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Preface

The first edition of *Coal Geology* has provided the coal geologist and those associated with the coal industry with the background to the origins and characteristics of coal together with exploration techniques including geophysics and hydrogeology. Details of coal mining techniques, resource calculations, alternative uses of coal and environmental issues were also described.

Although broadly following the layout of the first edition, additional information has been added to coal origins, geographical distribution of coal and coal exploration. The chapter on coal resources and reserves has been brought up to date with current resource classifications together with recent world reserves/production figures. The chapter on geophysics of coal has been enlarged and the alternative uses of coal, in particular, methane extraction and underground coal gasification have been expanded to reflect the increase in activity in these areas. Developments in environmental requirements have also been updated.

Again, numerous sources of information have been consulted, the majority of which are listed in the bibliography. International Standards relating to coal, listed in Appendix 1, have been updated and expanded to include P. R. China, India and Russia.

I would like to thank all those colleagues and friends who have helped and encouraged me with the second edition. In particular, special thanks are due to Steve Frankland of Dargo Associates Ltd, Rob Evans for his invaluable help with coal geophysics, Paul Ahner in the USA for providing data on underground coal gasification, and to the following for their contributions and support: Professor Vladimir Pavlovic of Belgrade University, Mike Coulitas, Dave Pearson of Pearson Coal Petrography, Oracle Coalfields plc and Robertson Geologging, as well as the staff at John Wiley & Sons, Ltd.

I also thank those authors and organisations whose permission to reproduce their work is gratefully acknowledged.

Finally I would like to thank my wife Sue for her support, forbearance and assistance with the manuscript.

Larry Thomas
Dargo Associates Ltd
Preface To First Edition

The *Handbook of Practical Coal Geology* (Thomas 1992) was intended as a basic guide for coal geologists to use in their everyday duties, whether on site, in the office or instructing others. It was not intended as a definitive work on all or any particular aspect of coal geology, rather as a handbook to use as a precursor to, or in conjunction with, more specific and detailed works.

This new volume is designed to give both the coal geologist and others associated with the coal industry background information regarding the chemical and physical properties of coal, its likely origins, its classification and current terminology. In addition I have highlighted the currently known geographical distribution of coal deposits together with recent estimates of world resources and production. I have also outlined the exploration techniques employed in the search for, and development of, these coal deposits and the geophysical and hydrogeological characteristics of coal-bearing sequences, together with the calculation and categorisation of resources/reserves.

Chapters are devoted to the mining of coal, to the means of extracting energy from coal other than by conventional mining techniques, and to the environmental concerns associated with the mining and utilisation of coal.

Also covered is the development of computer technology in the geological and mining fields, and the final chapter is a condensed account of the marketing of coal, its uses, transportation and price.

Many sources of information have been consulted, the majority of which are listed in the reference section. A set of appendices contains information of use to the reader.

I would like to thank all those colleagues and friends who have helped and encouraged me with the book from conception to completion. In particular special thanks are due to Steve and Ghislaine Frankland of Dargo Associates Ltd, Alan Oakes, Rob Evans, Dr Keith Ball, Professor Brian Williams, Mike Coultas, Reeves Oilfield Services, IMC Geophysics Ltd, Datamine International and Palladian Publications, as well as the staff at John Wiley & Sons Ltd.

I should also like to thank those authors and organisations whose permission to reproduce their work is gratefully acknowledged.

Finally I would like to thank my wife Sue and my family for their support, encouragement and assistance with the manuscript.

Larry Thomas
Dargo Associates Ltd
1.1 Scope

The object of this book is to provide both geologists and those associated with the coal industry, as well as teachers of courses on coal, its geology and uses, with a background of the nature of coal and its varying properties, together with the practice and techniques required in order to compile geological data that will enable a coal sequence under investigation to be ultimately evaluated in terms of mineability and saleability. In addition, the alternative uses of coal as a source of energy together with the environmental implications of coal usage are also addressed.

Each of these subjects is a major topic in itself, and the book covers only a brief review of each, highlighting the relationship between geology and the development and commercial exploitation of coal.

1.2 Coal geology

Coal is a unique rock type in the geological column, it has a wide range of chemical and physical properties, and has been studied over a long period of time. This volume is intended to be a basic guide to understanding the variation in coals and their modes of origin, and to the techniques required to evaluate coal occurrences.

The episodes of coal development in the geological column (e.g. Carboniferous, Cretaceous, Paleogene and Neogene Periods – note that the Paleogene and Neogene Periods are sometimes referred to collectively as Tertiary) are given together with the principal coal occurrences worldwide. It is accepted that this is not totally exhaustive and that coal does occur in small areas not indicated in the figures or tables.

Current estimates of global resources and reserves of coal together with coal production figures are listed, and although these obviously become dated, they do serve to indicate where the major deposits and mining activity is currently concentrated.

