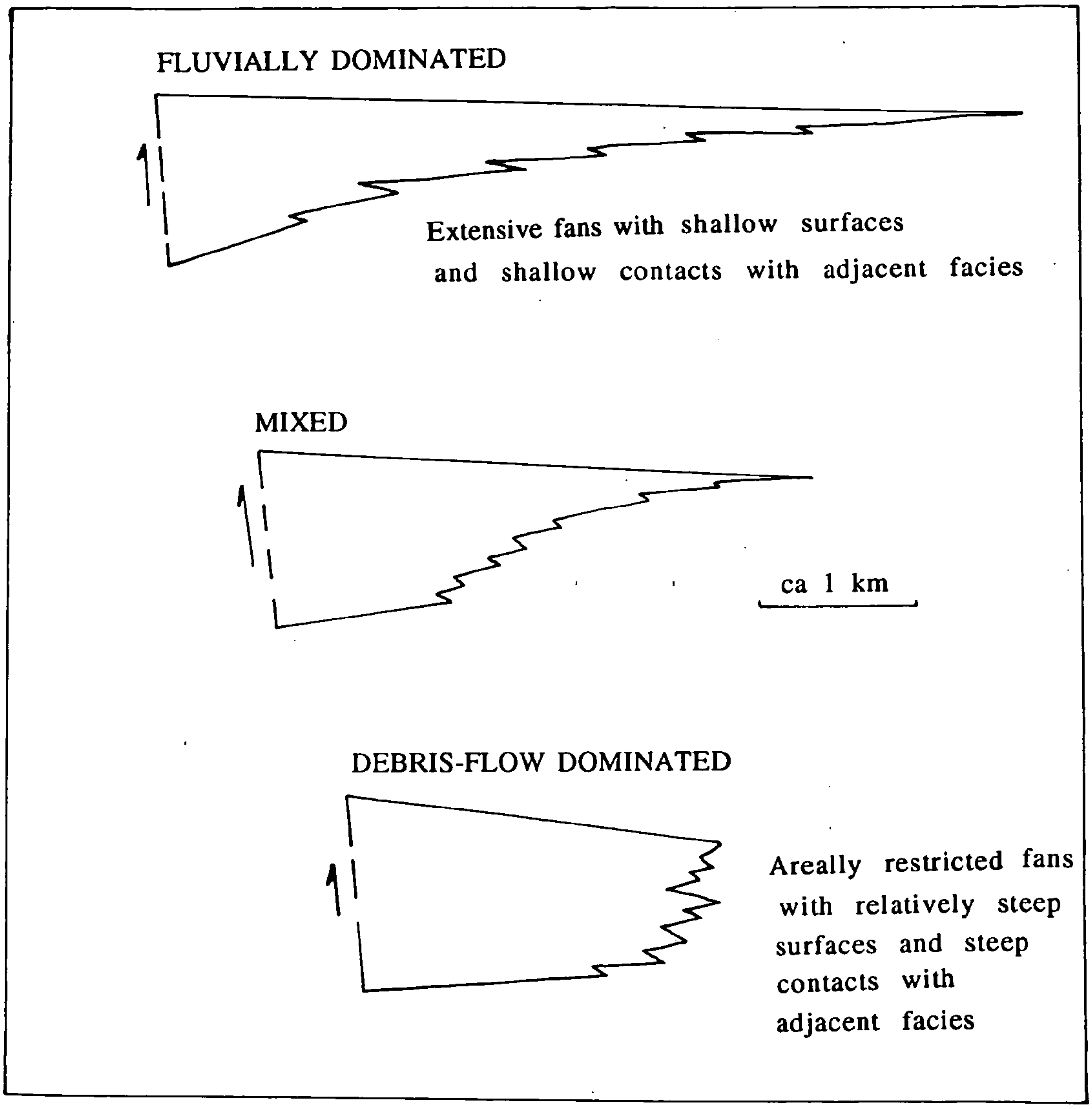




(b) Fan delta
The small, wet Chachagual fan delta of Northern Honduras. Based on Schramm (1981).

Note coastal reworking of sand-grade sediment into barriers behind which silt and clay accumulates locally in swamps.

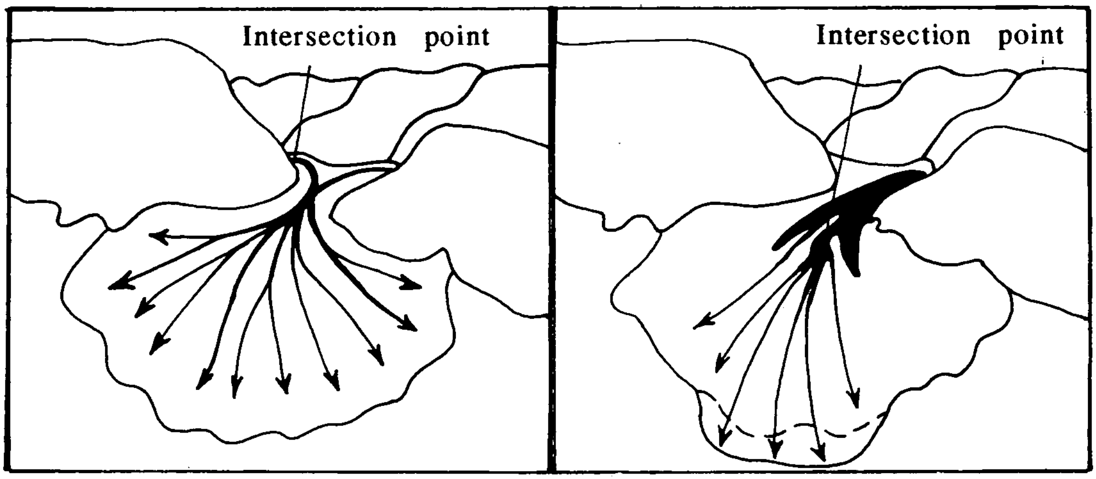
THE INFLUENCE OF VARIED DEPOSITIONAL PROCESSES
ON THE GEOMETRY OF SEDIMENTARY WEDGES



Modified from studies by Gloppen & Steel (1981) on Devonian sedimentary rocks from Norway.

CLIMATIC CONTROL ON FANS

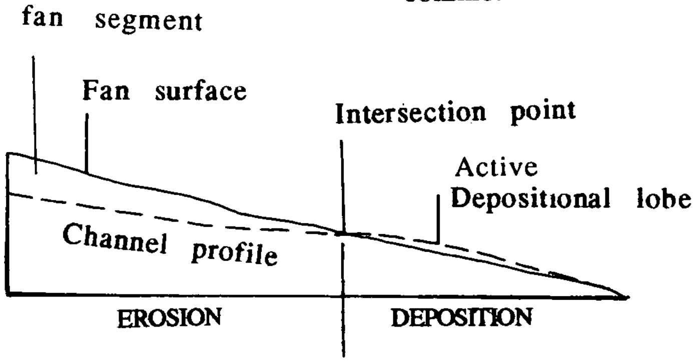
In many low-latitude locations wet (pluvial) and semi-arid conditions have alternated many times in the Quaternary leading to switching of fan type and dominant sedimentary processes. Based on Lustig (1965).



FAN UNDER PLUVIAL (WET) CONDITIONS

FAN UNDER SEMI-ARID CONDITIONS

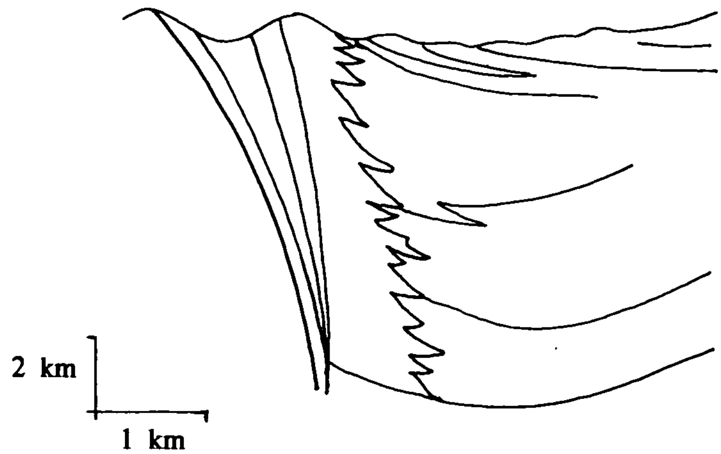
Note entrenchment of upper channels as intersection point migrates down fan. Mudflows and debris flows become more common in the lower fan.



TECTONIC CONTROL ON FAN-BODY GEOMETRY

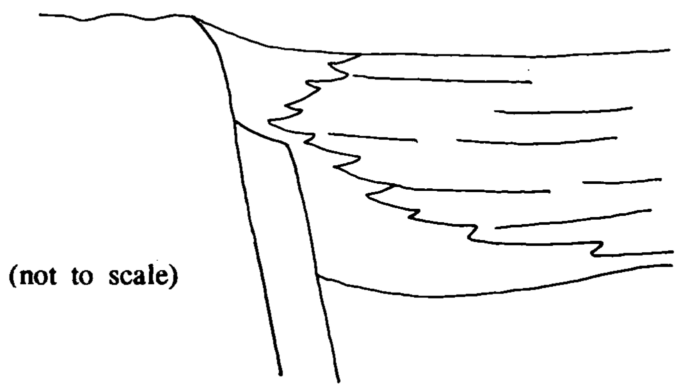
Basin margin faults commonly control fan development and preserved geometry.

A PERSISTENT BASIN-MARGIN FAULT ZONE



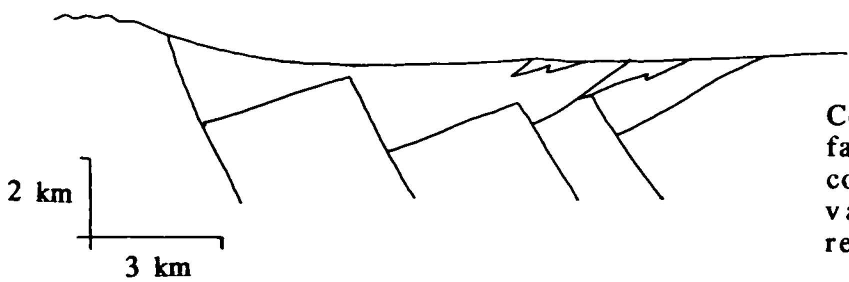
Fault stays essentially in one place. Subsidence produces fringe of fanglomerate, which forms a deep vertical body of restricted lateral extent.

B LIMITED BACK-FAULTING



Some migration of faulting activity through time. More irregular fan geometry produced.

C REPEATED BACK-FAULTING



Considerable migration of faulting activity. A coarse-grained sheet of variable thickness results.

(After Heward 1978)

FLUVIAL SYSTEMS

Fluvial systems can be broadly classified into three types of river:

Bedload
Mixed load
Suspended load

These are commonly developed in this order along a fluvial tract, reflecting the decreasing energy of most fluvial systems downdip. Intermediate types are common.

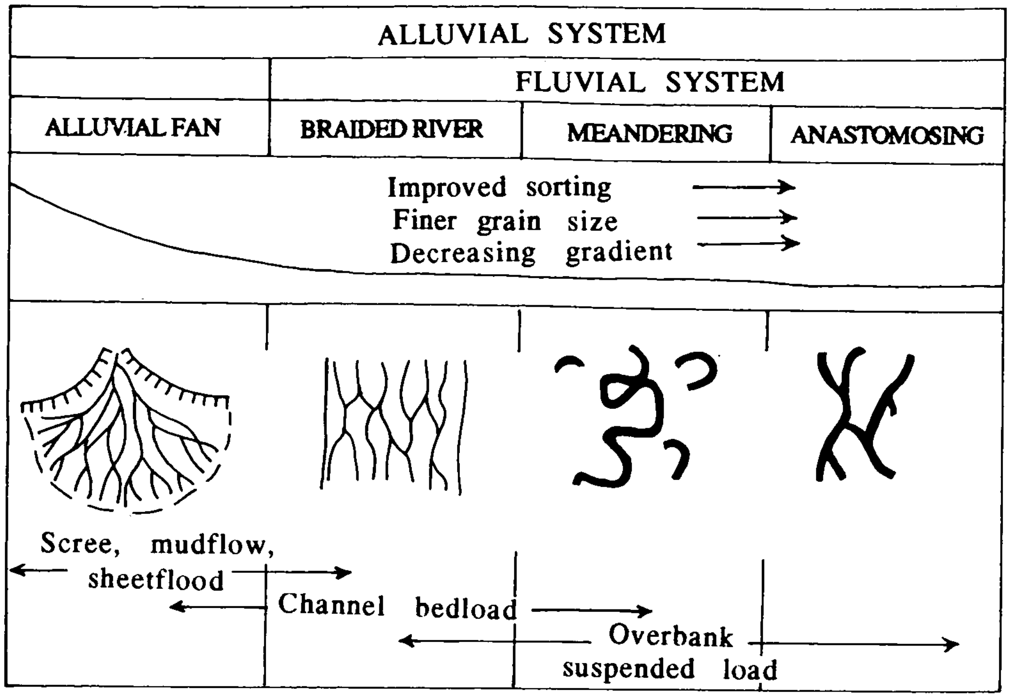
From a hydrogeological point of view, probably the two most important features when comparing these types of alluvial system are:

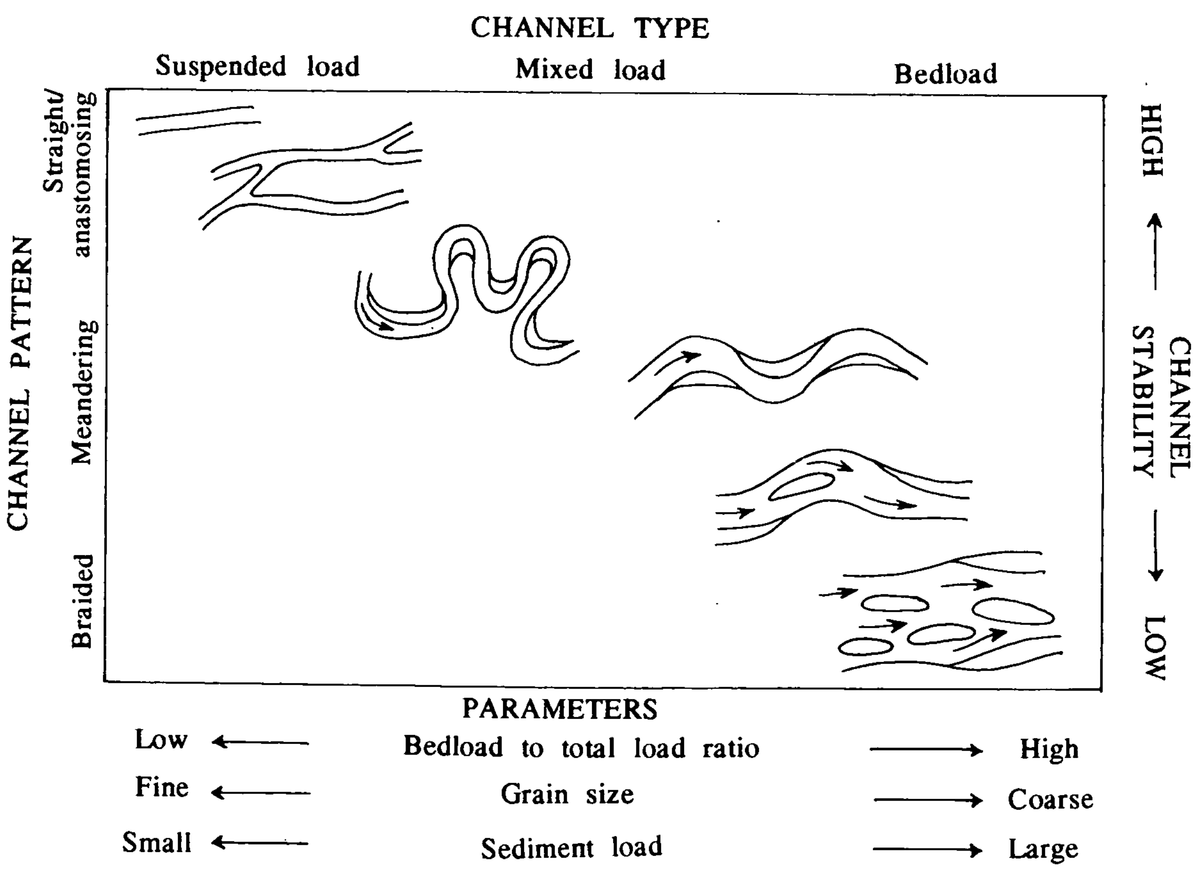
- Ratio of sand and gravel to mud. This is highest in the bedload, and lowest in the suspended load systems.

- Sand/gravel body shape and arrangement ('alluvial architecture'). This varies from largely sheet-like in the bed load systems, to irregular and pod-like in the suspended load systems.

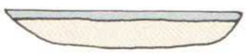
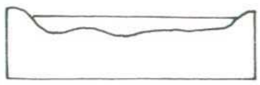
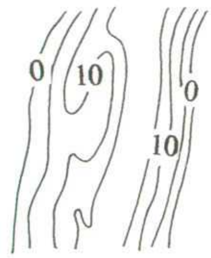
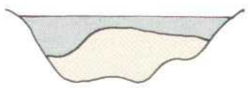
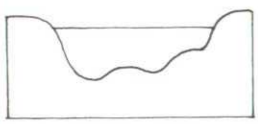
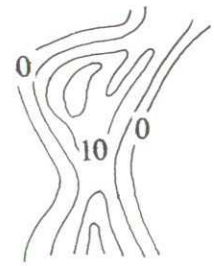
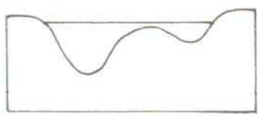
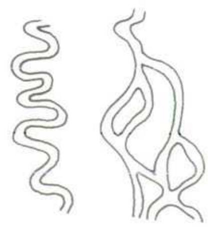
Many important aquifers have been developed within unconsolidated fluvial sediment systems throughout the world, and these provide large quantities of water for irrigation and industry as well as urban and rural supply. These aquifer systems are commonly unconfined, occur at shallow depth, and are therefore vulnerable to contamination by industrial wastes and agro-chemicals.

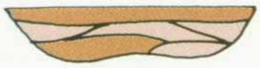
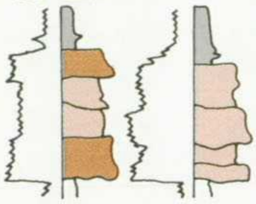
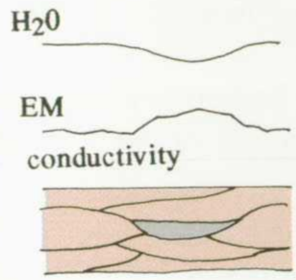
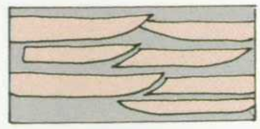
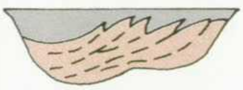
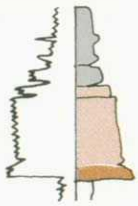
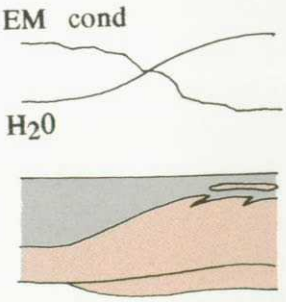
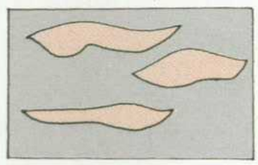
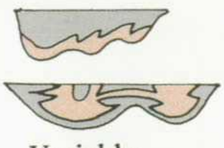
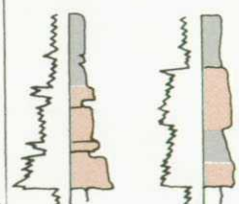
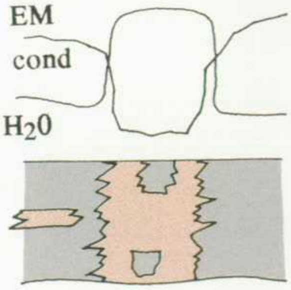
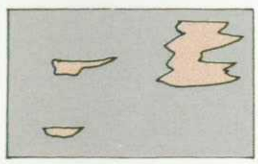
The sediments of the Nile valley, for example, form one of the largest aquifers in the world, with sands and gravels up to 250 m thick with a transmissivity of up to 8 000 m^2/day and a hydraulic conductivity of 10 m/day. These are extensively developed in Egypt but have yet to be developed in Sudan. In Pakistan, highly productive late Quaternary fluvial aquifers underlie the Indus Plains. These have been extensively developed: by 1980 some 176 000 tube wells had been installed, pumping some 40 000 000 m^3 of groundwater per annum. Similar aquifers have been developed in Burma (Irrawaddi River), India (Ganges valley), Bangladesh (Brahmaputra valley) and China.





Based on Schumm & Meyer (1979)

TYPE	LITHOLOGICAL DISTRIBUTION	CHANNEL MORPHOLOGY		
		CROSS SECTION	PLAN VIEW	SAND & GRAVEL ISOLITHS
BEDLOAD CHANNEL		 High width/depth Low to moderate relief on basal scour		
MIXED LOAD CHANNEL		 Moderate width/depth ratio High relief on basal scour		
SUSPENDED LOAD CHANNEL		 Low width/depth ratio High relief on basal scour		

INTERNAL STRUCTURE		WATER POTENTIAL GEOPHYSICAL SIGNAL	LATERAL RELATIONS
FABRIC	VERTICAL SEQUENCE		
 Lenticular bar and channel deposits. Rare silt/clay abandoned channel-fills	SP Lith 		 Multilateral channel-fills commonly exceed overbank deposits
 Fining upwards sequences. Laterally accreted sand and gravel overlain by vertically accreted silt and clay			 Multi-storey channel-fills embedded within overbank deposits
 Variable: a) migrating channels, fining upwards b) fixed channels with vertically continuous facies			 Sequence dominated by overbank deposits with ribbons of sand and gravel

Modified from Galloway (1977)

BEDLOAD (BRAIDED) RIVERS

- During deposition, these are characterised by braided, constantly switching low sinuosity channels separated by bars.

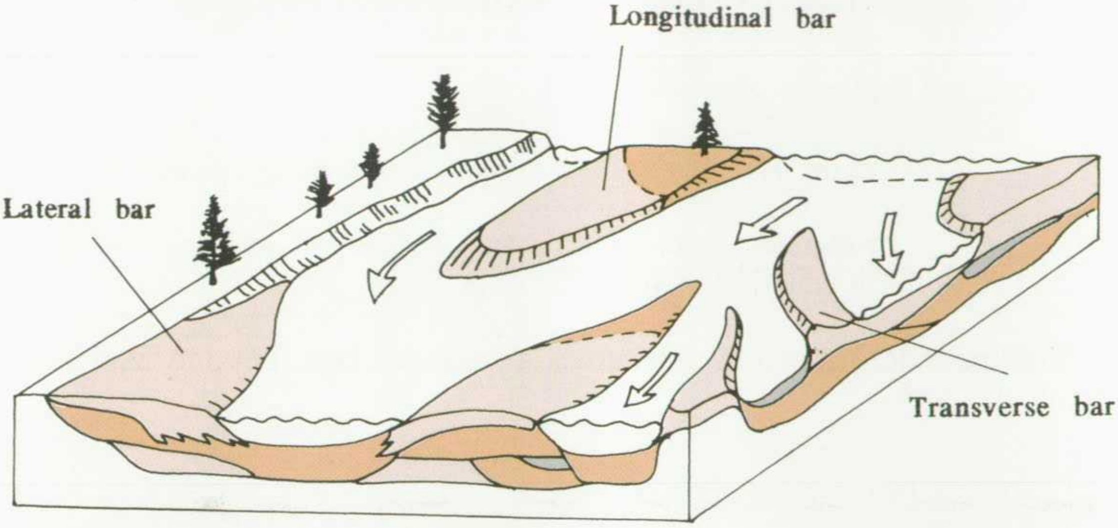
- Sandbodies tend to be sheet-like, with good lateral and vertical continuity. Mud deposits, where preserved, tend to be lenticular in form, laid down in abandoned channels. There may have been a great deal of mud suspended in the river water, but little of it would remain within this part of the alluvial tract.

- This facies may be constructed of sands or gravels or both. Most commonly gravelly upstream reaches of bedload systems give way downstream to sandy reaches.

- Much information about these systems comes from studies of proglacial drainage systems, which have predictable seasonal discharges. Systems from semi-arid environments are characterised by a more irregular discharge pattern, with major floods spreading sheet sands that can cover wide areas flanking the channel.

- Bedload alluvial systems give rise to a variety of vertical facies sequences. These are generally formed by the lateral migration of either channels or bars, the former characteristically producing fining-up cycles.

- These systems can contain important groundwater resources. For instance, coarse-grained gravelly bed-load sediments (permeabilities of 30-80 m/day) form highly productive aquifer zones within the late Quaternary aquifers of Bangladesh.



Braided river, Grand Teton National Park, USA.

MIXED LOAD (MEANDERING) RIVERS

- These are typically characterised by:

  - channels with a markedly sinuous (meandering) pattern.

  - a clearer separation into channel (coarse) and overbank (fine) deposits than in braided, low sinuosity rivers.

- The meandering channel occupies a meander belt, beyond which are distal overbank deposits.

- Channels move in two ways:

  - active meandering, in which erosion of the outer bank of the channel meander is accompanied by the deposition of sandy point bars on the inside of the meander. The migration of a channel leads to lateral accretion of the point bars, eventually forming a sand sheet. Typically, the sequence so produced fines upwards. Deposition of the point bar and associated levées leads to growth of the meander belt above the level of the adjacent floodplain. This situation is unstable and leads to:

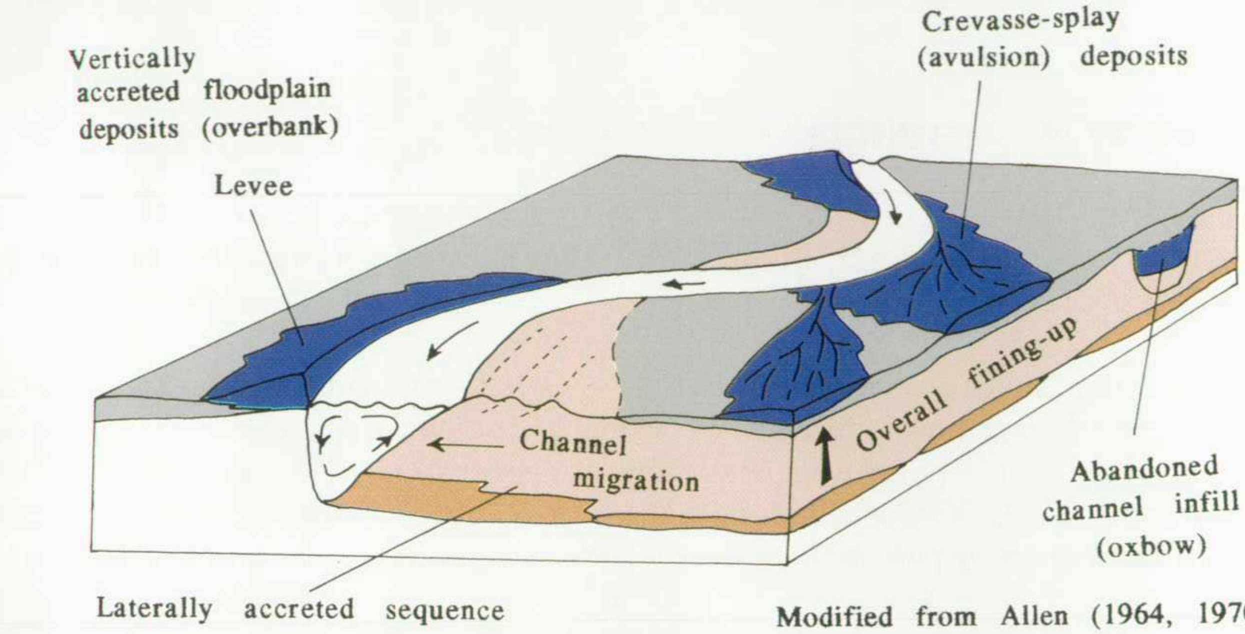
  - *avulsion*, or wholesale shifting of the channel to a lower part of the floodplain, where a meander belt forms anew. A combination of meandering and avulsion typically gives rise to sand sheets embedded within muddy flood plain deposits.

- Sedimentation outside the active channels is characterised by vertical accretion of mud, upon which soils may form. Coarse units within these floodplain deposits include:

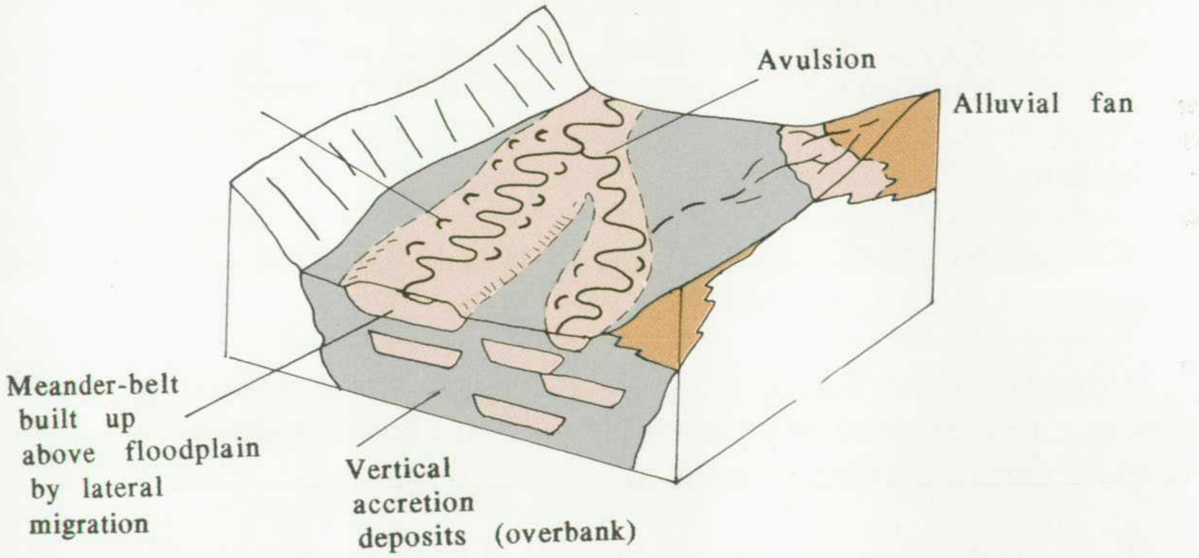
  - levées: wedge-shaped bodies of silt and fine sand flanking channels, deposited from suspension by flood waters which overtop the channel sides; finer, muddy material settles more distally on the floodplain.

