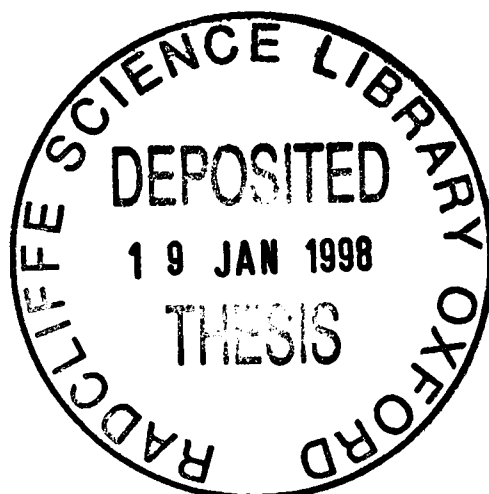


Thesis submitted for the degree of Doctor of Philosophy

*Early to Middle Jurassic
stratigraphic development, vegetation
and climate change in north-western
Europe*

by

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Abstract

The aim of work presented in this thesis was to explore the inter-relationships of cyclic sedimentation, relative sea-level change, and palaeoclimate as inferred from plant megafossils. To this end, the investigation focused on the classic plant-bearing Middle Jurassic succession of Yorkshire.

The Middle Jurassic (Aalenian-Bathonian) Ravenscar Group of the Cleveland Basin (Yorkshire) comprises a predominantly fluvio-deltaic succession intercalated between thinner, laterally persistent marine units. There is a pronounced lateral facies change across the basin, from mainly alluvial sediments in the north to more marine deposits in the south. Although variable in character, the facies composing the sequence are described by four principal environments of deposition: alluvial, estuarine, lagoonal and marine. In an attempt to achieve a more accurate stratigraphic control on the succession, sequence-stratigraphic concepts are applied to outcrop exposures and subsurface cores. The identification of 'key surfaces' in the sequence resolves a series of lithological cycles which reflect relative sea-level fluctuations. Using this approach the Aalenian-Bathonian sequence can be subdivided into two large-scale (second-order) transgressive-regressive cycles onto which six medium-scale (third-order) cycles of transgression and regression are superimposed. The potential for correlating these lithological cycles regionally has been assessed by comparing coeval sections from southern Scandinavia. Plant-bearing fluvio-deltaic sequences from Bornholm and Scania were chosen as a means for appraising the lateral continuity of the cycles, and assessing what factors might have controlled their development.

Study of floral remains from the Ravenscar Group within the context of this stratigraphic framework yields valuable palaeoclimatic information. Growth-ring analysis of fossil wood of Late Pliensbachian to Late Bathonian age indicates a distinctly seasonal climate with low to moderate interseasonal variation in tree growth. Significant intraseasonal influences on wood production are implicit in the abundance of false rings. Consideration of these results within a stratigraphic context suggests that conditions during the Bathonian were comparatively hostile: a finding which is interpreted to be due to more frequent and extended water shortages associated with a drier climate. These palaeoclimatic inferences are substantiated by evidence obtained from the examination of the flora using Correspondence Analysis (CA). This approach verifies the presence of a temporal fluctuation in the flora found by previous investigations and, furthermore, highlights physiognomic trends in the flora with time. The results from CA also indicate adverse growing conditions during the Bathonian, emphasized by the prevalence of xeromorphic taxa.

Early to Middle Jurassic stratigraphic development, vegetation and climate change in north-western Europe

Helen Sarah Morgans

Long abstract

In order to investigate Early to Middle Jurassic stratigraphic development, vegetation and climate change in north-western Europe, a fully integrative stratigraphical, sedimentological and palaeobotanical study of the Middle Jurassic Ravenscar Group of the Cleveland Basin (Yorkshire) has been undertaken. This sequence was chosen as a basis for this study because (1) it comprises a predominantly fluvio-deltaic succession which is cyclic on a small-, medium- and large-scale, and (2) it contains a diverse and abundant flora from which meaningful palaeoclimatic data can potentially be obtained. To the findings gained from this investigation, coeval sections from Scandinavia are compared. Examination of the stratigraphies of Bornholm and Scania reveals the regional pervasiveness of the lithological cycles identified in Yorkshire, and aids an assessment of the controls on their development.

The Ravenscar Group attains a maximum thickness of some 250 m and is best exposed along the Yorkshire coast where the full extent of the sequence can be examined clearly. The group is composed predominantly of fluvio-deltaic sediments which are intercalated between thinner marine units. The lithologies which comprise these deposits are very diverse and vary considerably in a lateral sense: on a large scale, alluvial sediments predominate in the north of the basin, and marine deposits to the south. Despite this variability, fieldwork showed that separate facies types can be distinguished on the basis of lithology, sedimentary structures, grain size, presence of rootlets and plant material, and occurrence of marine body fossils and trace fossils. As a result, four principal depositional environments are identified within the sequence, which represent alluvial, estuarine, lagoonal and marine settings that comprise eighteen different facies in all. The alluvial facies association includes five individual facies types and volumetrically forms the most important part of the succession. Alluvial sediments can be divided into those which were deposited as part of a fluvial channel and those which were laid down in an overbank environment. Facies pertaining to the overbank setting display the greatest diversity, including crevasse-splay, lacustrine, poorly drained and well-drained environments.

Compared to the alluvial deposits, estuarine, lagoonal and marine facies associations constitute a lesser proportion of the sequence. Estuarine deposits are relatively few and are confined to the Long Nab Member of the Scalby Formation. Only two facies are identified as being estuarine in type, characterized by the presence of bi-polar cross-bedded sands, reactivation surfaces, flaser bedding, abundance of mud-grade sediment and intense bioturbation. Tidal

channel and channel mouth-bar depositional environments are suggested on the presence of these features. Overall, estuarine sediments precede or succeed marine intervals in the Ravenscar Group. Lagoonal facies are closely associated with both estuarine and marine beds, and are distinguished by their predominantly argillaceous character, marine microplankton content, and association with rootlets and fragmentary plant material. As a whole, the facies are interpreted as representing interdistributary bay, restricted brackish bay, and coastal facies environments. Marine deposits comprise the most diverse facies, including eight different types. Their commonly calcareous nature, rippled or cross-laminated character, presence of marine fauna and trace-fossil assemblages diagnose these sediments from estuarine and lagoonal varieties. Sediments deposited within the marine realm generally make up the lower portions of transgressive phases and sharply overlies alluvial deposits. They are in turn commonly overlain by estuarine and lagoonal sediments. Marine facies wholly compose the Millepore Bed, and the Eller Beck and Scarborough Formations.

In an attempt to achieve a more accurate stratigraphic control on the siliciclastic and subordinate carbonate deposits which form the Ravenscar Group and underlying Dogger Formation, sequence-stratigraphic concepts have been applied to the succession. In combination with the conclusions drawn from the arrangement of sedimentary facies within the sequence, the identification of 'key surfaces' has allowed lithological cycles to be recognized on a series of levels. Key surfaces correspond to comparatively short-lived periods during which relative sea level significantly altered: the surfaces can be summarized as unconformities, transgressive surfaces, and maximum-flooding surfaces. This approach has enabled the stratigraphic interval in question to be successfully subdivided into two large-scale cycles onto which six medium-scale cycles are superimposed. Judging by the temporal extent of these cycles, it is probable that the large-scale examples correspond to second-order cycles (*c.* 3-10 m.y.) and the medium-scale examples relate to third-order cycles (*c.* 0.5-3 m.y.). From regional mapping of these depositional sequences it is clear that both sets of cycles can be correlated intrabasinally. However, in order to investigate the possibility of interbasinal correlation, a comparison with coeval successions is made.

Lower and Middle Jurassic successions of Bornholm and Scania were chosen as a means for appraising the lateral continuity of the lithological cycles found in the Cleveland Basin (and it was also hoped that palaeoclimatic data might be obtained from the fossil plants). The sedimentary sequences under scrutiny are broadly similar in character to the Ravenscar Group in that they comprise a predominantly non-marine, plant-bearing succession, within which lithological cycles on a variety of scales occur. Until now, a detailed comparison of these successions with the Yorkshire sequence has not yet been carried out and so, in order to achieve this goal, fieldwork was undertaken to obtain a complete as lithological succession as possible. As a result of this work, it was found that the stratigraphic development of the Yorkshire and

the Scandinavian basins are broadly congruent. In all, five second-order cycles (spanning the Hettangian-Bathonian) are recognized, which compare well in character and stratigraphic extent with those previously identified in Yorkshire. Third-order cycles are not as clearly developed, preventing correlation of those found in the Ravenscar Group. Their apparent absence may, however, be a product of the rather poor biostratigraphic control available on Bornholm, and the somewhat isolated and discontinuous nature of the exposure. Based upon the regionally pervasive aspect to the second-order cycles, and the more restricted extent of the third-order cycles, inferences have been made as to the possible controls on their formation.

Collection of plant material from within the stratigraphic framework constructed for the Ravenscar Group has allowed accurate palaeoclimatic information to be obtained from the rich and diverse flora. Acquisition of palaeoclimatic data from the succession entails two separate approaches: the first involves growth-ring analysis of fossil wood, and the second is based on examination of the flora using a statistical treatment known as Correspondence Analysis (CA). As a result of this work, a temporal fluctuation in the flora has been noted, which may relate to palaeoclimatic change.

Apart from noting the presence of growth rings, previous studies of fossil wood from Yorkshire have been confined to their examination for the purposes of taxonomic classification. In light of this, a collection was made of wood ranging from the Late Pliensbachian to Late Bathonian from which palaeoclimatic information could potentially be gleaned. After detailed anatomical investigation and comparison, the wood specimens were assigned to five genera of Mesozoic coniferous wood (*Cupressinoxylon* spp., *Taxodioxygen* spp., *Cedroxylon* spp., *Xenoxylon* and *Araucarioxylon*). In two cases, samples were identified to species level (*Xenoxylon phyllocladoides* and *Araucarioxylon lindlei*). In the context of this stratigraphic and taxonomic information, the growth rings of the wood were analysed.

Growth-ring characteristics which are argued to be a function of climate include their presence or absence, ring width, interannual variability of ring width, the presence of false rings, and ratio of earlywood to latewood. This method of obtaining climatic information has been successfully used in previous investigations and forms the basis for this study. Most notably, growth-ring analysis shows that the climate during the Pliensbachian-Bathonian interval was markedly seasonal, with a low to moderate interseasonal variation in wood production. Intraseasonal variations in wood growth are evidenced in the abundance of false rings. These findings provide a high-resolution record of fluctuations in growing conditions during the Jurassic in Yorkshire, from which we can infer environmental or palaeoclimatic changes. Perhaps most important is the evidence for an accentuated annual dry spell and comparatively stressed growing environment during the Bathonian: wood specimens from the Scalby Formation display narrow rings of variable width, an only narrow latewood zone with a sharp

transition from the earlywood, and an abundance of false rings. This environmental change towards the Bathonian is inferred to be associated with a significant fall in relative sea level.

The possible change in growing conditions towards the Bathonian is supported by the results recovered from subjecting the floral remains to CA. It is understood that plants are forced to develop a close relationship with the environment in which they grow in order to maximize their photosynthetic capabilities. As a consequence, the environment of plant growth is strongly reflected in its structure and architecture. This is no more so than in leaves, whose function is to photosynthesize whilst minimizing water loss. Plants produce leaves in abundance, and this factor in conjunction with their reasonable strength, gives them a high preservation potential. In contrast to pollen, spores and fossil wood, leaves are not physically robust enough to be transported great distances from their source before deposition, or to be reworked once deposited. As a result, leaves are both good indicators of a relatively local environment and have the potential to yield a high-resolution climate signal.