In relation to the extraction of coal, understanding of the geophysical and hydrogeological properties of coals is an integral part of any coal-mine development, and these are reviewed together with the principal methods of mining coal. The increasing use of computer technology has had a profound impact on geological and mining studies. Some of the applications of computers to these are discussed.

An important development in recent years has been the attempts to use coal as an alternative energy source by either removing methane gas from the coal and coal mines in situ, or by liquefying the coal as a direct fuel source, or by underground gasification of coal in situ. These technologies together are particularly significant in areas where conventional coal mining has ceased or where coal deposits are situated either at depths uneconomic to mine, or in areas where mining is considered environmentally undesirable.

1.3 Coal use

The principal uses of traded coals worldwide is for electricity generation and steel manufacture, with other industrial users and domestic consumption making up the remainder.

Lack of environmental controls in the use of coal in the past has led to both land and air pollution as well as destruction of habitat. Modern environmental guidelines and legislation are both repairing the damage of the past and preventing a re-occurrence of such phenomena. An outline is given of the types of environmental concerns that exist where coal is utilized, together with the current position on the improvements in technology in
mining techniques, industrial processes and electricity generation emissions.

The marketing of coal is outlined together with the contractual and pricing mechanisms commonly employed in the coal producer/coal user situation.

1.4 Background

In most industrial countries, coal has historically been a key source of energy and a major contributor to economic growth. In today’s choice of alternative sources of energy, industrialized economies have seen a change in the role for coal.

Originally coal was used as a source of heat and power in homes and industry. During the 1950s and 1960s cheap oil curtailed the growth of coal use, but the uncertainties of oil supply in the 1970s led to a resumption in coal consumption and a rapid growth in international coal trade. This in turn was followed by an increasingly unfavourable image for coal as a contributor to greenhouse gas (GHG) emissions and thus closely identified with global warming. The coal industry has responded positively to this accusation and modern industrial plants have much lower emissions levels than in previous years. Currently coal accounts for 20% of all GHG emissions.

The world consumption of fossil fuels, and thus emissions of CO₂, will continue to increase, and fossil fuels still meet around 90% of primary energy requirements. The objectives of the ‘United Nations Framework Convention on Climate Change’ (UNFCCC) signed at the 1992 Earth Summit in Rio de Janeiro, is to ‘stabilise GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system’. No set levels were identified but emissions in developed countries were expected to be reduced to 1990 levels. A series of annual meetings by the international body under UNFCCC – the Conference of the Parties (COP) – have taken place, notably COP-3 in Kyoto, Japan in 1997, at which the Kyoto Protocol was drawn up, setting emissions targets for all the countries attending. However, Government Ministers at COP-6 in The Hague in November 2000 failed to agree on the way forward to meet the Kyoto Protocol targets. This placed the whole of the Kyoto Protocol’s ambitious and optimistic plan for a global agreement on GHG emissions reduction in an uncertain position (Knapp, 2001). This could be an indication of overambitious goals rather than any failure in the negotiations and it is up to the parties concerned to establish a realistic set of targets for emissions reductions in the future. The Copenhagen Accord in 2009 reinforced the need for emissions reductions together with providing financial assistance to help developing countries cut carbon emissions. It still remains to be seen whether such ambitions can be translated into a binding international agreement.

It remains a fact that many economies still depend on coal for a significant portion of their energy needs. Coal currently accounts for 29% of the world’s consumption of primary energy, and, importantly, coal provides fuel for the generation of around 42% of the total of the world’s electricity. In 2010, traded black coal amounted to 938 Mt of which 676 Mt was steam coal and 262 Mt was coking coal.

Coal reserves are currently estimated to be around 860 billion tonnes, and the world coal reserves to production ratio is nearly six times that for oil, and four times that for natural gas. This, together with the globally democratic distribution and secure nature of coal deposits, will ensure that coal will continue to be a major energy resource for some considerable time to come.

With this scenario in mind, this volume is intended to assist those associated with the coal industry, as well as educationalists and those required to make economic and legislative decisions about coal.

The philosophy and views expressed in this book are those of the author and not the publisher.
2 Origin of Coal

2.1 Introduction

Sedimentary sequences containing coal or peat beds are found throughout the world and range in age from Upper Palaeozoic to recent.

Coals are the result of the accumulation of vegetable debris in a specialized environment of deposition. Such accumulations have been affected by synsedimentary and post-sedimentary influences to produce coals of differing rank and differing degrees of structural complexity, the two being closely interlinked. The plant types that make up coals have evolved over geological time, providing a variety of lithotypes in coals of differing ages.

Remarkable similarities exist in coal-bearing sequences, due for the greater part to the particular sedimentary associations required to generate and preserve coals. Sequences of vastly different ages from geographically separate areas have a similar lithological framework, and can react in similar fashions structurally.