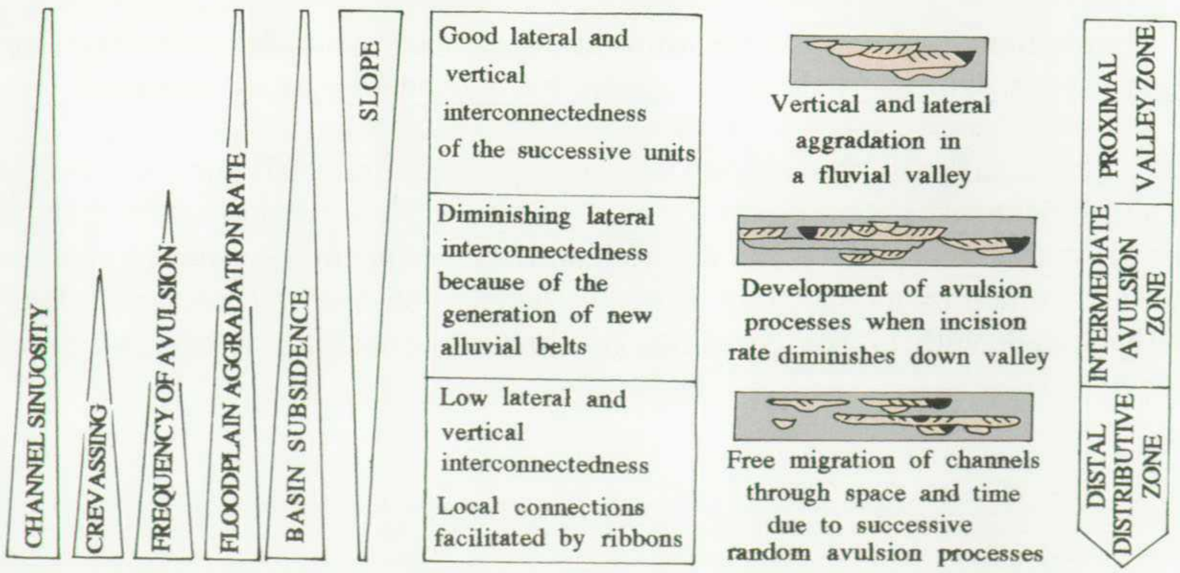
  - crevasse splay deposits, fan-shaped bodies of sand and silt which spread out on to the flood plain when a levée is breached by flood waters. Individual proximal crevasse splay units can resemble channel meander deposits, but are typically thinner.

- Mixed load systems can contain significant groundwater; for instance, fining upwards cycles of coarse to fine sands (permeabilities of 40-70 m/day) form secondary aquifers within the late Quaternary aquifers of Bangladesh.



Modified from Allen (1964, 1970)





Factors controlling the architecture of fluvial sandbodies. After Marzo et al. (1989).

Anatomy of a meander belt

One of the most detailed studies of the internal architecture of a mixed load fluvial system is by Jordan & Pryor (1992), investigating a meander belt in the Mississippi.

Two fluvial suites are superimposed: (a) relatively homogeneous Pleistocene sands and gravels laid down during an episode of bedload river activity; and (b) an overlying, internally heterogenous suite of deposits laid down as a meander belt in recent times. This meander belt has several levels of heterogeneity as regards the distribution of potential aquifers (sands and gravels) and aquicludes (muds):

1. The entire meander belt is composed of amalgamated meander scrolls (sediment bodies built up by the lateral migration of point bars). The lateral continuity of these sands is broken by numerous low-permeability clay plugs. Widespread overbank muds form an impermeable clay cap outside the active meander belt.

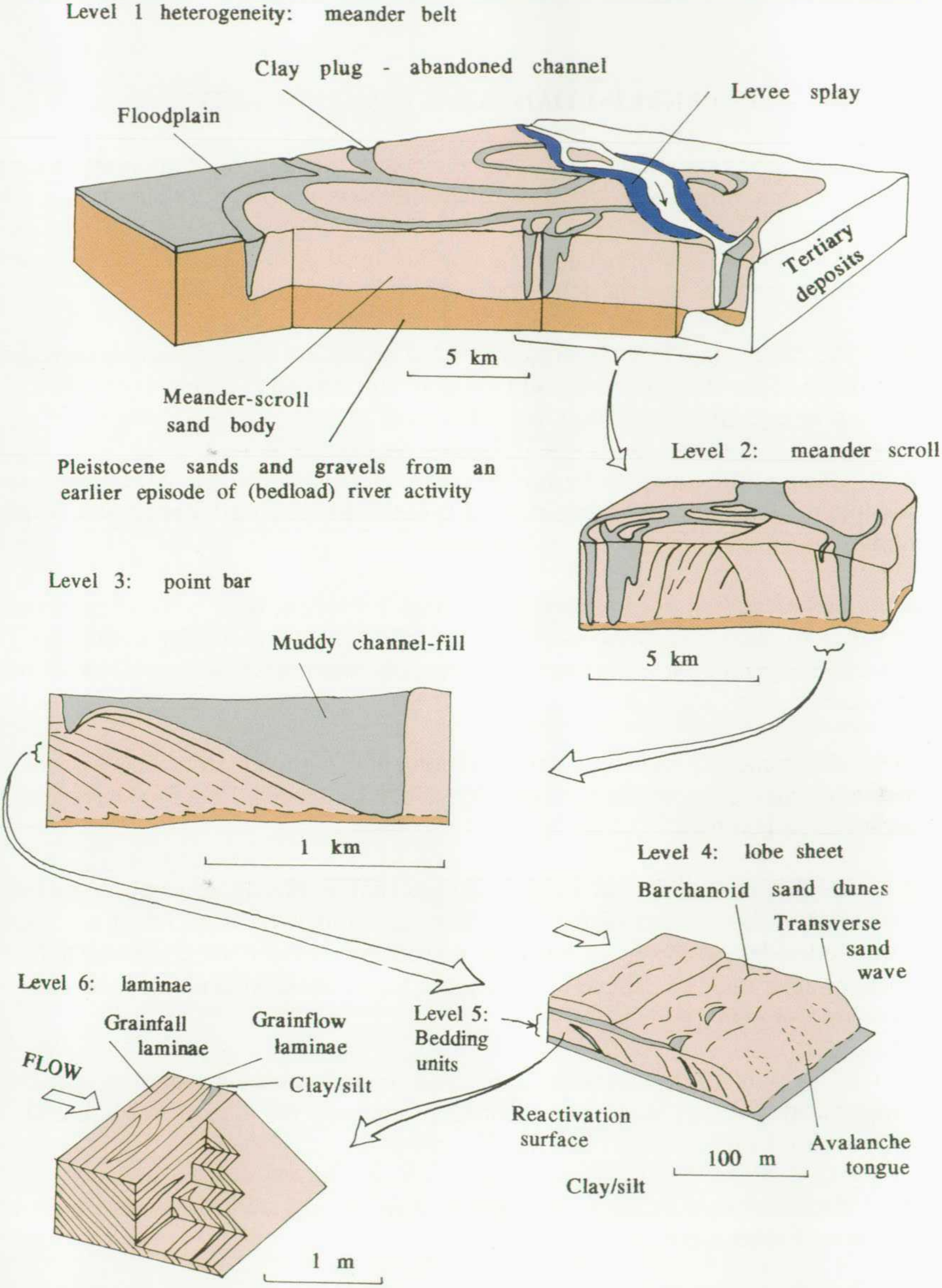
2. Individual meander scrolls comprise laterally accreted point bar sands, commonly with a basal lag gravel.

3. Individual point bars consist of sand layers (lobe sheets) separated by numerous thin sheets of low-permeability mud laid down as drapes on the point bar surface during episodes of ponding at high river stage.

4. Lobe sheets comprise sequentially stacked bedding units of sand.

5. Individual bedding units within the lobe sheets comprise permeable cross-bedded sands with internal discontinuous low-permeability mud layers.

6. Individual cross-laminae are of two types: (a) grain-fall laminae, deposited from turbulent suspension on the lee side of dunes; these are uniform in thickness, laterally continuous and well sorted with uniform permeability; and (b) grain-flow laminae, formed by avalanching down the lee side of dunes; these are lenticular, poorly sorted, with higher porosities but lower permeabilities than the grainfall laminae.



After Jordan & Pryor (1992)

SUSPENDED-LOAD (ANASTOMOSING) RIVERS

- These are characterised by relatively stable channels, with an anastomosing pattern, within a muddy floodplain. Channels may be straight or sinuous.

- Anastomosing channel systems develop on very low gradient slopes, such as occur in marshes and on delta tops.

- Active channel meandering is restricted by the low energy of the system and, commonly, the cohesive strength of the floodplain deposits. Channels change their position rarely, and then mainly by avulsion.

- Channel stability may be further enhanced by thick vegetation cover on the floodplain; thus, anastomosing channel systems are often associated with warm, humid climates.

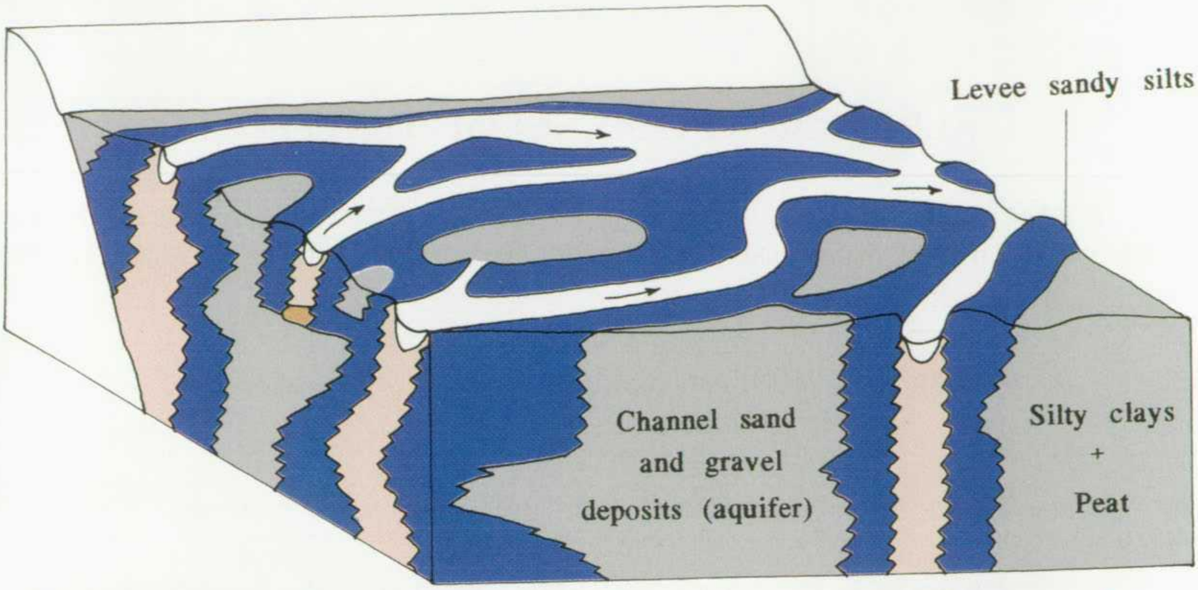
- Sedimentation occurs mainly be vertical accretion, both in the channels and on the floodplain. Thus the sand bodies tend to have a markedly ribbon-like or curtain-like geometry. Channels are typically associated with well-developed levées.

- Anastomosing channel systems commonly occur in environments associated with high rates of sediment accumulation and subsidence. Thus they have a high preservation potential.

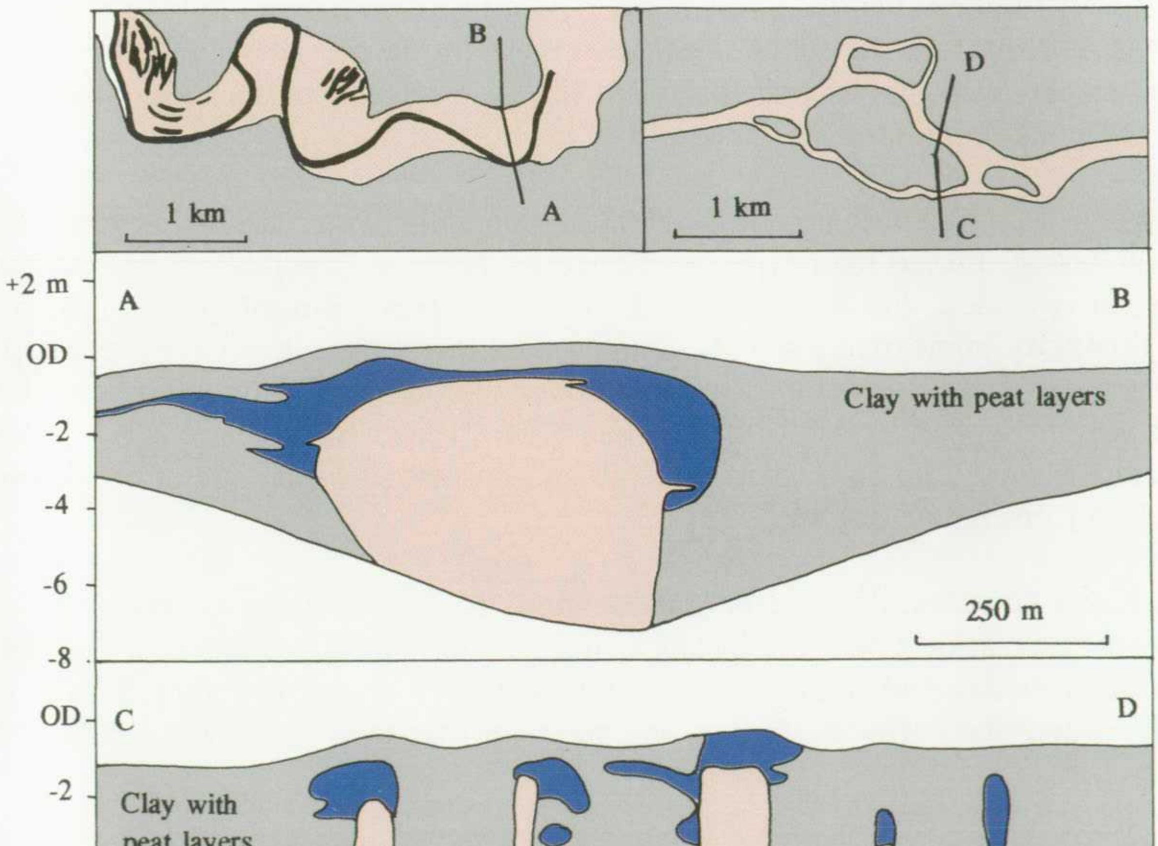
- In Holocene marginal marine settings, anastomosing channels have been associated with episodes of rapid sea level rise and vertical sediment accretion. During episodes of slower sea level rise and accretion, the channels tended to form meandering systems. Thus the two types of channel system may be closely associated in many regions.

- The ribbon-like channel geometries makes locating aquifers difficult. Geophysical methods (e.g. ground conductivity) may prove particularly useful in such environments.

- Anastomosing systems are comparatively poorly studied; further research may reveal other types of facies geometry.



The anastomosing Alexandra and North Saskatchewan rivers, Canada. After Smith & Smith (1980)



Meandering and anastomosing river channel geometries compared. Both examples from the Rhine-Meuse delta plain, after Törnqvist (1993).

ALLUVIAL SYSTEMS - CLIMATIC EFFECTS

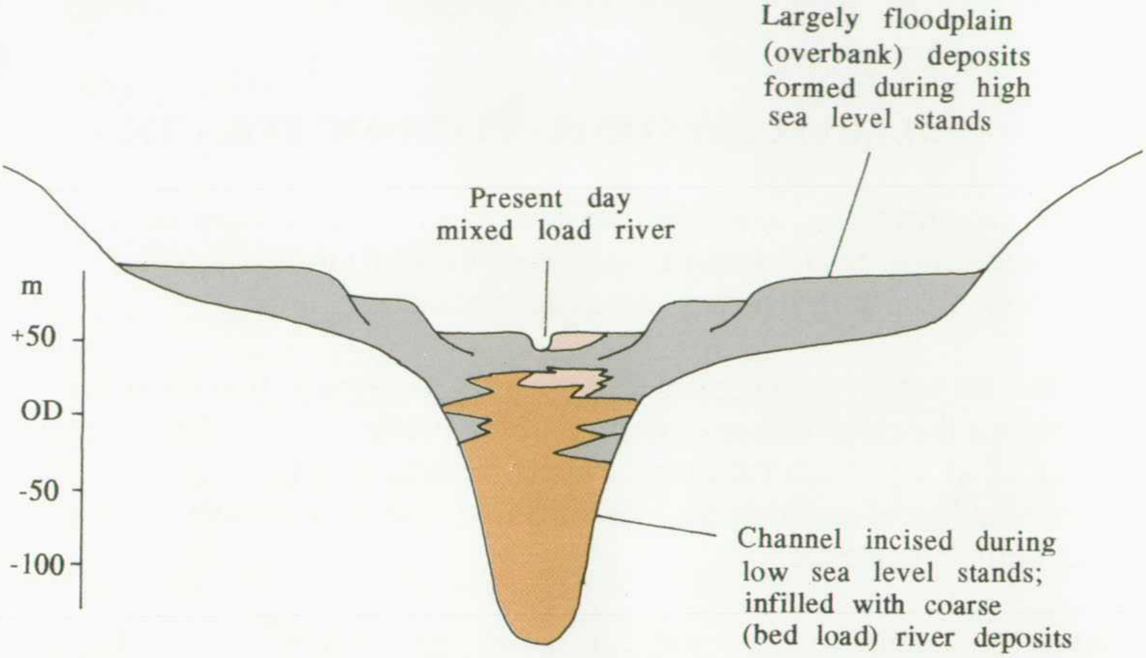
The climatic oscillations of the Quaternary led to marked environmental changes, which were variously expressed in different parts of the world. Effects on alluvial systems included:

- Changes in sea level, resulting in changes in base level for rivers draining into the sea.
- Changes in precipitation (and thus discharge) patterns.
- Changes in vegetation, and thus changes in the erodability of source material and alluvial sediments.
- Changes in input of sedimentary material, particularly in areas influenced by glaciation.

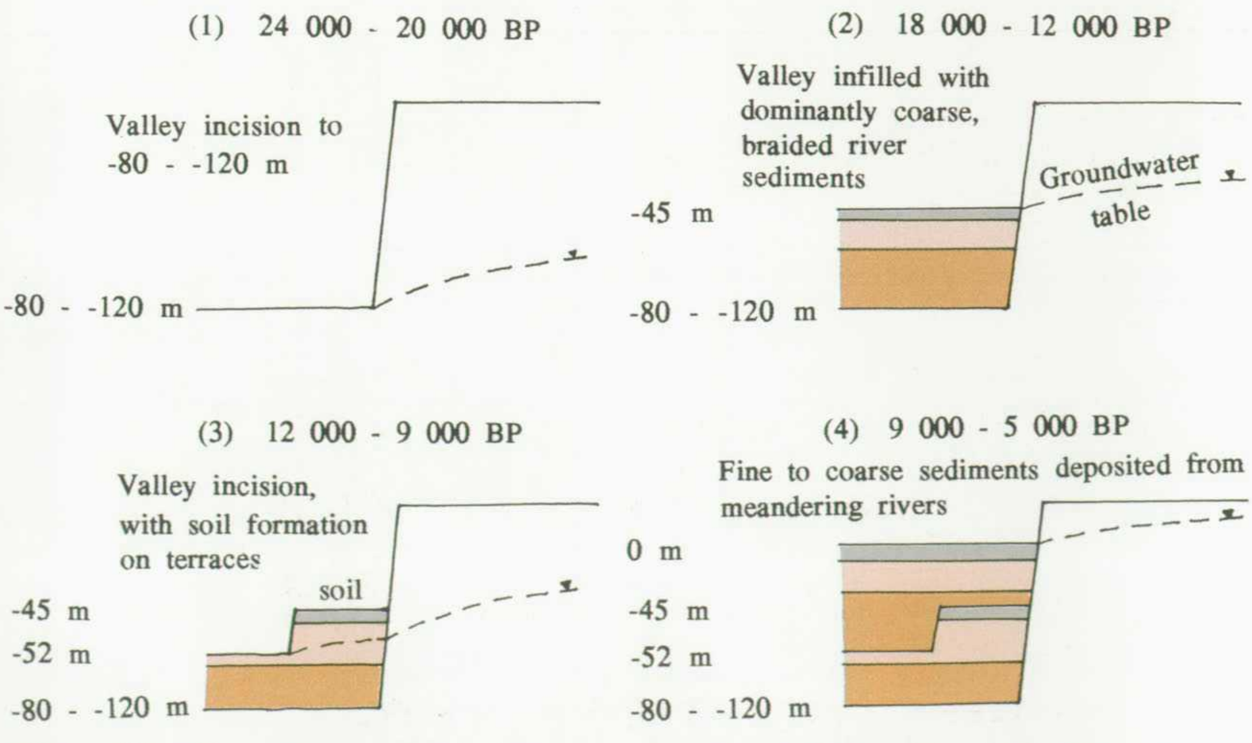
It is thus unlikely that the present day dynamics of any river, and the architecture of its deposits, are the same as those formed during preceding climatic episodes. Present-day deposits of one facies are likely to have deposits of another, earlier facies stacked underneath them, and/or laterally to them.

In temperate climates such as those of Europe, many rivers which currently are of meandering, mixed-load type functioned as bedload (braided) rivers during the glacial episodes, due to increased discharge (in part from meltwaters), increased sedimentary input (part glacially sourced) and lower base levels. Recent deposits commonly comprise complexly interbedded aquifers and aquicludes (see above); the earlier deposits, which lie underneath the present flood plain, and/or laterally to it as terraces, are dominated by sands and gravels characteristic of braided rivers and so form better aquifers.

At lower latitudes, the effects of these climatic changes were generally different. Present-day arid zones, for instance, have undergone a sequence of oscillations between wetter and drier phases. This will have drastically altered patterns of fluvial activity . On the Indian subcontinent, monsoon activity is likely to have changed.



Schematic cross-section of a typical river on Fiji, showing deposits accumulated during various sea level stands of the Quaternary. After Davies (1992).



Effect of late Quaternary sea level changes upon erosion and deposition in the Jamuna Valley, north-east Bangladesh. After Davies (in press).

ALLUVIAL SYSTEMS - TECTONIC EFFECTS

Rivers in tectonically active areas are likely to have their flow patterns modified by faulting or crustal warping. This will lead to systematic, and locally predictable, changes in patterns of aquifer geometry.

In floodplains which are laterally tilted (e.g. by flowing within an active graben or half-graben), the river will tend to migrate or avulse towards the downthrow side, resulting in an asymmetrical meander-belt. Sandbodies (i.e. aquifers) will tend to be elongated laterally within the area of tilting, and to be concentrated in the areas of maximum subsidence.

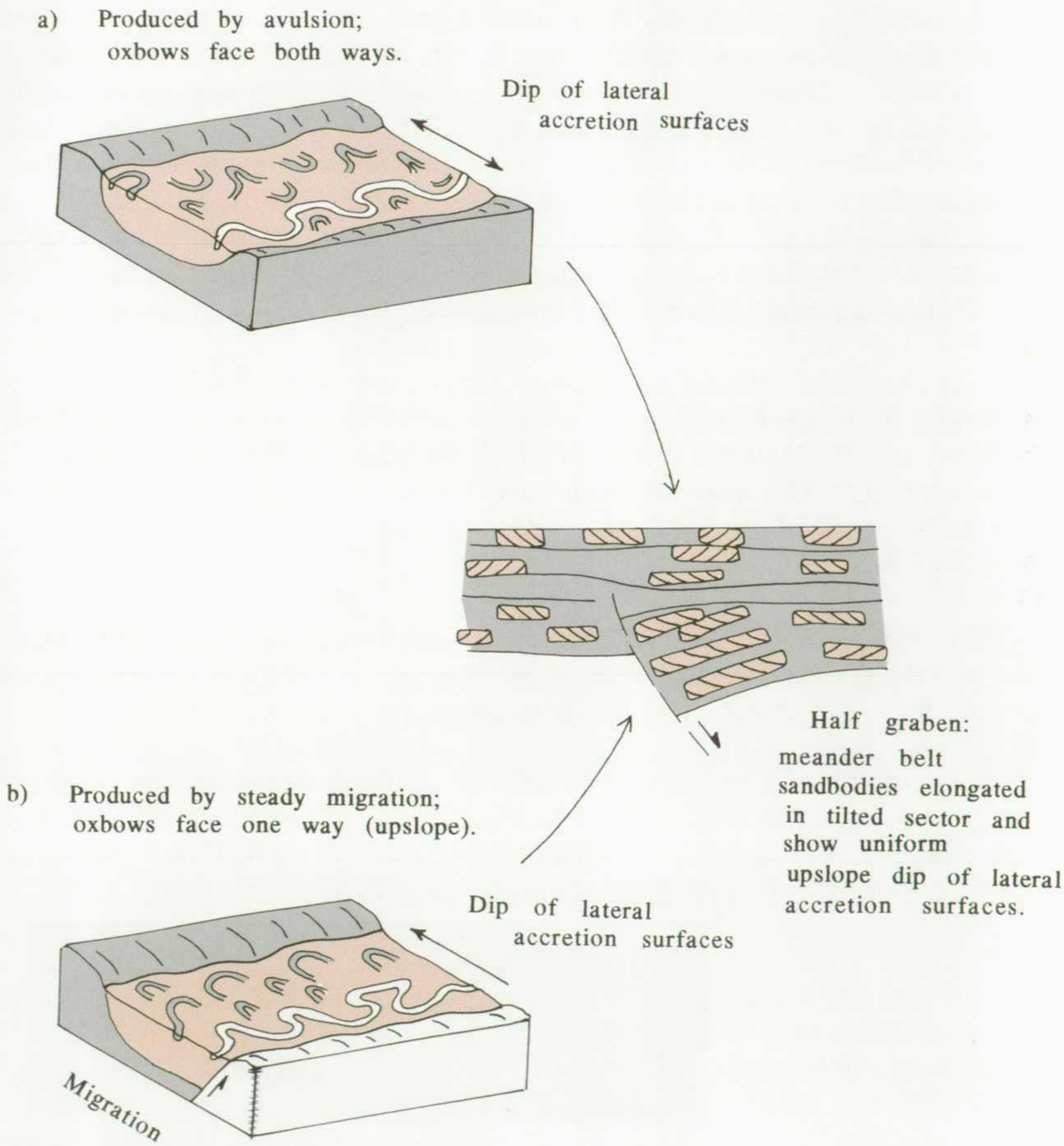
Conversely, the side of the floodplain which is systematically tilted upwards will be marked by a preponderance of muddy overbank deposits, and may be expected to have relatively poor aquifer potential.

Analysis of tectonically active areas by means of aerial photography, remote sensing or geological surveying should provide indications of tilting.

Areas which are uplifting rapidly as a result of tectonic compression or isostatic readjustment will be characterised by steep gradient and a high sediment supply. Alluvial fans and braided streams are likely to be common.

ASYMMETRICAL MEANDER BELTS

After Leeder & Alexander (1987).



DELTAIC DEPOSITS

GENERAL & CLASSIFICATION

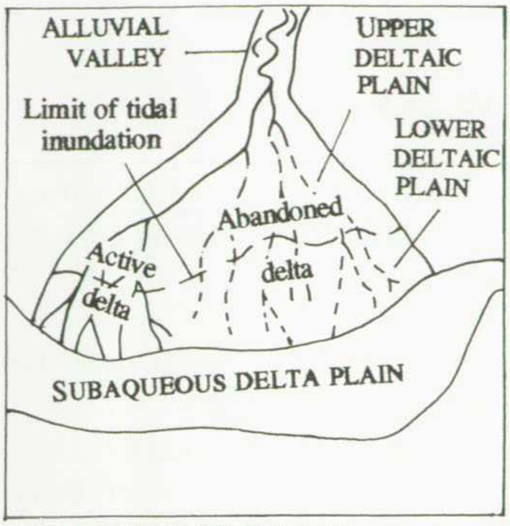
- A delta is formed where a river meets a body of standing water, and where sediment is deposited more rapidly than it can be transported away by waves and/or currents. Deltas are normally sites of rapid sedimentary accumulation. Deceleration of river flow results in the deposition of much of the sediment load; the coarser material is deposited first, in the area around the river mouth, finer material tending to settle further offshore. Where sediment is deposited faster than the combined effects of sediment reworking and subsidence, then *delta progradation* takes place, with proximal deposits being built outwards to overly the more offshore deposits. A coarsening-upwards sequence is thus characteristic.

- The shape and internal sedimentary architecture of a delta is controlled by the interplay and relative strengths of *constructional* forces, associated with fluvial deposition, and *destructional* forces, in which the sediment is reworked by waves, currents or winds. This interplay is the basis for the classification of deltas. *River dominated, wave dominated* and *tide dominated* deltas are end members of a broad spectrum of delta types.

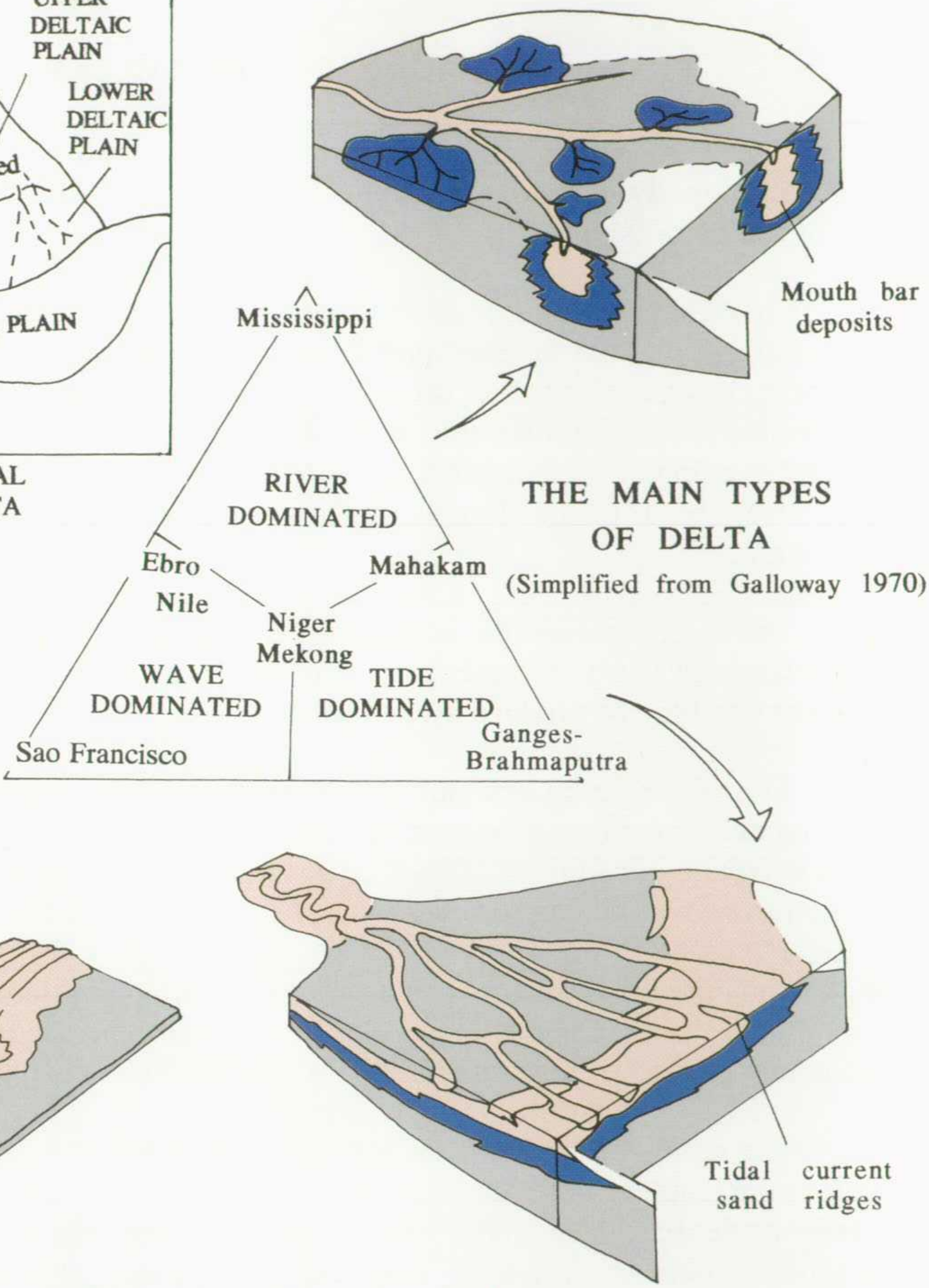
- Climate, water discharge rate, sediment quantity and grain-size, the tectonics of the receiving basin and the relative densities of the river and basin water are important factors in determining the delta geometry.

