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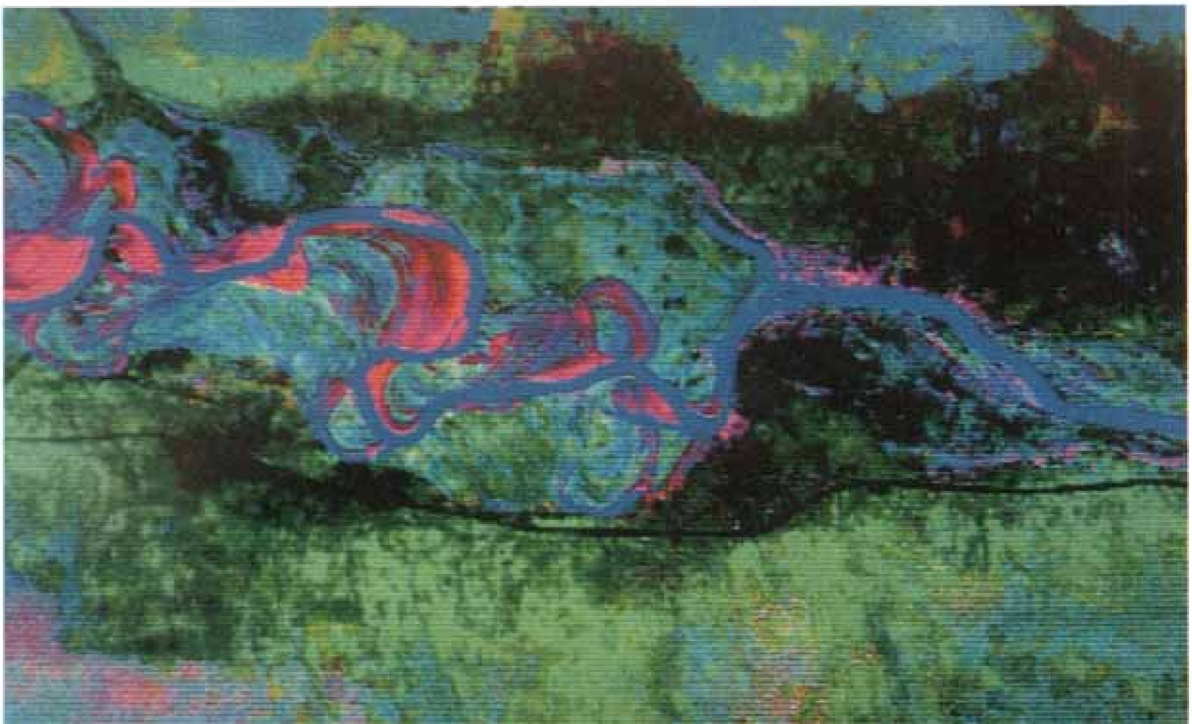
ODA

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.

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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:

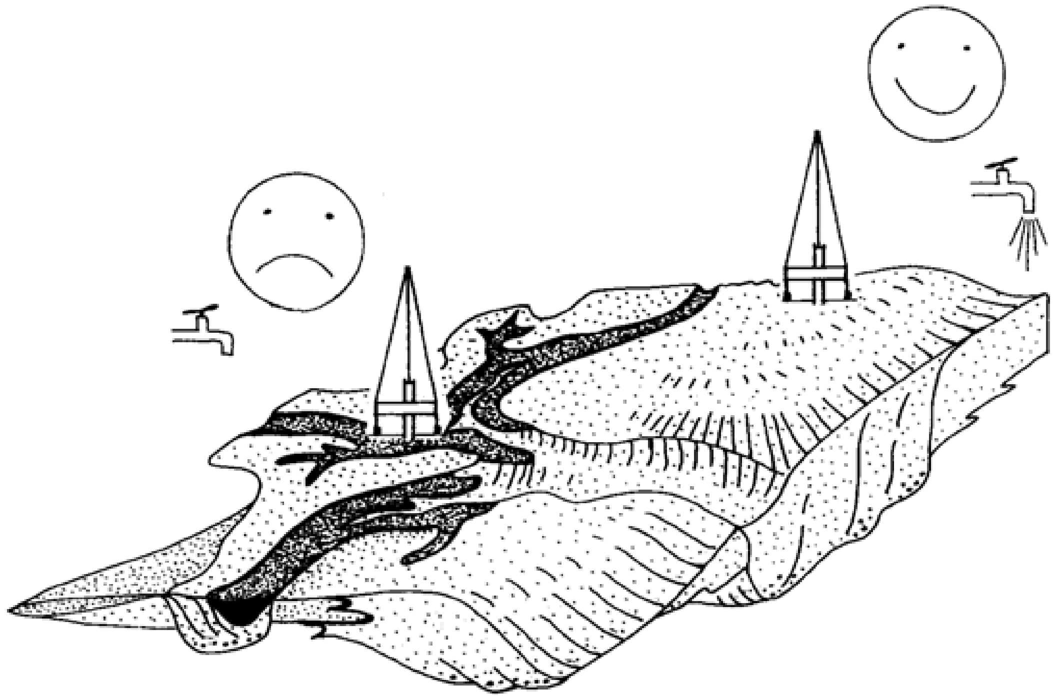
"The search for ground water most commonly starts with an investigation of nonindurated sediments. There are sound reasons for this preference. First, the deposits are easy to drill or dig so that exploration is rapid and inexpensive. Second, the deposits are most likely to be found in valleys where 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.*