It is a fact, however, that the origin of coal has been studied for over a century and that no one model has been identified that can predict the occurrence, development and type of coal. A variety of models exist which attempt to identify the environment of deposition, but no single one can adequately give a satisfactory explanation for the cyclic nature of coal sequences, the lateral continuity of coal beds, and the physical and chemical characteristics of coals. However, the advent of sequence stratigraphy has recognized the pattern of geological events leading to the different phases of deposition and erosion within coal-bearing sequences.

2.2 Sedimentation of coal and coal-bearing sequences

During the past 35 years, interest has grown rapidly in the study of sedimentological processes, particularly those characteristic of fluviatile and deltaic environments. It is these in particular that have been closely identified with coal-bearing sequences.

It is important to give consideration both to the recognition of the principal environments of deposition, and to the recent changes in emphasis regarding those physical processes required, in order to produce coals of economic value. In addition, understanding of the shape, morphology and quality of coal seams is of fundamental significance for the future planning and mining of coals. Although the genesis of coal has been the subject of numerous studies, models that are used to determine the occurrence, distribution and quality of coal are often still too imprecise to allow accurate predictions.

2.2.1 Depositional models

The recognition of depositional models to explain the origin of coal-bearing sequences and their relationship to surrounding sediments has been achieved by a comparison of the environments under which modern peats are formed and ancient sequences containing coals.

Cecil et al. (1993) suggest that the current models often concentrate on the physical description of the sediments associated with coal rather than concentrating on the geological factors that control the genesis of coal beds. They also suggest that models that combine sedimentation and tectonics with eustasy and chemical change have not yet been fully developed. Such integrated models would give an improved explanation of physical and chemical processes of sedimentation. It should be noted that the use of sequence stratigraphy in facies modelling is based on physical processes and does not take into account chemical stratigraphy. This will prove a deficiency when predicting the occurrence and character of coal beds.

The traditional depositional model used by numerous workers was based on the ‘cyclothem’, a series of lithotypes occurring in repeated ‘cycles’. This concept has been modified to a model that relates lateral and vertical...
sequential changes to depositional settings that have been recognized in modern fluvial, deltaic and coastal barrier systems. The traditional model is based on the work carried out in the United States by Horne (1979), Horne et al. (1978, 1979), Ferm (1979), Ferm et al. (1979), Ferm and Staub (1984), Staub and Cohen (1979) in a series of studies in the 1970s. The sequences or lithofacies are characterized by the sedimentary features listed in Table 2.1. Other workers include Thornton (1979) and Jones and Hutton (1984) on coal sequences in Australia, and Guion, Fulton and Jones (1995) in United Kingdom.

Table 2.1  Sedimentary features used to identify depositional environments.