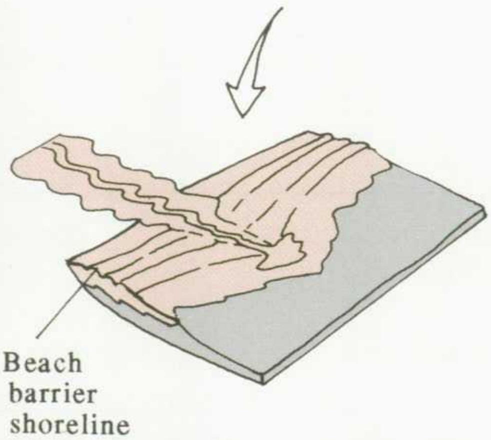
- The groundwater resources of a delta are difficult to evaluate and develop. Coarse grained aquifers tend to occur as lenticular to ribbon-like units embedded within finer grained deposits. Although intensively studied by petroleum geologists, little is known of the groundwater potential of many major deltas.

The steeply inclined foresets of a classical *Gilbert-type delta*; the hilly surrounding topography indicates that it may be fed by an alluvial fan and so be a *fan-delta* (see pp. 55-56). Wasach Mts, adjacent to the former Lake Bonneville, USA.



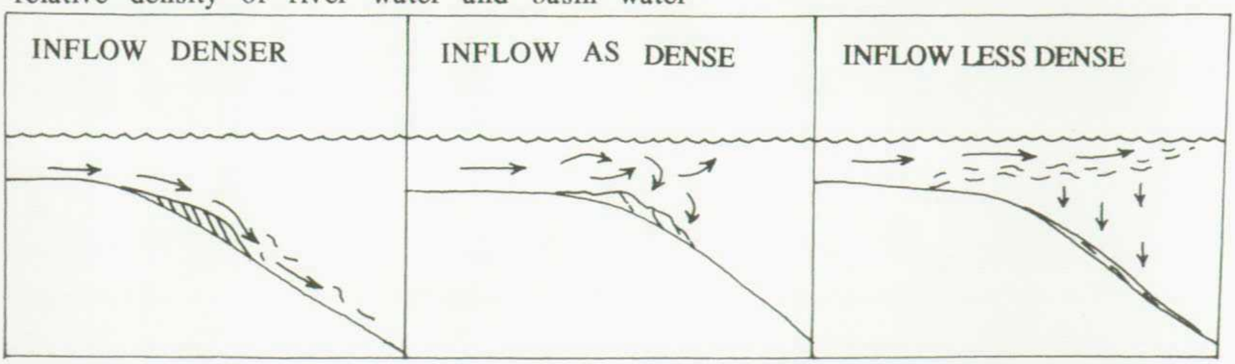
MAIN MORPHOLOGICAL FEATURES OF A DELTA





THE MAIN TYPES OF DELTA
(Simplified from Galloway 1970)

An important feature controlling delta sedimentation is the relative density of river water and basin water



RIVER-DOMINATED DELTAS

- Where waves and current are weak, deposits laid down in a fluvial setting may build rapidly outwards to form a river-dominated ('birdsfoot') delta such as that of the Mississippi.

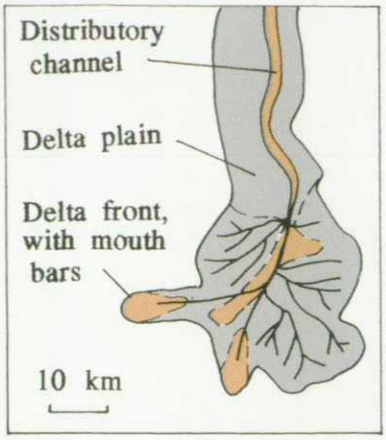
- Characteristic features of such environments include the deposition of the coarser fraction of the sediment just beyond the river mouth as a *mouth bar*. Finer sediment is carried further offshore. Where channels are relatively stable, progressive sedimentation results in the deposition of a ribbon-like 'barfinger' body of sand, commonly at a high angle to the shoreline. The channel deposits themselves tend to be largely filled with fine-grained sediment following abandonment.

- The space between the advancing main channels is filled with finer grained floodplain and levée/crevasse splay deposits. The channel and between-channel deposits combine to produce a delta lobe.

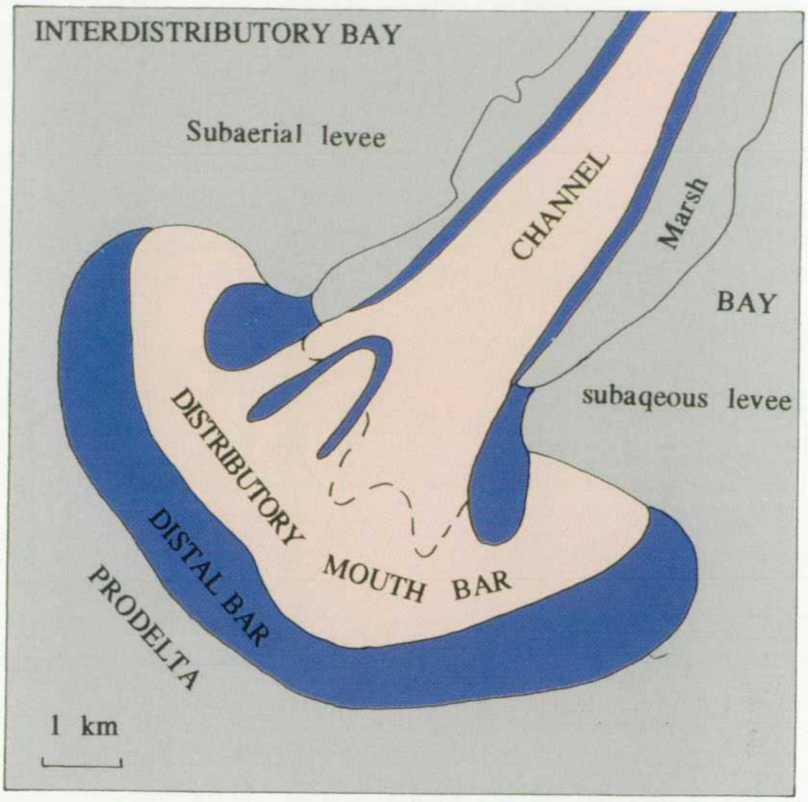
- After the channel has built out a certain distance, the gradient becomes too low and the channel is abandoned by avulsion, active deposition beginning to build out a new lobe of sediment at another position. Continuing subsidence may result in the drowning and partial reworking of the abandoned lobe.

- Thus the delta advances as a series of overlapping lobes, the main aquifers (the mouth bar sands) forming elongate bodies enclosed within fine-grained sediments laid down beyond and adjacent to the main channels.

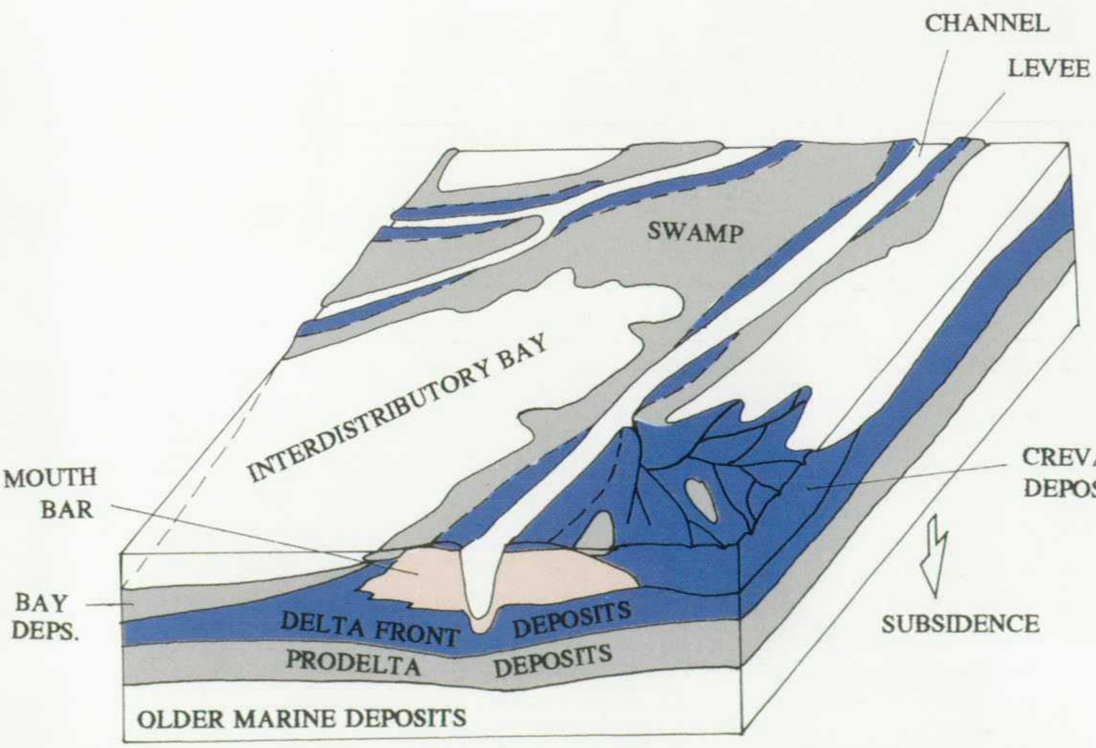
- The rapid accumulation of sediment which is often fine-grained and has a high water content commonly leads to large-scale sediment deformation. The relatively dense channel/mouth bar sands may sink into the soft, plastic muds, continuing deposition giving enhanced thicknesses of sand, these thickened sandbodies often being separated by upwardly displaced diapirs of mud.



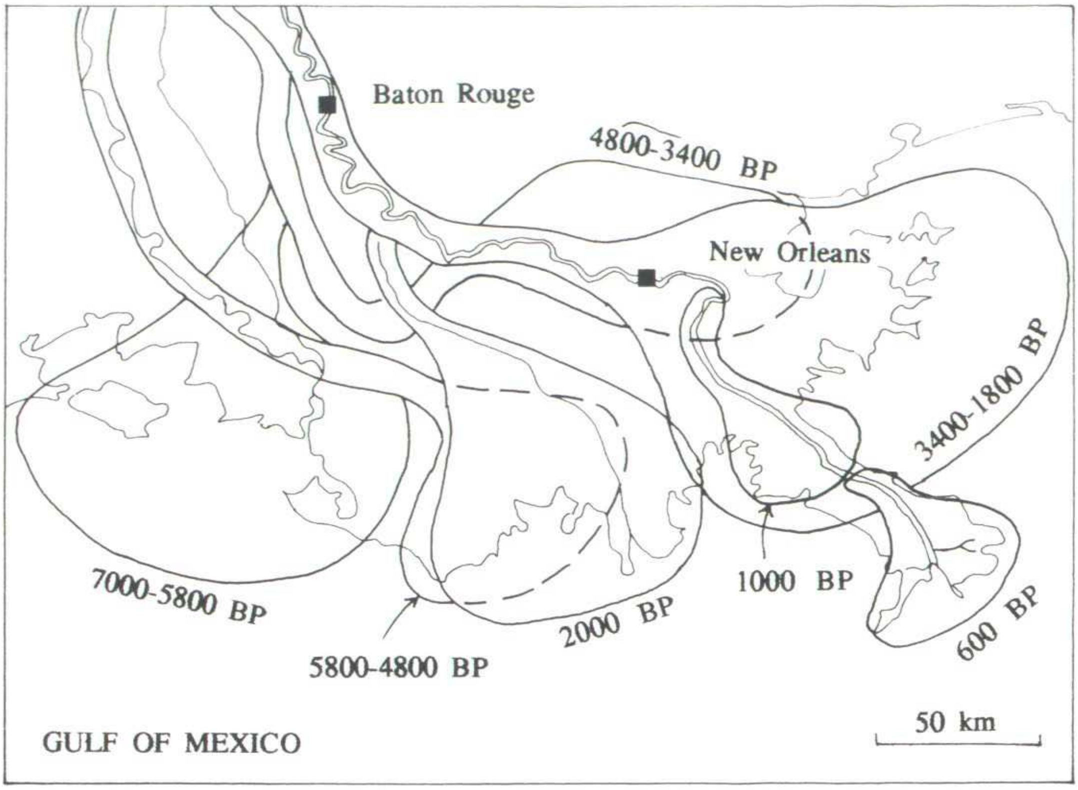
Part of the Mississippi delta, a river-dominated delta (after Fisher *et al.* 1969)



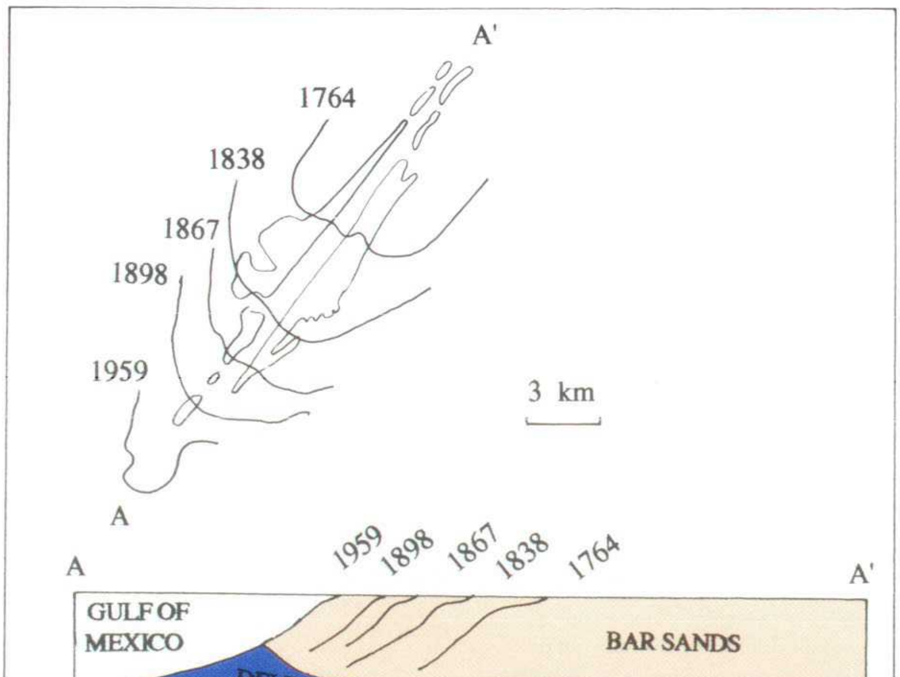
Plan view of a distributory mouth in a river-dominated delta (after Coleman & Gagliano 1965).



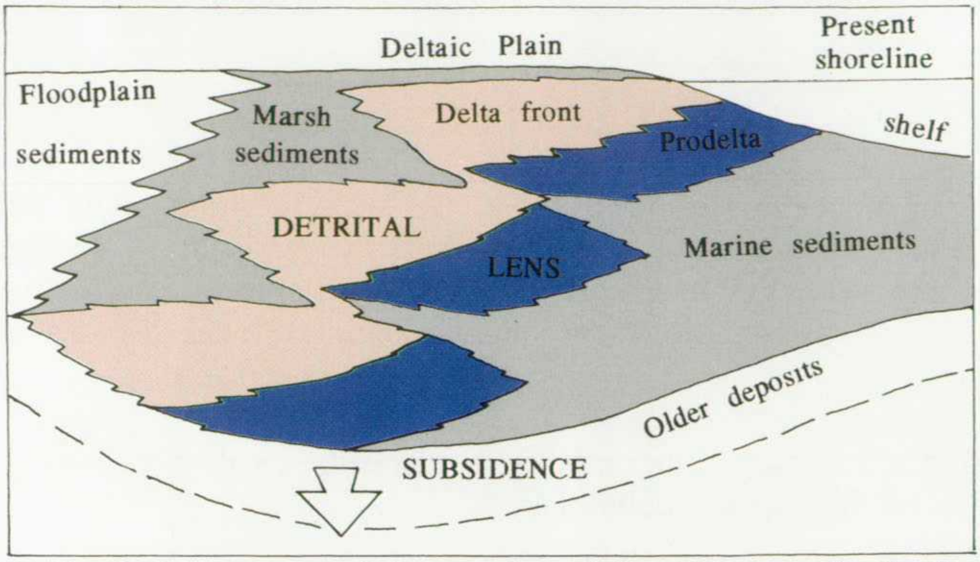
Block diagram illustrating facies associated with the progradation of a channel lobe (after Coleman 1981).



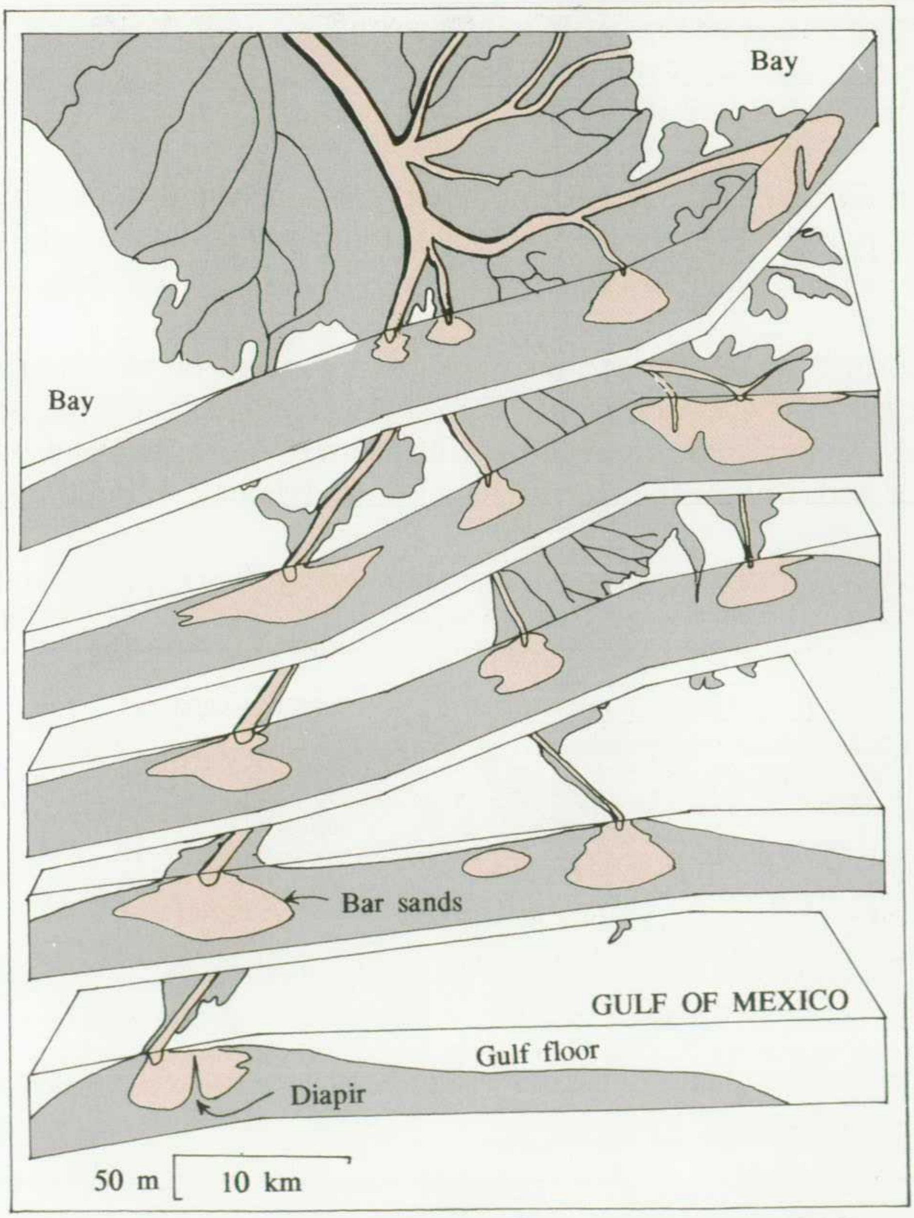
Age of the Mississippi River delta lobes (modified from Kolb & Van Lopik 1958).



Seaward migration of a distributory mouth bar on the Mississippi river over two centuries (modified after Gould 1970).



Idealized delta progradation cycles (after Coleman & Gagliano 1964).



Anatomy of the Mississippi delta (after Fisk 1961).

WAVE-DOMINATED DELTAS

- On open, wave-dominated shorelines such as those along much of the Atlantic and Pacific coast, the sediment initially deposited at the delta front is reworked into a series of beach bars, oriented parallel to the coast, while much of the mud may be winnowed out and transported much further offshore or alongshore.

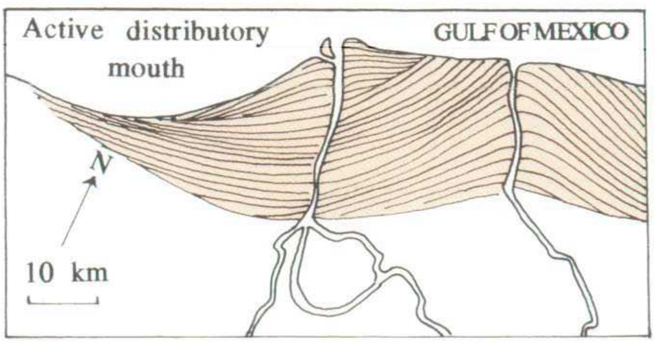
- Wind action may further modify the deposits, creating a capping of aeolian dune fields on the exposed delta plain.

- The three-dimensional geometry of the delta deposit depends upon the interaction of the shoreline/river mouth geometry with the pattern and angle of wave activity. Where waves are oblique, creating a pattern of longshore drift, the entire delta will become re-oriented downcurrent.

- Progradation of the delta front tends to be slow and to take place along the whole length of the delta front. The delta front tends to be smooth, and the coast-parallel beach ridges should be obvious on remotely sensed images.

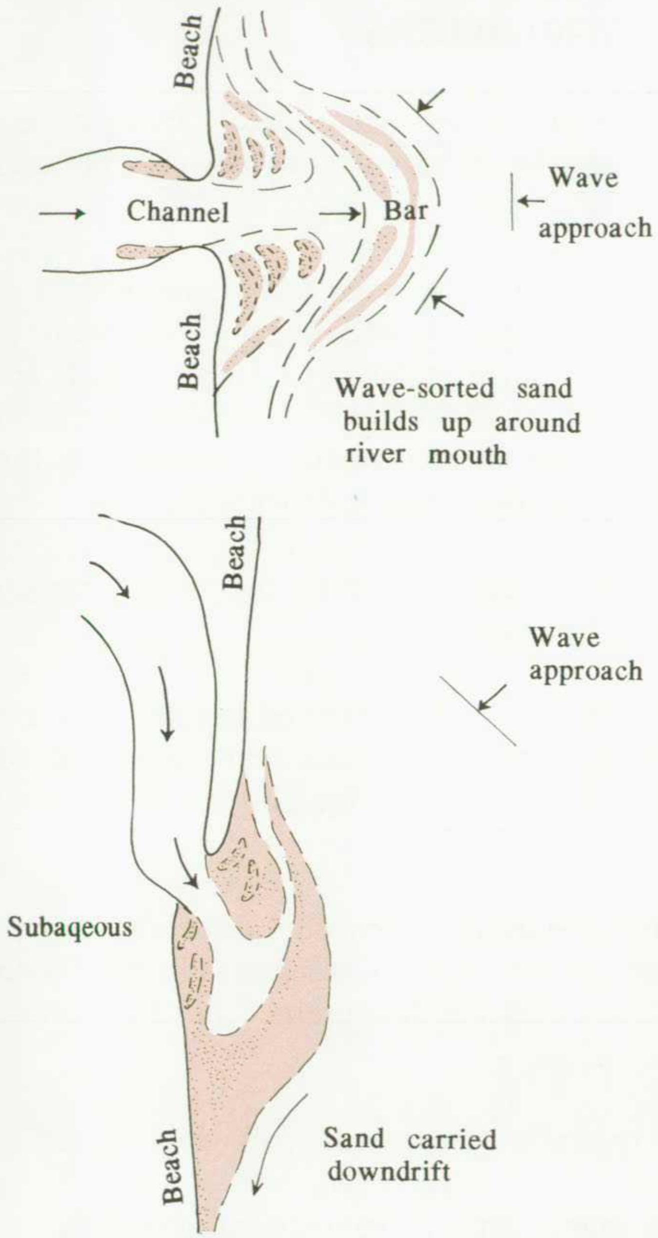
- The sand bodies formed on such deltas tend to be well-sorted and have a sheet-like geometry, in contrast to the 'shoestring' geometry of river-dominated delta sands. Typically, they show a coarsening-upwards trend. If subsidence keeps pace with sedimentation, then thick sand bodies can build up.

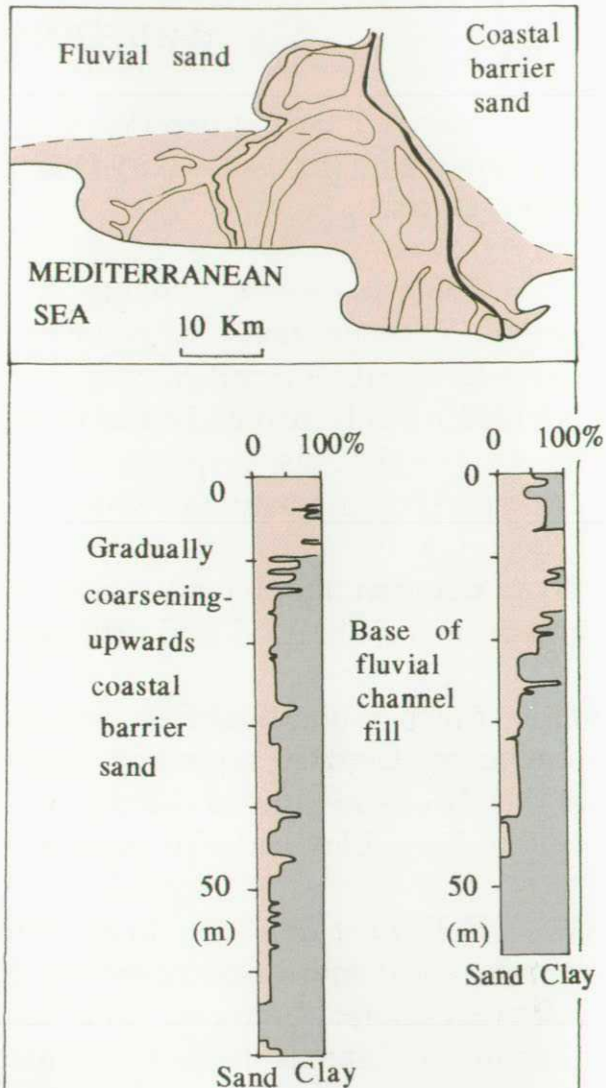
- The beach ridge sands may be punctuated by distributory channel-fill sands, which tend to show a fining-upwards trend.



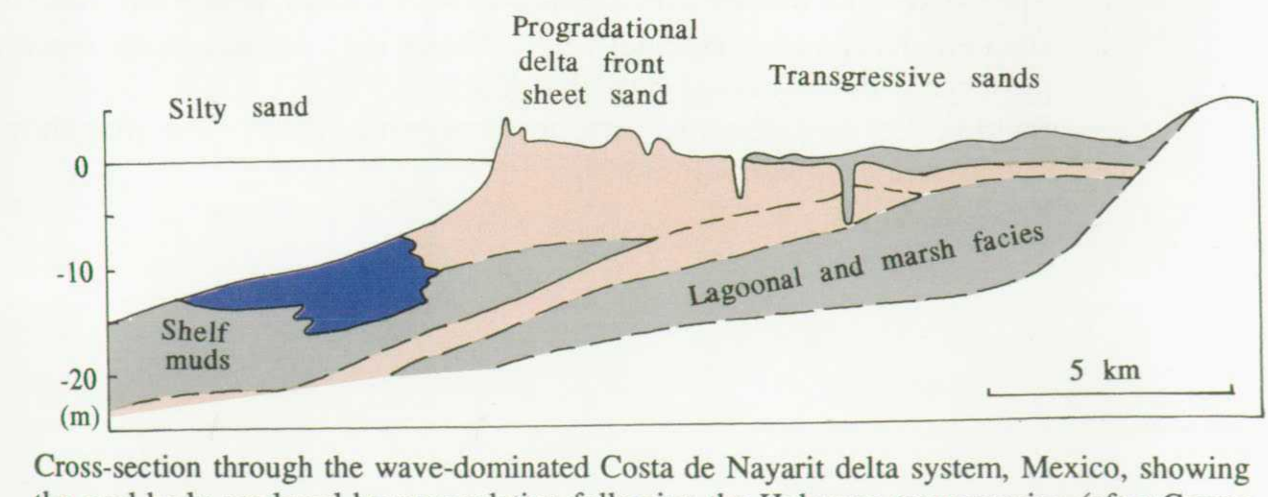
The wave-dominated Grijalva delta (after Psuty 1967), comprising a complex of laterally stacked beach ridges.

WAVE-DOMINATED RIVER MOUTHS
VARIATIONS IN ANGLE OF WAVE ATTACK





The Rhône delta, with typical coarsening-upward borehole sequences (after Oomkens 1967).



Cross-section through the wave-dominated Costa de Nayarit delta system, Mexico, showing the sand body produced by progradation following the Holocene transgression (after Curray, Emmel & Crampton, 1969).

TIDE-DOMINATED DELTAS

In coastlines characterised by a high tidal range (macrotidal), the sediments associated with the distributary channels may be redistributed by powerful ebb and flood currents.

- The estuarine distributory channels tend to be wide and funnel-shaped, a geometry which tends to increase tidal range. Sediment within them is characteristically reworked into a series of linear tidal sand ridges, which are oriented roughly perpendicular to the coastline and extend seaward of the delta mouth. This coast-perpendicular orientation of sand bodies contrasts with the coast-parallel orientation of sand bodies in wave-dominated estuaries.

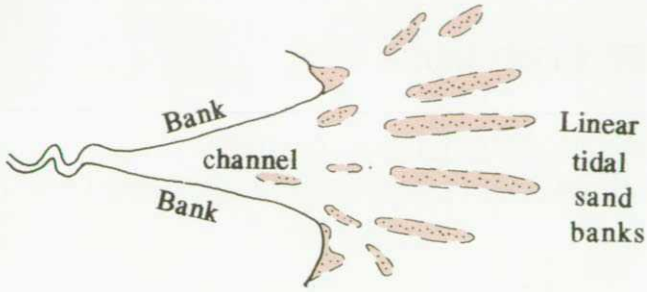
- Between distributary channels, the subaerial part of the delta mostly comprises fine-grained sediment deposited as tidal flats.