Physiognomic methods for extracting palaeoclimatic information from floral assemblages use morphological adaptations of leaves to track environmental changes. This approach is favoured over floristic methods which assume that a fossil plant's Nearest Living Relative (NLR) can be used to gain palaeoclimatic data — a basic assumption which is flawed as it implies evolutionary stasis. In this study, the task of recovering climatic information from the Yorkshire Jurassic flora is performed using CA: a statistical treatment which reduces the dimensionality of the data by representing ~70% of the variation in the dataset in two principal axes. Based upon trends within the resultant CA plots, palaeoclimatic and environmental inferences can be made.

To accomplish this objective, floral lists are compiled for leaf taxa within individual stratigraphic units. Three separate matrices were created from this dataset: lists of genera and species were generated for the entire Ravenscar Group, and also selected plant beds. The principal outcome of this study is the elucidation of a physiognomic trend in the flora with time. In summary, these temporal trends reflect successive floral groups, which can be summarized as (1) a fern-dominated Aalenian; (2) the presence of mixed macrophyllous ferns, ginkgophytes, cycadophytes and coniferophytes in the Bajocian; and (3) the occurrence of proportionally more microphyllous, xeromorphic taxa in the Bathonian. This temporal fluctuation in the flora has been noted by previous researchers using alternative means, and may correspond to a climatic change. In combination with sedimentary evidence and data from growth-ring analysis, it seems possible that this alteration in the flora reflects a change towards a more seasonal climate during Bathonian times, with a prolonged dry season.

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Chapter 1

Chapter 1

Introduction

1.1 Aims of the project

This research establishes a picture of the stratigraphic development, constituent flora and palaeoclimatic conditions during Early and Middle Jurassic times in north-western Europe. Given the wide-ranging nature of this task, it was realized early on that it would be most beneficial to base the project on a single sedimentary sequence to which other coeval sections could be compared. The Middle Jurassic Ravenscar Group of Yorkshire (Cleveland Basin) most satisfactorily fulfils the criteria for this research, as it was deposited in a fluvio-deltaic environment open to the effects of sea-level fluctuations, contains a most exceptionally well-preserved flora from which palaeoclimatic information can be drawn and, until now, has not been examined using a fully integrative sedimentological and palaeobotanical approach. The following paragraphs discuss the depositional environments which led to the formation of the Ravenscar Group, and assesses its potential for elucidating the controls on stratigraphic development and palaeoclimatic change during the Middle Jurassic period.

1.2 The structural setting

The history of the Cleveland Basin (Fig. 1.1) began towards the end of Permian times with differential subsidence, which continued during much of the Jurassic and Cretaceous until inversion halted and reversed the process in late Cretaceous or Tertiary times. The effects of subsidence during the Permian were, however, minor compared to those which caused the development of the basin during the late Triassic (Kent 1980). Deposition during this period was controlled to some extent by the structure of the buried Carboniferous landscape beneath (Kent 1980). The basin is bounded to the west and north-east by less subsident or uplifted blocks which formed the Pennine and Mid-North Sea highs (Fig. 1.1). The southern limit of the basin is defined by the Market Weighton High, which during early to mid-Jurassic times acted as a hinge zone in this area of eastern England and greatly influenced stratal thicknesses.

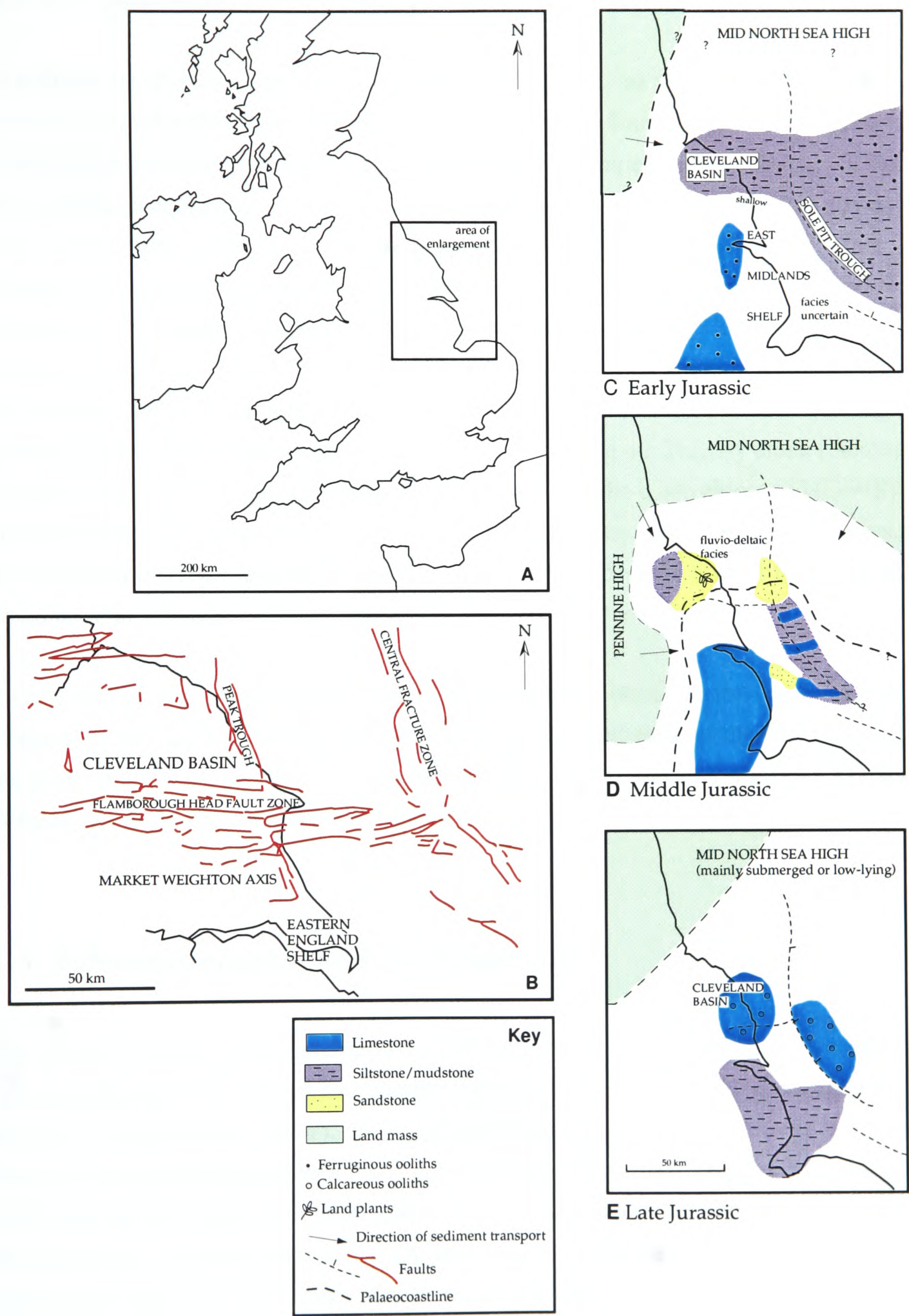


Fig. 1.1 Palaeogeographic and structural maps for the Cleveland Basin during Jurassic times. A. Map of UK showing location of study area; B. Structural map of the Cleveland Basin, redrawn from Kirby & Swallow (1987) and Milsom & Rawson (1989); C-E. Palaeogeographic maps simplified from Bradshaw *et al.* (1992).

The block is currently thought to be underlain by granite (Sellwood & Jenkyns 1975; Bott *et al.* 1978; Kent 1980; Donato 1993). To the south-east, the Cleveland Basin extends into the Sole Pit Trough of the Southern North Sea Basin (Kent 1980; Hemingway & Riddler 1982).

Few faults are known within the basin, except along the coast where a number of north-south oriented normal faults exist. The most significant are the Runswick, Whitby, Peak, Scarborough and Red Cliff Faults which developed intermittently from Triassic to Tertiary times (Milsom & Rawson 1989). Recent acquisition of seismic data has allowed the Peak Fault to be mapped offshore, revealing that the fault forms the western margin of the Peak Trough (Milsom & Rawson 1989). The trough is a 5 km wide, graben-like feature which is bounded to the east by a series of faults between Scarborough and Cayton Bay. East-west oriented faults in the Vale of Pickering were active in the late Jurassic and Cretaceous (Kirby & Swallow 1987). Subsidence was terminated by a phase of inversion either during the Late Cretaceous and early Tertiary times (Kent 1980), or during the Tertiary alone (Hemingway & Riddler 1982). This inversion resulted in broad uplift of the basin along a ENE-WSW oriented plane (the Cleveland axis) flanked to either side by minor domes and basins, such as the Robin Hood's Bay Dome (Rawson & Wright 1992). Several normal faults were also reactivated at this time, with reverse, strike-slip and oblique-slip motion.

Today, the Jurassic rocks exposed in the Cleveland Basin dominate the coastline from Teesside in the north to Filey in the south and outcrop westwards to the Hambleton Hills. To the south-west, the exposure thins to a narrow strip which continues south via Market Weighton and South Cave into Lincolnshire.

1.3 Palaeogeography and environments

The Middle Jurassic (Aalenian-Bathonian) of Yorkshire consists largely of fluvial and deltaic sediments with subordinate marine intercalations and, as a whole, the sequence is known as the Ravenscar Group. Regional uplift and creation of an extensive landmass over much of the central and northern North Sea culminated at the beginning of the Aalenian and was followed soon after by a concomitant fall in sea-level and a change in palaeogeography. Fluvio-deltaic sediments poured into the subsiding Cleveland Basin from these newly uplifted areas to the north (*e.g.* Alexander 1989). Intermittently, the shallow sea covering central and eastern England spilled into the basin, eased by the Yorkshire area's gentle southerly slope. Four marine transgressions represent these incursions of saline water across the delta-plain: two extended from the east (Eller Beck and Scarborough Formations) and two came from the south (Blowgill and Millepore Beds).

Across the delta grew a diverse and abundant flora which has been vividly demonstrated by the work of Seward (1900), Black (1929), Harris (1943-53, 1961-79) and Hill (1974a, 1980). Currently the flora is known to include 260 species which after restoration and removal of the detached organs (such as male and female fructifications) leaves 200 'natural' species (Hill 1980). The flora has been collected from some 600 plant beds across the basin, although only a few of these beds have yielded more than 15 species and about 10 have revealed more than 50 species (Hill 1974a). It is upon these more diverse plant beds that most work has focused over the last 150 years. Whether the wealth of documented species corresponds to the intrinsic richness of the flora, or the sheer enormity of its research, the flora is nevertheless considered as the standard for Euro-Sinian floral provinces (Vakhrameev 1991).

Although early work implied a spatial variation in the flora from a predominantly Bennettitalean flora in the north to a fern-dominated flora in the south, such a clear separation is currently disputed following compilation of a larger floral database. Variation has, however, been recognized in a temporal sense by researchers such as Harris (1952b), Couper (1958) and Florin (1958), but its relationship to climatic change has not been clear. Currently, the Yorkshire area is thought to have occurred within a warm-temperate biome during the Middle Jurassic period (*e.g.* Krassilov 1981; Ziegler *et al.* 1993), as evinced by the constituent flora (*e.g.* Spicer & Hill 1979), reaction temperature of early diagenetic minerals (Kantorowicz 1990), and high kaolinite content of the sequence (especially in the Bajocian) (Sellwood & Sladen 1981; Kantorowicz 1984, 1990). More specifically, analysis of the isotopic composition of non-ferroan calcite from the sequence indicates freshwater precipitation at 20°C (Kantorowicz 1990).