<table>
<thead>
<tr>
<th>Recognition characteristics</th>
<th>Fluvial and upper delta plain*</th>
<th>Transitional lower delta plain*</th>
<th>Lower delta plain*</th>
<th>Back-barrier*</th>
<th>Barrier*</th>
</tr>
</thead>
<tbody>
<tr>
<td>I Coarsening upwards</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A Shale and siltstone</td>
<td>2–3</td>
<td>2</td>
<td>1</td>
<td>2–1</td>
<td>3–2</td>
</tr>
<tr>
<td>sequences &gt; 15.24 m (&gt;50 ft)</td>
<td>4</td>
<td>3–4</td>
<td>2–1</td>
<td>2–1</td>
<td>3–2</td>
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<tr>
<td>1.524–7.62 m (5–25 ft)</td>
<td>2–3</td>
<td>2–1</td>
<td>2–1</td>
<td>2–1</td>
<td>3–2</td>
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<tr>
<td>B Sandstone sequences</td>
<td>3–4</td>
<td>3–2</td>
<td>2–1</td>
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<td>&gt; 15.24 m (&gt;50 ft)</td>
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<td>1.524–7.62 m (5–25 ft)</td>
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<td>3–2</td>
<td>2–1</td>
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<tr>
<td>II Channel deposits</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>A Fine grained abandoned</td>
<td>3</td>
<td>2–3</td>
<td>1–2</td>
<td>2</td>
<td>3–2</td>
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<tr>
<td>fill</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Clay and silt</td>
<td>3</td>
<td>2–3</td>
<td>1–2</td>
<td>2</td>
<td>3–2</td>
</tr>
<tr>
<td>Organic debris</td>
<td>3</td>
<td>2–3</td>
<td>1–2</td>
<td>2–3</td>
<td>3</td>
</tr>
<tr>
<td>B Active channel sandstone</td>
<td>1</td>
<td>2</td>
<td>2–3</td>
<td>2–3</td>
<td>2</td>
</tr>
<tr>
<td>fill</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Fine grained</td>
<td>2</td>
<td>2</td>
<td>2–3</td>
<td>2–3</td>
<td>2</td>
</tr>
<tr>
<td>Medium and coarse</td>
<td>1</td>
<td>2–3</td>
<td>3</td>
<td>3</td>
<td>2–3</td>
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<tr>
<td>grained</td>
<td></td>
<td></td>
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<td></td>
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<td>Pebble lags</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2–3</td>
<td>3–2</td>
</tr>
<tr>
<td>Coal spars</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2–3</td>
<td>3–2</td>
</tr>
<tr>
<td>III Contacts</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abrupt (scour)</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2–1</td>
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<tr>
<td>Gradational</td>
<td>2–3</td>
<td>2</td>
<td>2–1</td>
<td>2</td>
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</tr>
<tr>
<td>IV Bedding</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Cross beds</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1–2</td>
<td>1–2</td>
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<tr>
<td>Ripples</td>
<td>2</td>
<td>2–1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>Ripple drift</td>
<td>2–1</td>
<td>2</td>
<td>2–3</td>
<td>3–2</td>
<td>3–2</td>
</tr>
<tr>
<td>Trough cross-beds</td>
<td>1</td>
<td>1–2</td>
<td>2–1</td>
<td>2</td>
<td>2–1</td>
</tr>
<tr>
<td>Graded beds</td>
<td>3</td>
<td>3</td>
<td>2–1</td>
<td>3–2</td>
<td>3–2</td>
</tr>
<tr>
<td>Point-bar accretion</td>
<td>1</td>
<td>2</td>
<td>3–4</td>
<td>3–4</td>
<td>3–4</td>
</tr>
<tr>
<td>Irregular bedding</td>
<td>1</td>
<td>2</td>
<td>3–2</td>
<td>3–2</td>
<td>3–2</td>
</tr>
<tr>
<td>V Levee deposits</td>
<td>Irregularly interbedded sandstones and shales, rooted</td>
<td>1</td>
<td>1–2</td>
<td>3–2</td>
<td>3</td>
</tr>
<tr>
<td>VI Mineralogy of sandstones</td>
<td>Lithic greywacke</td>
<td>1</td>
<td>1</td>
<td>1–2</td>
<td>3</td>
</tr>
<tr>
<td>Orthoquartzite</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3–4</td>
<td>1–2</td>
</tr>
<tr>
<td>VII Fossils</td>
<td>Marine</td>
<td>4</td>
<td>3–2</td>
<td>2–1</td>
<td>1–2</td>
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<tr>
<td>Brackish</td>
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<td>3</td>
<td>2</td>
<td>2–3</td>
<td>3–2</td>
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<tr>
<td>Fresh</td>
<td>2–3</td>
<td>3–2</td>
<td>3–4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Burrow</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

*1, abundant; 2, common; 3, rare; 4, not present.
Source: from Horne et al. (1979).
More recent studies have compared such established depositional models with modern coastal plain sedimentation, for example in equatorial Southeast Asia, and have concentrated in particular on modern tropical peat deposits: Cecil et al. (1993), Clymo (1987), Gastaldo, Allen and Huc (1993), McCabe and Parrish (1992). Studies by Hobday (1987), Diessel et al. (1992), Lawrence (1992), Jerzykiewicz (1992), Dreesen et al. (1995), Cohen and Spackman (1972, 1980), Flint, Aitken and Hampson (1995) and McCabe (1984, 1987, 1991) have all further developed the model for coal deposits of differing ages, using the traditional model but relating it to modern sedimentary processes.

In parallel with this work, detailed studies of peat mires have both raised and answered questions on the development of coal geometry, that is thickness and lateral extent, together with the resultant coal chemistry. The traditional model is still a basis for modern coal studies, but linked to a better understanding of peat development and preservation.

2.2.2 The traditional model

2.2.2.1 Coastal barrier and back barrier facies

The coastal end of the depositional model is characterized by clean barrier sandstones, which, in a seaward direction become finer grained and intercalate with red and green calcareous shales and carbonate rocks, the latter containing marine faunas. Landwards they grade into dark grey lagoonal shales with brackish water faunas, and into marginal swamp areas on which vegetation was established. The barrier sandstones have been constantly reworked and are therefore more quartzose than those sandstones in surrounding environments with the same source area.

They exhibit a variety of bedding styles: first, extensive sheets of plane-bedded sandstones with rippled and burrowed upper surfaces, interpreted as storm washover sands; second, wedge-shaped bodies that extend landward, can attain thicknesses of up to 6 m, and contain landward dipping planar and trough cross-beds, interpreted as floodtide delta deposits; and third, channel-fill sandstones which may scour to depths of over 10 m into the underlying sediments, interpreted as tidal channel deposits.

A depositional reconstruction is shown in Figure 2.1a based on studies by Horne et al. (1979).