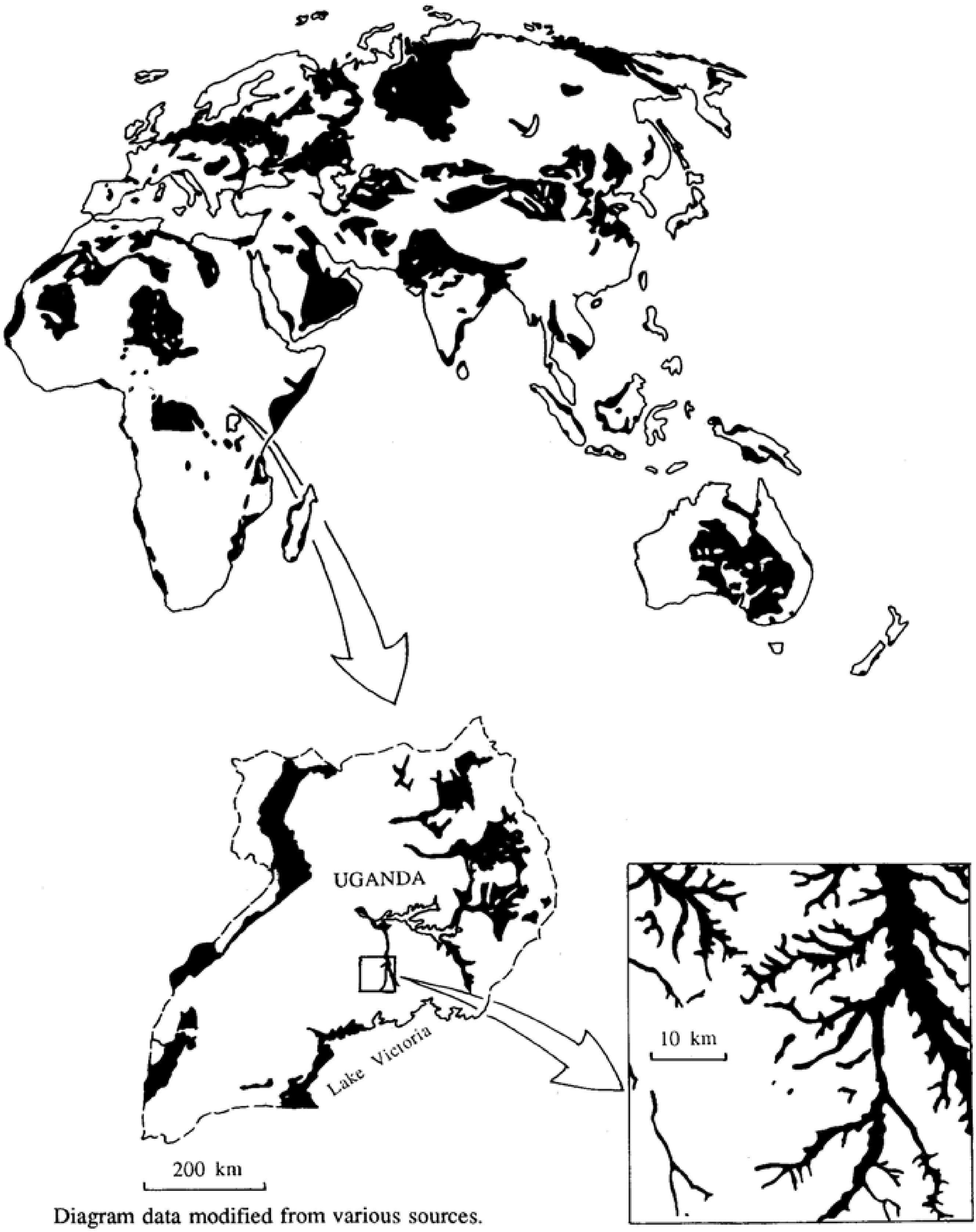


Diagram data modified from various sources.