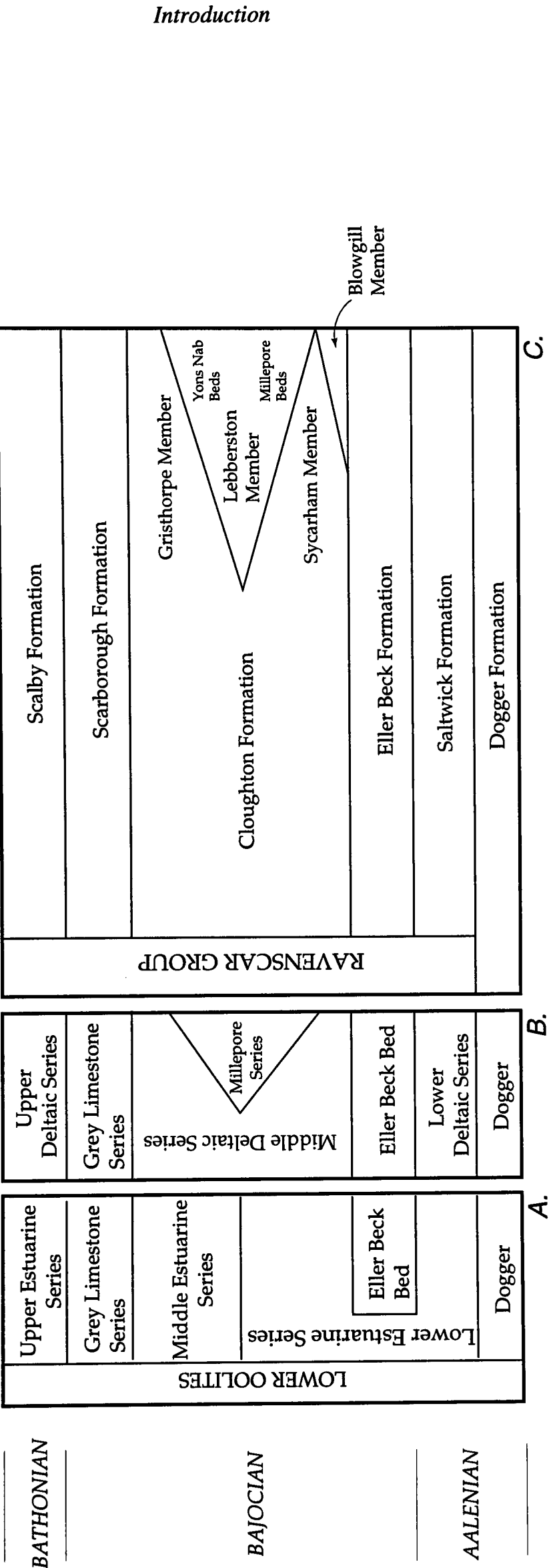
In a more general sense, the conventional view of a globally homogeneous Mesozoic climate and vegetation was challenged in the 19th century by Heer and Nathorst. Valuable contributions have since been made to these early studies by the likes of Vakhrameev (1982, 1991), Barnard (1973) and Wesley (1973) who plotted select taxa on present-day or palaeogeographic maps. Many of these studies have subsequently been criticized, however, as they are based on only a few key taxa within poorly constrained stratigraphic frameworks and were plotted on inaccurate palaeogeographic maps (*e.g.* Krassilov 1981). Today, a clearer understanding of Early and Middle Jurassic climates has been achieved within the context of improved palaeomagnetic maps, which indicate that many of the apparent changes we see in Mesozoic floras actually developed as a product of continental drift. Ziegler *et al.* (1996) elucidate this point by comparing Asian and North American floras: whereas a warming and drying through the Middle and Late Jurassic is indicated by floras in Asia, those in North America show that the climate became seasonally wet over the same period. This

they interpret as the result of clockwise motion about an axis in Europe, which led to Asia moving towards the equator and North America shifting poleward. Therefore, if this is true, one would not expect to perceive a change in the latitudinal position of Britain during the Middle Jurassic interval (~35°N) and, as a consequence, any changes we do see in the Yorkshire flora may be attributable to global climate change.

1.4 Middle Jurassic depositional history

The Ravenscar Group achieves a maximum thickness of 250 metres and is composed of a sequence of fluvio-deltaic units: namely the Saltwick, Cloughton and Scalby Formations, intercalated with two thinner though laterally persistent marine horizons known as the Eller Beck and Scarborough Formations (Hemingway & Knox 1973). In contrast, the Blowgill and Lebberston Members are relatively localized in occurrence. The group was originally named the Lower, Middle and Upper Estuarine Series (divided by the marine units) by Fox-Strangways (*e.g.* 1892) but, in light of the sedimentary studies of Kendall & Wroot (1924) and Black (1928, 1929, 1934*a*), it was revised to the Lower, Middle and Upper Deltaic Series by Hemingway (1949). Despite criticism which followed the proposal of this new scheme (*e.g.* Sylvester-Bradley 1949), the revised nomenclature enjoyed common usage for many years until it was replaced by the environmentally neutral Ravenscar Group (Hemingway & Knox 1973) (Fig. 1.2). A summary of the biostratigraphic and lithostratigraphic history of Yorkshire's Lower and Middle Jurassic sequence is discussed in Section 1.5 (p.14), but for the purposes of this section the reader is referred to Figs. 1.3 and 1.4 which outline the stratigraphic basis for this study; these figures also incorporate stratigraphic details of the coeval Scandinavian sequences discussed in Chapter 3. For a comprehensive review of the underlying Lower Jurassic sediments, Hesselbo & Jenkyns (1995, 1997) should be consulted. Details of the overlying Upper Jurassic are provided by Coe (1992, 1996; and references therein). The remaining part of this section is intended as a general overview to the Ravenscar Group, which is elaborated upon in Chapter 2.

At the end of the Toarcian, the Yorkshire area experienced uplift, folding and subsequent erosion, which some have ascribed to domal upwarping and accompanying vulcanism in the Central North Sea area (see Knox 1984; Underhill & Partington 1993). As a result of these tectonic movements, a late Toarcian/early Aalenian erosion surface cuts into folded Toarcian strata in Yorkshire: the surface is planar in the east and attributed to marine erosion (Hemingway 1974), but irregular in the west and inferred to be a product of river incision (Black 1934*a*). The Dogger Formation overlies this erosion surface which is inferred to represent the uppermost *aalensis* subzone of the Toarcian (Hemingway 1974; Cope *et al.*



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STAGE	Ammonite		Yorkshire		Bornholm		Scania			
	Zone	Subzone	Formation	Member						
TOARICIAN	levesquei	aalensis	Blea Wyke Sandstone	Yellow Sandstone	Baga Formation (lower part: Levka & Sorthat Beds)	Rya Formation	Rydeback Member			
		moorei		Grey Sandstone						
		levesquei		Fox Cliff						
		dispansum								
	thouarsense	fallaciosum striatulum	Whitby Mudstone	Peak Mudstone						
	variabilis									
	bifrons	crassum fibulatum commune		Mulgrave Shale						
		falciferum		falciferum exaratum						
	tenuicostatum	semicelatum tenuicostatum clevelandicum paltum		Grey Shales						
		spinatium	hawskerense apyrenum	Cleveland Ironstone				Kettleness		
margaritatus	gibbons subnodosus stokesi		Penny Nab							
	davoei		figulinum capricornus maculatum	Staithes Sandstone						
ibex			luridum valdani masseanum	Redcar Mudstone	'Ironstone Shales'	Hasle Formation	Katslosa Member			
		jamesoni	jamesoni brevispina polymorpha taylori		Pyritous Shales					
			raricostatum		aplanatum macdonnelli raricostatoides densinodulum			'Siliceous Shales'	Galgeløkke Member	?
	oxynotum				oxynotum simpsoni					
obtusum					denotatus stellare obtusum	Doshult Member				
		turneri			birchi brooki					
			semicostatum		resupinatum scipionianum lyra			Munkerpup Member		
	bucklandi				rotiforme conybeari				Helsingborg Member	
angulata					complanata extranodosa	Hoganas Formation				
		liasicus			laqueus portlocki					Hoganas Formation
			planorbis	johnstoni planorbis	Hoganas Formation					

Fig. 1.3 Correlation chart showing the Lower Jurassic stratigraphy of Yorkshire, Bornholm & Scania.

See Fig. 1.4 for accompanying text and references.

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CALLO-STAGE VIAN	Ammonite		Yorkshire		Bornholm	Scania							
	Zone	Subzone											
BATHONIAN	macrocephalus	kamptus ----- macrocephalus	Cornbrash		Baga Formation (upper part: Båga Beds)	?	Fortuna Marl						
	discus	discus ----- holandi	Scalby Formation	Long Nab Member		Vilhelmsfält Formation	-----?						
	orbis			Moor Grit Member			Glass Sand (Central & western Scania)						
	morrissi							?					
	subcontractus												
	progracilis												
	tenuiplicatus												
	zigzag	yeovilensis ----- macrescens ----- convergens											
BAJOCIAN	parkinsoni	bomfordi ----- truelli							Baga Formation (upper part: Båga Beds)	Vilhelmsfält Formation	?		
	garantiana	acris ----- tetragona ----- dichomata											
	subfurcatum	baculata ----- polygyralis ----- banksi											
	humphries- ianum	blagdeni ----- humphriesianum ----- cycloides										Scarborough Formation	further subdivided
	sauzei											Cloughton Formation	Gristhorpe Member
	laeviscula	laeviscula ----- trigonalis ----- sayni											Lebberston Member
	ovalis												
	discites												
AALENIAN	concauum	formosum ----- concauum	Saltwick Formation		Baga Fm. (lower part)	Vilhelmsfält Formation							
	bradfordensis	gigantea ----- bradfordensis											
	murchisonae	murchisonae ----- obtusiformis ----- haugi	Dogger Formation										
		scissum						comptum ----- lineatum					
	opalinum	opalinum											

Fig. 1.4 Correlation chart showing the Middle Jurassic stratigraphy of Yorkshire, Bornholm & Scania.

This chart is a compilation of information obtained from both a variety of literature sources and observations from field work. Yorkshire's lithostratigraphic nomenclature is based on Hemingway & Knox (1973); Bornholm's on Gravesen *et al.* (1982); and Scania's on Sivhed (1984). The Bornholm succession is dated using miospore zonation (Koppelhus & Nielsen 1994), and the Scanian sequence employing ostracodes (Norling 1972; Sivhed 1980). By correlating these zonations with the ammonite biostratigraphy compiled by Cope *et al.* (1980*b*), Calloman & Chandler (1990, 1994) and Cope (1993) for Yorkshire, the Scandinavian and British sections could be compared. It should be noted that the stratigraphic extent of the Dogger Formation relates to that for the basin as a whole.

1980b). To the east ferruginous sands and oolitic ironstones represent the older part of the formation (*opalinum* Zone: Cope *et al.* 1980b; Kent 1980; Riding 1984), and to the west younger beds occur composed of conglomerates, ironstones and limestones which are best developed in the deepest parts of palaeovalleys, where they are overlain by *murchisonae*-Zone ammonites (Black 1934a; Hemingway 1974). The formation becomes progressively ferruginous and sandy to the south-east.