The lagoonal back-barrier environment is characterized by upwards coarsening, organic-rich grey shales and siltstones overlain by thin and discontinuous coals. This sequence exhibits extensive bioturbation zones, together with bands and concretions of chemically precipitated iron carbonate (sideritic ironstone). The extent of such sequences is considered to be in the order of 20–30 m in thickness and 5–25 km in width. A typical vertical sequence of back barrier deposition is shown in Figure 2.1b.

2.2.2.2 Lower delta plain facies

Lower delta plain deposits are dominated by coarsening upwards sequences of mudstone and siltstone, ranging from 15 to 55 m in thickness, and 8–110 km in lateral extent. The lower part of these sequences are characterized by dark grey to black mudstones with irregularly distributed limestones and siderite (Figure 2.2a).

In the upper part, sandstones are common, reflecting the increasing energy of the shallow water as the bay fills with sediment. Where the bays have filled sufficiently to allow plant growth, coals have formed. Where the bays did not fill completely, bioturbated, siderite-cemented sandstones and siltstones have formed.

This upwards coarsening pattern is interrupted in many areas by crevasse-splays Figure 2.2b. In American Carboniferous rocks, crevasse-splay deposits can be 10+ m in thickness and 30 m to 8 km wide.

In many cases, a transitional lower delta plain sequence is characteristic, featuring alternations of channel, inter-distributary bay and crevasse-splay deposits: a depositional reconstruction is shown in Figure 2.3a, and generalized vertical sequence in Figure 2.3b.

Overlying and laterally equivalent to the bay-fill sequences are thick lithic sandstones up to 25 m in thickness and up to 5 km in width. These are interpreted as mouth bar deposits of distributary channels, they are widest at the base and have gradational contacts. They coarsen upwards and towards the middle of the sand body. In some places, fining upwards sequences are developed on top of the distributary mouth bar and bay-fill deposits. These distributary channel-fill deposits have an irregular sharp basal contact, produced by scouring of the underlying sediments. At the base, pebble and coal-fragment lag deposits are common.

Because of the rapid abandonment of distributaries, fine-grained mudstone fills are common in lower delta plain deposits. They represent silt and organic debris that has settled from suspension in the abandoned distributary. In some areas, thick organic accumulations filled these channels, resulting in the formation of lenticular coals. Apart from those formed in the
Figure 2.1 (a) Barrier and back-barrier environments including tidal channels and flood-tidal deltas, based on exposures in Kentucky, United States. (From Horne et al., 1979.) (b) Generalized vertical section through back-barrier deposits in the Carboniferous of eastern Kentucky, United States. (From Horne et al., 1979.)
Coal
Seat earth, clayey
Sandstone, fine to medium grained
Multi-directional planar and
Festoon cross beds
Sandstone, fine grained, rippled
Sandstone, fine grained, graded beds
Sandstone, flow rolls
Sandstone, fine grained, flaser bedded
and siltstone

Silty shale and siltstone with calcareous
Concretions, thin-bedded, burrowed
Occasional fossil

Clay shale with siderite bands, burrowed
Fossiliferous

**Figure 2.2** Generalized vertical sequences through lower delta plain deposits in eastern Kentucky, United States. (a) Typical coarsening-upward sequence. (b) Same sequence interrupted by crevasse-splay deposits. (From Horne et al., 1979.)
Figure 2.3 (a) Reconstruction of transitional lower delta plain environments in Kentucky, United States. (From Horne et al., 1979.) (b) Generalized vertical sequence through transitional lower delta plain deposits of eastern Kentucky and southern West Virginia, United States. (From Horne et al., 1979.)
abandoned channels, coals are generally relatively thin and widespread. Such coals are oriented parallel to the distributary patterns.

2.2.2.3 Upper delta and alluvial plain facies

In contrast to the thick fine-grained sequences of the lower delta plain facies, upper delta plain deposits are dominated by linear, lenticular sandstone bodies up to 25 m thick and up to 11 km wide. These sandstones have scoured bases and pass laterally in the upper part into grey shales, siltstones and coals. The sandstones fine upwards with abundant pebble conglomerates in the lower part that include coal clasts. The sandstones are characterized by massive bedding and are overlain by siltstones.

These sandstone bodies widen upwards in cross-section and are considered to have been deposited in the channels and on the flanks of streams that migrated across the upper delta plain, see Figure 2.4a. Coal seams in the upper delta plain facies may be 10 m in thickness, but are of limited lateral extent. Figure 2.4b illustrates a vertical sequence of upper delta plain facies from eastern Kentucky and southern West Virginia, United States.

Between the upper and lower delta plains, a transition zone exhibits characteristics of both sequences. This zone consists of a widespread platform on which peat mires are formed. This platform is cut by numerous channels and the sequence is disrupted by crevasse-splay deposits. The coals formed on the platform are thicker and more widespread than the coals of the lower delta plain: such a sequence is shown in Figure 2.3b.