- Much of the tidal flats, though, may be not be preserved because they are eroded by laterally migrating distributory channels, which leave a swathe of relatively coarse-grained channel deposits in their wake. Sand bodies thus formed tend to have a lenticular to sheet-like geometry.

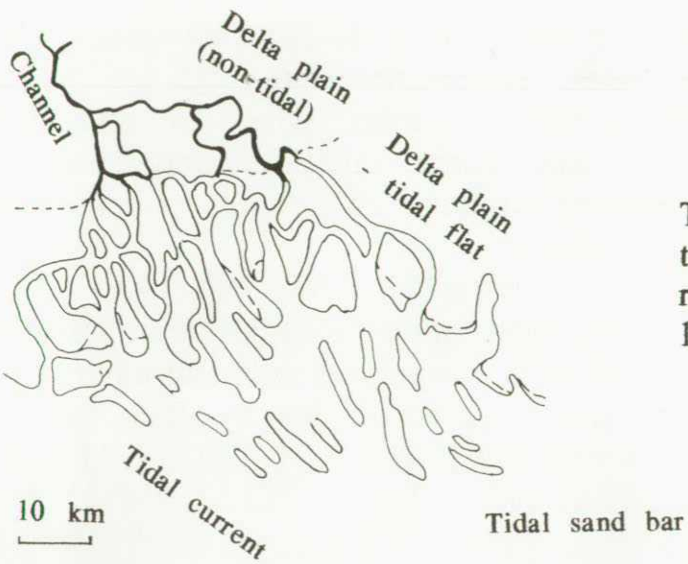
- Following final abandonment, channels in tide-dominated deltas continue to be winnowed and reworked by the tidal currents, and so are generally filled with relatively coarse sediment. This contrasts with the fine-grained infill typical of abandoned channels in river-dominated deltas.

Progradation of a tide-dominated delta typically produces the following sequence:

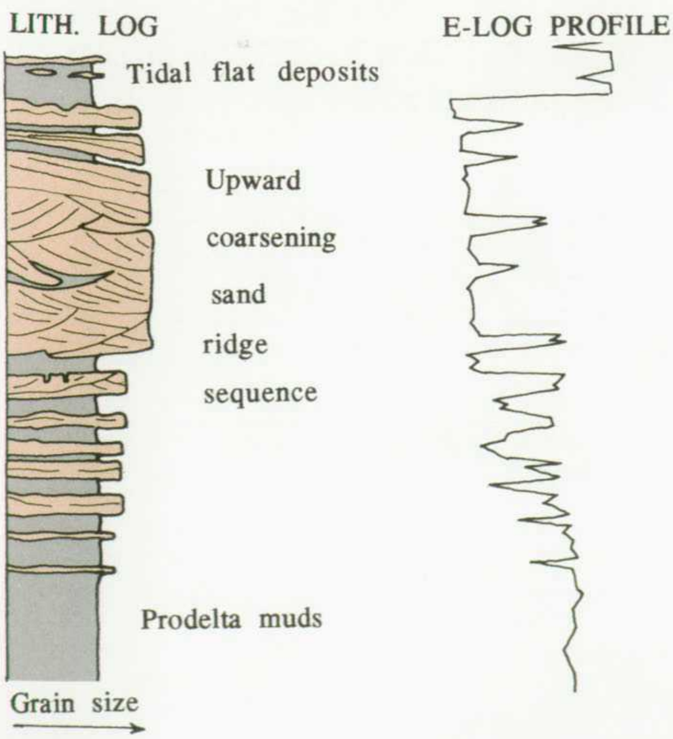
(4) A capping of tidal flat/salt marsh deposits (mostly fine-grained).
(3) Sheet-like sand bodies with a fining-upwards trend, which are laterally stacked distributory channel-fills. These may be interspersed with preserved, finer-grained tidal flat deposits.
(2) Sand bodies laid down as offshore tidal sand ridges: these may show a coarsening-upwards trend.
(1) Prodelta muds.



Idealised plan view of a tide-dominated river mouth (after Wright 1977).



The tide-dominated delta of the Ganges-Brahmaputra rivers (after Fisher et al. 1969).



Generalised vertical profile through a tidal current sand ridge (after Galloway & Hobday 1983)

CLIMATIC CONTROLS

The formation of many deltas at the land/ocean interface means that they are highly sensitive to the changes in climate and sea level associated with the Quaternary glaciations.

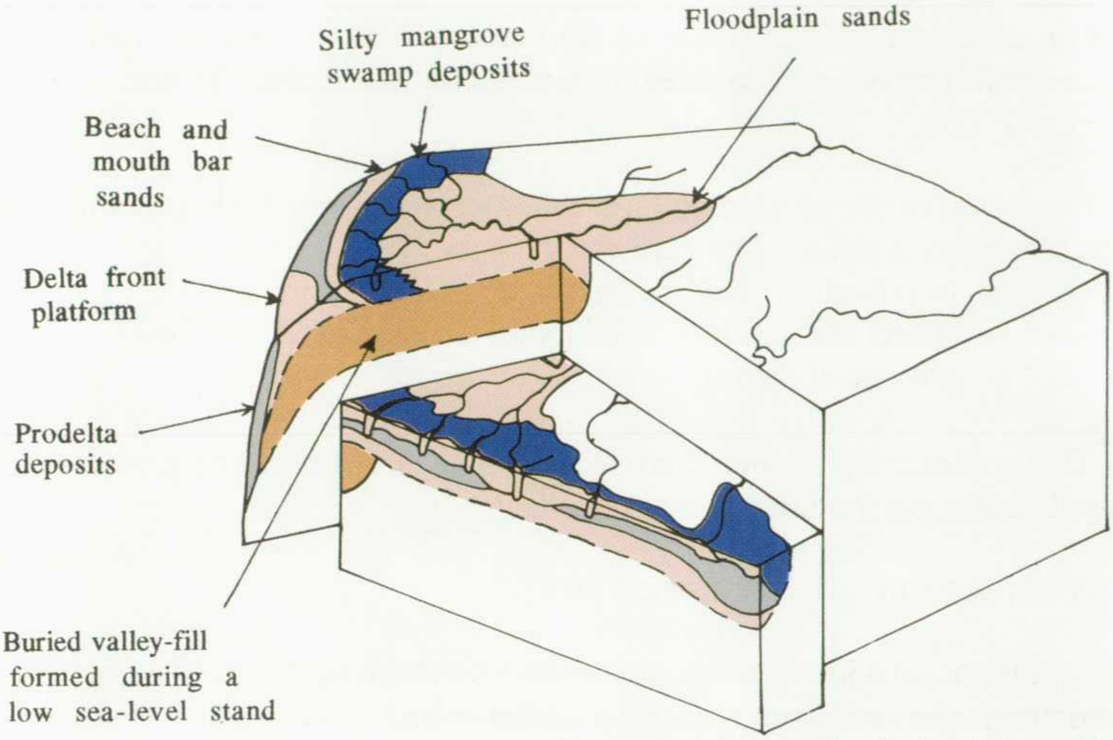
The pre-Holocene history of many of today's large deltas is poorly understood. However, the following sequence of events may have affected many of these deltas:

(1) Glacial lowstand. With much water locked up in the polar ice-caps, sea level was up to 100 m lower than at present. Deltas were left 'high and dry' and dissected by downcutting, rejuvenated fluvial systems. The valleys so formed filled with relatively coarse sediment. Such buried valley-fills may be expected beneath deltas, and are important potential aquifers. In favourable circumstances they may be located by geophysical methods.

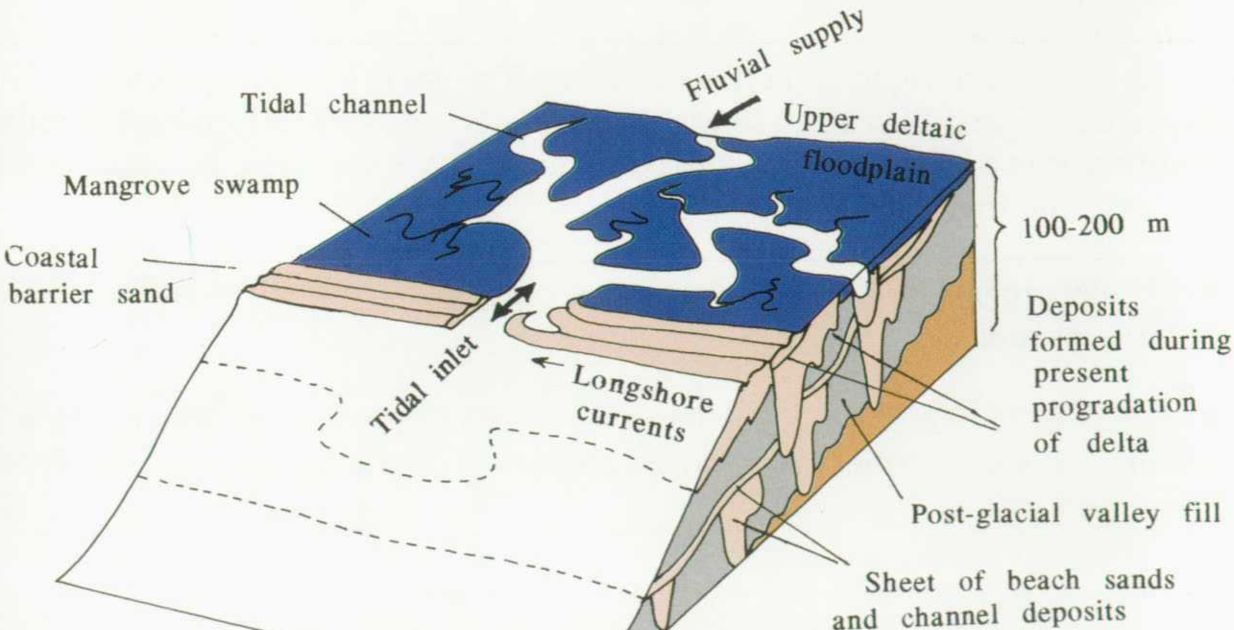
(2) Transgression. The rapid rise in sea level following deglaciation drowns the eroded delta surface. If (relative) subsidence is rapid and sediment input is high, then a 'transgressive' sequence of nearshore deposits overlain by offshore deposits may be preserved (by being buried more quickly than it can be reworked by waves and currents).

(3) Progradation. After sea level has stabilised, the delta will begin to build out once more. The 'transgressive' sequence will be overlain by a 'regressive' or progradational sequence, the characteristics of which will reflect the physical forces controlling the make-up of the delta (see previous pages).

EVOLUTION OF THE NIGER DELTA DURING THE QUATERNARY



Generalised model of the Niger delta (after Allen 1976).



Geometry of the Niger delta deposits resulting from the Holocene transgression and subsequent delta progradation (after Oomkens 1974).

FAN-DELTAS

- Fan-deltas are formed where an alluvial fan meets a body of standing water. They are small to medium-sized features, commonly less than 25 km^2 in subaerial extent.

- Fan-deltas occur adjacent to high-relief terrain, where high-gradient, braided streams flow into a basin. They are common in
  - intermontane lake basins
  - coasts along which subduction occurs (e.g. Cordillera)
  - proglacial settings

- They are coarser-grained than 'normal' deltas, with steeper gradients. They commonly have good aquifer potential.

- A fan-delta may be subdivided into:

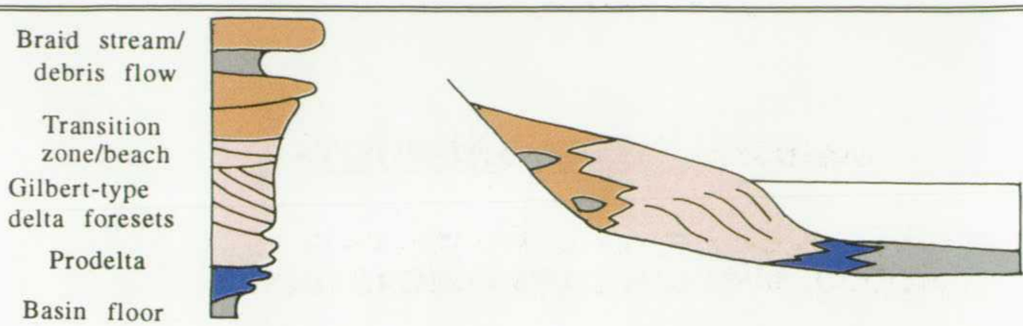
  - a subaerial portion, dominated by fluvial processes, with sediments and structures characteristic of an alluvial fan, which may be semi-arid or humid.

  - a transitional zone, where fluvial processes interact with shoreline processes such as waves and tides. Beach or tidal flat deposits commonly occur in this zone.

  - a subaqueous portion, dominated by gravity settling processes. This may have the well-developed foreset structures typical of a Gilbert-type delta or, where there is a steep submarine slope adjacent to the shoreline, be characterised by slump and mass-flow deposits.

- The progradation of fan-deltas typically gives rise to sequences which coarsen upwards.

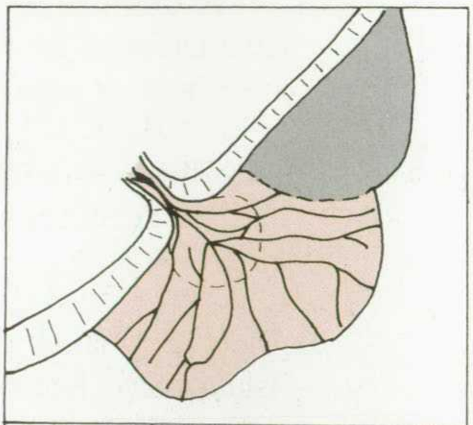
- Fan-deltas are subject to the same kind of response as alluvial fans to tectonically- and climatically-controlled changes in base level, sediment supply and discharge.



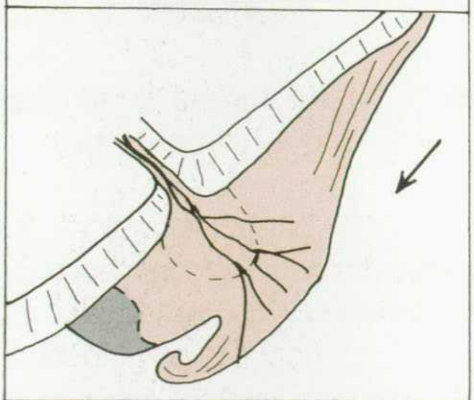
Idealized vertical sequence and longitudinal section through a fan-delta with a Gilbert-type subaqeous portion. Modified from Wescott and Ethridge (1990).

FAN DELTA GEOMETRY

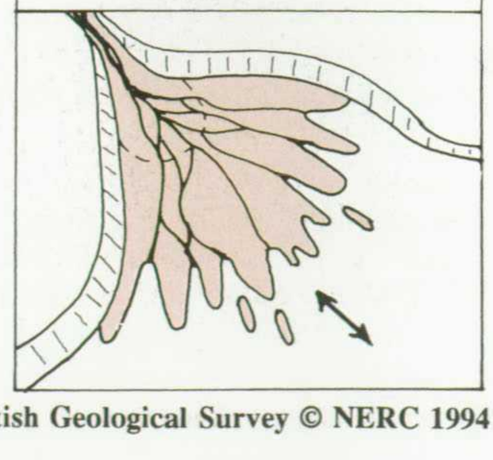
1. ALLUVIAL DOMINANT/ LACUSTRINE TYPE
Alluvial input dominant, fed into lake or microtidal sea. Depositional form builds straight out into water body, largely without modification.



2. WAVE-REWORKED TYPE
Alluvial sediment reworked, mainly by wave action, leading to longshore drift of sediment in prevailing wind direction, and formation of spits, barriers and lagoons.



3. TIDALLY MODIFIED TYPE
Rectilinear tidal currents scour major channels, resulting in an embayed coastline.



COASTAL DEPOSITS

SILICICLASTIC COASTLINES

- Emergent coastline deposits comprise sediments accumulated in the *shore zone*, the high energy-transitional environment between land and sea. Sediment is supplied by longshore transport from river mouths, by onshore transport from the shelf and by local erosion.

- Shoreface sedimentation is governed by the interplay of two major energy sources, waves and tides. Three major categories can be recognised:

  - Wave-dominated coasts (microtidal - tidal range 0-2 m). These are characterised by coast parallel beaches which may be attached to the mainland or separated from them (as barrier islands) by lagoons.

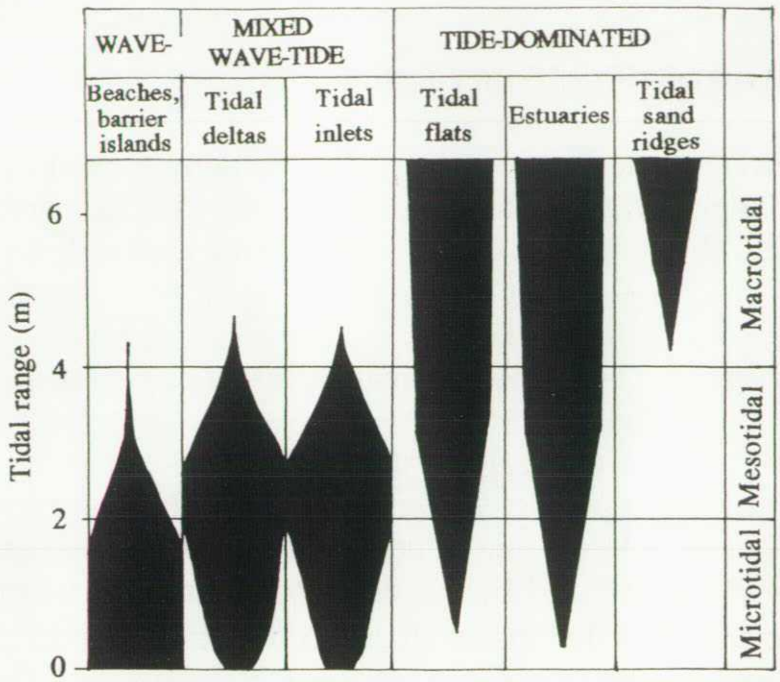
  - Mixed wave- and tide-dominated coasts (mesotidal - tidal range 2-4 m). In these settings, barrier islands are broken up into segments by tidal inlets.

  - Tide-dominated coasts (macrotidal - tidal range >4 m). Barrier islands have been re-oriented into coast-perpendicular tidal sand ridges separated by channels, and the shore is fringed by tidal flats.

- Major controlling factors in determining these categories are the shape of the coastline and the nearshore bathymetry:

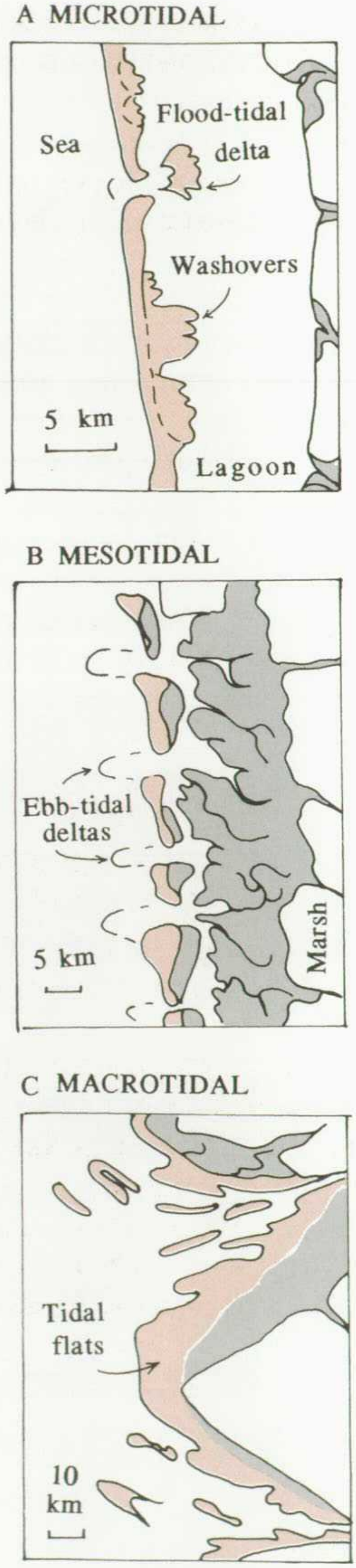
  - Wave energy is greatest along open coastlines, and at headlands, particularly where the shoreline faces narrow or relatively deep shelves. Broad and shallow shelves tend to dissipate wave energy.
  - Tidal range, and thus tidal energy, is magnified in embayments such as estuaries and where shelves are broad and narrow.

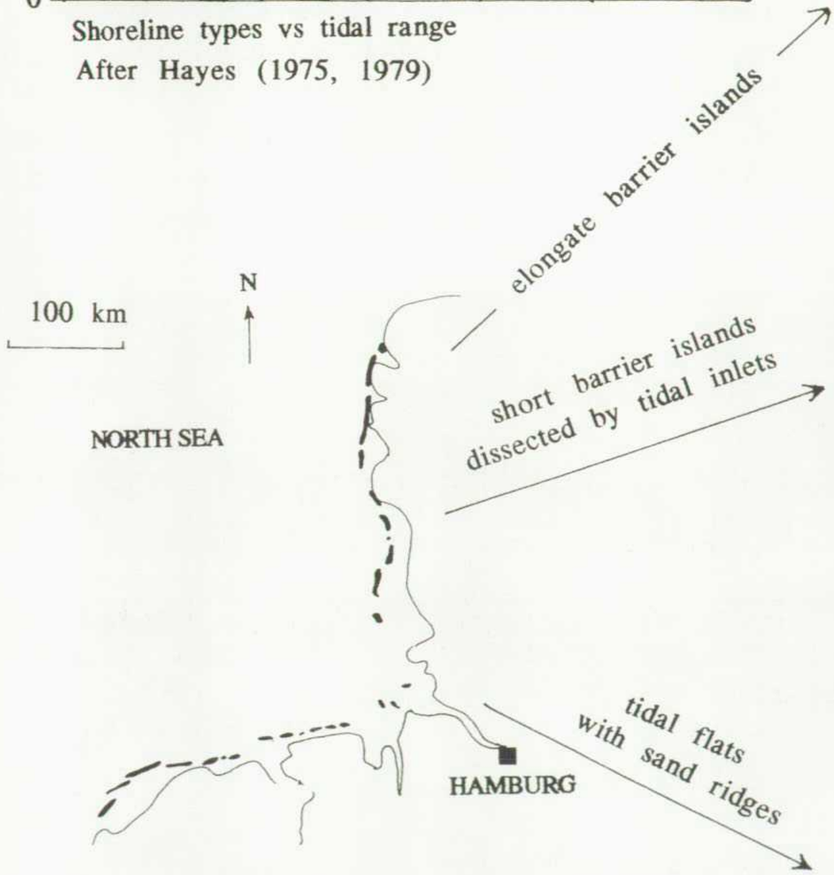
- Shoreline sediments normally include a great deal of well sorted sand and locally gravel and are thus potentially useful aquifers where problems of saline intrusion can be overcome. On arid coastlines, evaporites, also deleterious to groundwater, commonly form.



Shoreline types vs tidal range
After Hayes (1975, 1979)

Shorelines sedimentation is largely controlled by the relative strengths of waves and tidal currents (Barwis & Hayes 1979)





The western European coastline shows a range of morphologies which reflect the tidal range (after Hayes 1975)

Wave-dominated siliciclastic coastlines

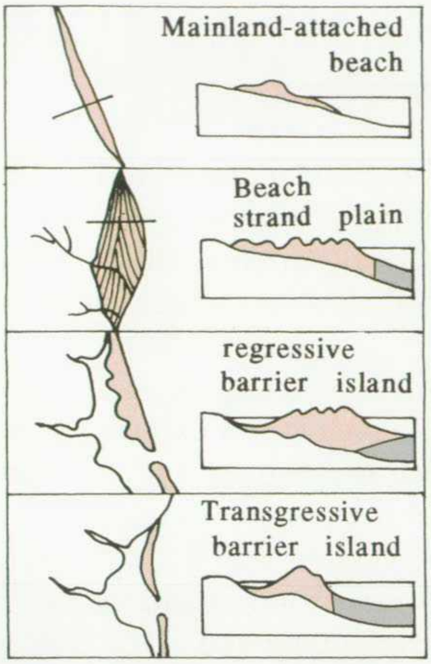
- In microtidal settings, barrier islands and beaches are commonly formed by the transport and sorting of sedimentary grains by wind-driven waves. Sediment is transported along the shoreline (by longshore drift), when waves approach the coast at an angle.

- Barrier island/lagoon systems are present along many present-day coasts.

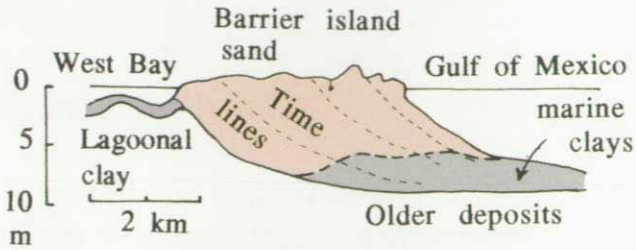
- Beaches commonly have a coarsening-upward structure reflecting the variation in wave energy across the beach profile. Lower shoreface sediments may contain appreciable amounts of mud. Middle and upper shoreface and foreshore (beach face) sediments are powerfully affected by waves, rip currents and swash and backwash processes. They are often dominated by sands and gravels.

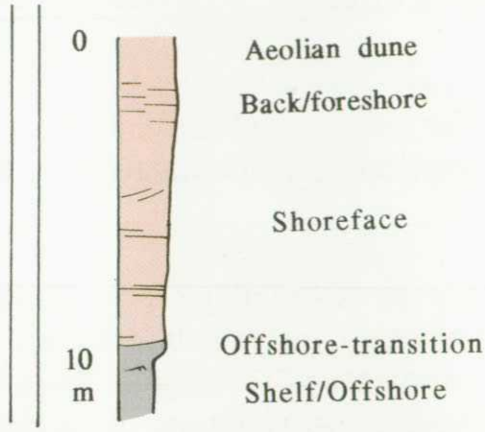
- Present-day beaches have formed since the rise in sea level following the end of the last glaciation. Thus they commonly overlie an eroded transgressive surface. Where sediment supply has been abundant, a succession of parallel beach ridges may have built out (prograded). The lateral stacking of these beach ridges can form a sheet of well-sorted sediment which is potentially an excellent aquifer.

A microtidal beach, St. Elena Peninsula, Costa Rica.

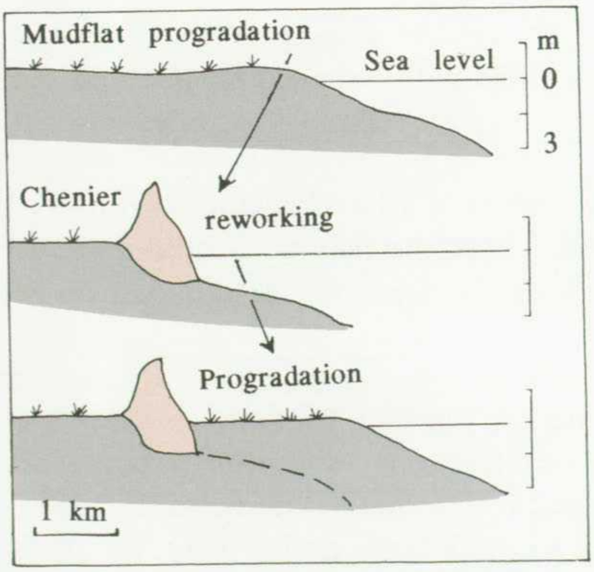


The formation of beaches and barrier islands results from the interaction of coastal morphology and wave action (after Reinson in Walker 1984).

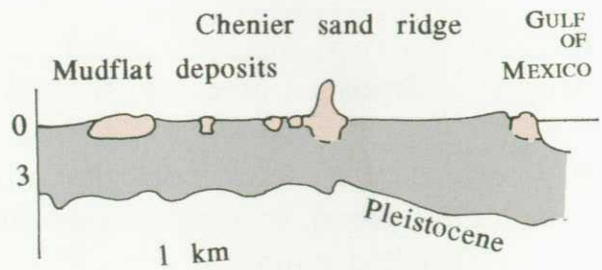




Seaward migration (progradation) of a beach or barrier island produces a sheet of sand with a coarsening-up trend, as in this example from Galveston Island, Texas (after Bernard et al. 1962; McCubbin 1982).



Chenier formation by alternating mudflat progradation and wave reworking (after Hoyt, 1969).



Cross-section through the Louisiana chenier plain (after Gould & McFarlan 1959).

On coastlines where there is an abundant mud supply cheniers can form. These are long, isolated bodies of sand within a mud plain. The sand bodies form where there is a reduction in mud supply, allowing waves to rework the plain.

Tide-dominated siliciclastic coastlines

- Coastal embayments and estuaries in areas of high tidal range are important areas of sediment accumulation at the present day.
These embayments, which funnel and enhance the tidal currents, are commonly fringed by extensive tidal flats and contain clusters of tidal sand ridges near their axes.

- They can be subdivided into a subtidal zone, which is not exposed even at low water, and an intertidal zone, the area between the highest and the lowest tides.

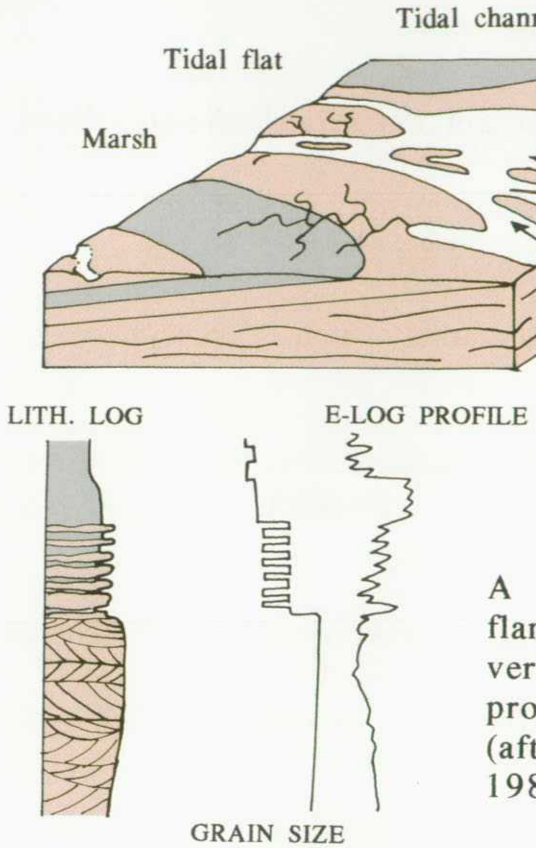
- The basic building blocks of tidal regions are tidal channels and intervening bars or shoals. In the subtidal zone, both are entirely submerged. The bars and shoals progressively emerge at low tide on moving up through the intertidal zone, to become plains which are dissected by networks of tidal channels and creeks.

- During flood periods tidal waters enter the channels, overtop the banks and inundate the adjacent flats. At high tide there is a period of stillstand, allowing fine muds to be deposited; then during the ebb phase the tidal waters drain via the channels and re-expose the flats.