The Dogger passes either abruptly or gradationally into the overlying non-marine Saltwick Formation and in places is penetrated by roots, and occasionally dissected by distributary channels from the younger unit — such channels can be seen between Whitby (NZ 900 116) and Ravenscar (NZ 980 016) on the coast. Evidence for subaerial erosion and uplift prior to deposition of the Saltwick Formation is supported by the local development of a thin coal resting on the Dogger Formation (Alexander 1989). The Saltwick Formation attains a maximum thickness of some 57 m and forms the lowermost portion of the Ravenscar Group. The succession records the progradation of a delta-complex from the north-east across the vestiges of a shallow-marine shelf, which remained from Dogger-Formation times. A range of delta-plain sub-environments are represented by high- and low-sinuosity fluvial distributary channels, levees, crevasse splays, both drained and stagnant areas of floodplain, freshwater and saline swamps and freshwater lakes.

A vertical transition in channel type can be recognized in the Saltwick Formation, ranging from a predominance of major bedload channels near the base, to fewer, more isolated mixed-load channels towards the top (Livera & Leeder 1981). This temporal change is also shown in the overbank deposits: whereas sediments at the base of the formation indicate a well-drained floodplain environment, evidence from overlying beds indicates a shift with time towards more poorly-drained, marshy conditions (Livera & Leeder 1981). Significantly, the upper part of the formation has fewer roots but an increased amount of drifted plant material. There is also less evidence for desiccation, but more soft-sediment deformation and an early siderite cement, indicating suboxic conditions after deposition. Such vertical changes reflect gradual abandonment of the delta lobe, and are interpreted to be due to subsidence and concomitant rise in sea level due to sediment consolidation (Alexander 1986). Palynofacies work carried out by Hancock & Fisher (1981) on shales from the upper part of the formation in the Hayburn Wyke vicinity, reveal a variety of marine microplankton including acritarchs, leiospheres and the dinocyst *Nannoceratopsis gracilis*. These findings indicate deposition in distal, saline swamps dominated by gymnosperms.

Deposition of the Saltwick Formation was terminated by a rapid incursion of saline waters across the low-lying delta plain. This transgression, originating from the east of the basin, marks the base of the Eller Beck Formation (Knox 1969, 1973). The surface across which the

marine waters flooded is highlighted at Iron Scar (TA 015 968) by the occurrence of innumerable *Diplocraterion* burrows penetrating into the top of the Saltwick Formation. Subsequent to the initial transgression from the east, marine waters washed in from the south and southwest to result in a basin-wide shallow sea no deeper than 7 m (Bate 1965). It was in this shallow sea that the Eller Beck Formation was deposited, ranging in thickness from 4.2-8.2 m (Knox 1973; Hemingway 1974; Powell & Rathbone 1983). The interval comprises thin ironstone and siltstone beds at the base, overlain by a thicker siltstone or limestone sequence, and succeeded by sandstone. The basal Ironstone Member represents a time of slow sedimentation teamed with an abundance of iron, producing a unit ranging from a fossiliferous, sideritic mudstone to berthierine oolite. Genesis of the ironstone was halted by the introduction of a terrigenous mud which formed the Shale Member (Knox 1973). This fine-grained clastic supply was, however, discontinuous, as indicated by the development of a thin micritic limestone (northerly equivalent to the Ellerker Limestone) as well as a sandstone derived from the west of the basin (Gowland & Riding 1991). The Eller Beck Formation is capped by a wave-generated Sandstone Member which is intensely bioturbated about the middle and rooted at the top. This final interval probably represents progradation of a sandy barrier-bar or shoreline across shallow-marine muds (Knox 1973).

Progradation continued until deltaic conditions became established once again. As a consequence, the approximately 50 m thick non-marine Sycharham Member was deposited, forming the lower portion of the Cloughton Formation. Although exposure of this unit is poor because of recent rock falls and mud slides, the best outcrop exists along the coast between Iron Scar and Rodger Trod to the south (TA 021 955). Study of this rather incomplete section reveals a succession of laterally accreted and cross-bedded channel sandstones intercalated with mudstones and siltstones representing renewed delta-plain progradation (Livera & Leeder 1981). Some 5.2 m above the base of the succession at Iron Scar, a horizon exists within which *in situ Equisetum* and the lower portion of a tree can be found. From this evidence it is possible to infer that a truly freshwater environment was established by this level of the Sycharham Member, at this locality at least.

A marine incursion from the south of the basin across the delta-plain resulted in the deposition of the Lebberston Member: a richly fossiliferous, sandy calcareous oolite laid down in shallow-marine to coastal settings south of the basin, correlative with thinner, poorly fossiliferous, bioturbated sandstones in the north, typical of beach and lagoonal environments (Livera & Leeder 1981). The unit is poorly constrained biostratigraphically, but is thought to be laterally equivalent to the Cave and Whitwell Oolites (Lower Bajocian) exposed to the south of the Market Weighton High (Bate 1959, 1967; Parsons 1974; Cope *et al.* 1980*b*). The siliciclastic Yons Nab Beds have, in the past, been described as the regressive phase of the underlying calcareous Millepore Bed. Work on the macrofauna, ostracod fauna

(Sylvester-Bradley 1953; Bate 1959) and palynofacies (Hancock & Fisher 1981) shows a difference between the two units which reflects a gradual transition from fully marine conditions to an essentially freshwater swamp.

The Millepore Bed occurs along the coast from Yons Nab (TA 081 844) northwards to Peak (NZ 980 025), together with several scattered inland exposures. Detailed work by Bate (1964, 1967) on the ostracod fauna of the Millepore Bed and Whitwell Oolite has shown that close similarities exist with the Lower and Upper Lincolnshire Limestone. The Millepore Bed succession typically comprises a cross-bedded, subarkosic sandstone and oolite, with a distinct change from calcareous facies in the south to more arenaceous, ferruginous facies in the north. The overlying Yons Nab Beds consist of some 5 m of cyclic flaggy alternations of shale and sandstone. Bivalves are numerous, including *Lima*, *Gervillia*, *Trigonia* and *Pecten* (Bate 1959) — as are ostracodes, *Pentacrinus* ossicles, plant fragments and soft jet (Hemingway 1974). To the north of Common Cliff (NZ 993 008), the Yons Nab Beds are absent and seem to be — particularly in the central and northern parts of the basin — somewhat aberrant in their development. The occasional absence of the unit led Hemingway (1974) to postulate that this may be because of proximity to the nearby delta marsh, which thus encouraged strictly non-marine deposition. The local occurrence of the Yons Nab Beds, and difficulty in differentiating them from the overlying Gristhorpe Member, has led some to consider the beds to be simply the quasi-marine lower part of the Gristhorpe Member (*e.g.* Knox *in* Rawson & Wright 1992).

The Gristhorpe Member marks a return to more paralic sedimentation. The sequence attains a maximum thickness of some 30 m and typically comprises a succession of crevasse-splay sandstones, intercalated with plant-bearing mudstones and siltstones laid down in a flood-plain environment. Evidence for channel development is rare, with the exception of a laterally-accreted channel sandstone cutting down into the Yons Nab Beds from the base of the Gristhorpe Member at Yons Nab. An intermittent marine influence is indicated by the presence of *Diplocraterion* burrows. One horizon containing burrows is a basin-wide phenomenon and particularly prominent. This bed is inferred to have been deposited either during a small sea-level rise, or alternatively through delta-lobe switching. However, the regional occurrence of this horizon supports the possibility of a slight sea-level rise.

The Scarborough Formation is the thickest marine unit in the Ravenscar Group, the environments of deposition ranging from a brackish sandy embayment, nearshore sandy and muddy shelf, and offshore mud-dominated shelf (Gowland & Riding 1991). An ammonite fauna from the interval between the Spindle Thorn Limestone and White Nab Ironstone Members allowed Parsons (1977) to constrain the age of the unit to the *humphriesianum* Zone. The lowermost unit of the formation, the Helwath Beck Member, was originally

considered to form the upper portion of the Gristhorpe Member (Parsons 1977). However, on realizing its marine affinities, Gowland & Riding (1991) placed the unit at the base of the Scarborough Formation. Essentially composed of calcareous sandstones, sandy limestones, siltstones and calcareous mudstones with subsidiary nodular, sideritic ironstones, the formation broadly fines upwards to mid-way through the Ravenscar Shale Member, above which a coarsening upwards sequence occurs within the *humphriesianum* Subzone. It is, however, unclear at what level the maximum transgression (which originated from the east of the basin: Bate 1965) was attained. Lithological evidence suggests a level within the Ravenscar Shale Member, but this contrasts with evidence supplied by marine palynomorphs (Gowland & Riding 1991). Indigenous marine species of dinoflagellate cysts, for example, reach their maximum relative abundance and diversity in the overlying supposedly nearshore muds and sands of the Bogmire Gill Member (*blagdeni* Subzone). Gowland & Riding (1991) suggest that minor dilution around the delta front by the contemporaneous fluvial system of the Scalby Formation may have allowed marine microplankton to become concentrated and hence result in this discrepancy. The possibility of the Scalby Formation being contemporaneous remains debatable as explained below.

The nature of the contact between the Scarborough Formation and overlying Scalby Formation has stimulated much speculation over the years: although there is no doubt of its erosive nature (at least locally), the time-interval that this junction represents is rather more conjectural. In preference to the delta envisaged by Black (1929), Leeder & Nami (1979) have proposed an alluvial mode of deposition for the Scalby Formation, suggesting that sedimentation took place over a period of one million years. On the basis of an observed gradual transition between the Scalby Formation and overlying Cornbrash, they suggested that a lengthy erosive period occurred at the base of the Scalby Formation. However, subsequent findings present new evidence to suggest that the formation is not alluvial (*e.g.* *Ophiomorpha* burrows and abundance of mud-grade sediment in the channels, found by Livera & Leeder, 1981 in the Long Nab Member), but instead represents deposition in an estuarine environment; a theory first put forward by researchers such as Fox-Strangways (1880).

In a subsequent study, Fisher & Hancock (1981) highlighted the presence of acanthomorph acritarchs in shales associated with the meander-belt and explained their presence by the penetration of saline waters into active channels on the delta-plain, reinforcing the probability of deposition in an estuarine environment. Fisher & Hancock were later (1985) able to restrict the age of the Long Nab Member to the *garantiana-parkinsoni* Zones, sandwiched between a number of minor hiatuses during the time-interval represented by the *humphriesianum* to *macrocephalus* Zones. In fact they went as far as to infer compaction, lithification, uplift, erosion and burrowing of the top Long Nab Member prior to deposition of the Cornbrash

(*contra* Wright 1977). Further to this, Riding & Wright (1989) reassessed the palynomorph assemblages collected by Fisher & Hancock (1985), and disputed their interpretations. Based on the absence of *Nannoceratopsis gracilis*, Riding & Wright suggested the deposition of the Moor Grit Member occurred soon after the Scarborough Formation with only a minor stratigraphic break between. Therefore, soon after the Scarborough Formation was laid down, there was almost continuous deposition of the formation from Late Bajocian to Late Bathonian times.