2.2.3 Modern peat analogues

The principal characteristics of a coal are its thickness, lateral continuity, rank, maceral content and quality. Apart from rank, which is governed by burial and subsequent tectonic history, the remaining properties are determined by factors controlling the mire where the peat originally formed. These factors include, type of mire, type(s) of vegetation, growth rate, degree of humification, base-level changes and rate of clastic sediment input (McCabe and Parrish, 1992).

About 3% of the earth’s surface is covered by peat, totalling 310 million hectares (WEC, 1998). This includes the tropical peats (>1 m thick) of South-east Asia which cover almost 200,000 km².

During the last 15 years, numerous studies have attempted to understand more fully how peat producing wetlands or mires are developed and maintained, and in particular how post-depositional factors influence the formation of coals.

Diesel (1992) divides peat producing wetlands into ombrogenous peatlands or mires (owing their origin to rainfall), and topogenous peatlands (owing their origin to a place and its surface/groundwater regime). A great variety of topogenous peats form when waterlogging of vegetation is caused by groundwater, but ombrogenous peats are of greater extent but less varied in character.

Based on this distinction, Diesel (1992) gives a classification of peatlands or mires as shown in Table 2.2. This is illustrated in Figure 2.5, which shows the relationship between ombrotrophic and rheotrophic mires in terms of the influence of rainwater and groundwater in their hydrological input. The inorganic content of mires is seen to increase in the topogenous, rheotrophic mires.

The classification of the two hydrological categories of mire lists a number of widely used terms. Moore (1987) has defined a number of these.

**Mire** is now accepted as a general term for peat-forming ecosystems of all types.

**Bog** is generally confined to ombrotrophic peat-forming ecosystems.

**Bog forest** consists of ombrotrophic forested vegetation, usually an upper storey of coniferous trees and a ground layer of *Sphagnum* moss.

**Marsh** is an imprecise term used to denote wetlands characterized by floating vegetation of different kinds including reeds and sedges, but controlled by rheotrophic hydrology.

**Fen** is a rheotrophic ecosystem in which the dry season water table may be below the surface of the peat.

**Swamps** are a rheotrophic ecosystem in which the dry season water table is almost always above the surface of the sediment. It is an aquatic ecosystem dominated by emergent vegetation.

**Floating swamps** develop around the fringes of lakes and estuaries and extend out over open water. These platforms can be thick and extensive particularly in tropical areas.

**Swamp forest** is a specific type of swamp in which trees are an important constituent, for example mangrove swamps.

The resultant characteristics of coals are primarily influenced by the following factors during peat formation: type of deposition, the peat-forming plant communities, the nutrient supply, acidity, bacterial activity, temperature and redox potential.
Figure 2.4 (a) Reconstruction of upper delta plain–fluvial environments in Kentucky, United States. (From Horne et al., 1979.) (b) Generalized vertical sequence through upper delta plain–fluvial deposits of eastern Kentucky and southern West Virginia, United States. (From Horne et al., 1979.)
Table 2.2 Classification of mires.

<table>
<thead>
<tr>
<th>Peatlands (Mires)</th>
<th>Topogenous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ombrogenous</td>
<td>Mineralotrophic = mineral fed</td>
</tr>
<tr>
<td>Ombrotrophic = rain fed</td>
<td>Rheotrophic = flow fed</td>
</tr>
<tr>
<td>Oligotrophic = poorly fed</td>
<td>Eutrophic = well fed</td>
</tr>
</tbody>
</table>

Raised bog
- Sphagnum bog
- Bog forest

Tree cover increases
- Marsh
- Fen
- Swamps
- Floating swamps
- Swamp forest

Transitional or mixed mires
- Mesotrophic

Source: adapted from Diessel (1992).

Figure 2.5 Proposed relationship between mires in terms of the relative influence of rainwater and groundwater in their hydrological input. (Moore, 1987.)

In order for a mire to build up and for peat to accumulate, the following equation must balance:

\[
inflow + \text{precipitation} = \text{outflow} + \text{evapotranspiration} + \text{retention}.\]

The conditions necessary for peat accumulation are therefore a balance between plant production and organic decay. Both are a function of climate, plant production and organic decay, and such decay of plant material within the peat profile is known as humification. The upper part of the peat profile is subject to fluctuations in the water table and is where humification is most active. The preservation of organic matter requires rapid burial or anoxic conditions (McCabe and Parrish, 1992), the latter being present in the waterlogged section of the peat profile. In addition, an organic-rich system will become anoxic faster than an organic-poor one as the decay process consumes oxygen. This process is influenced by higher temperatures, decay rates being fastest in hot climates.
Rates of humification are also affected by the acidity of the groundwater, as high acidity suppresses microbial activity in the peat.