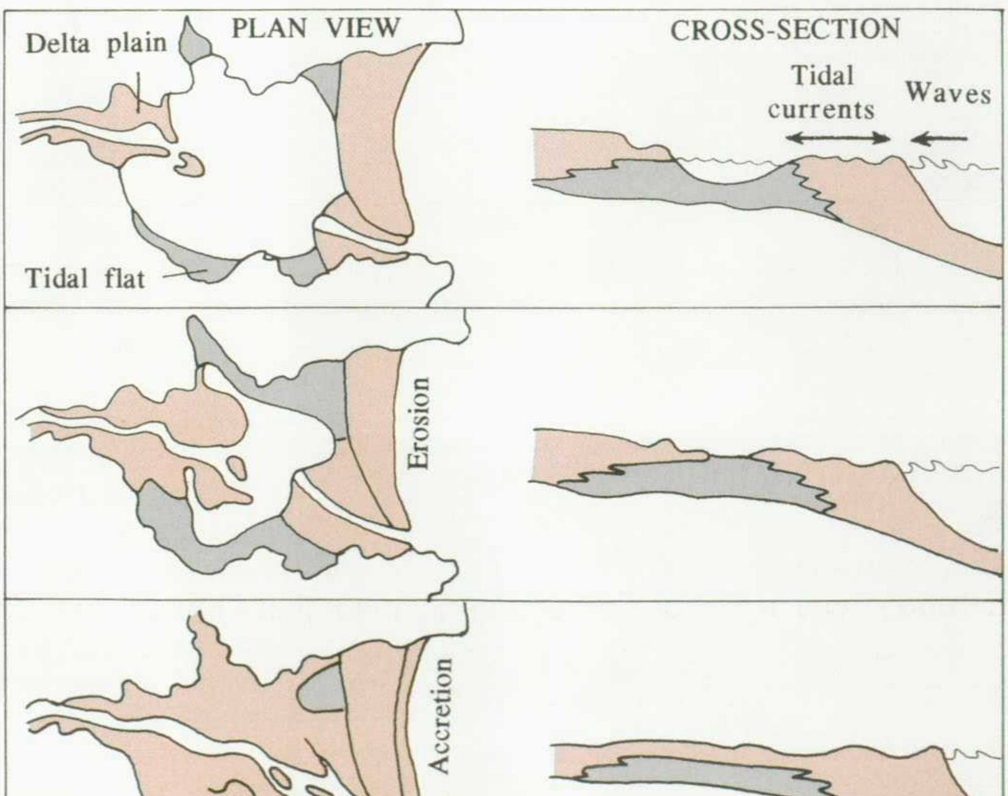
- As in rivers, coarser material is mostly held within the channels, while finer material is deposited over the intertidal flats during overbank flooding.

- Intertidal channels normally migrate laterally (thus behaving similarly to meandering rivers), eroding into the intertidal flats and leaving behind a sheet of laterally stacked point bar deposits. Much of the area of the flats can be thus reworked.

- Tidal currents progressively lose energy, through friction, as they travel landwards, and they carry successively finer fractions of sediment landward. Where there is a range of grain sizes available, intertidal flats normally show a landward fining sequence from sand flats to mud flats, giving way yet further inland to salt marshes. As an intertidal zone builds out (progrades), they form an overall fining-upwards sequence, though this trend is complicated by the presence of the tidal channel deposits.



A macrotidal estuary and flanking tidal marsh, and the vertical sequence formed by progradation of the coast (after Galloway and Hobday 1983).



Stages in the infilling of an idealised tidal estuary (after Roy *et al.* 1980)

Mixed wave- and tide-dominated siliciclastic coastlines

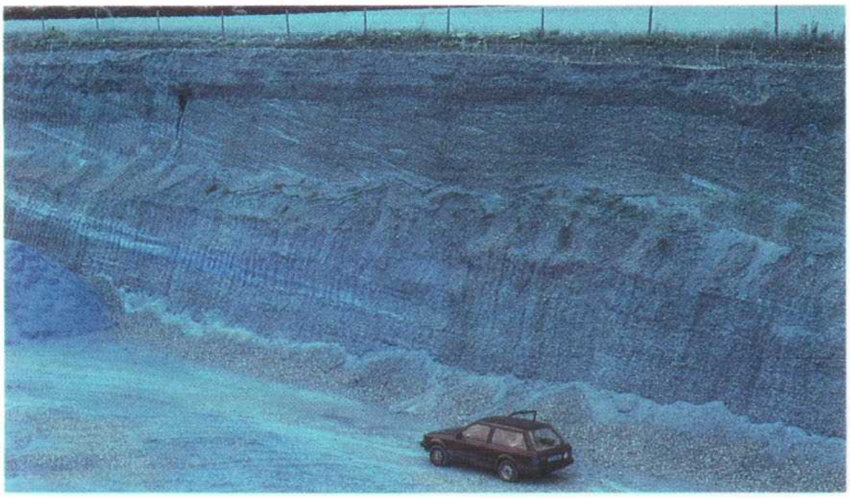
- These are characteristic of mesotidal settings, and share features of both wave-and tide-dominated coastlines.

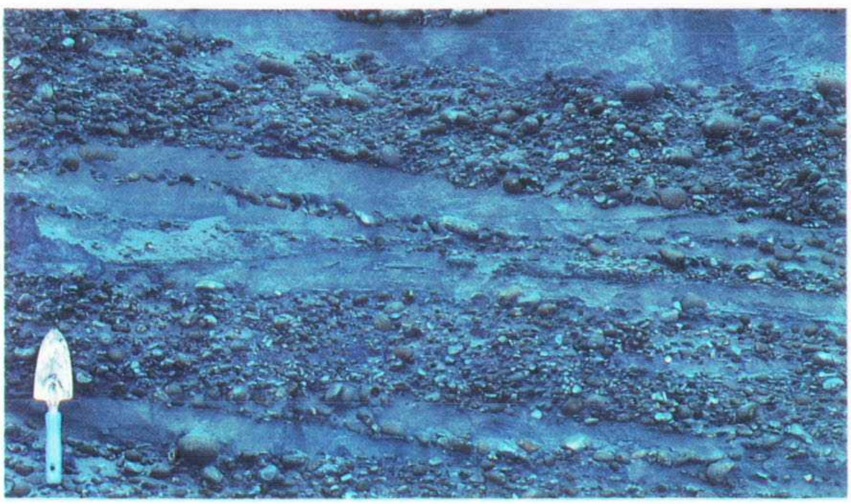
- Normally they have a seawards facies which is wave-affected, i.e. barrier beaches of well-sorted sand.

- These are dissected by tidal currents. Sand reworked from the barrier forms accumulations of sand (flood tidal and ebb tidal deltas) landward and seaward of the inlet.

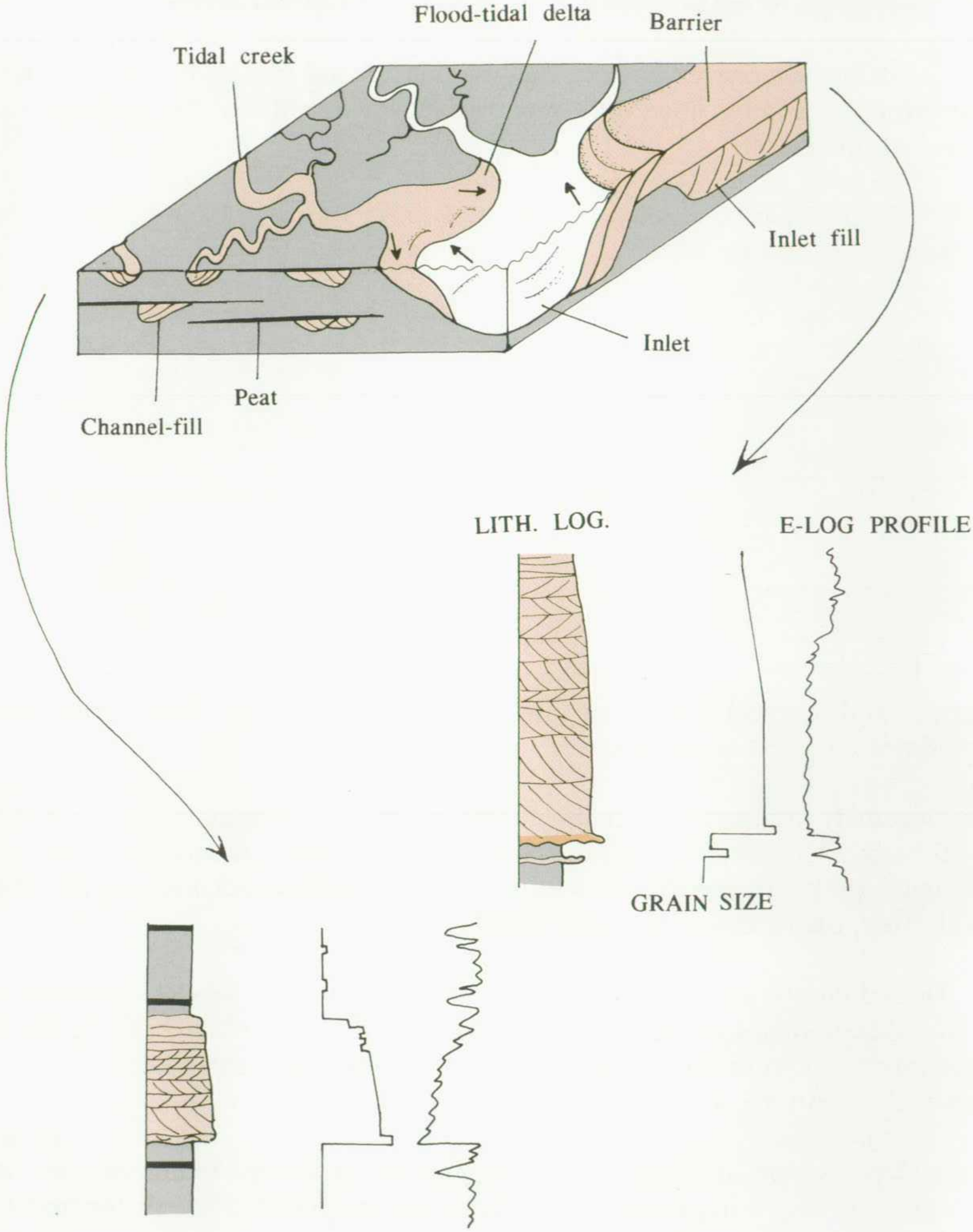
- The tidal inlets migrate laterally and rework much of the barriers.

- Landward of the beach barrier system, tidal creek/tidal flat systems show a landwards fining trend.





This preserved Plio-Pleistocene gravel beach in eastern England probably formed in a meso- or macrotidal setting. Wave action was the dominant sedimentary process, probably because the deposit was laid down on a promontory or headland. Such well-sorted coarse-grained deposits have excellent aquifer potential. They are likely, though, to be associated with less permeable sands and muds which formed in more sheltered, adjacent positions within a mesotidal coastal system.



Idealized mesotidal barrier/tidal inlet, and characteristic vertical sequences produced (after Galloway & Hobday 1983, Barwis & Hayes 1979).

CARBONATE-EVAPORITE COASTLINES

- Shallow marine carbonates may be detrital and similar to their siliciclastic counterparts. Many, however, were laid down essentially by biogenic and/or chemical processes.

- Shallow marine carbonates tend to form in warm water in the photic zone, in 'subtidal carbonate factories' at low latitudes.

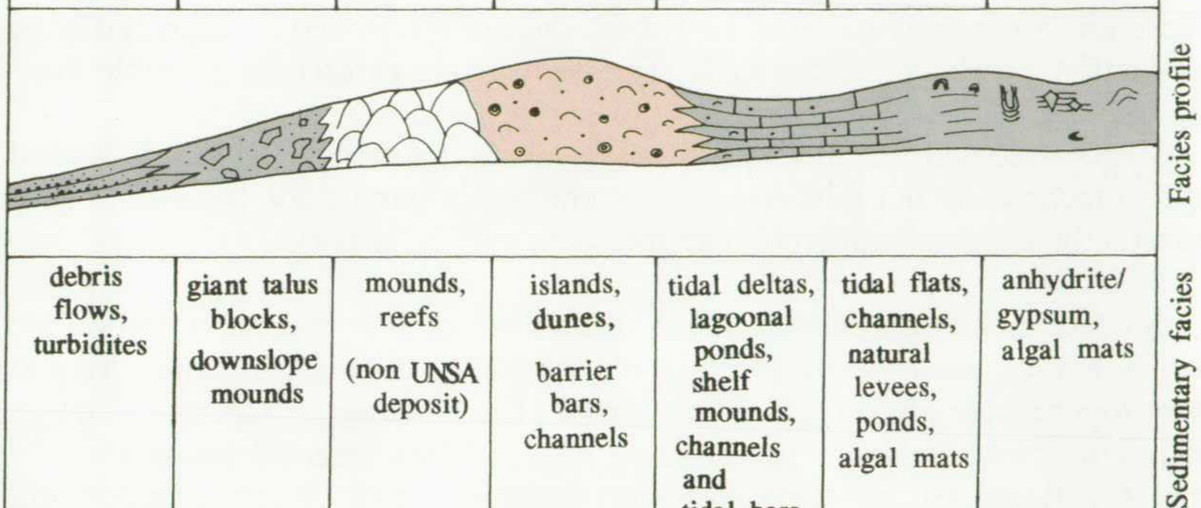
Supra- and intertidal zones at low latitudes on protected, meso- to macrotidal coastlines include two main types:

1. Extremely arid, very hot areas. Intertidal areas are dominated by stromatolitic algal mats. On supratidal areas (sabkhas) evaporation dominates. Porewaters become highly saline; evaporites form and dolomitization occurs. e.g. the Persian Gulf coast, Shark Bay in western Australia.

2. Humid coastlines, often with highly seasonal rainfall, develop extensive tidal flats and supratidal marshes. These are dominated by bioturbated sub- to intertidal lime-muds and laminated carbonate mud supratidal algal marsh deposits. e.g. the west side of Andros Island (Bahamas), Florida.

Both deposits are dominated by fine-grained sediment, which is commonly indurated through early cementation. They are unsuitable locations for freshwater aquifers.

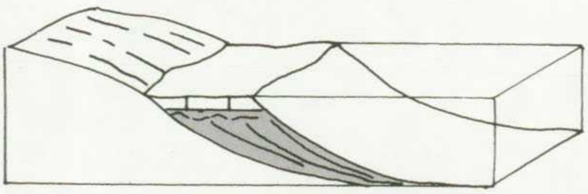
					Inter/supratidal zones	
DEEP SHELF MARGIN	FORESLOPE	ORGANIC BUILD-UP	WINNOWED EDGE SANDS	LAGOON	TIDAL FLATS	SABKHAS/ SUPRATIDAL MARSH
debris flows, turbidites	giant talus blocks, downslope mounds	mounds, reefs (non UNSA deposit)	islands, dunes, barrier bars, channels	tidal deltas, lagoonal ponds, shelf mounds, channels and tidal bars	tidal flats, channels, natural levees, ponds, algal mats	anhydrite/ gypsum, algal mats



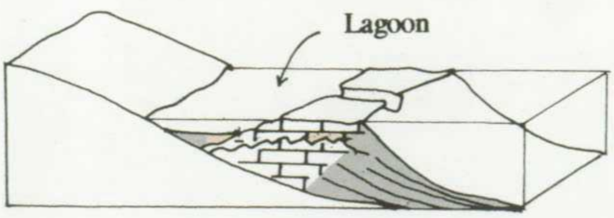
Idealised section through a carbonate/evaporite coastline showing complete development of facies belts (after Wilson 1975).

REEF MORPHOLOGY AND GEOMETRY

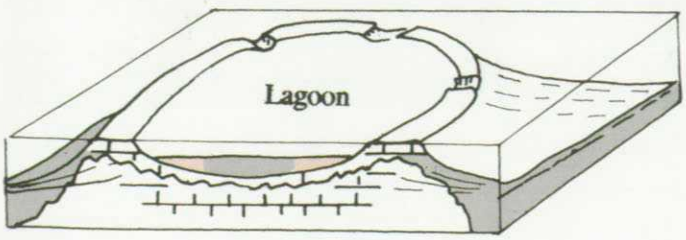
The three main types of present-day reefs (after Selley 1985).



FRINGING REEF:
Indurated (non-UNSA) reef limestones and fine foreslope deposits.



BARRIER REEF:
Lagoon often contains sorted bioclastic carbonates (UNSAs) of sand to mud grade.



ATOLL:
Circular development of sorted bioclastic carbonates (UNSAs) within a ring of reef limestone.

Carbonate platforms

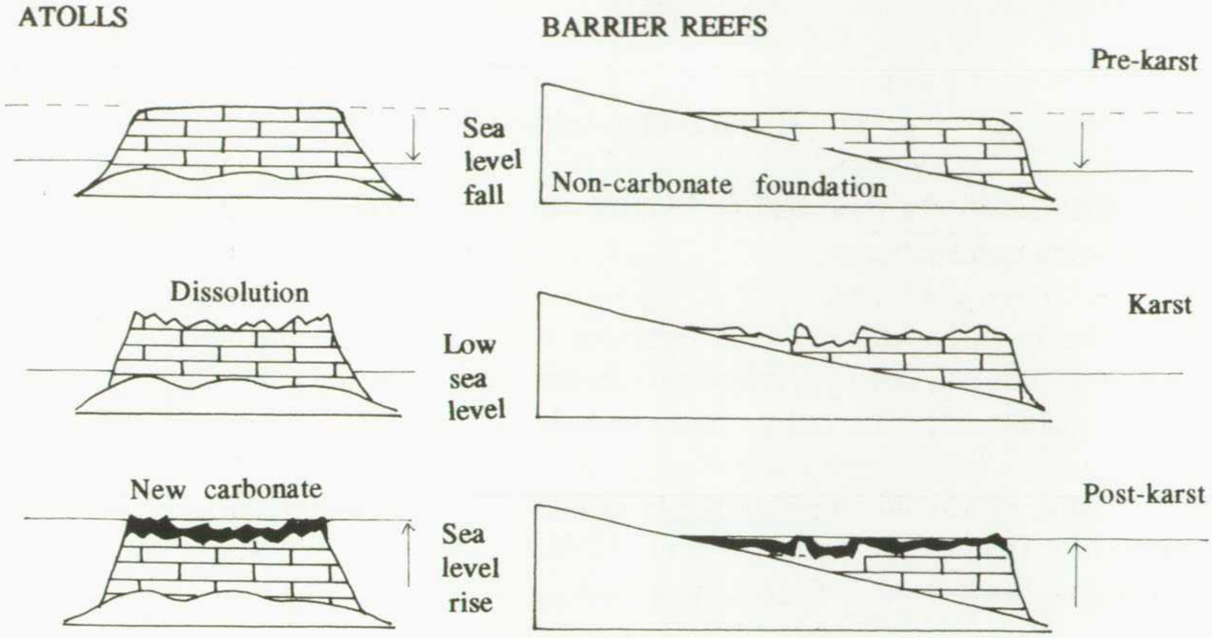
These are warm, subtidal shallow-water zones characterised by high carbonate production ('carbonate factories'). The deposits are essentially divisible into:

1. **Reefs**: skeletal features with a wave-resistant structure (largely indurated and so technically not UNSAs). These are highly porous and permeable and commonly are good aquifers. The reef core may be massive.

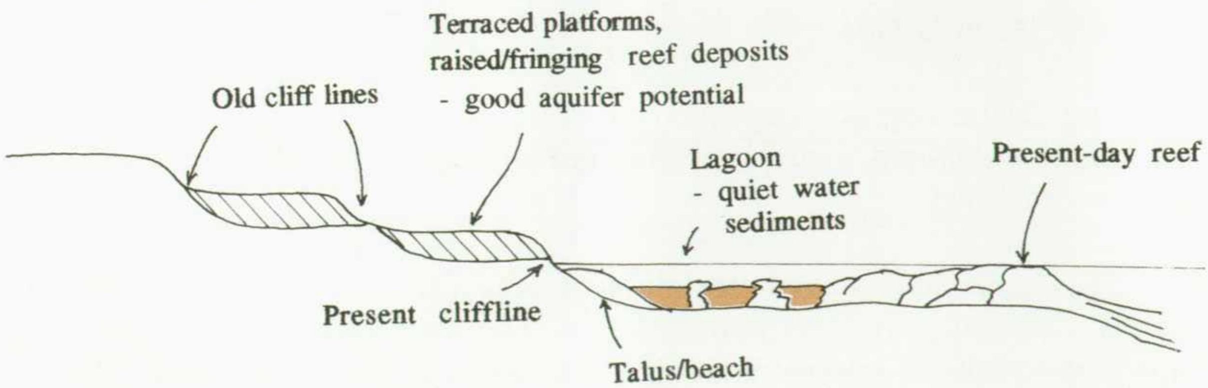
2. **Sorted carbonate debris**: these accumulate in inter-reef areas and on reef flanks, largely being derived from wave-erosion of the reef structure. May also form topographic highs (e.g. oolite shoals) or in channels or lagoons. The grain size varies from carbonate sand to lime muds. Many recent deposits are UNSAs. Being less resistant to erosion than reefs, their preservation potential is low once emergent.

Small but locally important volumes of groundwater are abstracted from groundwater lenses within carbonate shoreline deposits occurring on small islands within the Caribbean and Pacific areas.

A coarse-grained skeletal carbonate beach gravel. Deposits of this type have good aquifer potential. Netherlands Antilles.



EFFECTS OF FLUCTUATING SEA LEVEL ON REEF DEPOSITS (after Purdy 1974).



EMERGENT CARBONATE COASTLINES
e.g coastline of Netherlands Antilles

VOLCANIC DEPOSITS

GENERAL & CLASSIFICATION

- Volcanoes are found along extensional and compressional plate boundaries and at intra-plate hotspots.

- The location and eruptive styles of volcanoes are controlled by the earth's internal dynamics, not by surface processes; therefore they intersect, modify and control surface depositional patterns.

- Some products are indurated (e.g. lava flows, welded tuffs). However, they commonly occur as layers within UNSAs and are important modifiers of hydrological behaviour. Therefore the whole volcanic spectrum is considered here.

- Volcanic products may be an important component in many UNSA-forming environments, notably in lacustrine, alluvial and shallow marine systems. Aquifers within volcanic sequences are important sources of groundwater on islands such as Hawaii; however, their complex geometry makes prediction difficult, and yields tend to be variable.

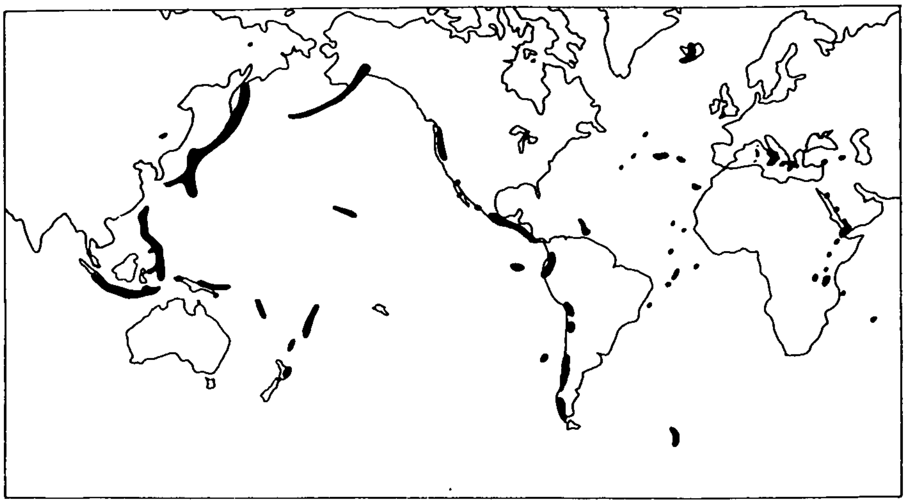
- Volcanoes emit two principal products from gas-charged magma:

    Lava flows (liquid, commonly with gas held within vesicles, cooling to a solid).

    Pyroclastic deposits (clastic deposits of disrupted magma generally termed *tuffs*)

- Pyroclastic deposits deposited on steep slopes are inherently unstable. If they become saturated with water they are commonly remobilised downslope as mudflows *(lahars).*

- The lateral extent and thickness of lava flows is variable - composition controls variability in flow morphology. They are commonly lobate, tongue-shaped, up to tens of kilometres long and hundred of kilometres thick. They may be derived either from volcanic vents or from rifts/fissures. The main parts of many lava flows are solid and impermeable. However, water movement along brecciated tops and bases and fractures means that some can be useful aquifers.



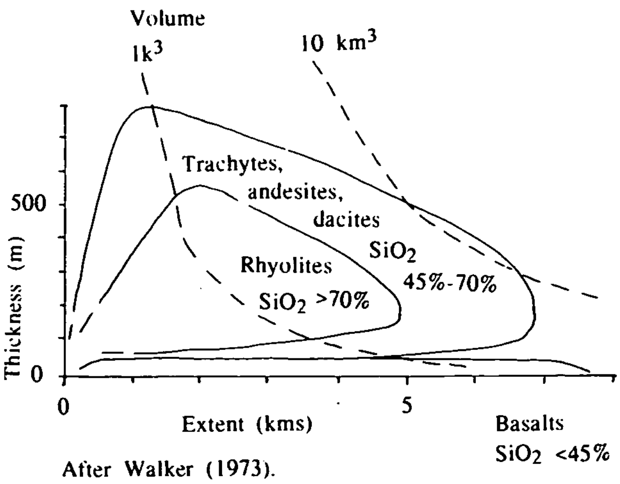
Distribution of active volcanoes. Simplified after Williams & McBirney (1979).

LAVA FLOWS

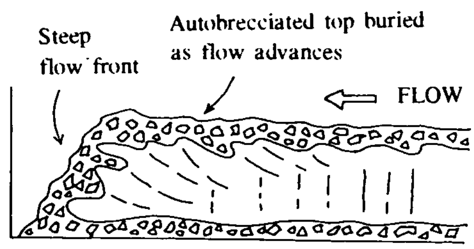
Composition of the erupted magma exerts a primary control on the geometry of lava flows. Basic flows with low SiO_2 content have low viscosity and spread to form relatively thin and extensive sheets. Intermediate and acidic lavas are often highly viscous and tend to form thick flows close to the point of eruption. Hence basaltic lavas are more likely to extend away from source and be interbedded with fluvial and lacustrine facies (after Walker 1973).

Many lava flows develop an autobrecciated surface layer which is progressively bulldozed beneath the flow as it advances. This tends to produce a relatively permeable blocky top and base to many lavas. Weathered palaeosols developed on many lavas may also form relatively permeable layers within lava sequences.

Where lava flows enter water bodies they may produce fragmented breccias termed hyaloclastites. These are likely to form permeable lateral extensions of marine/lacustrine lava flows.



After Walker (1973).



PYROCLASTIC DEPOSITS

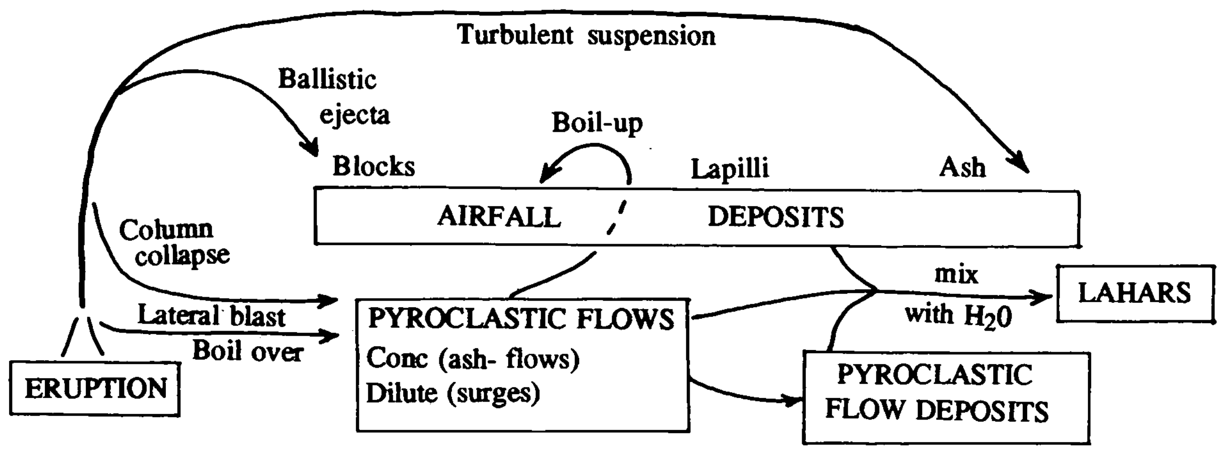
Three principal types of pyroclastic deposits with distinct character, grain-size and geometry may be identified; these, though, may be closely related:

Airfall tuffs: ballistically ejected tephra; generally well-sorted. Marked decrease in thickness and grain size (blocks>lapilli>ash> dust) away from vent. Distribution controlled by ejection mechanics and wind patterns. May cover very wide areas as thin (cm-scale) ash layers producing blanketing layers, tending to alter to clay minerals (producing thin barriers). Potentially present in most environments. Most non-welded.

Surge deposits: produced by entrainment and deposition of loose fragments by the high-velocity evacuation (shock) wave of a volcanic explosion. Deposition of fragments from low-density gas/fragment turbulent mixture results in dune-like bedforms and planar laminated beds. Individual sheets are up to a few metres thick, thinning over highs. Most non-welded. May cover wide areas.

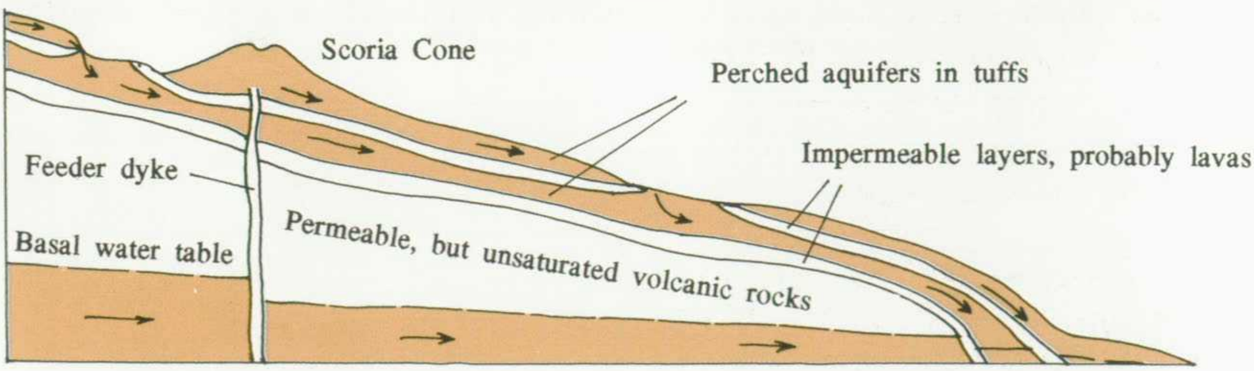
Ashflow tuffs: produced by several mechanisms (e.g. column collapse, lateral blast, boil-over). Deposited from high density gas/fragment gravity flows. They follow topographic lows, commonly plugging valleys. Individual flow deposits can be tens of metres thick up to 100 km from source. Can be welded (aquiclude) or non-welded (possible aquifer) or both depending on temperature of eruption and burial history. Commonly associated with acid-intermediate stratovolcanoes and the process of caldera collapse. Also known as ignimbrites, nuée ardente deposits.

Processes by which subaerial pyroclastic flow and fallout deposits originate are complex and closely inter-related:



Adapted from Fischer & Schminke (1984).