Since these findings, more recent investigations suggest that there is in fact a stratigraphic break at the base of the formation, representing a significant time-interval. Petrological studies carried out by Lott & Humphreys (1992) indicate a major hiatus, concurring with the earlier work of Leeder & Nami (1979). Palynological investigations by Hogg (1993) confirm this major stratigraphic break: on the presence of key dinoflagellate cysts, Hogg inferred that a substantial portion of the Long Nab Member falls within the uppermost Bathonian *discus* Zone, and the Moor Grit Member therefore represents the previous *orbis* Zone. Thus a prolonged period of non-deposition and/or erosion from Late Bajocian to Late Bathonian times is implied. In support of this theory, a negligible stratigraphic break at the top of the Scalby Formation is indicated by the more-or-less gradational boundary with the Cornbrash, with only minor reworking, relatively little erosion due to marine transgression, and absence of a lag deposit containing phosphatized pebbles and a water-worn fauna (Wright 1977; Leeder & Nami 1979). These inferences are compatible with the Middle Jurassic large-scale sedimentary cycles discussed in the context of southern England by Hesselbo & Jenkyns (1995).

The nomenclature of Yorkshire's Late Bajocian to Late Bathonian sequence has altered over the years: originally referred to as the Upper Deltaics, comprising the Current Bedded and Level Bedded Series (Black 1929), the names have since been revised to the Moor Grit and Long Nab Members respectively (Hemingway & Knox 1973). The basal Moor Grit Member comprises a maximum thickness of 8 m and is characterized by coarse-grained, low-sinuosity channels. Nami (1976) showed that the member comprises a meander-belt featuring cross-cutting point bars trending southwards, which is well exposed on the foreshore of Burniston Wyke for a distance of 2 miles. To the south of Scarborough, the Moor Grit Member is absent (Black 1929). Leaf debris increases upwards into the levee deposits on top of the point-bar system, and the succeeding shales and sandstones of the Long Nab Member contain marine palynomorphs (Hancock & Fisher 1981). The succession is interpreted as representing a swamp across which occasional incursions of sea water washed (Kantorowicz 1990), terminating the record of deltaic deposition in Yorkshire.

1.5 Biostratigraphic framework for the Ravenscar Group

1.5.1 Introduction

The age of the Ravenscar Group is constrained by ammonite finds from the marine bands it is sandwiched between, *i.e.* the underlying Dogger Formation of the Aalenian *murchisonae* to *opalinum* ammonite Zones, and overlying Callovian Cornbrash Limestone Formation of the *macrocephalus* Zone (Cope *et al.* 1980*b*). Similarly, ages for the constituent units of the group rely principally on ammonite finds from the interbedded marine sediments which, unfortunately, are rare at best and presently confined to the Scarborough Formation. Fortunately, however, several sedimentological and palaeontological aspects of the other marine units comprising the group (Eller Beck Formation and Millepore Bed) are sufficiently unusual to allow tentative correlation to the south of the region where ammonites are commonly found, and thus ages are better constrained.

As a result of such correlations, a biostratigraphic scheme has been created for this thesis which differs slightly from the conventional tables of Cope *et al.* (1980*b*) (compare Cope *et al.*'s Figs. 4*b* and 6*b* with Fig. 1.6 of this thesis). The construction of a precise biostratigraphic scheme is essential not only for intrabasinal correlation (which is often less of a problem because of sufficiently distinct lithologies, particularly at marine/non-marine transitions), but also for comparison with the Scandinavian sections (Chapter 3). Furthermore, because many of the lithostratigraphic units discussed here are lenticular and thin rapidly when traced in a lateral sense, it was essential to have a biostratigraphic framework against which to compare the various sections. A step in this direction has been made, most notably, for the Scarborough Formation by Bate (1967) and Parsons (1977), who demonstrated the lateral uniformity of some units using ostracod and ammonite distributions. For the purposes of this research, however, it was necessary to compile a biostratigraphic scheme for the entire sequence. Figs. 1.3-1.4 show the resultant framework for Yorkshire and illustrate the correlation of the Scandinavian sections (Bornholm and Scania). While the Yorkshire interval is dated primarily using ammonites, miospores and dinoflagellate cysts constrain the Scandinavian beds. Therefore in order to correlate fully these separate localities, relevant North Sea zonations (calcareous nannofossils, foraminifera, ostracodes) are employed as a point of reference. The resulting biostratigraphic charts are shown in Figs. 1.5-1.6.

The following section presents a brief discussion of the history of biostratigraphic work conducted on the Middle Jurassic succession of Yorkshire. For details regarding the region's Lower Jurassic ammonite zonation the reader is referred to Cope *et al.* (1980*a*) and Cope

STAGE	Ammonite		Miospores	Dinoflagellate cysts		Calcareous Nannofossils	Foraminifera	Ostracodes (Sweden only)																					
	Zone	Subzone																											
TOARICIAN	levesquei	aalensis	Spheripollenites - Leptolepidites Zone	Nannoceratopsis gracilis Superzone	Mancodinium semitabulatum Zone	c	E. britannica	JF16	absent																				
		moorei								b																			
	levesquei	a																											
	dispansum					a																							
	thouarsense	fallaciosum						A. cylindratus		JF12	b																		
	striatulum	JF15				a																							
variabilis				JF14	JF13																								
bifrons	crassum	JF11				JF10																							
	fibulatum			JF9	b																								
	commune	a				a																							
falciferum	falciferum			C. crassus	JF8																								
	exaratum	P. liascicus				JF7																							
tenuicostatum	semicelatum		Dapcodinium priscum Zone	b																									
	tenuicostatum	a			JF4																								
	clevelandicum		C. primulus	JF2																									
	paltum	A. arkellii			JF1																								
PLIENSCHACHIAN	spinatum		hawskerense	Chasmatosporites Zone		Luehdeia spinosa Zone	Mendicodinium reticulatum Zone	A. cylindratus	JF9	b	Grammannella apostolescui-Kinkellinella (klinglerella) foveolata Subzone																		
		apyrenum	C. crassus		P. liascicus							Dapcodinium priscum Zone	b																
	margaritatus	gibbosus												Dapcodinium priscum Zone	b														
		subnodosus														Dapcodinium priscum Zone	b												
		stokesi																Dapcodinium priscum Zone	b										
	davoei	figulinum																		Dapcodinium priscum Zone	b								
	capricornus	Dapcodinium priscum Zone				b																							
	maculatum		Dapcodinium priscum Zone		b																								
ibex	luridum						Dapcodinium priscum Zone	b																					
	valdani								Dapcodinium priscum Zone	b																			
	masseanum										Dapcodinium priscum Zone	b																	
jamesoni	jamesoni												Dapcodinium priscum Zone	b															
	brevispina	Dapcodinium priscum Zone		b																									
	polymorpha		Dapcodinium priscum Zone		b																								
	taylori					Dapcodinium priscum Zone	b																						
SINEMURIAN	raricostatum							anaplanatum	Cerebropollenites macroverrucosus Zone	Liasidium variabile Zone					Liasidium variabile Zone	P. liascicus	JF8	JF7	poorly understood ostracod fauna										
								macdonnelli			Liasidium variabile Zone	Liasidium variabile Zone								P. liascicus	JF8	JF7							
								raricostatooides					Liasidium variabile Zone	Liasidium variabile Zone									P. liascicus	JF8	JF7				
		densinodulum		Liasidium variabile Zone				Liasidium variabile Zone																		P. liascicus	JF8	JF7	
	oxynotum	oxynotum	Liasidium variabile Zone		Liasidium variabile Zone																								P. liascicus
		simpsoni				Liasidium variabile Zone	Liasidium variabile Zone																						
obtusum	denotatus	Liasidium variabile Zone								Liasidium variabile Zone					P. liascicus	JF8	JF7												
	stellare										Liasidium variabile Zone	Liasidium variabile Zone						P. liascicus	JF8	JF7									
	obtusum												Liasidium variabile Zone	Liasidium variabile Zone							P. liascicus	JF8	JF7						
turneri	birchi			Liasidium variabile Zone				Liasidium variabile Zone																P. liascicus	JF8	JF7			
	brooki		Liasidium variabile Zone		Liasidium variabile Zone																						P. liascicus	JF8	JF7
semicostatum	resupinatum					Liasidium variabile Zone	Liasidium variabile Zone																						
	scipionianum	Liasidium variabile Zone							Liasidium variabile Zone	P. liascicus					JF8	JF7													
	lyra										Liasidium variabile Zone	Liasidium variabile Zone					P. liascicus	JF8	JF7										
bucklandi	rotiforme												Liasidium variabile Zone	Liasidium variabile Zone						P. liascicus	JF8	JF7							
	conybeari			Liasidium variabile Zone				Liasidium variabile Zone															P. liascicus	JF8	JF7				
HETTANGIAN	angulata		complanata		Pinuspollenites & Trachysporites Zone																					Dapcodinium priscum Zone	Dapcodinium priscum Zone	C. primulus	JF3
			extranodosa			Dapcodinium priscum Zone	Dapcodinium priscum Zone																						
	liasicus	laqueus	Dapcodinium priscum Zone						Dapcodinium priscum Zone	C. primulus					JF3	JF2													
	portlocki	Dapcodinium priscum Zone									Dapcodinium priscum Zone	C. primulus					JF3	JF2											
planorbis	johnstoni												Dapcodinium priscum Zone	Dapcodinium priscum Zone					C. primulus	JF3	JF2								
	planorbis			Dapcodinium priscum Zone				Dapcodinium priscum Zone														C. primulus	JF3	JF2					

Fig. 1.5 Biostratigraphic correlation chart for the Lower Jurassic. Ammonite Zones compiled from Cope *et al.* (1980a) and Cope (1993); Miospore Zonation from Koppelhus (1991) and Koppelhus & Nielsen (1994); Dinoflagellate Cyst Zonation based on Woollam & Riding (1983), and emended using Riding & Thomas (1992); Calcareous Nannofossil Zones from Hamilton (1982); Foraminiferal Zones from Copestake (1989); Swedish Ostracod Zonation from Norling (1972) and Sivhed (1980).

CALLO-STAGE VIAN	Ammonite		Miospores	Dinoflagellate cysts		Calcareous Nannofossils	Foraminifera		Ostracodes (Yorks. only)	
	Zone	Subzone								
BATHONIAN	macrocephalus	kamptus ----- macrocephalus	Callialasporites - Perinopollenites Zone	C. ornatum - C. continuum Zone		S. bigotii	Saracenaria oxfordiana & S. phaedra		no zonation defined	
	discus	discus ----- holandi		Ctenidodinium combazii - Ctenidodinium sellwoodii Zone	b	S. speciosum	?	Faunule D		
	orbis							Faunule C4		
	morrissi							Faunule B2 - C3		
	subcontractus									Faunule B1
	progracilis									
	tenuiplicatus							Faunule A		
	zigzag	yeovilensis ----- macrescens ----- convergens								
BAJOCIAN	parkinsoni	bomfordi ----- truelli		Nannoceratopsis gracilis Superzone	Acanthaulax crispa Zone		E. keptalrempti	Epistomina parastelligera & Reinholdella dreheri	Glyptocythere scitula ----- G. polita ----- ?	
	garantiana	acris ----- tetragona ----- dichotoma			Nannoceratopsis gracilis Zone	c				
	subfurcatum	baculata ----- polygyralis ----- banksi								b
	humphries- ianum	blagdeni ----- humphriesianum ----- cycloides								
	sauzei									
	laeviscula	laeviscula ----- trigonalis ----- sayni			e					
	ovalis									
	discites									
AALENIAN	concavum	formosum ----- concavum	Mancodinium semitabulatum Zone			d	E. britannica	Citharina clathrata	no zonation defined	
	bradfordensis	gigantea ----- bradfordensis								
	murchisonae	murchisonae ----- obtusiformis ----- haugi								
	scissum	comptum ----- lineatum								
	opalinum	opalinum								

Fig. 1.6 Biostratigraphic correlation chart for the Middle Jurassic. Ammonite Zones compiled from Cope *et al.* (1980*b*), Callomon & Chandler (1990, 1994) and Cope (1993); Miospore Zonation from Koppelhus (1991) and Koppelhus & Nielsen (1994); Dinoflagellate Cyst Zonation based on Woollam & Riding (1983), and amended using Riding & Thomas (1992); Calcareous Nannofossil Zones from Hamilton (1982); Formainiferal Zones for Bathonian from Morris (1989), other foram zones denote those defined for Sweden alone by Norling (1972); Ostracod Zonation for Yorkshire based on Bate (1967).