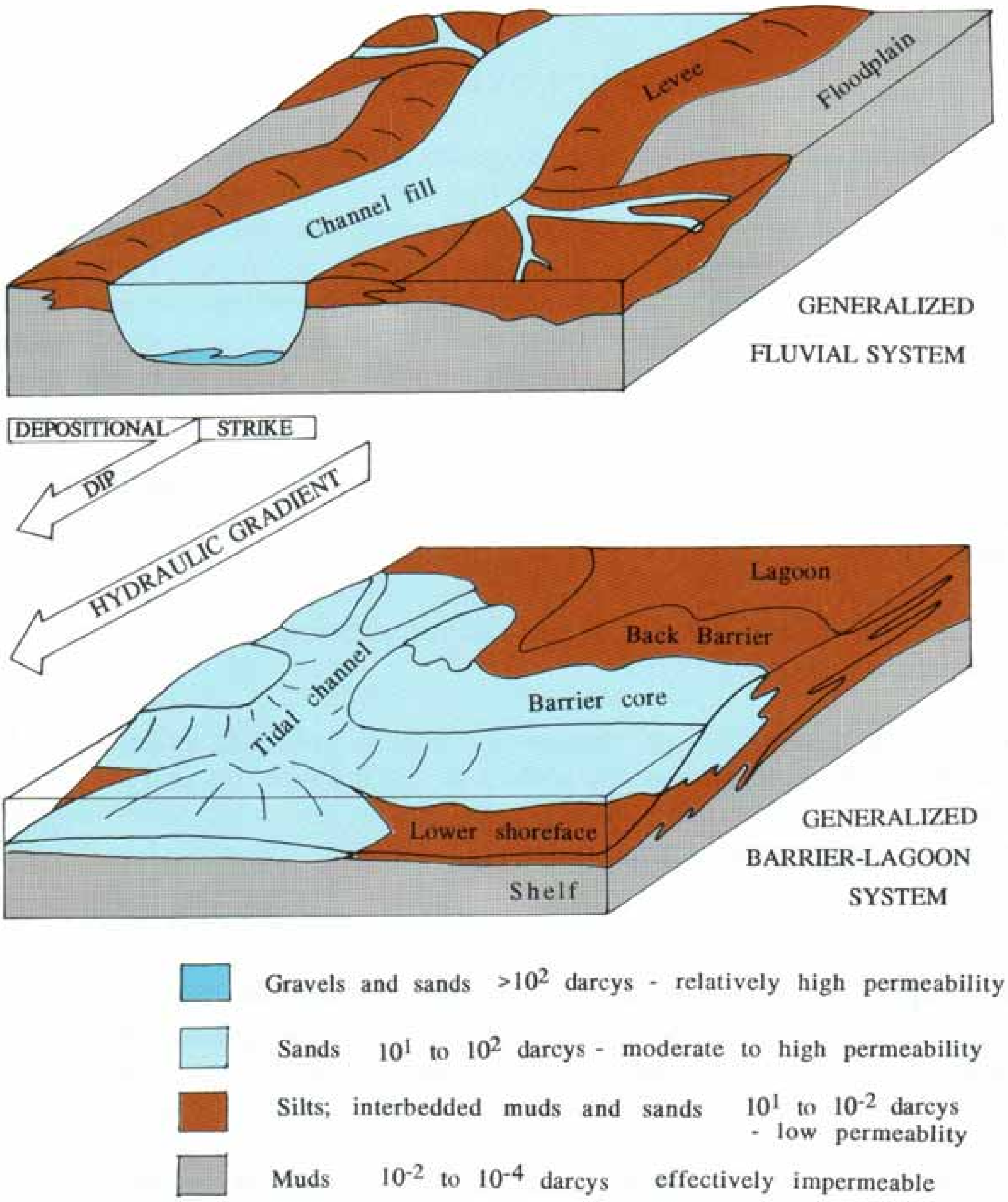
GENERAL SEDIMENTOLOGICAL MODELS

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.