Peat formation can be initiated by:

1. terrestrialization, which is the replacement of a body of water (pond, lake, lagoon, interdistributary bay) by a mire;
2. paludification, which is the replacement of dry land by a mire, for example due to a rising groundwater table.

As peat is relatively impermeable, its growth may progressively impede drainage over wide areas, so that low-lying mires may become very extensive. In those areas where annual precipitation exceeds evaporation, and where there are no long dry periods, a raised mire may develop. Such mires are able to build upwards because they maintain their own water table. The progression of a peat-forming environment from the infilling of a water course or lake, to a low-lying mire and finally to a raised mire should produce zonation in the peat accumulated, as shown in Figure 2.6.

Depositional models may show peat formation adjacent to and intercalated with areas of active clastic deposition. Such peats accumulating on interchannel areas on the delta plain may be disrupted by clastic contamination from crevasse-splays or by subsidence of the interchannel area resulting in submergence of the peat, cessation of peat development and clastic influx. Sediment may also be introduced into low-lying mires by floods, storm surges or exceptionally high tides. The overall result of clastic contamination is an increase in the ash content of the peat. Also inundation of mires by aerated waters helps to degrade the peat and enrich it with inorganics.

Basin subsidence combined with ombrogenous peat accumulation such that the rise in the peat surface continues to outstrip the rate of subsidence will lead to

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**Figure 2.6** Evolutionary sequence of swamp types showing the development of a raised swamp with distinct peat zonations. (From McCabe (1984), by permission of Blackwell Scientific Publications.)
the formation of thick and clean (low mineral matter content) coals (McCabe, 1984). Low-ash coals therefore must have formed in areas removed or cut off from active clastic deposition for long periods of time, for example centuries. Partings in coals, such as mudstone indicate the interruption of peat formation and may represent intervals of thousands of years.

For a thick peat layer to form in a topogenous setting it is essential that the rise in the water table and the rate of peat accumulation are balanced. In the case of a slower rise in water level, peat accumulation could be terminated by oxidation but in a very wet climate peat formation might continue under high moor conditions. Actual rates of peat accumulation or accretion vary in different climates and with the type of vegetation. Assuming a compaction ratio of 10:1 (Ryer and Langer, 1980) to operate in the transition from peat to bituminous coal, and considering that some of the coal seams are tens of metres thick, optimum peat-forming conditions must therefore require the maintenance of a high groundwater table over very long periods of time, that is 5–10 kyr for every metre of clean bituminous coal.

As peat accumulation is regulated by temperature and precipitation, tropical and subtropical regions are well suited for large-scale peat development, where rates of decay are higher. Most modern peats are situated in low terrains not far above sea level. However, even in conditions of slow plant accumulation, peat can still develop in large quantities. Diessel (1992) quotes evidence that most Gondwana coal deposits were formed under cool to temperate conditions, whereas the European Paleogene–Neogene coal formations began in tropical conditions in the Eocene, changing to temperate conditions in the Miocene.

A number of peat types have been summarized by Diessel (1992) as:

1. fibrous or woody peat which shows the original plant structures only slightly altered by decay and may include branches, trunks and roots of trees;
2. pseudo-fibrous peat, comprised of soft plastic material;
3. amorphous peat, in which the original structure of the plant’s cell tissue has been destroyed by decomposition, resulting in a fine organic plastic mass;
4. intermediate forms of peat consisting of more resistant elements set in an altered matrix.

Mixed peats are alternating layers of fibrous peat and amorphous peat. However, these types can display overlapping characteristics dependent upon types of vegetation and mire setting.

In contrast to the traditional depositional model, studies of modern environments suggest that significant areas of low-ash peats are not present on delta plains, and that most mires on coastal or floodplain areas are not sites of true peat accumulation. The exception appears to be those areas where raised mires have developed. Floating mires may also produce low-ash peats, but these are thought generally to be of limited extent. Examination of modern delta plain peats show that they have an ash content of over 50% on a dry basis, and that peats with less than 25% ash on a dry basis rarely exceed 1 m in thickness. These peats if preserved in the geological record would form carbonaceous mudstones with coaly stringers.

Studies of raised mires indicate that ash levels can be less than 5%, and over large areas may be as low as 1–2%. Rates of organic accumulation in raised mires outstrip rates of sedimentation from overbank or tidal flooding. However, although some low-ash coals have doubtless originated as products of raised mires, many coals are thought to have formed under palaeoclimates unsuitable for raised mire development. One suggestion is that low-ash coals originated as high-ash peats and were depleted in ash during the coalification process. Acidic waters may hasten the dissolution of many minerals, but not all mires are acidic and some may even contain calcareous material. Another concept is that peat accumulation was not contemporaneous with local clastic deposition, suggesting that resulting coals are distinct from the sediment above and below the coal. Those areas of the mire that have been penetrated by marine waters may be identified in the resultant coal by high sulfur, hydrogen and nitrogen contents.