(1993), and references therein. Chapter 3 of this thesis presents further information on the biostratigraphy of Bornholm and Scania, and their correlation with the Yorkshire sections.

1.5.2 The framework

The Saltwick Formation contains little biostratigraphic information and as a consequence is best dated by the marine units between which it occurs. The underlying Dogger Formation is a complex, heterolithic deposit, laid down over a long period of time during which there was minimum basin subsidence. As a result, the unit is condensed and biostratigraphic differentiation is rather poor. Nevertheless, ammonites pertaining to the *opalinum* Zone have been collected from the middle of the formation at Ravenscar, and *murchisonae*-Zone varieties (*haugi* Subzone) have been retrieved from more western areas (Kent 1980; Parsons 1980). Whilst no ammonites have yet been obtained from the intervening *scissum* Zone, that is not to say that deposition of the Dogger Formation was not continuous from lower *opalinum* to uppermost *murchisonae*-Zone times (*e.g.* see Cope *et al.* 1980b, Fig. 4a). Despite some evidence for subaerial exposure at the top of the Dogger (in the form of a thin coal), the base of the Saltwick Formation therefore most likely corresponds to the *bradfordensis* Zone. In turn, the top of the Saltwick Formation is most accurately dated by the age of the overlying Eller Beck Formation, which, for reasons given below, agrees with the *discites* Zone at the base of the Bajocian. Thus, the Saltwick Formation is inferred to span the Aalenian *bradfordensis* and *concovum* Zones.

The age of the Eller Beck Formation has previously depended largely upon age constraints imparted by the Hydraulic Limestone and Blowgill Member, of only local occurrence in the south-eastern area of the basin (Hemingway & Knox 1973). Regional mapping by the Geological Survey (Fox-Strangways *et al.* 1886, p.34) established that the ironstone-shale interval of the Eller Beck Formation becomes progressively more calcareous southwards, until a true limestone occurs which is referred to as the Hydraulic Limestone. The spatial association of the ironstone and limestone facies was initially accepted by Hemingway (1949, p.69), but rejected in later publications (Hemingway & Knox 1973; Hemingway 1974). Instead, Hemingway & Knox (1973) introduced the stratigraphically higher Blowgill Member, at the base of the Cloughton Formation. They described the member as resting chiefly on non-marine beds containing small marine bivalves and marine palynomorphs, being itself largely composed of shales with nodules and thin beds of concretionary limestone overlain by sandstone. These thin beds of concretionary limestone within the shales of the Blowgill Member, were considered by Hemingway & Knox (1973) to be laterally equivalent to the micritic Hydraulic Limestone.

Currently, a clearer picture of the age and lateral extent of the Eller Beck Formation exists, as a result of a regional review of the sequence carried out by Powell & Rathbone (1983). Their findings differ from those presented above in that they consider the Hydraulic Limestone to be a local development within the Eller Beck Formation, and the Blowgill Member to be a lateral equivalent of the formation's mudstone and succeeding sandstone beds; as a result, they reject the term Blowgill Member. Furthermore, Powell & Rathbone infer that the marine transgression which led to deposition of the Eller Beck Formation and Lower Lincolnshire Limestone were one of the same. On the basis of the ammonite-rich Lincolnshire Limestone, a *discites*-Zone age is therefore inferred for the Eller Beck Formation (Bate 1965, 1967; Ashton 1980; Parsons 1980).

To assess the validity of a *discites*-Zone age for the Eller Beck Formation, it is informative to compare the section with coeval intervals elsewhere. One of the most distinctive features of the formation is its junction with the underlying Saltwick Formation, which is inferred to correspond to a transgressive surface. A similar horizon exists in a coeval succession located in the Cotswolds. The base of the Lower Trigonía Grit — a highly fossiliferous limestone and marl unit, rubbly and iron-stained in part and attaining a maximum thickness of some 2 m (Arkell 1933, p.201) — is unconformable and transgressive, marking the 'Bajocian Transgression' of Arkell (1933) (Cycle 3 in this thesis, p.60). The nature and stratigraphic position of this surface is reminiscent of the base of the Eller Beck Formation and ammonites from the lower portion of the grit are also indicative of the *discites* Zone (Buckman 1895; Bate 1967; Parsons 1976; Cope *et al.* 1980*b*). In some regions above a prominent firmground, the lower part of the grit includes derived pebbles often thickly coated with limonite, serpulæ and bryozoans forming 'snuff boxes', or complex laminated concretions (Gatrall *et al.* 1972; Parsons 1976): 'snuff boxes' are characteristic of the so-called Snuff Box Bed in southern England, also of *discites* age (Cope *et al.* 1980*b*). These comparisons highlight the depositional similarities between the Eller Beck Formation and Lower Trigonía Grit, and provide strong supporting evidence for a *discites*-Zone age for the unit in Yorkshire (*contra* Cope *et al.* 1980*b*).

Maximum and minimum ages for the top of the Eller Beck Formation and base of the Millepore Bed (described below) suggest that the Sycharham Member must represent a mid- to uppermost *discites* Zone time-slot. This at first seems to be a short time-interval but, bearing in mind the often rapid nature of deltaic deposition, seems feasible. The regression that produced this unit extended southwards from Yorkshire to Lincolnshire, where a clastic sequence (Raventhorpe Member) within the marine Lincolnshire Limestone is apparent (Ashton 1975). An upper age limit for the Raventhorpe Member, and hence Sycharham Member, is yielded by the ammonite-bearing Kirton Cementstone Member, which is at least partly of *discites*-Zone age.

It has long been considered that the overlying Millepore Bed (at the base of the Lebberton Member) is laterally equivalent to both the Cave Oolite, confined to an area south of the Market Weighton High near the village of South Cave, and also the Whitwell Oolite found in the Howardian Hills and the southern part of the Hambleton Hills (Bate 1967; Senior & Earland-Bennett 1973; Hemingway 1974). Despite the lack of ammonites in the Lebberton Member as a whole, distinct faunal similarities exist between the member and the units with which it is correlated in the south. Hudleston (1884, p.112; 1887-96, p.211) noted the widespread presence of the nerineid gastropod *Ptygmatis*, while Richardson (1911) commented upon the discovery of the spinose rhynchonellid *Acanthothyris crossi* in the Whitwell Oolite, Lincolnshire Limestone and Buckmani Grit of the Cotswolds. Previously, these units have been dated as *discites* Zone (Arkell 1933, p.221-222; Senior & Earland-Bennett 1973), which corresponds to the age envisaged for the Millepore Bed by Bate (1967).

Since these studies, re-examination of the Cave Oolite has revealed ammonites characteristic of the *ovalis* Zone (Parsons 1974, p.115). Following the revamped ammonite zonation of Calloman & Chandler (1994), this *ovalis*-Zone age corresponds to the *ovalis* Subzone of the lower *laeviscula* Zone, suggesting that the Millepore Bed is of uppermost *discites* Zone to lowermost *laeviscula* Zone in age (Fig. 1.6). Interestingly, the maximum marine flooding surface found near the top of the Millepore Bed (see p.64) may correspond to the development of the Kirton Shale Member in South Humberside: a calcareous mudstone facies indicative of deepening in the *laeviscula* Zone (Cope *et al.* 1980*b*).

Although the overlying Gristhorpe Member provides little biostratigraphic evidence to provide an upper age limit for the Yons Nab Beds, the beds probably represent the mid to upper portion of the *laeviscula* Zone. As for the age of the Gristhorpe Member itself, work by Bradshaw & Bate (1982) has shown that attenuated lateral equivalents of the Gristhorpe Member and overlying Scarborough Formation occur in South Humberside and Lincolnshire. At Nettleton, north Lincolnshire, a succession of rooted sandstones and coals overlain by a thin marine unit occur, which are interpreted as representing the Gristhorpe Member and transgressive Scarborough Formation respectively. Based on ostracod finds from the Scarborough Formation, a *sauzei*-Zone age is inferred for the Gristhorpe Member (Bradshaw & Bate 1982).

Ammonite evidence from the Scarborough Formation (Fox-Strangways 1896, p.231; Buckman 1911, p.205-208; Hemingway 1951, p.119), has facilitated a precise correlation which is lacking in all other portions of the Ravenscar Group. The ammonite finds show that all three Subzones of the mid-Bajocian *humphriesianum* Zone (*cycloides*, *humphriesianum*, *blagdeni* Subzones) are represented by the upper part of the formation, *i.e.* the beds above the

Hundale Sandstone Member (Parsons 1977). The lower part of the unit must therefore be of either the *cycloides* Subzone or upper *sauzei* Zone (see Cope *et al.* 1980b, Fig. 5). The suggestion of initial deposition of the Scarborough Formation during the *sauzei* Zone was also made by Arkell on the basis of belemnite finds from the formation: he noted that *Belemnites ellipticus* is also common within the *sauzei* Zone in the Cotswolds (1933, p.221).

Because of the major palaeogeographical implications a significant stratigraphic break at the base of the Scalby Formation would invoke, a review of pertinent theories has already been given above (Section 1.4, p.13). Within the context of this biostratigraphic discussion it is simply important to note that a major hiatus spanning eight ammonite zones is assumed in this thesis, *sensu* Leeder & Nami (1979), Lott & Humphreys (1992), Hogg (1993) and Hesselbo & Jenkyns (1995). Evidence to support this supposition can also be gleaned from sedimentary successions further afield, including the prolonged hiatus between the Lower Bajocian Lower Lincolnshire Limestone and Upper Bathonian Great Oolite Limestone (Cope *et al.* 1980b) and, more specifically, the weathered, decalcified and eroded top to the Bajocian Cave Oolite of Humberside, which is overlain by the 'White Sands' of probable Bathonian age (Brasier & Brasier 1978).

Therefore, the biostratigraphic constraints discussed in this section suggest brief periods of rapid deposition of the non-marine units composing the Ravenscar Group, separated by long periods of non-deposition or erosion, or, in the case of the Scarborough Formation, an extended period of marine deposition.

1.6 Sedimentary cycles

Great discussion surrounds the relationship of lithologic cycles to sea-level change within the British Jurassic (*e.g.* Arkell 1933, p.54-55; Hallam 1964, 1967, 1975, 1988; Duff *et al.* 1967; Sellwood & Jenkyns 1975; Haq *et al.* 1988; Einsele *et al.* 1991; Hesselbo & Jenkyns 1997). Different levels in the hierarchy of sedimentary cycles have been assigned to orders relating to their inferred durations (Haq *et al.* 1988; Vail *et al.* 1991). In Yorkshire two scales of lithologic cycles dominate and are defined as:

- a) large-scale cycles (second-order cycles), thought to represent ~10 m.y., and
- b) medium-scale cycles (third-order cycles), thought to represent 0.5 to 3 m.y.