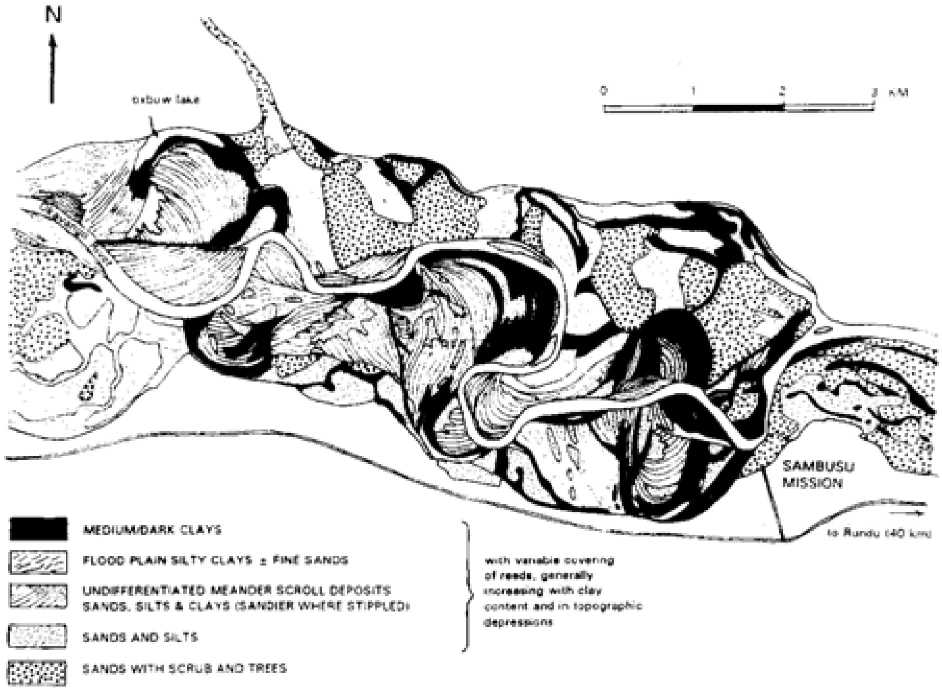
Thus, the general sedimentological models need to be tested in the field, using all available evidence, so that *specific working models* for each test area can be arrived at.

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

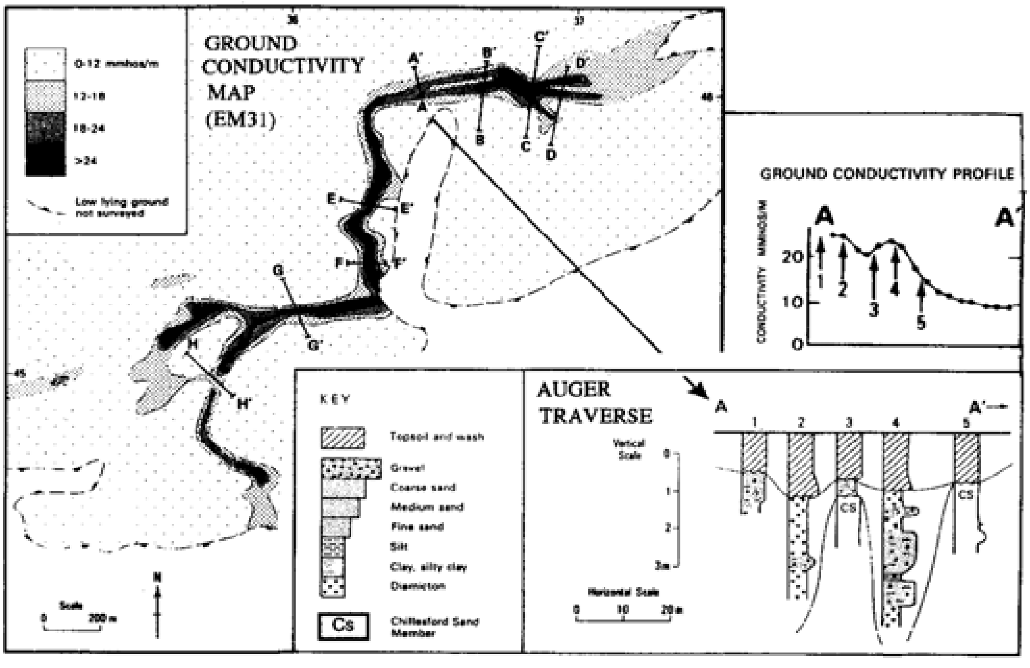
- An understanding of present-day patterns of sedimentation, and the controlling forces. This may be arrived at, for instance, by analysis of surface geomorphology revealed by aerial photographs or remotely sensed images, and knowledge of rainfall/discharge patterns.