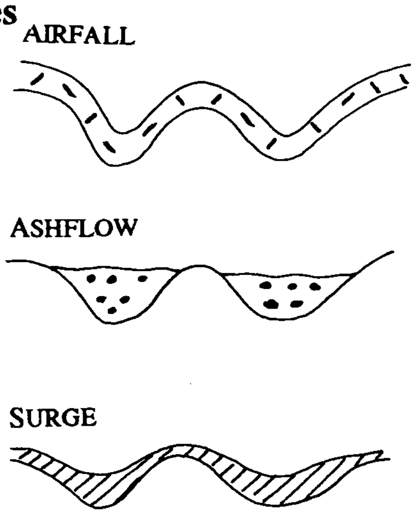
Miravalles volcano, Costa Rica.



Diagrammatic cross-section through a volcano on Fiji, showing hydrogeological units (after Woodhall in Gale & Booth, 1991).

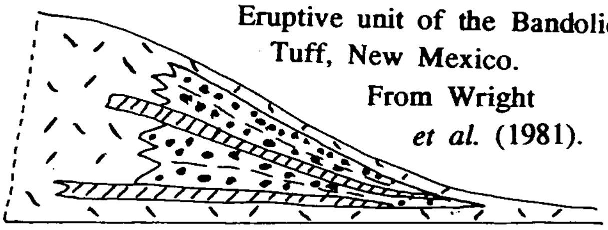
Geometry and inter-relations of pyroclastic types

The members of the pyroclastic spectrum can be characterised by their geometry. Airfall deposits are well-stratified and blanket the surface. Ashflow deposits are channelled into valleys since they are high-density gravity-driven flows; they are commonly massively bedded or unbedded. Surge deposits have an intermediate form, tending to occur as continuous sheets but thickening into topographic lows; they often exhibit cross- and horizontal lamination.



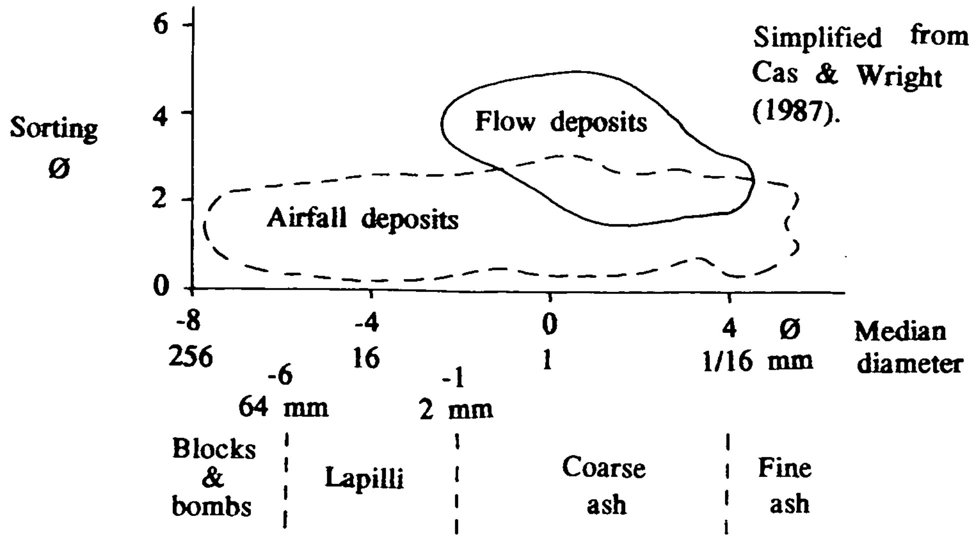
After Wright *et al.* (1980)

The complex mechanics of a single eruption can lead to extremely complex interbedding and lateral variation between distinct pyroclastic deposits; interbedding with other deposits produces even more complex patterns.



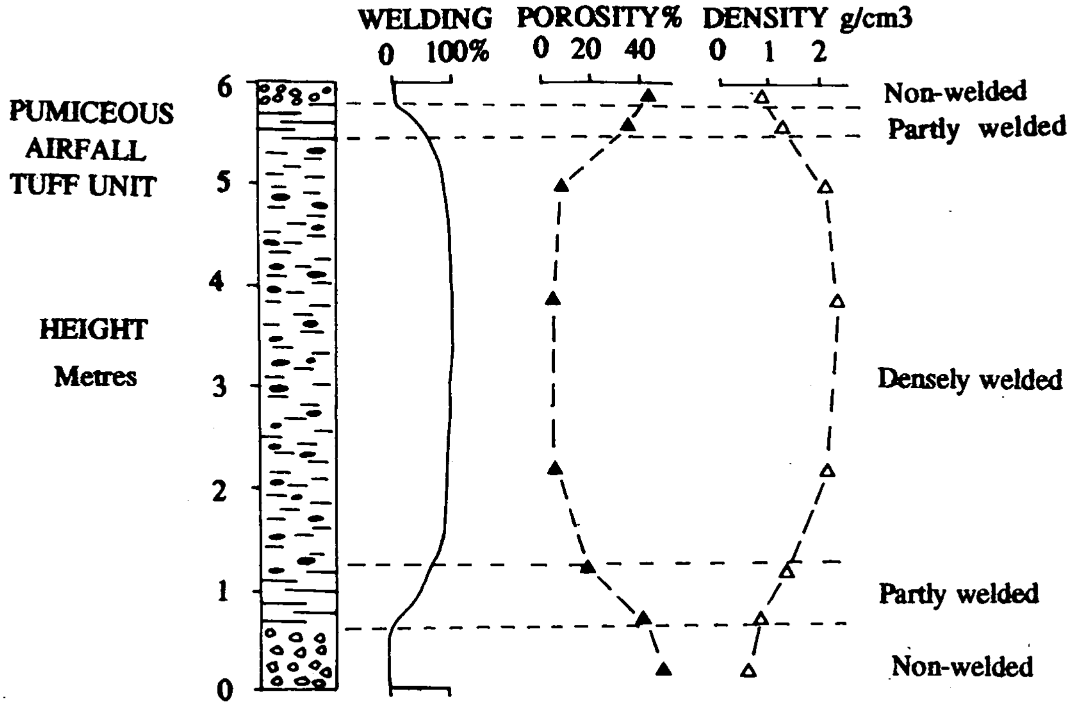
Eruptive unit of the Bandolier Tuff, New Mexico. From Wright *et al.* (1981).

Pyroclastic flows tend to produce lapilli and ash-deposits with moderately poor sorting. Pyroclastic falls produce better sorted deposits; any grain size is possible from blocks to fine ash; marked thinning and fining of deposits occurs with increasing distance from the vent.



Simplified from Cas & Wright (1987).

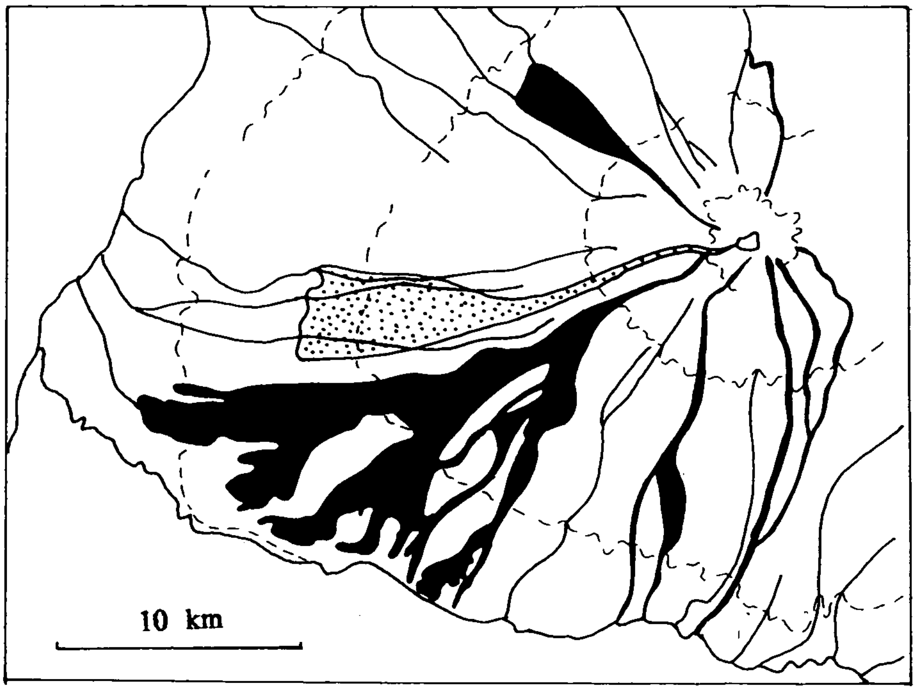
Effects of welding



Simplified from Sparks & Wright (1979).

Pyroclastic deposits show all degrees of welding from those deposits erupted at high temperatures and subsequently buried and compacted to form totally welded glassy rocks to unwelded, low-temperature deposits where the fragments retain their individual identity. Most airfall deposits, where fragments cool rapidly when ejected ballistically through the air, are unwelded. The figure shows the very variable degree of welding and therefore porosity that can occur even in, in this case, a thin airfall unit produced by a single eruptive event. Such variations lead to very complex patterns of groundwater storage and movement.

LAHARS



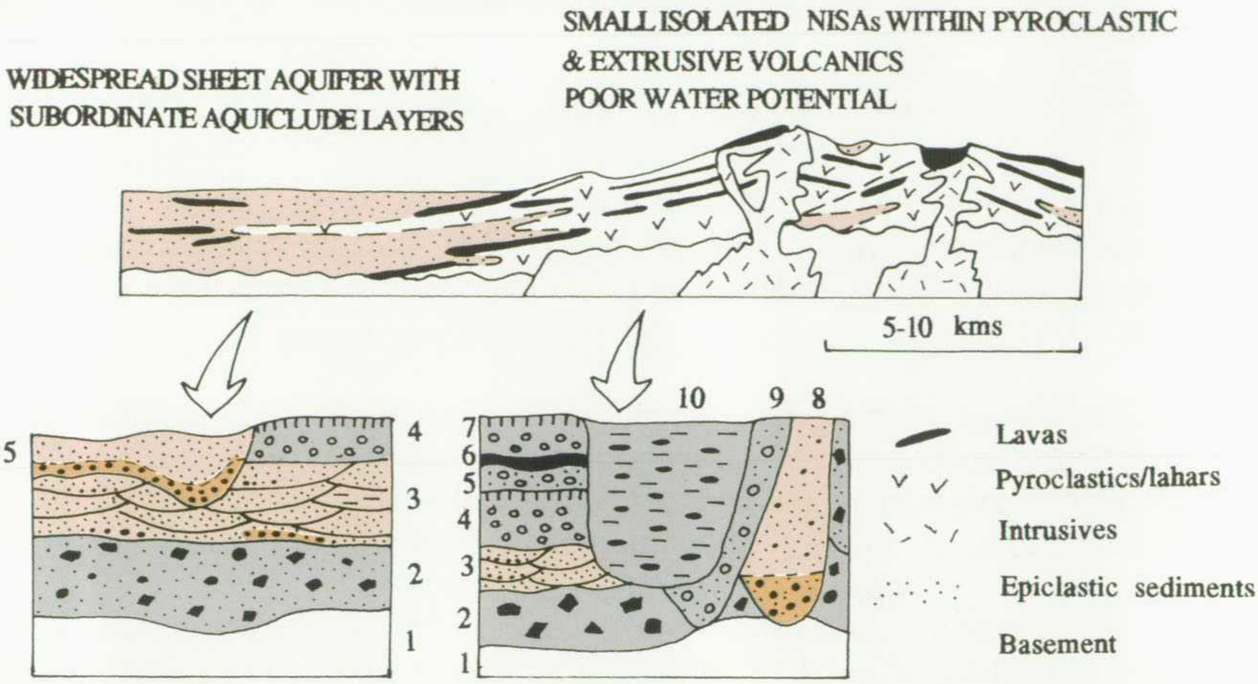
Lahars from the crater lake of Kloet (Kelut) Volcano, Java. 1919 flow shown in black; older lahars stippled. Contours in metres. After G L L Kemmerling.

- Lahars are generally low-temperature gravity-driven debris-flows generated within the volcanic environment. They flow downhill along drainage lines and spread out at the foot of the slope. Characteristically a few metres thick, they are very poorly sorted with massive boulders set in a clay-silt matrix. Commonly triggered by heavy rainfall and/or earthquakes on steep unconsolidated ash-covered slopes of volcanoes, they feed into the drainage system.

- Lahars are lobate in shape and commonly form valley-fills. They are very poorly sorted, normally with a high fines content; thus in general they are aquicludes.

VOLCANIC FACIES MODELS - INTEGRATED MODELS AND TECTONIC RELATIONS

a) Arc/Cordilleran setting, dominated by calc-alkaline acid-intermediate pyroclastics and intermediate-basic flows. Activity cyclic; caldera collapse common.

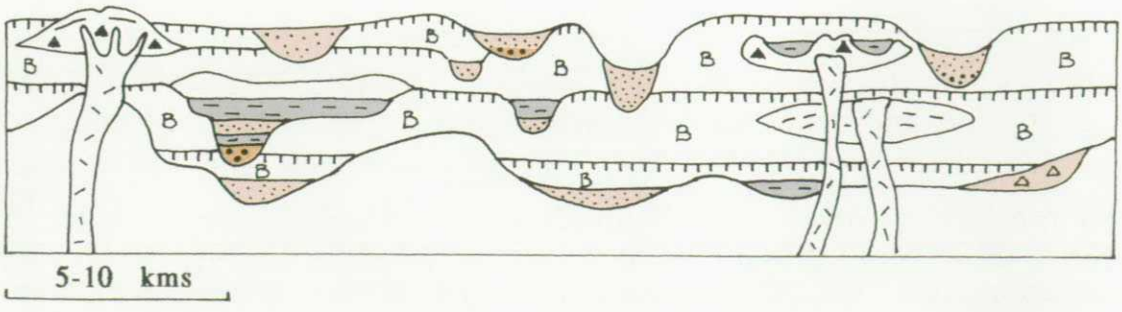


1 Basement
2 Lahar
3 Epiclastic Fluvial -lacustrine deposits
4 Airfall tuff
5 Fluvial channel

1 Basement
2 Lahar
3 Fluvial deposit
4 Airfall with palaeosol
5 Airfall
6 Lava
7 Pyroclastic flow

Box canyon infills:
8 Fluvial channel-fill
9 Non-welded tuff: flow
10 Welded tuff: flow

b) Continental flood basalt 'trap' terrain; extrusive low-viscosity basic lavas with subordinate pyroclastic and phreomagmatic deposits. NISAs are small perched and confined aquifers (channel and basin infills) within lava sequence.



Basement
Fluvial channel infill
Lacustrine deposits
Alluvial fan
Soil horizon
B Basalt lava
Intrusive rocks
Lava shield
Pyroclastic cinder cone/tuff ring

After Cas & Wright (1987).

GLACIAL DEPOSITS

ICE-SHEETS IN TIME AND SPACE

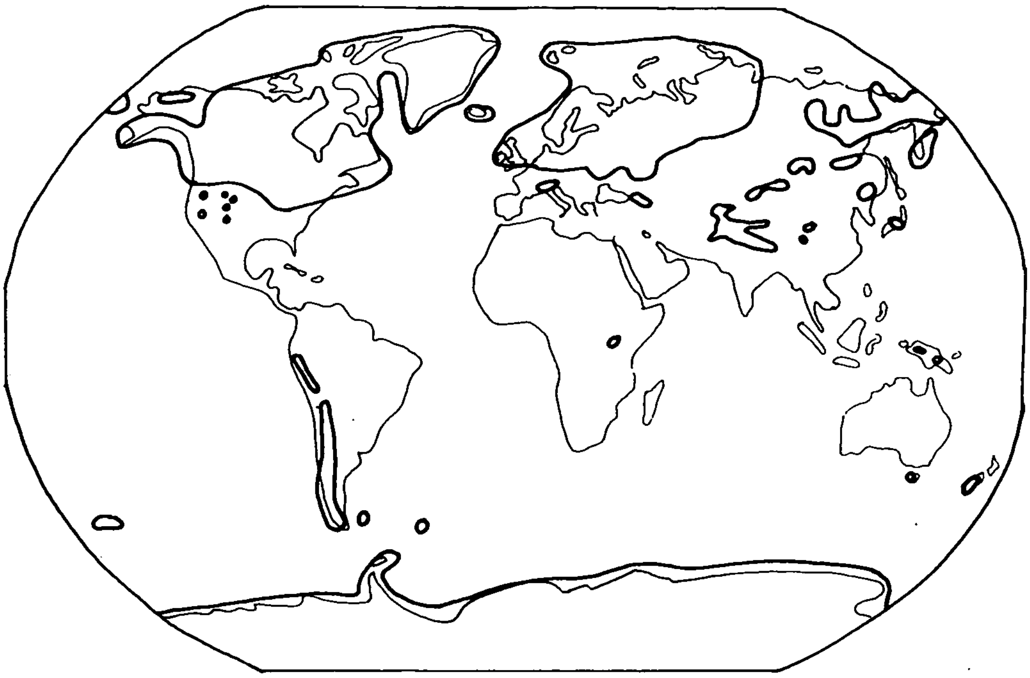
- Glaciation is one of the hallmarks of our fluctuating climate since late Neogene-Quaternary times. This 'ice-house' state, though, is not unique in the geological record, with widespread glaciations reported from past geological periods.

- The causes of glaciation remain poorly understood, although the global distribution of continents and oceans probably exerts a major influence. Within glaciations, the regular glacial-interglacial oscillations are probably driven by systematic variations in the earth's rotation and orbit around the sun.

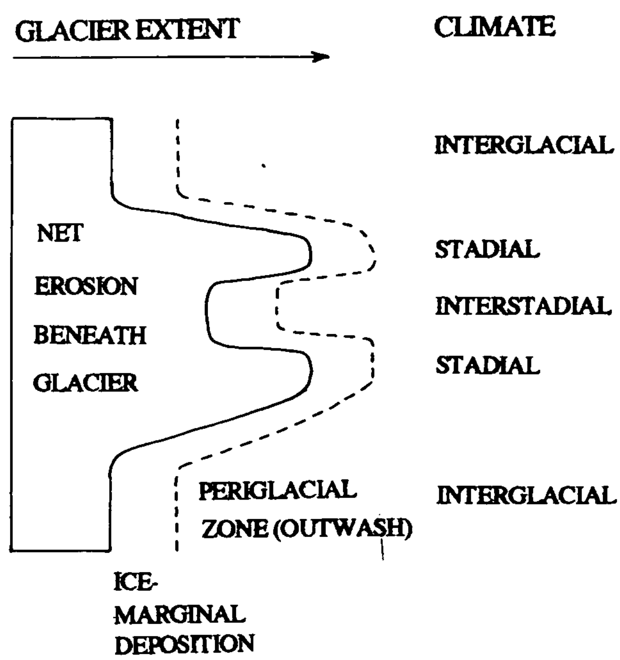
- The earth did not get uniformly colder during glacial phases of the Quaternary. The cold polar climatic areas expanded, but the tropical regions did not diminish greatly in size. Between these two zones, the temperate climatic zones of the earth were compressed and pushed towards lower latitudes.

- During the coldest phases of the Quaternary, ice extended to cover much of North America and northern Europe and Asia. The Antarctic ice-sheet covering the southern polar area, isolated from other land-masses, was not greatly different from its present extent. Between the two major polar expanses numerous smaller ice-caps grew on major mountain chains such as the Alps, Andes and Himalayas. Close to the equator, glaciation was restricted to the highest peaks (e.g. Mt. Kenya and Kilimanjaro in E Africa).

- The fluctuating Quaternary climate has resulted in the alternate expansion and decay of polar ice-sheets, perhaps 20 times or more. This resulted in shifting zones of erosion and deposition of glacially transported sediment through time. At high latitudes, ice-cover has been almost continuous, and has resulted in prolonged erosion. At mid-latitudes, ice-cover has been intermittent, though complex sequences of glacial deposits figure prominently in the Quaternary sedimentary record. This shifting zonal pattern of erosion and deposition applies equally, but on a different scale, to smaller ice-caps and valley glaciers.



Areas of the world intermittently subjected to glaciation.



Shifting of facies zones during glacial/interglacial cycles. Simplified from Boulton & Jones (1979).

GLACIGENIC DEPOSITS

- Glacigenic deposits are of two main kinds:

  - Ice-transported sediments, i.e. *tills*. These are commonly unsorted mixtures (diamicts) of all grain sizes from clay to boulders. Tills may be deposited by flow (supraglacial debris flows), by meltout (englacial and subglacial passive deposition), by lodgement (subglacial frictional retardation) or by deformation (subglacial disturbance of any of the other three types). All of these normally have low permeabilities and so tend to be aquicludes.

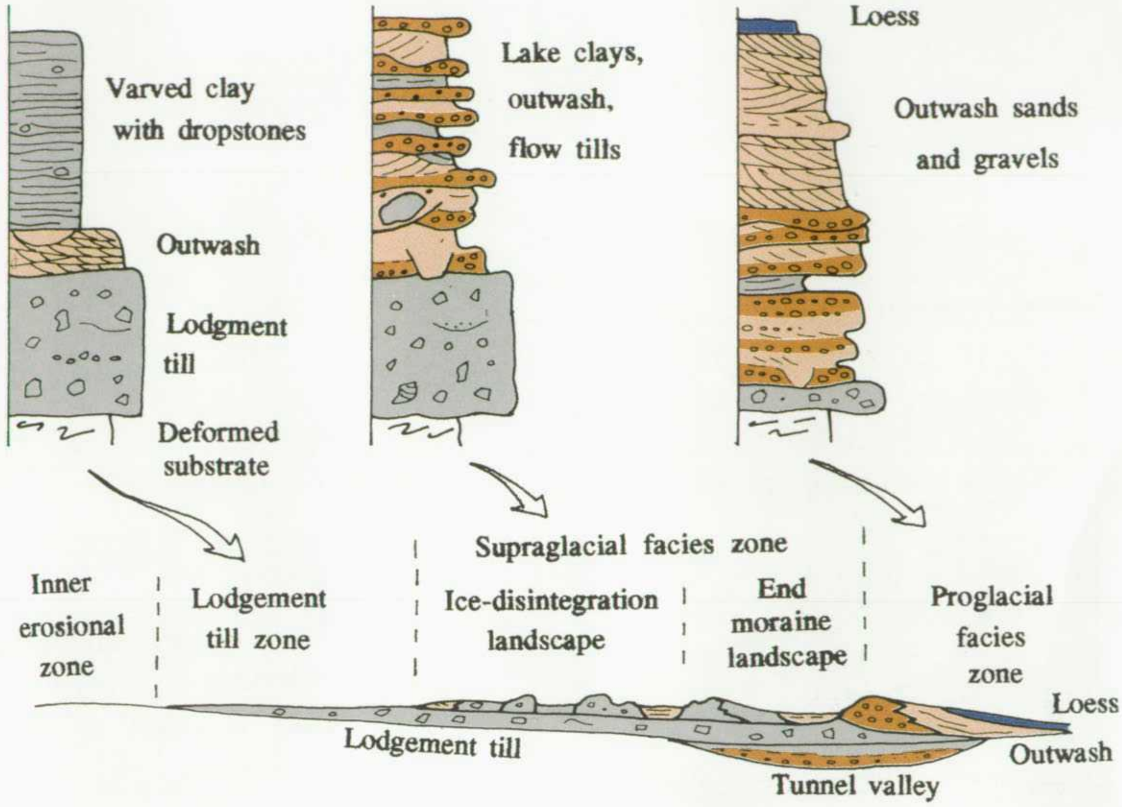
  - Water-sorted sediments, laid down from glacial meltwater . These include aquifers (sands and gravels) formed on fans, fan-deltas, alluvial and fluvial subenvironments of the ice margin; and aquicludes (silts and clays) laid down in bodies of standing water.

- Idealised sections through the deposits produced at the margins of a large continental ice-sheet show that significant bodies of sands and gravels tend to be formed at the fringes of ice-sheets as alluvial/fluvial outwash and morainic deposits. This picture is complicated by:

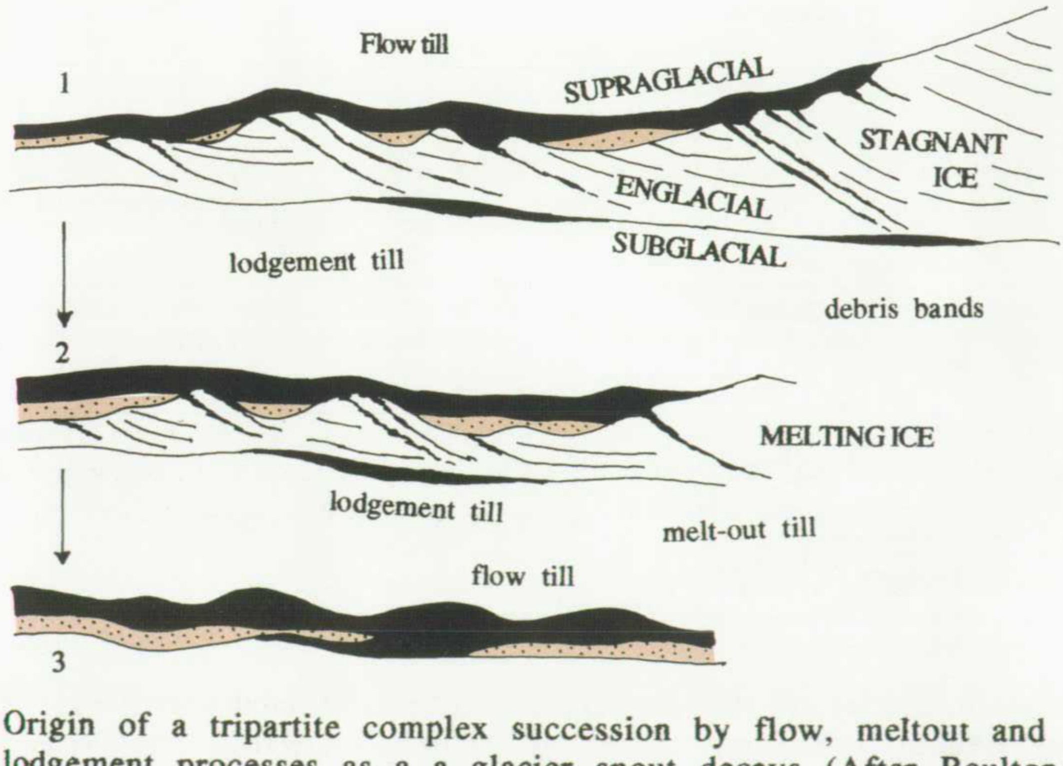
  - Glacitectonic bulldozing of proximal outwash during renewed ice-advance. This leads to chaotic and disturbed sequences. Such areas are almost impossible to decipher in the absence of good exposure. Ice melting and collapse commonly further disrupt the sequence in ice-contact deposits.

  - Repeated ice advance and decay. These produce complexly interstratified sequence of water-sorted (outwash) and unsorted (till, debris flow) glacigenic deposits with typically highly variable hydrological properties. Complex sequences can result from even a single episode of ice-advance and decay, in which tills of various types are interwoven with water-washed sediments.

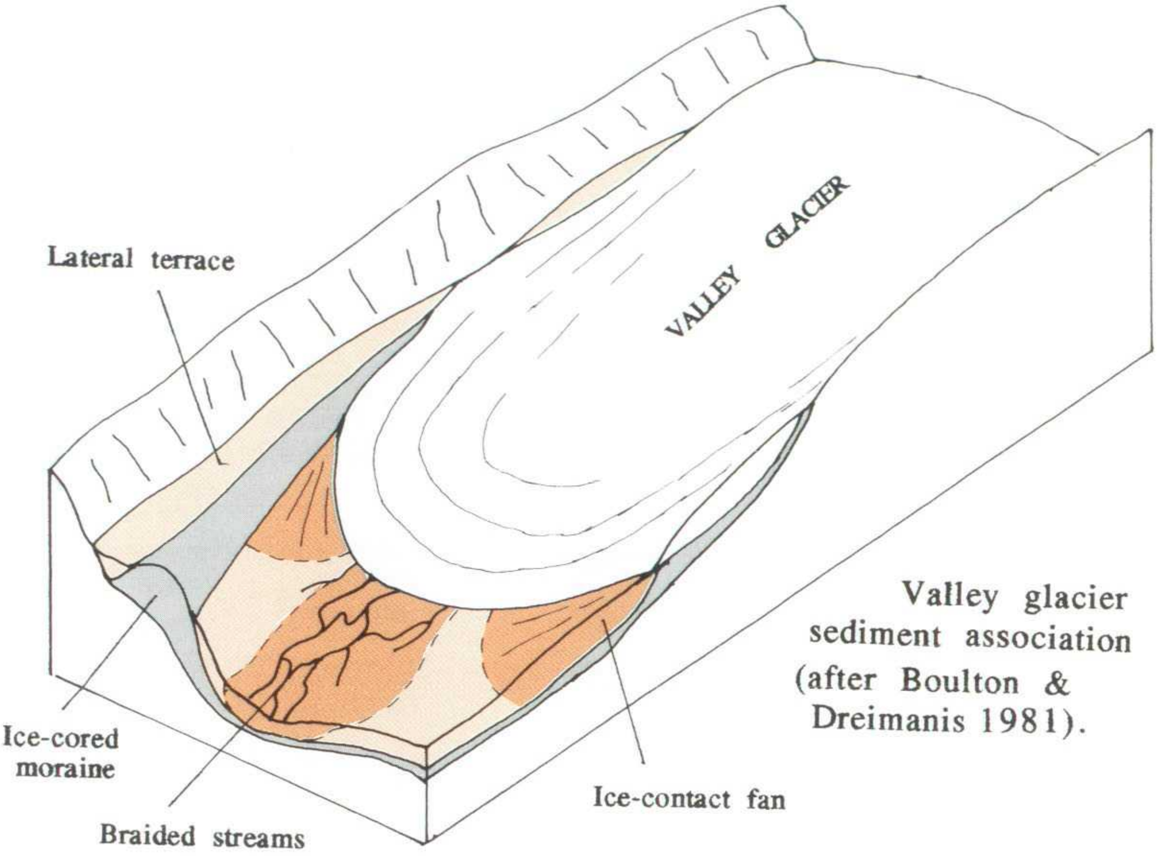
- Glacigenic deposits can contain important water resources. For instance, coarse glacial fan and outwash deposits supply much of the water to New Zealand cities such as Christchurch; high rates of abstraction may be sustained from these highly permeable sediments. In low-lying countries such as Denmark ribbon-like glaciofluvial (esker) deposits are also locally important sources of water.