Smaller scale lithologic cycles (fourth-order) also occur, but are localized in their occurrence and the biostratigraphic resolution possible in the non-marine Middle Jurassic strata hinders their regional correlation. Nevertheless cycles comprising argillaceous sandstones overlain by

Introduction

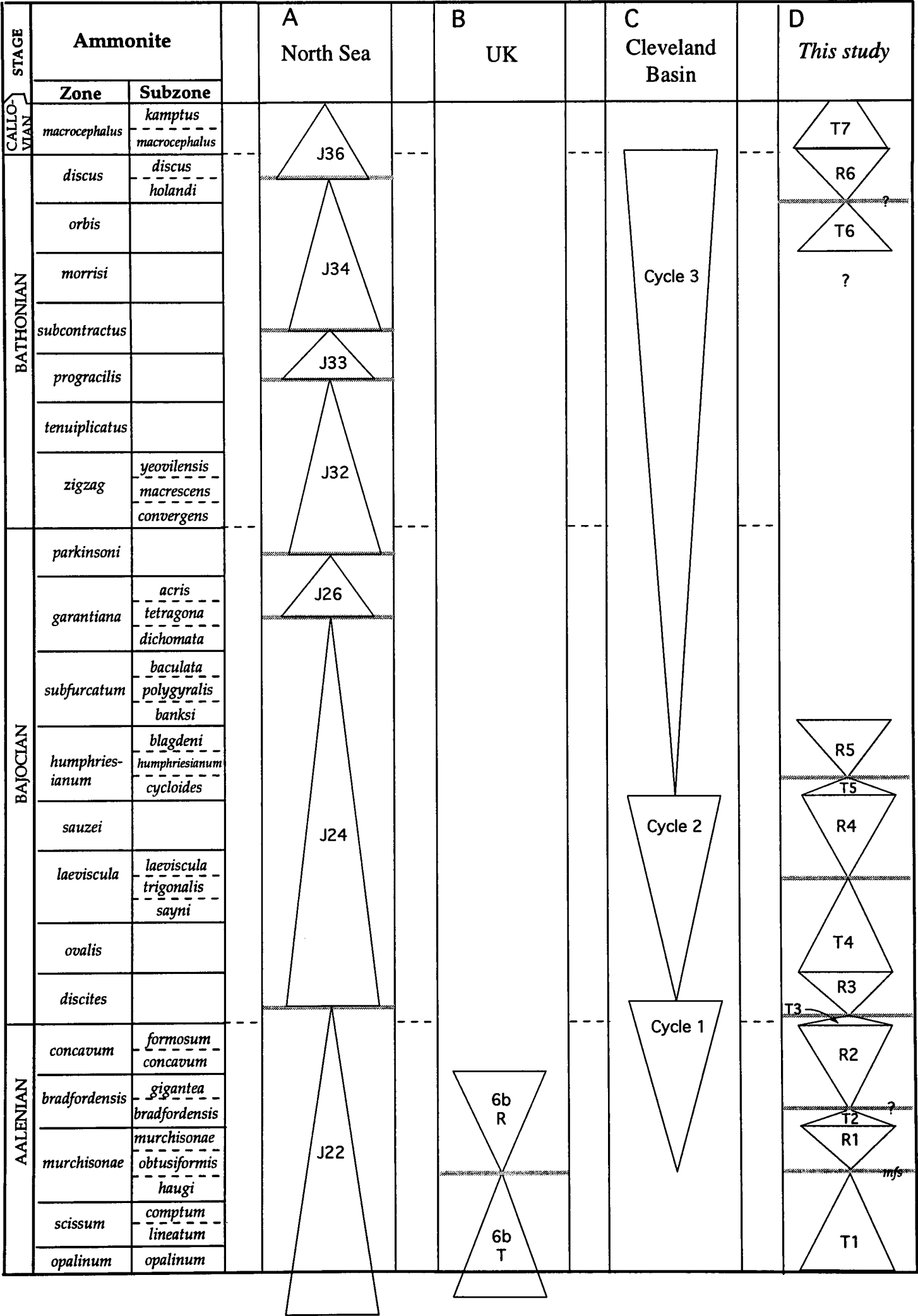


Fig. 1.7 Selected sequence stratigraphic interpretations for the Middle Jurassic strata of the Cleveland Basin and the wider North Sea area, compared to the scheme of transgressive-regressive cycles constructed for this study. A, after Partington *et al.* (1993); B, Graciansky *et al.* (1997); C, Knox *et al.* (1990). Horizontal bars mark the position of maximum-flooding surfaces.

silts, a leached underclay and culminating in a carbonaceous clay or low-grade coal are common, particularly in the Saltwick Formation. These cycles, up to 3 m in thickness, are interpreted to have been initiated by crevasse splaying across the floodplain whereby the sediment aggraded to near water-level, followed by subsequent plant colonisation (Hemingway 1974).

To date, the majority of work has been concerned with Lower Jurassic lithologic cycles (*e.g.* Arkell 1933; Hallam 1964, 1967, 1975; Hesselbo & Jenkyns 1997). However, there have been two previous attempts to explain the deposition of the Middle Jurassic Ravenscar Group in terms of sea-level change, both within a sequence stratigraphic context. Firstly, Eschard (1989) described the group in terms of five depositional sequences, and secondly, Knox *et al.* (1990) recognized three major transgressive-regressive cycles of varying durations (summarized in Fig. 1.7). In the present study, two unconformities bounding large-scale cycles are recognized within the Aalenian to Bathonian strata of the Cleveland Basin (including the underlying Dogger Formation), which were formed by erosional and non-depositional processes during relative sea-level falls. They are therefore interpreted as sequence boundaries (Van Wagoner *et al.* 1988; Vail *et al.* 1991). Onto these two large-scale cycles spanning the Aalenian to Bathonian stages, six medium-scale cycles of relative sea-level change are superimposed.

This initial work forms a frame of reference against which sedimentary sections from Scandinavia are compared. Chapter 2 summarizes the variety of sedimentary facies composing the Ravenscar Group and, in turn, describes the nature of the large and medium-scale lithologic cycles recognized in the basin. Subsequently, Chapter 3 discusses the correlation of the strata across the North Sea.

1.7 The Yorkshire flora

The palaeobotanical literature concerned with the Yorkshire flora is dominated by systematic and phylogenetic studies. The history of this work can be traced as far back as the early pioneering studies by Young and Bird in 1822, which were succeeded by progressively sophisticated investigations that culminated in a series of monographs produced by Harris (1961-1979). Over the years, the relationship of the plant remains to their depositional setting has asserted an increasingly dominant role, chiefly through the work of Black (1928, 1929), Harris (1952*a,b*, 1953) and Hill (1974*a*). Their approaches essentially fall into two types. The first encompasses the work of Black and Harris who investigated the representation of the flora, as a whole, in different depositional contexts. While the resultant classification of 'plant

bed types' created by the authors made considerable progress in eliminating what Harris (1953, p.63) termed a "lamentable cleavage" between sedimentological and palaeobotanical aspects of the Ravenscar Group, it did not succeed in fully categorizing the flora. In contrast, Hill adopted a more cautious approach, choosing simply to analyse the Hasty Bank exposure of the basal Saltwick Formation. Using a better constrained stratigraphy than was available to either Black or Harris, Hill was able to assess with greater care the palaeoecological conditions during this comparatively narrow time interval.

Continuation of Hill's work for every plant-bearing section in the basin would of course provide us with a greater understanding of palaeoecological conditions during deposition of the Ravenscar Group. However, such a close examination of the sequence is clearly beyond the scope of this study. Nevertheless, one of the main concerns in carrying out this research has been to locate precisely the plant beds within the stratigraphic framework constructed for this thesis. The main advantages of this approach include the easy correlation of plant beds to other areas of the basin, the provision of an age for a plant assemblage, and an association with a sedimentary facies. Perhaps most importantly in the context of this study is the use of the stratigraphic framework, which has allowed the temporal distribution of the flora to be detailed on a scale not before attempted for the Ravenscar Group.

Until now, studies investigating the temporal distribution of the flora have employed the comparatively poorly constrained Estuarine and Deltaic Series nomenclature. Furthermore, the floral remains were simply associated with one of the broad stratigraphic divisions, and no attempt has been made to assemble the plant beds by their relative age within these units. As a result, the significance of the climatic data generated by these studies was diminished (Harris 1947, p.176). While previous authors have detected a temporal fluctuation in various elements of the flora (*e.g.* Harris 1952*a*; Florin 1958; Couper 1958), they have been reticent in regard to offering explanations for its cause, perhaps because the climate signal was lessened through poor stratigraphic control. One of the main aims of thesis is to establish the nature of a climate signal through the Middle Jurassic, using diverse aspects of the Yorkshire flora within the newly devised stratigraphic framework. This aspect to the work is divided into two sections, which entail two approaches: one is based on growth-ring analysis of fossil wood, and the other subjects the flora to a multivariate statistical treatment.

1.8 Outline aim of this thesis

While the ultimate aim of this research is to elucidate the nature of stratigraphic development, vegetation and palaeoclimatic change during the Lower and Middle Jurassic in areas of north-

western Europe, the work is based principally upon a thorough investigation of the Middle Jurassic sequence of Yorkshire. The early part of this thesis is therefore concerned with the nature of stratigraphic development in the Yorkshire area. Detailed examination of the Ravenscar Group outcrops has revealed a great deal of information on the environments of deposition during the Middle Jurassic period, which are described in Chapter 2 along with details of a new stratigraphic framework based on these observations. Appendix 1 comprises the sedimentary logs recorded in the Cleveland Basin, upon which this framework is essentially based. The framework serves as a point of reference throughout the remainder of the thesis and, in Chapter 3, is compared to coeval stratigraphic sections located in parts of Scandinavia. In Chapters 4 and 5 it provides a secure means of constraining Yorkshire's floral remains for palaeoclimatic investigation.

The palaeoclimatic study is detailed by two parts. Chapter 4 describes growth-ring analysis carried out on a selection of fossil woods collected from the sequence and discusses the valuable information they provide regarding the interpretation of past climates. To understand these findings fully, it is necessary to consider the results in the context of the entire floral database; this is discussed in Chapter 5. Its main aim is to examine a temporal fluctuation in the flora found by previous palaeobotanists using a multivariate statistical method. It is hoped that by using a combination of sedimentological, stratigraphical and palaeobotanical information, the environmental and climatic conditions during the Early and Middle Jurassic in areas of north-western Europe will be elucidated. The conclusions drawn from this work are summarized in Chapter 6.

Chapter 2

Chapter 2

Stratigraphic framework for the Middle Jurassic Ravenscar Group of Yorkshire

2.1 Introduction

The aim of this chapter is two-fold. The first objective is to present detailed sedimentary descriptions and interpretations of the diverse lithologies recognized in the Aalenian-Bathonian sequence of the Cleveland Basin; and the second goal is to elucidate the varying character, frequency and magnitude of the lithological cycles comprising the succession. As a result of this work, a stratigraphic framework has been constructed which provides (1) a secure means by which the Yorkshire flora can be stratigraphically constrained, and (2) a frame of reference against which coeval sections can be compared.