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

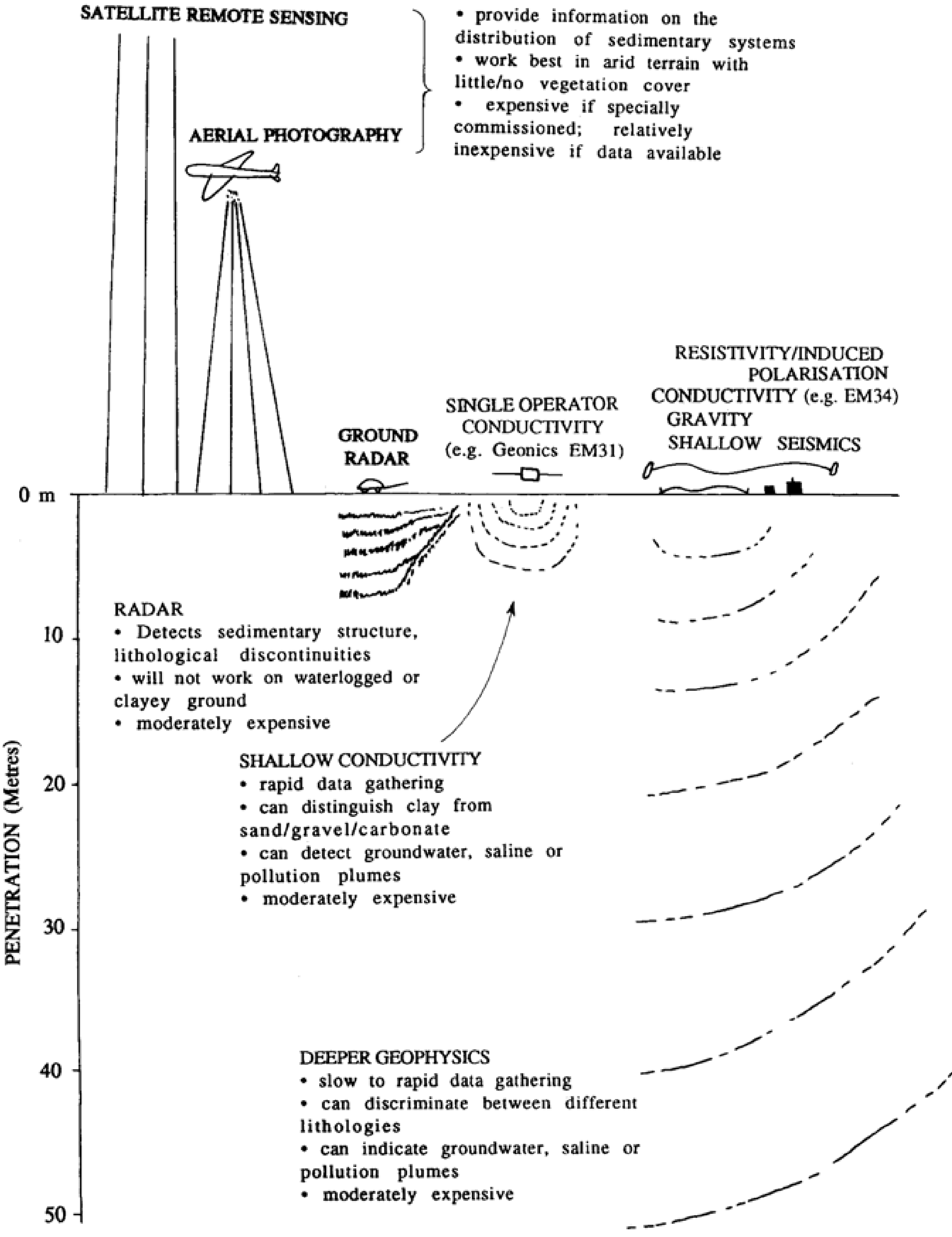
- The use of an appropriate combination of geophysical and direct (drilling, augering) investigative techniques. The shape and composition of sedimentary bodies is reflected in measurable properties such as gravity, electrical conductivity (or resistivity) and acoustic velocity. Thus geophysics can be 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).