As a corollary to the mechanism of clastic contamination of peats, those raised mires that are able to keep pace with channel aggradation could confine the fluvial sediments to defined narrow courses. If this is so, the presence of thick peats could influence the depositional geometry of adjacent clastic accumulations (Figure 2.7).

The majority of coals are developed from plants that have formed peat close to where they grew. Such coals are underlain by seat earths or rootlet beds, and are known as autochthonous coals. However, coals that have formed from plant remains which have been transported considerable distances from their original growth site are known as allochthonous coals. These coals have formed under palaeoclimates unsuitable for raised mire development. Allochthonous coals do not have an underlying rootlet bed, but rest directly on the bed below. In the Cooper Basin, South Australia, thick Gondwana (Permian) coals show evidence of both autochthonous and allochthonous deposition. The allochthonous coals are closely associated with lacustrine
2.2.3.1 Palaeobotanical composition of ancient mires

The petrographic composition of a coal seam is genetically linked to the composition of its ancestral peat deposit. This is determined by the kinds of peat-forming plants and the biochemical conditions under which they were converted to peat.

Cellulose, pectin and lignin form the bulk of material contained in plant cells and are therefore significant contributors to the composition of a coal seam.

The plant communities that make up the composition of peat have changed and evolved over geological time. Land plants first appeared in the Early Devonian, and are significant in becoming life forms on land rather than in water, although most began in swampy environments. The carbonaceous shales of Emsian age (Early Devonian) found in the Eifel (Germany) contain thin layers of vitrinite derived from land plants (Diessel, 1992). Coal accumulation reached a peak in the Carboniferous Period in the Northern Hemisphere. This was a period of slow and repeated subsidence in tectonic basinal settings. The lycans predominated plant group was the pteridophytes consisting of lycopsids (lycopods), sphenopsids (horsetails) and pteropsids (true ferns). These are all wetland plants with shallow root systems susceptible to changes in the groundwater levels. A drop in groundwater level resulted in such vegetation dying back, and this accounts for the numerous thin stringers and bands of coal found throughout the Carboniferous coal measures of Europe. Collinson and Scott (1987) described those plant features which influence peat formation as being anchoring systems, reproductive biology, leaf and shoot biology and the detailed structure of woody axes. The lycans were not a diverse group, and had a poorly developed root system, of which *Stigmaphyllon* is an example. Other associated forms had root systems for which details are poorly known. The lycans reproduced using the heterosporous technique, that is the ability to produce both megaspores and microspores, for example *Lepidocarpon* and *Sigillaria*, whereas some ferns were homosporous producing only one kind of spore. All of these groups are thought to have had difficulty surviving in drier environments. Raymond *et al.* (2010) examined *ordaieteans* from the Carboniferous of the United States. These are an extinct group of gymnosperm trees and shrubs characterized by large strap leaves and woody stems and were seed bearing; their nearest living relatives are the modern conifers. Plants in *Cordiates*-dominated peats probably grew in coastal mires in climate zones with seasons of low rainfall. Some authors interpret such *Cordiates*-rich peats as indicative of mangrove habitats.

Zhao and Wu (1979) examined Carboniferous macrofloras from South China and established a *Lepidodendron gaolishense*–*Eolepidodendron* assemblage for the early Carboniferous, and *Neuropteris gigantea*–*Mariopteris acuta f. obtusa* assemblage for the middle Carboniferous. The Late Carboniferous is represented by transgressive marine strata with no plant content. Wang (2010) studied the Late Palaeozoic (Carboniferous–Permian) macrofossil assemblages in the Weibei Coalfield, Central Shaanxi Province, China. Four floral assemblages were established, each reflecting the impact of climate changes, the so-called ‘ichouse–greenhouse’ climatic changes (Gastaldo, Dimichele and Pfefferkorn, 1996). Within these assemblages, some plant types are present throughout the period, for example, species of *Lepidodendron*, *Stigmaphyllon*, *Sphenophyllum*, *Calamites* and *Cordiates* (Figure 2.8) as well as forms of *Pecopteris*.
and Neuropteris. Correlation of these Cathaysian floras with Euroamerican floras is still problematic, this is in part influenced by the very nature of sedimentation in peat-forming areas, creating the persistent problem of difficulties in correlation between chronostratigraphic and lithostratigraphic units.

Bartram (1987) studied the distribution of megaspores (Figure 2.9) and the relationship to coal petrology using the Low Barnsley Seam (Westphalian B) from Yorkshire, United Kingdom. Six megaspore phases were recognized within the Barnsley Seam that suggested a floral progression with changing environment (Figure 2.10). However,