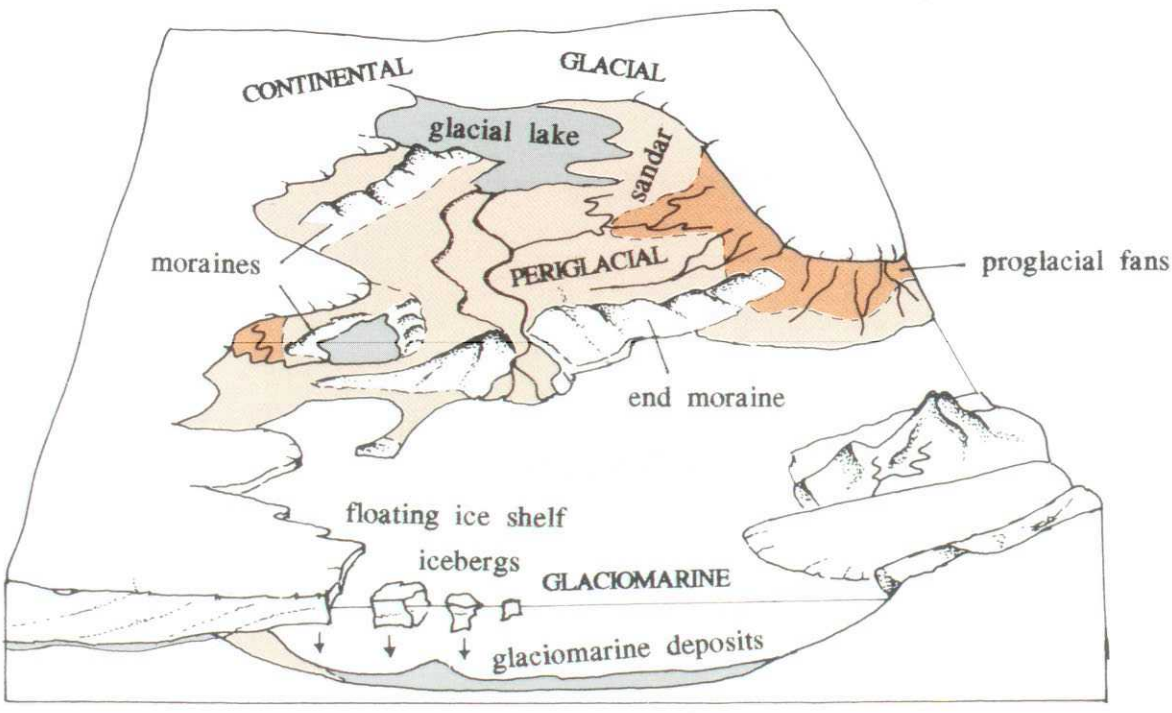
Glacial facies belts. After Edwards (1986).



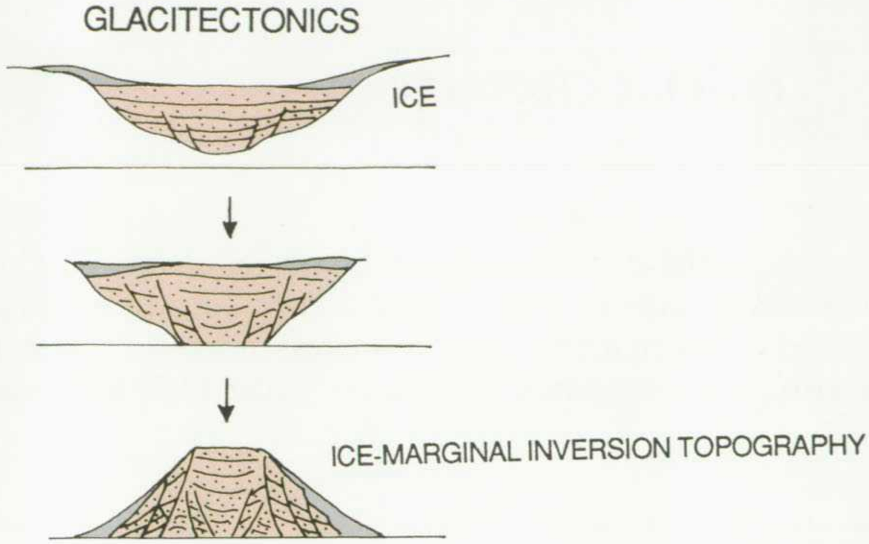
Origin of a tripartite complex succession by flow, meltout and lodgement processes as a a glacier snout decays (After Boulton 1972).



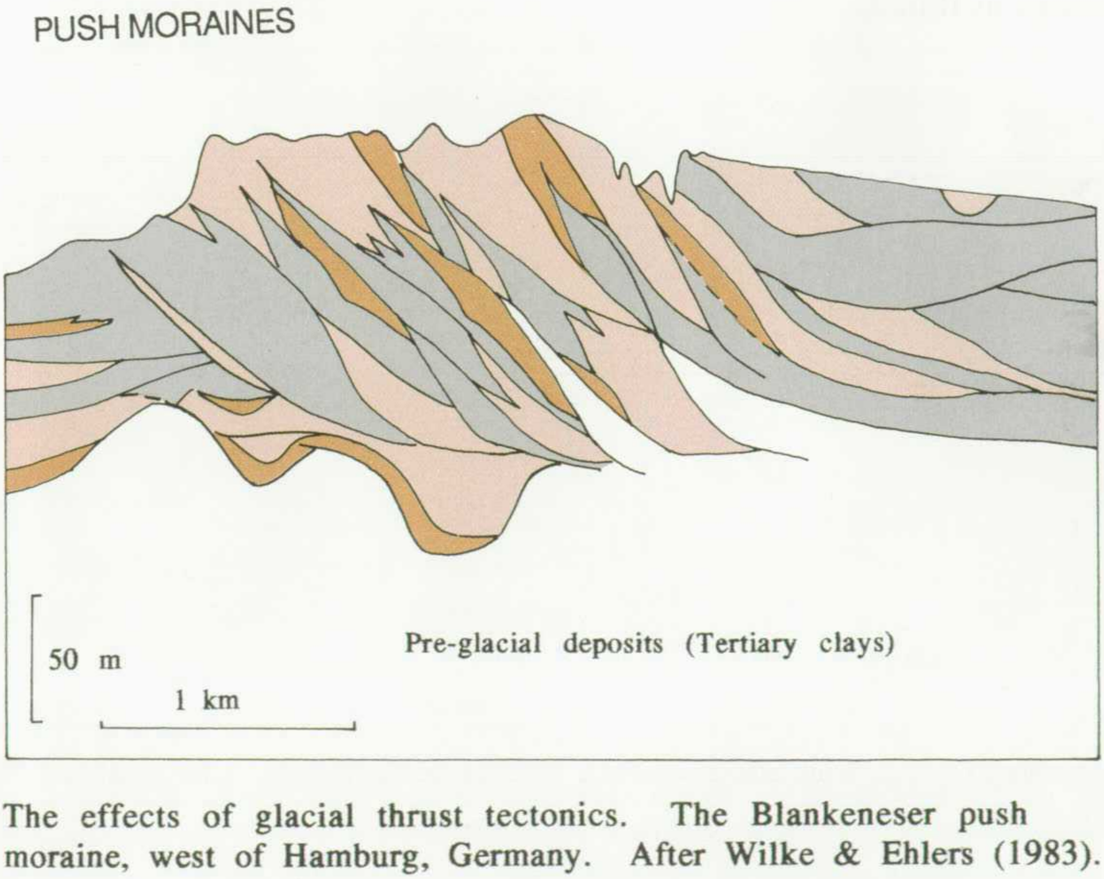
Valley glacier sediment association (after Boulton & Dreimanis 1981).



Schematic model of the glacial and periglacial environments. Simplified after Reading (1988) and Edwards (1978).



The formation of inversion topography as ice melts beneath supraglacial deposits. After Boulton (1972).



The effects of glacial thrust tectonics. The Blankeneser push moraine, west of Hamburg, Germany. After Wilke & Ehlers (1983).

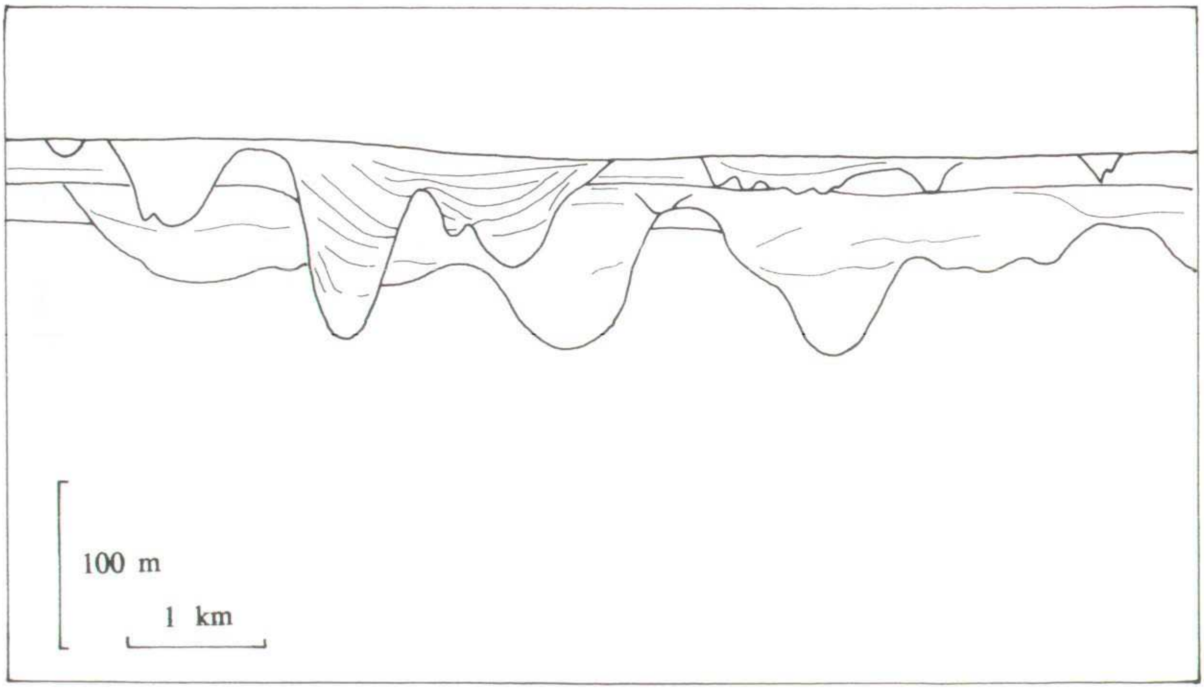
GLACIAL CHANNELS

Channelling

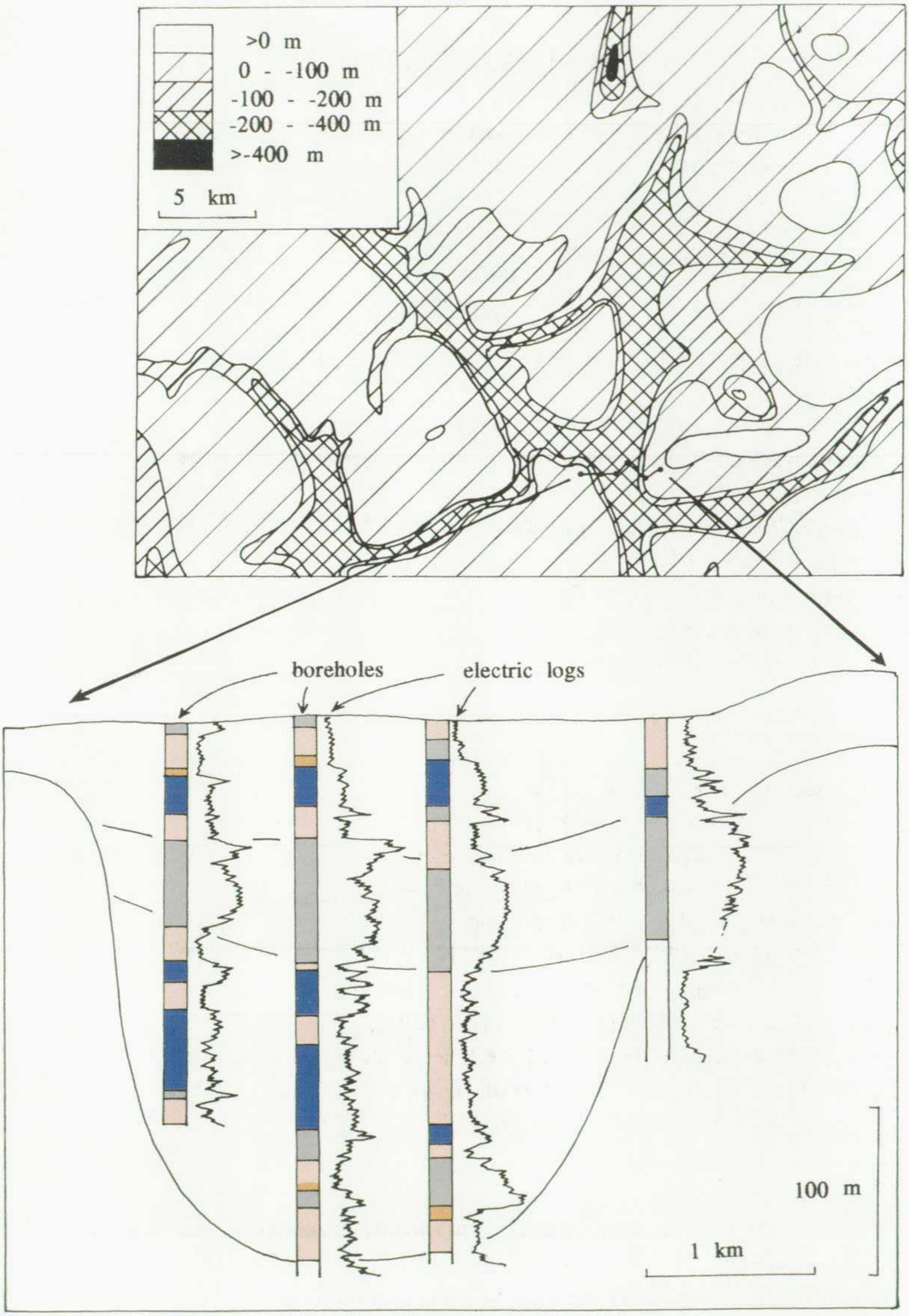
- A common feature of glacial deposits is the presence of channels, which may be of several generations in any one area. These may be formed by simple fluvial incision during times of lowered base level or increased stream power, by glacial scouring, or by erosion by subglacial meltwaters under high hydrostatic pressure.

- Notable examples are the rinnen of the north German Plain and the tunnel-valleys of eastern England. Where they contain significant sands and gravels they are locally important aquifers; where the infill is finer-grained, then they may act as lateral barriers within the more horizontally continuous sheets of glacigenic sediment in which they are incised.

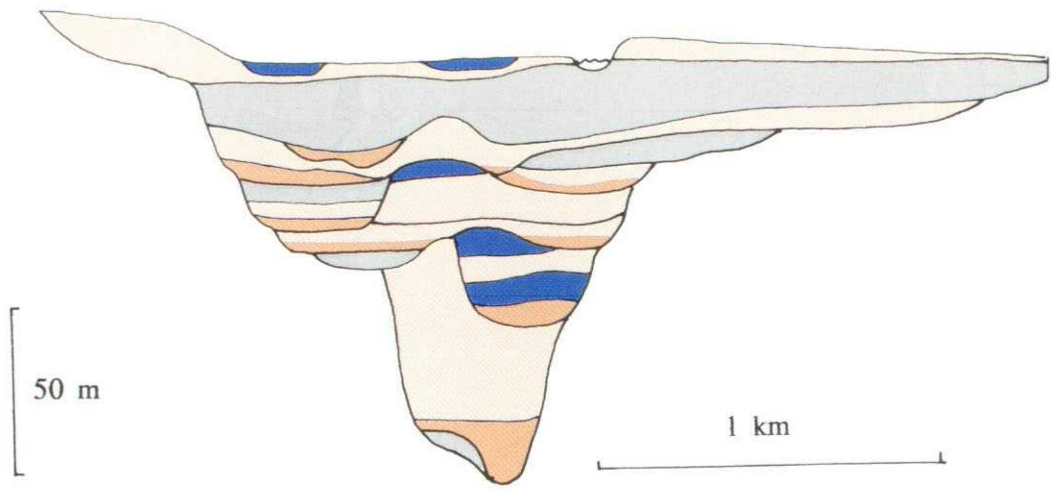
- An example in the central USA is the Teays-Mahomet Bedrock Valley system, which was incised by glacial meltwaters derived from the Great Lakes glaciers, and then infilled with thick permeable sandy outwash sediments. It now forms a major linear aquifer system supplying groundwater to cities, farms and industries in Illinois.



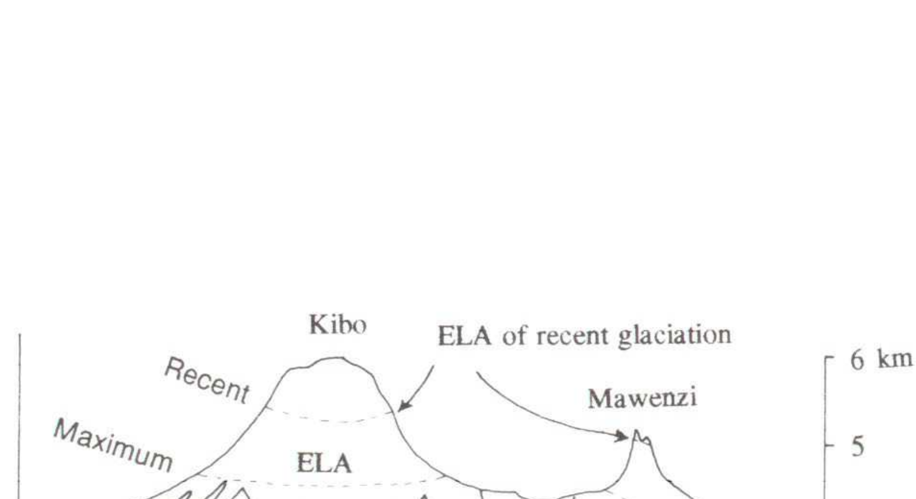
The geometry of large-scale glacial channels beneath the North Sea. After Ehlers & Wingfield (1991).



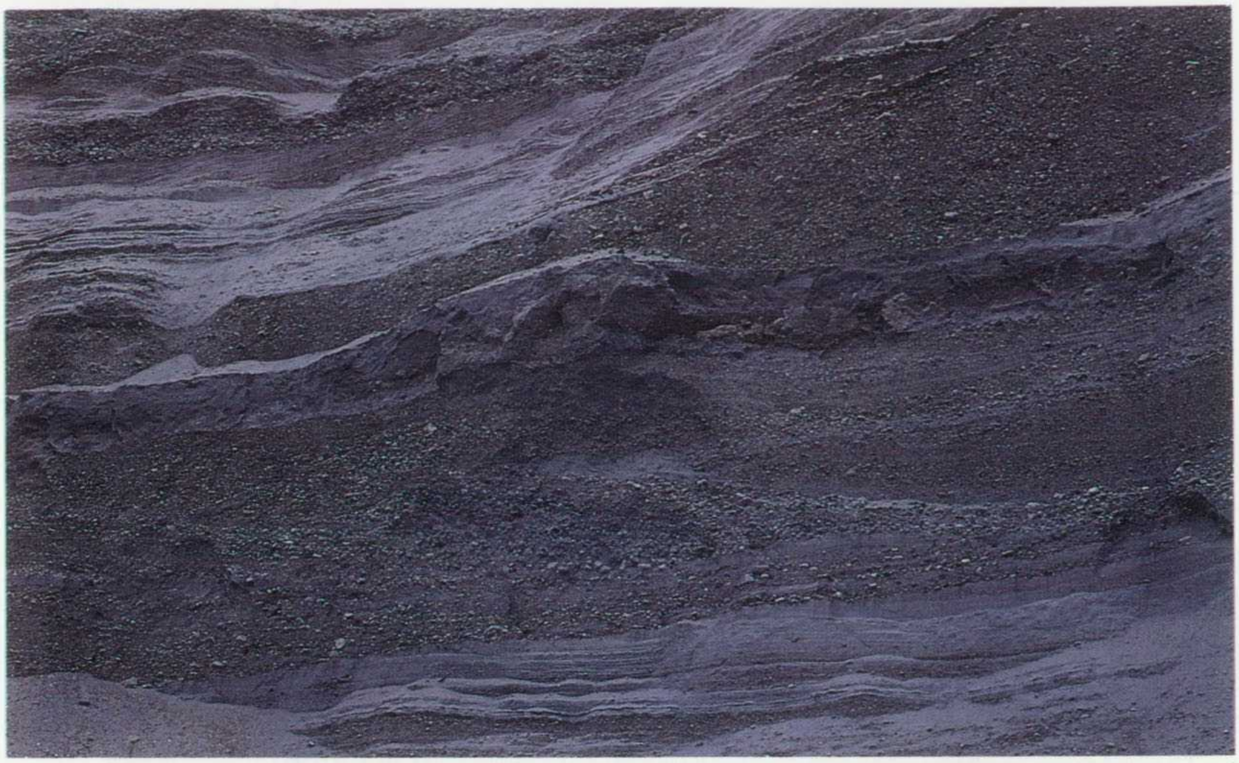
Contour map showing glacial channel geometry on the north German plain, and section through a channel. After Ehlers & Linke (1989).



Cross section through a buried channel at Serniki, eastern Poland. After Mojski (1982).



Glacial deposits in low-latitude mountainous areas: the Kibo and Mawenzi peaks of Mt. Kilimanjaro. After Osmaston (1989). ELA = Equilibrium Line Altitude.



Complexly interbedded glacial sands and gravels, with a mud-rich till bed in the centre of the photograph. Near Wrexham, U.K.

Popocatapetl volcano, Mexico, a low-latitude high-altitude volcano with a permanent snow and ice cover

LACUSTRINE DEPOSITS

GENERAL & CLASSIFICATION

- Lakes are landlocked bodies of water, either permanent or ephemeral.

- Lakes constitute 1% of the land area at present - a very small component of the hydrosphere.

- Lakes occur in basins produced by regional tectonics (e.g. Lake Baikal, rift lakes of east Africa), volcanism (e.g. Crater Lake, Oregon), deflation, solution collapse, thawing of permafrost, glacial excavation/deposition and meteorite impact.

- Large tectonic lake basins are usually characterised by continued subsidence so preservation potential is good; thick sequences can accumulate quickly. Lakes are very sensitive to climatic change so facies belts are liable to migrate rapidly.

- Different lakes show highly variable combinations of clastic, biogenic and lacustrine sedimentation.

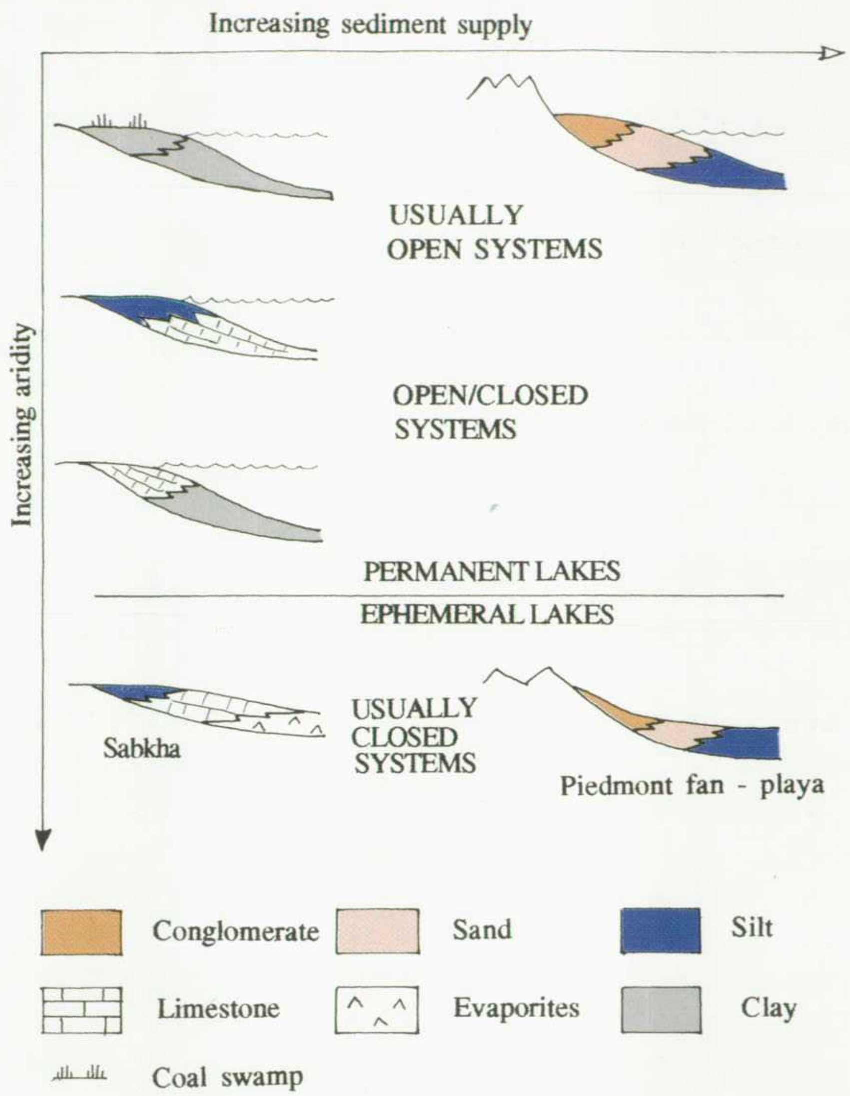
- Lake sediments are generally poor prospects for locating substantial aquifers, although small bodies of sand and gravel deposited at present or former lake margins may be useful (as in the Lake Chad area of NE Nigeria). This is because:

  - Rapid lateral changes of facies/lithology zoning leads to a rarity of extensive coarse layers.

  - Much of the lacustrine sedimentation is of fine-grained clastic material and chemical/biological sediments which usually constitute aquicludes. Potential aquifers comprise mainly littoral/fan delta bodies of restricted lateral extent.

  - Where basins are closed and/or evaporative losses are greater than the freshwater input, high ionic concentrations tend to develop in porewaters; they are thus unsuitable for abstraction.

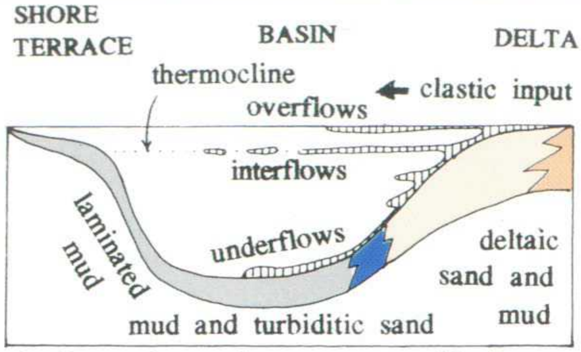
  - Where large freshwater lakes exist (usually in open systems), aquifers may not be needed as surface abstraction can take place.



Cartoons illustrating the relationship of lakes to sediment supply and aridity. After Selley (1985).

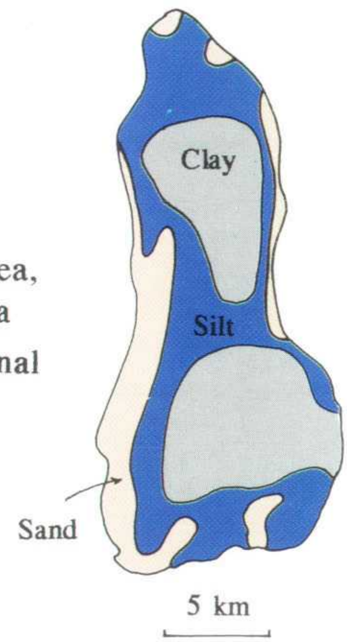
Two important parameters that control the sedimentary architecture of lake basins are precipitation (aridity) and clastic sediment supply. Various combinations of these two key variables give rise to different arrangements of facies belts. Water-bearing strata are most likely to be found fringing lakes (deposited as alluvial fans, fan-deltas or reworked by waves as beaches). Most lakes with a pronounced clastic input show simple distal fining to the basin centre.

Common physical processes in a lake dominated by clastic sedimentation. The density of the sediment-laden input water versus that of the lake water determines whether overflow, underflow or interflow plumes develop.

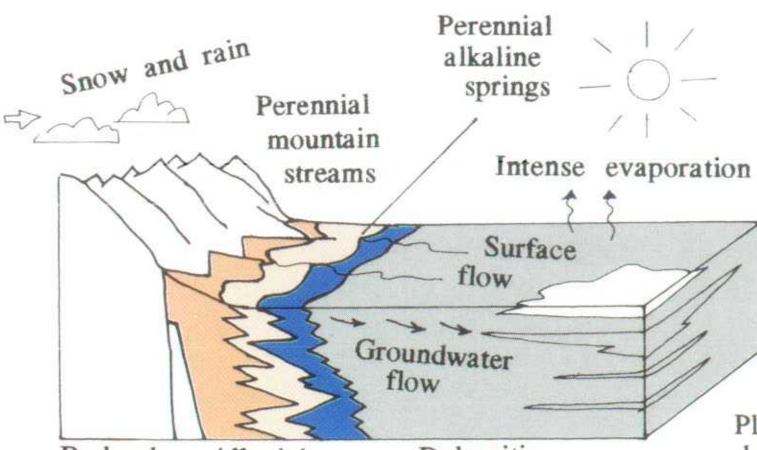


Sedimention in a stratified temperate lake (after Sturm & Matter 1978)

Zonal arrangement of lake-bed sediments, fining to the basin centre.



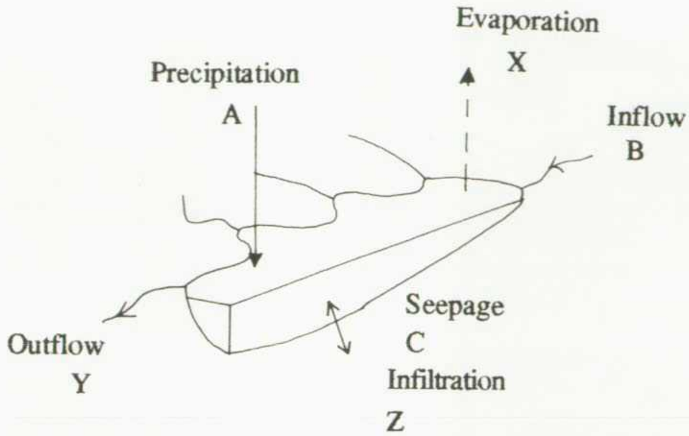
Salton Sea, California After Arnal (1961).



Cartoon of an alluvial fan/playa lake system (after Eugster & Hardie 1975).

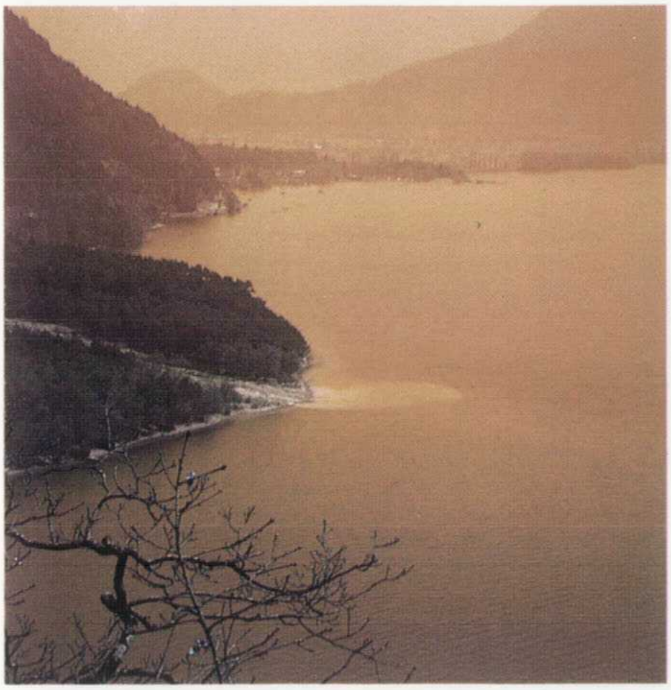
In fault-controlled subsiding basins, potential aquifers are usually restricted to the basin edge giving way to fine sediments in the centre.

KEY PARAMETERS IN THE WATER BUDGET OF A LAKE

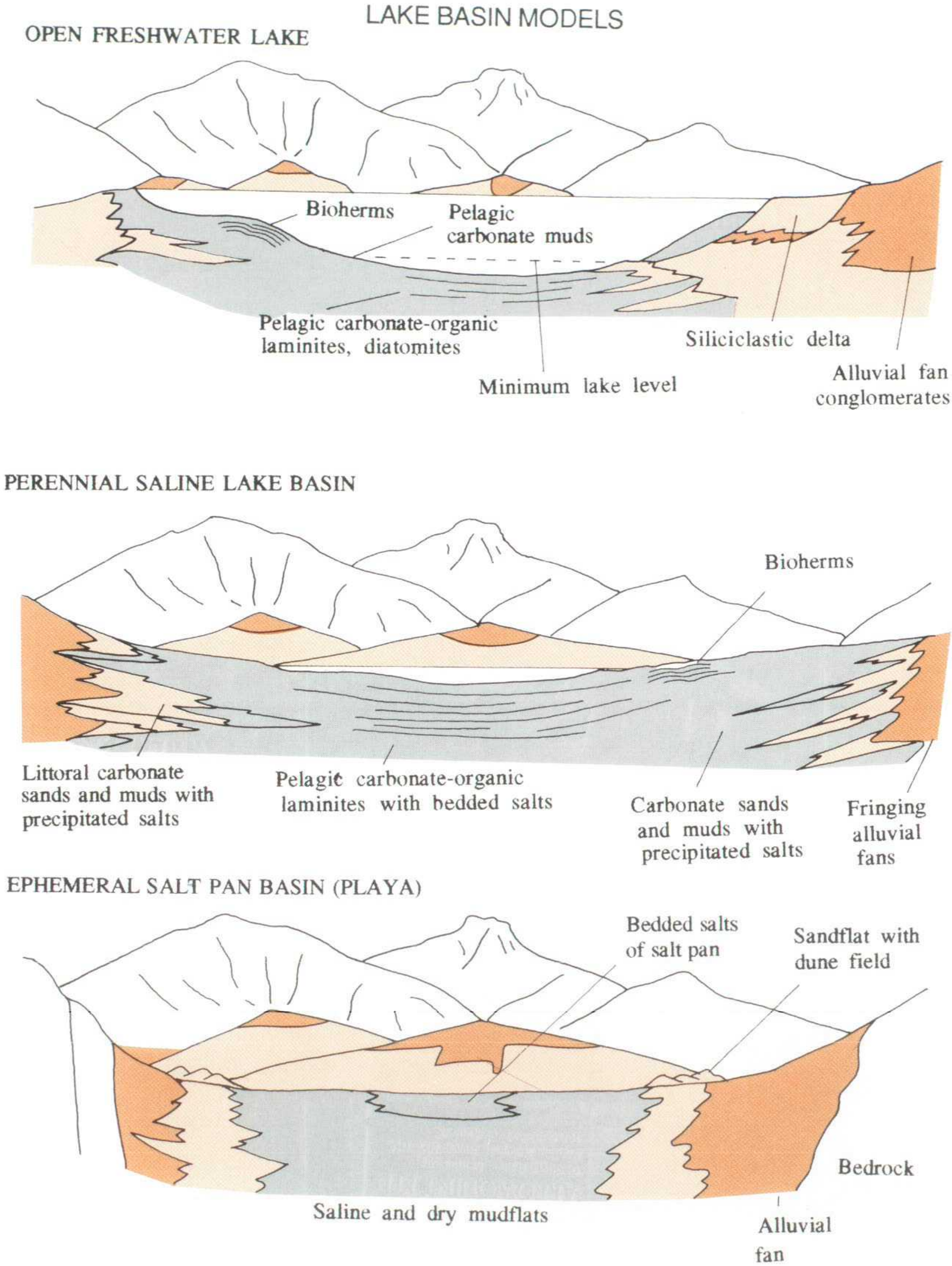


Open System	$A + \underline{B} + C = X + \underline{Y} + Z$	Stable water body; little shoreline fluctuation; clastic and biogenic sedimentation.
Closed System	$A + B + C << \underline{X} + \underline{Z}$	Ephemeral or widely fluctuating size of water body; shoreline and facies migrate rapidly; high ionic concentrations often envelop favouring chemical sedimentation with smaller clastic and biogenic components.

Most important parameters in each system are underlined.



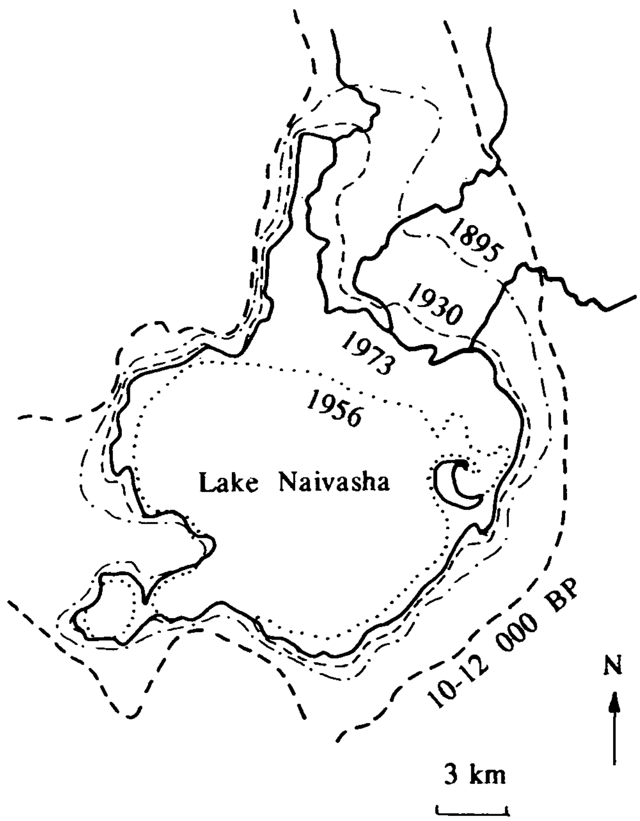
Sediment inflow into a permanent lake. Note the sediment plume next to the small marginal fan-delta. The fan-delta itself is likely to contain the most permeable sediments within the lake basin. Lake Thun, Switzerland.



Lake models after Eugster & Kelts (1983). Note marked grain-size zonation in all models. Potential aquifers only at fringe of lakes and in surrounding fluvial/alluvial deposits.

CLIMATIC EFFECTS

LOW-LATITUDE, TECTONIC (RIFT VALLEY) LAKE : CLOSED SYSTEM SHOWING RAPIDLY FLUCTUATING LAKE LIMITS



After Vincent et al (1989).

VARIABLE EXTENT OF LAKES DURING THE QUATERNARY

Pluvial events led to widespread lacustrine sedimentation flooring most of the basins of the western USA. After Williamson (1966).

Terrace cut into the margin of former Lake Bonneville, over 150 m above the present-day basin floor. Eastern part of the Great Salt Lake Basin, U.S.A.

Lake Nakuru, Kenya, showing evaporate (sodium carbonate) flats near the lake margin.

AEOLIAN DEPOSITS

GENERAL & CLASSIFICATION

- Aeolian (windblown) deposits are characteristic of arid climatic regions - deserts. These are often, but not always hot regions; they can be present at high altitudes and latitude, e.g. in upland Chile. Desert conditions are also commonly present in Arctic environments, though there aeolian deposits are generally subordinate to glacial/proglacial sediments. Limited spreads of aeolian dunes are also present along some shorelines.

- Most present-day deserts are present in sub-tropical latitudes, associated with descending masses of air derived from the equatorial zone. Other regions are associated with rain shadows in the lee of mountain belts.

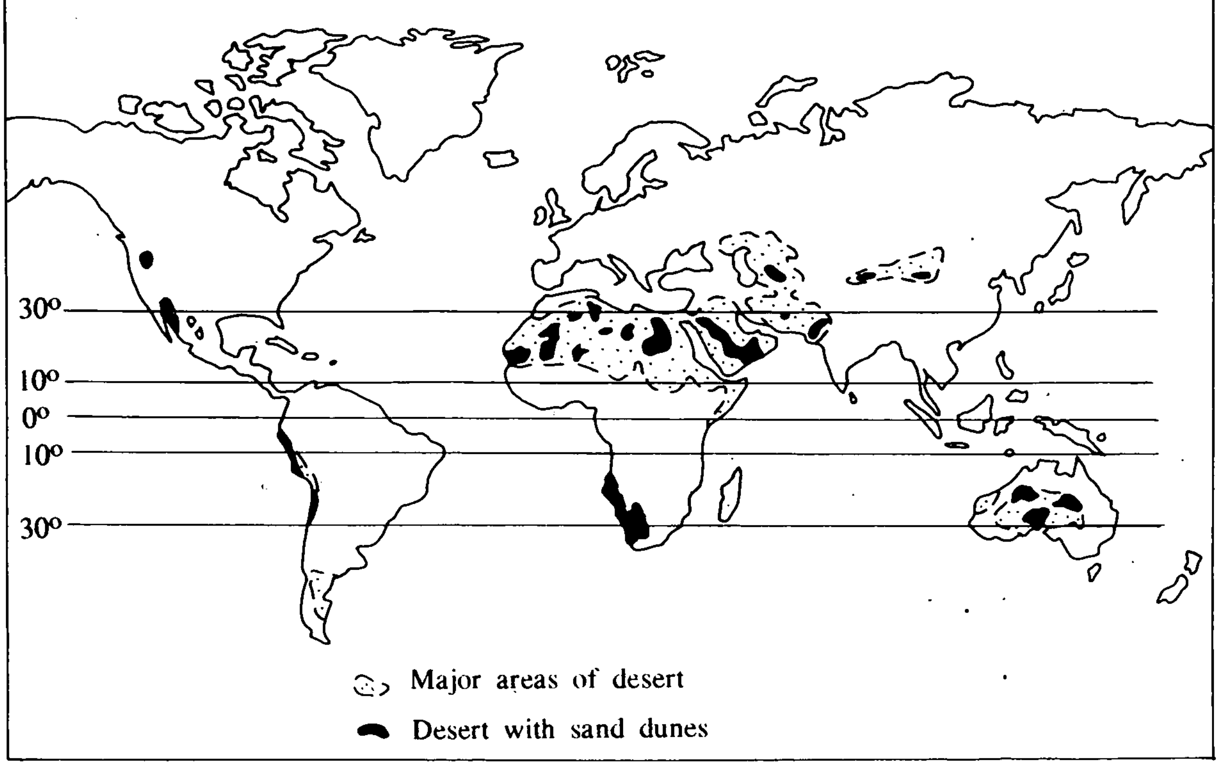
- The lack of water means that aeolian transport and deposition of sediment is dominant. Sand is blown from areas of deflation to areas of accumulation where it piles up as sand seas or *ergs*.

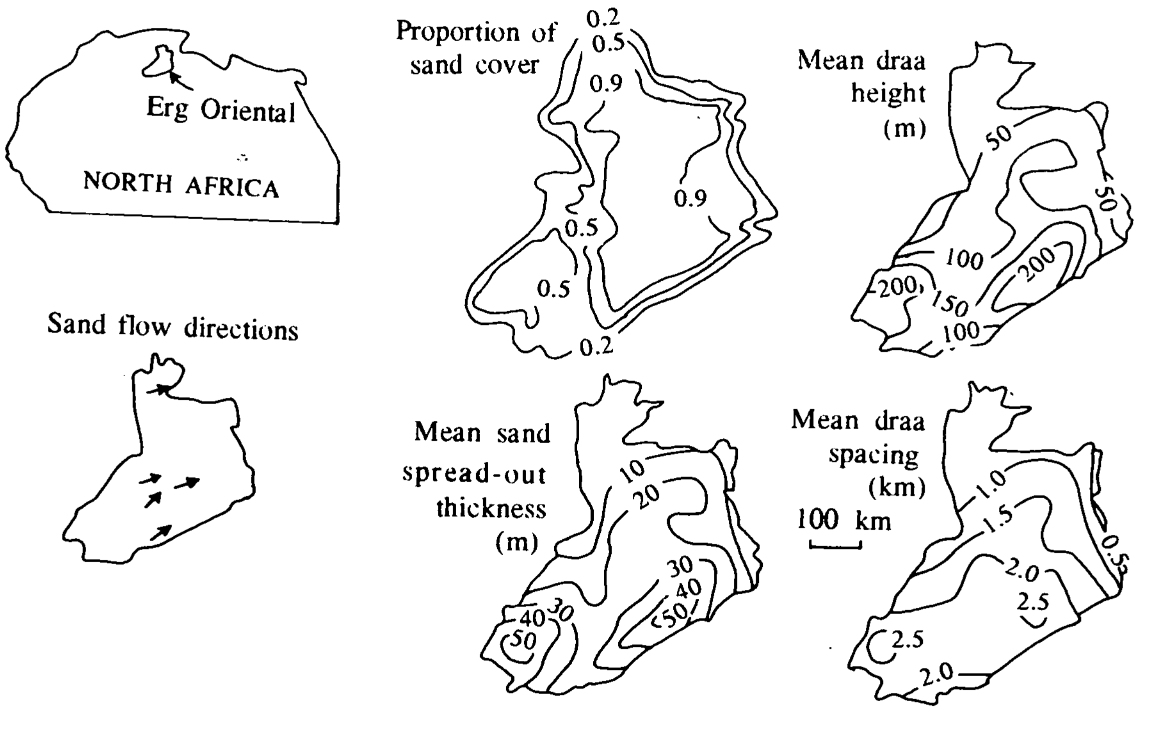
- Wind is an efficient sorter of sediment. Gravel is left behind as a lag deposit. Sand moves as bedload. Finer material goes into suspension and can be carried long distances from source, where it accumulates as fine-grained *loess* (see below). The sand that accumulates in ergs is well rounded and well sorted, and thus can form an excellent aquifer, with high porosity and permeability.

- Sand deposits accumulate as dunes of various sizes, with a variety of internal bedforms. In terms of their hydrogeological properties, these are essentially homogenous. Non-aeolian interbeds may, though, form internal aquicludes.

- Sand accumulations are thin and discontinuous at their margins, and thicken toward their centres. The thickness of the deposits can be related to external features of the deposit, such as the height of the major dune-like bedforms (draas). Analysis of such features through remote sensing thus offers a means of predicting the overall geometry of the deposit.

Distribution of the world's major deserts. After Glennie (1970).





The Erg Oriental, Algerian Sahara. After Wilson (1973).

AEOLIAN SAND DEPOSITS - INTERNAL ORGANISATION AND INTERBEDDED FACIES

- Accumulations of aeolian sand include internal discontinuities known as first order bounding surfaces. These are extensive and near-horizontal, and may reflect deflation of the sand pile to the level of the water table. Local cementation at this level, by the precipitation of minerals from evaporating water, may create aquicludes and reduce recharge potential (as in aeolian sands of the Kalahari and Okavango regions of Africa).

- Sand accumulations include near-horizontal levels of thinner-bedded sands and locally silts/muds. These are interdune deposits, laid down by a variety of aeolian and aqueous processes (depending on the level of the water table) between individual aeolian dunes, which are buried by subsequent dune migration. Where fines-rich, they can form significant aquicludes.

- Aeolian sand deposits are commonly associated with other facies typical of arid environments, such as playa lake deposits, which are dominated by fine-grained sediments and may include evaporites, and, near the margin of the basin, alluvial fan and ephemeral stream deposits.

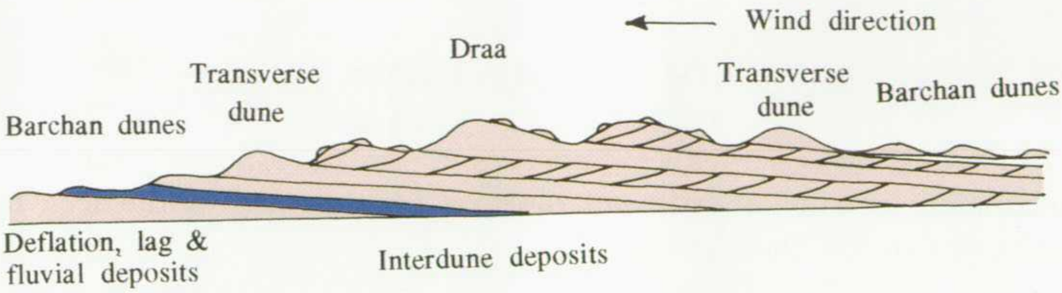
- The thickness and distribution of aeolian sand deposits is strongly controlled by local tectonics as well as climate:

  - In graben and half-graben basins, the degree of subsidence will control such features as sediment input and the water table, and thus will control whether aeolian or aqueous deposits will be formed. Fluctuations in sediment supply, climate and rate of subsidence can lead to a complex interbedding of these facies, and aeolian deposits may be very limited in extent.

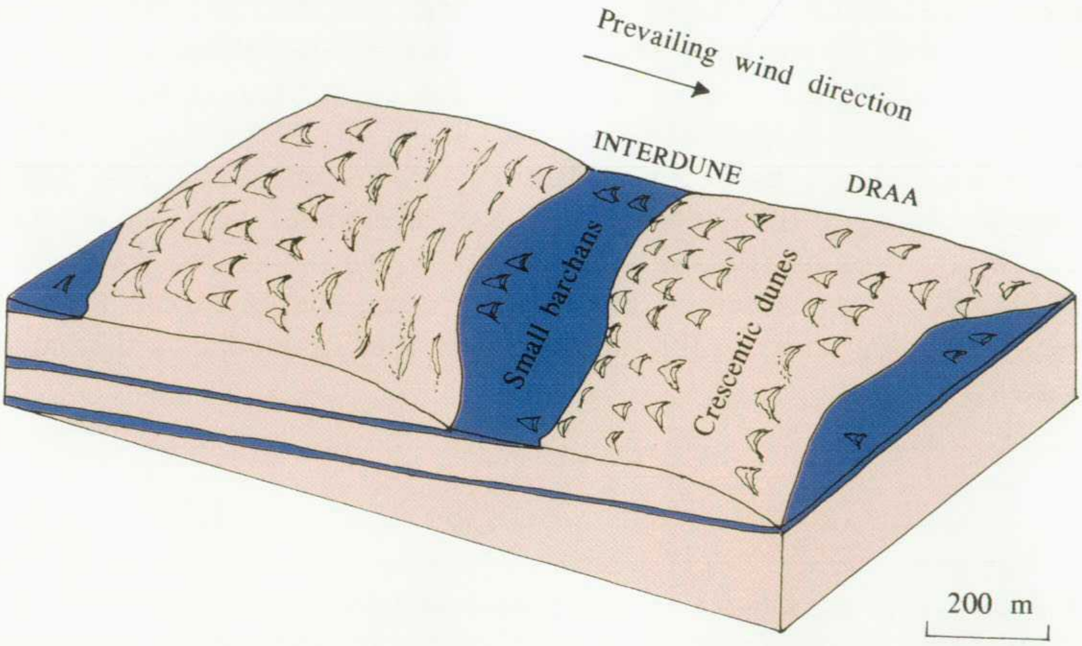
  - In larger cratonic basins which are less tectonically active, the more stable conditions can lead to the formation of quite extensive sand seas.

- The inception of sand accumulation in an erg is commonly due to a topographic depression (an erg, once formed, then growing by 'positive feedback' as the dunes trap more sand). Thus, 'traps' for water may be present beneath major sand accumulations.

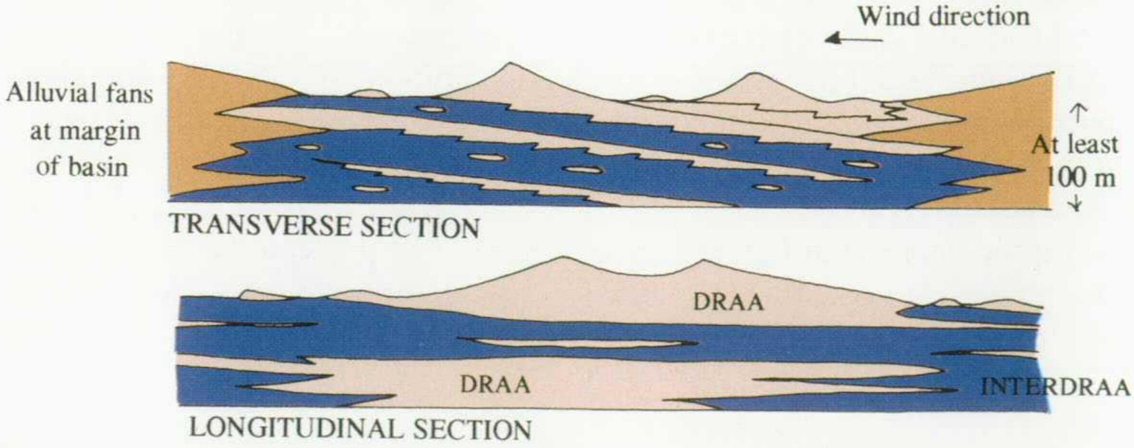
- Fine grained aeolian sands may be difficult to develop as water sources, having low permeability and being difficult to screen.



Characteristic features of an erg. Vertical scale exaggerated. After Brookfield (1992).



Geometry of draa/interdune environments. After Clemmensen & Abrahamsen (1983).



Model of desert in an enclosed basin. After Brookfield (1992).

CLIMATIC CONTROLS

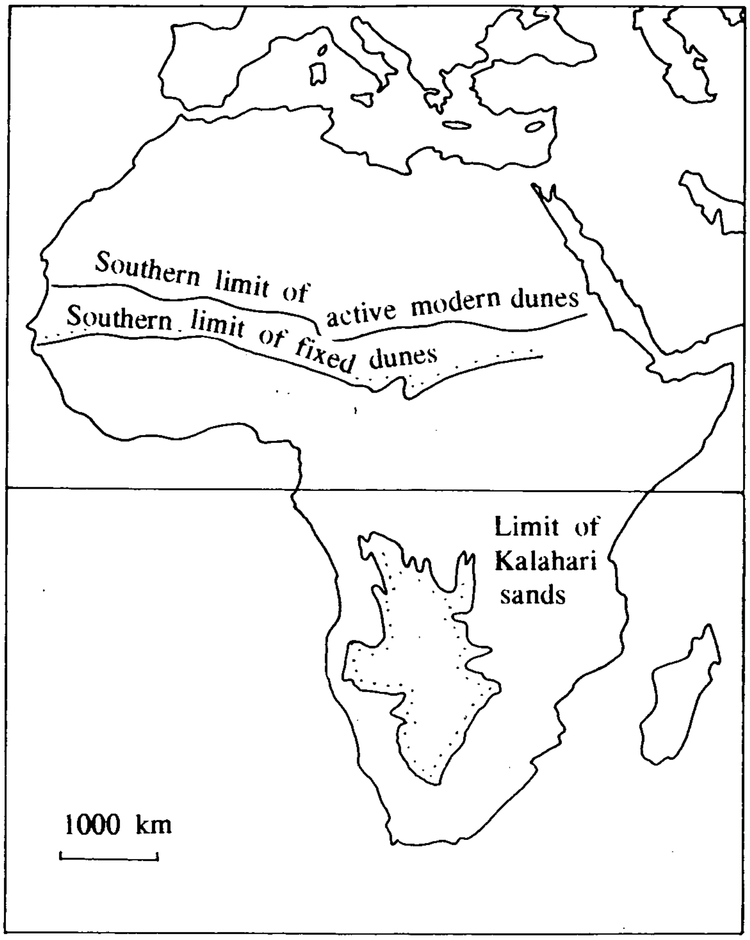
Aeolian sedimentation is particularly sensitive to climate, especially rainfall. The extent and nature of aeolian sedimentation has been strongly influenced by the climatic changes of the Quaternary.

A widely held model for the interpretation of environmental change in desert (and tropical) regions of the world has been the concept of 'Pluvial' and 'Interpluvial' periods. These would correspond to the Glacial and Interglacial periods of higher latitudes. Thus, during glaciations, the climate at low latitudes would be cooler and wetter; lake levels would rise, and aeolian sedimentation would be restricted.

This model, though, has been overturned by recent studies, in particular by radiometric dating of the deposits. The 'wet' periods of high lake level are 'post-glacial' in age (notably 10 000 to 8 000 BP), while the glacial maximum (20 000 to 10 000 BP) was marked by increased dryness, and an expansion of the areas covered by aeolian dunes. The Sahara desert, then, extended further south than it does now.

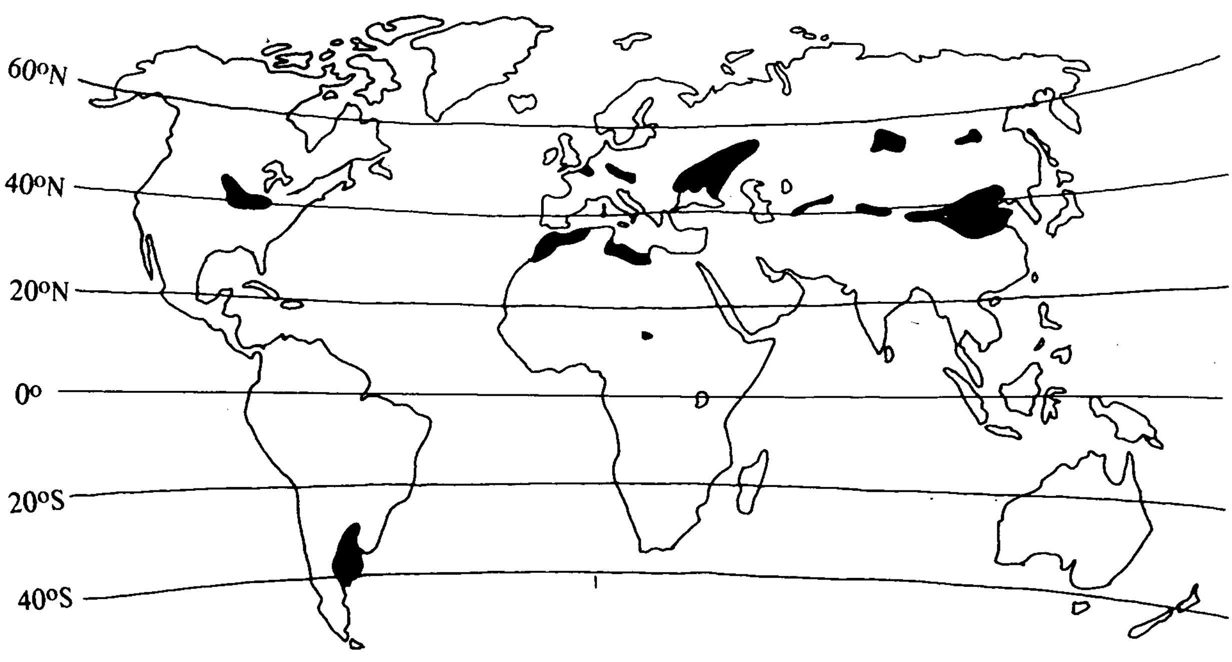
LOESS

At higher latitudes, glacial episodes also coincided with increases in aeolian sedimentation. In particular, the strong winds blowing off the ice-caps removed much fine-grained material from the vegetation-free proglacial landscape and transported it long distances. Thick accumulations of silt-rich loess formed in areas such as central Europe and central China. The latter are very extensive forming a low permeability (K=0.003-0.15 m/day) groundwater source that has proved difficult to develop except via spring systems. The overall permeability of loess is often further decreased through the common presence of widespread clayey palaeosol layers, which formed during warmer climatic episodes. Loess deposits as a whole may be generally more evident as aquicludes where they drape more permeable sediments.



Changing patterns of aeolian dune activity in Africa. After Hamilton (1982).

Loess regions of the world. After Burnett (1965).



Aeolian sand dunes, Death Valley, USA. Note mud-rich interdune deposits to the right of the large dune in the centre of the photo.

Aeolian sand dunes adjacent to a marine coastline. Sigatoka, Viti Levu, Fiji.

GLOSSARY

Aeolian, (also spelt eolian), refers to processes involving wind action and the deposits so formed.

Avulsion, The wholesale switching of a river course by breaching of its banks.

Bioturbation, the displacement of sediment through the action of organisms.

Chenier, an isolated beach ridge usually composed of sand set within coastal mudflats.

Craton (also spelt Kraton), a major structural component of the earth's crust, consisting of stable areas composed mainly
of ancient igneous and metamorphic rocks. The term 'shield' is almost synonymous.

Detrital, sedimentary particles or rocks derived from the physico-chemical breakdown of pre-existing rocks.

Diamict, a sedimentary rock containing a mixture of particles of all sizes from large clasts to clay (e.g. a boulder clay).

Diapir, An intrusion of igneous or sedimentary origin which moves upwards in the crust due to gravitational instability, piercing and arching the overlying levels and commonly developing a balloon- or mushroom-form.

Distal, far from the source, beyond the *proximal* zone.

Draa, The largest scale of aeolian bedform found in deserts, which may have superimposed dunes and ripples.

Englacial, The environment within a glacier or ice-sheet.

Erg, an extensive spread (sea) of sand found in hot deserts.

Facies, a part of a sedimentary unit that possesses a distinct combination of characteristics; such as fauna, grain size, bedforms etc.

Floodplain, the flat area on a valley floor adjacent to the river which is inundated during flooding; alluvium is deposited over this area.

Graben, a downthrown block between two sub-parallel bounding faults (e.g. a rift valley); a half graben possesses only one faulted margin.

Interpluvial, Quaternary arid periods at low-latitudes which alternate with *pluvial* (wet) episodes.

Levée, a raised bank flanking a river, formed by deposition during flooding; the bank helps confine the river flow within the channel.

Loess, a homogenous, poorly-stratified, unconsolidated brownish silt deposit which covers extensive areas and is usually formed by *aeolian* processes.

Moraine, a ridge, mound or bank of glacigenic sediment formed at the margin of a glacier/ice-sheet.

Overbank, refers to the floodplain area of a river valley beyond the river and its banks.

Palaeosol, a fossil soil horizon.

Playa, An ephemeral lake that forms in an intermontane basin with an arid climate.

Pluvial, a Quaternary 'wet' period at low-latitude which alternated with *interpluvial* (arid) periods.

Prograde, the incremental advance of a constructional sedimentary form (e.g. a delta) into a sedimentary basin.

Proglacial, the environment immediately beyond the limits of a glacier or ice-sheet.

Proximal, close to the source, farther away is *distal.*

Pyroclastic, the explosive volcanic eruption of fragmental debris, usually produced by the rapid expansion of volatile components such as water within the magma.

Sandur, An extensive *proglacial* outwash plain characterized by braided (bed-load) rivers and sandy sediments.

Siliciclastic, an adjective applied to detrital sedimentary rocks composed principally of fragments of silicate minerals and rocks.

Subduction, the process by which dense oceanic crust is gravitationally deflected downwards beneath lighter continental crust along ocean trenches as part of a convection-driven cell involving lateral movement of the earth's crust; it is a major component of plate tectonics.

Subglacial, The environment beneath a glacier or ice-sheet.

Supraglacial, the surface environment of a glacier or ice-sheet.

Tephra, a general term for *pyroclastic* ejecta.

Till, a heterogenous mixture of rock and mineral fragments brought together and deposited by the direct action of ice. Lithologically many tills are *diamicts.*

Varves, a sedimentary unit that is deposited during one year; this may comprise a single bed or laminae or a pair of distinct laminae formed by seasonally dependent processes.

Welding, the process by which hot *pyroclastic* fragments fuse together soon after eruption and deposition.

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