2.2 Data collection

Yorkshire's Middle Jurassic succession is best exposed along the coast, where it forms a nearly continuous outcrop extending from Whitby in the north to Cayton Bay in the south (Fig. 2.1). A record of these coastal exposures is shown in Appendix 1, where the sedimentary logs are accompanied by locality descriptions, maps and field photographs (figures in this appendix are referred to throughout Section 2.4, p.30-52; denoted by the prefix 1). The basis to the sedimentological facies analysis carried out on these outcrops is the measurement and description of exposed sections. On the logs are recorded bed thickness and bounding relationships, lithology, colour, form and orientation of their sedimentary structures, and trace or body fossils. While care was taken to record all accessible exposures of the Ravenscar Group, greatest effort was devoted to the non-marine parts of the sequence: not only because this thesis is mainly concerned with the plant-bearing (usually non-marine) sections of the group, but also because a wealth of literature already exists for the marine beds (*e.g.* Bate 1964, 1965; Knox 1973; Powell & Rathbone 1983; Gowland & Riding 1991). In addition, because the Dogger Formation is understood to be genetically related to the Saltwick Formation, coastal exposures of that formation were also described: further details of the Dogger Formation's

Stratigraphic framework

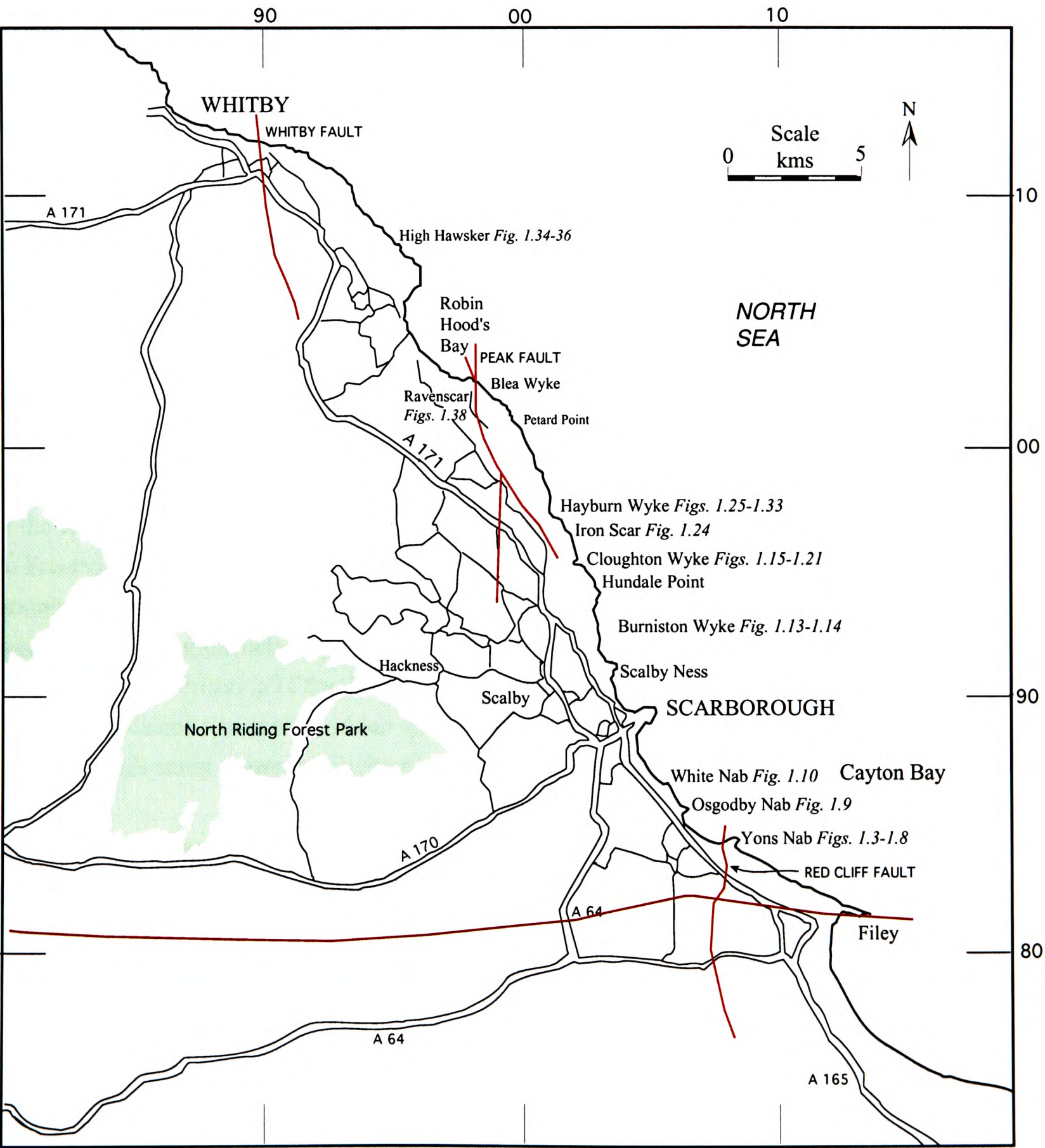


Fig. 2.1 Map of the North Yorkshire coast showing the position of the main field localities. Figure numbers relate to some of the sedimentary logs included in Appendix 1. All major and a selection of minor roads are shown. The position of the major faults is also illustrated.

facies in a regional context were obtained from Hemingway (1974), Know *et al.* (1990) and Young (1993).

The account of Yorkshire's coastal exposure is supplemented by a record of several inland outcrops and cores. At the outset, it was hoped that inland equivalents of the coastal exposures could be incorporated into the stratigraphic framework; both for the sake of completeness, and also to address the possible presence of lateral facies changes and modifications in, for example, channel-body architecture. However, after a reconnaissance survey, it was realized that this would involve more work than could be adequately accomplished in the time available, particularly given the general paucity and poor quality of the inland exposure at present, and lack of biostratigraphic control. Boreholes, in contrast, tend to present a more complete stratigraphic record, providing a valuable insight into lateral facies variations.

Boreholes drilled at three separate sites in the Cleveland Basin were examined. The Scalby Ness Borehole (TA 0363 9108) drilled by the Yorkshire Water Authority, cored a 76 m sequence from the Scalby Formation to Sycharham Member of the Cloughton Formation. This core is lodged at the British Geological Survey, Keyworth, Nottinghamshire and was first documented by Lott & Humphreys (1992) as part of a study into the stratigraphy and petrology of the Ravenscar Group sediments. Additionally, two of the many cores drilled by the Institut du Français Pétrole into the Ravenscar (NZ 980 016) and Long Nab (TA 030 328) cliffs were examined (cores RV18 and LN16). These cores are housed at the Institute in Paris and have been described in great detail by Eschard (1989), as part of a sequence stratigraphic and geometric characterisation of the deltaic deposits as a whole. The last point is noteworthy as very few published works exist which document and interpret the complete succession. In contrast to this study, however, Eschard's approach concentrates primarily on sub-surface data.

Thus, all the stratigraphic sections included in this thesis have been remeasured, incorporating previous published data where possible, and are designed as a secure means by which the Yorkshire flora can be stratigraphically constrained, forming a new lithostratigraphic framework against which coeval sections can be compared.

2.3 Overview of the Ravenscar Group's sedimentary facies

Before proceeding with detailed sedimentological descriptions of the facies composing the succession, it is appropriate to provide an overview to their character (Table 2.1). The Ravenscar Group is a 250 m thick sequence showing pronounced lateral facies changes, from

predominantly alluvial sediments in the north of the Cleveland Basin to more marine sediments in the south. The facies correspond to four principal environments of deposition: that is, alluvial, estuarine, lagoonal and marine. Alluvial sediments dominate the sequence, forming units up to 57 m thick, and are intercalated with the other facies types. They are distinguished on the basis of their lithology, sedimentary structures, grain size, association with rootlets, and abundance of well-preserved plant fossils, but general absence of marine body and trace fossils. Sediments of this type are inferred to have been deposited within two main settings: fluvial channel and interchannel flood-basin. Interchannel, or overbank, deposits predominate over the fluvial channels, comprising four facies which often intergrade laterally. These are crevasse-splay, lacustrine, poorly drained floodplain, and well-drained flood-plain. Subordinate meandering and braided channel bodies are enclosed within these overbank sediments. Pockets of well-preserved plant material are common within this facies association and form the basis of the collections examined and described in Chapters 4 and 5.

Sediments of an estuarine origin are most commonly found in the Long Nab Member. They are characterized by a distinctive suite of sedimentary structures and textures, which can be summarized by bi-polar cross-bedded sands, the presence of reactivation surfaces, flaser bedding and mud-draped foresets, an overall abundance of mud-grade sediment, and intense bioturbation. Facies of this type are restricted to tidal channel, and channel mouth-bar environments. In contrast, lagoonal sediments consist of fine sand, silt and clay, indicating low-energy conditions, and often contain marine microplankton (Hancock & Fisher 1981), with sparse root beds suggesting occasional shallow or emergent conditions. The lagoonal association was established to incorporate a limited suite of beds closely related to marine and estuarine sediments, uniting interdistributary bay, restricted brackish basin, and coastal marsh facies.

Marine deposits are diagnosed by what are commonly calcareous sandstones, siltstones or lime-mudstones, which may be structureless (possibly due to thorough bioturbation) or display planar, low-angle ripple cross-lamination, or cross-bedding. A rich shelly fauna, the (albeit rare) presence of ammonites and diverse trace fossil assemblages are also notable characteristics. Sediments of this type include brackish sandy-embayment, nearshore sandy and muddy shelf, and offshore mud-dominated shelf facies (Gowland & Riding 1991), which generally make up the lower portions of transgressive sequences and sharply overlie alluvial, estuarine and lagoonal deposits. These facies compose the Millepore Bed, and Eller Beck and Scarborough Formations.

Table 2.1 Summary of sedimentary facies in the Ravenscar Group

Facies association	Lithology	Interpretation
Alluvial Facies		
A1a	Sandy, low-angle inclined stratification within lenticular bodies	Meandering river-point
A1b	Erosive-based, coarse-grained lenticular bodies	Braided river sediments
A1c	Mudstone lenses	Abandoned channels
A2	Sharp-bottomed, planar laminated silty sandstones	Crevasse splays
A3	Heterolithic sandstone and siltstone	Lake sediments
A4	Dark, organic-rich mudstones	Poorly-drained areas of the floodplain
A5	Heavily-rooted silty mudstones	Well-drained areas of the floodplain
Estuarine Facies		
E1	Bi-directional cross-bedded sandstones and siltstones	Tidal channel deposit
E2	Bioturbated, muddy sheet-sandstone	Littoral sand
Lagoonal Facies		
L1a	Structureless sandy siltstone	Brackish interdistributary bay
L1b	Laminated sandy siltstone	Brackish interdistributary bay
L2	Weakly bioturbated, rippled, flaser and lenticular bedded fine sandstone and siltstone	High-energy interdistributary bay
L3	Plant-rich, heterolithic sandstones, siltstones and mudstones	Coastal marsh
Marine Facies		
M1	Bioturbated, heterolithic sands and silts	Siliciclastic embayment
M2	Wave-rippled and hummocky cross-stratified sands	Shoreface deposits
M3	Coarsening-upward sandy limestone sequence	Siliciclastic shelf shoal
M4	Cyclic bioturbated siltstones and sandy limestones	Mixed siliciclastic/carbonate shelf
M5	Black silty mudstone	Muddy outer shelf
M6	Sideritic silty sandstone	Nearshore environment
M7	Wave-rippled silty sandstones, containing plant debris and marine trace fossils	Prograding sandy shoreface
M8	Cross-stratified sandy oolite	Tidal sand belt

2.4 The sedimentary facies

2.4.1 Alluvial facies

Channel facies associations include the coarsest sediments within the Ravenscar Group, and are identified on the basis of their basal erosion surfaces, overall morphology and internal sedimentary structures. A wide range of channel bodies have been recognized in the sequence, which can be summarized as (1) simple channel facies, relating to solitary channels in overbank deposits, showing no evidence of lateral accretion and interpreted to be formed through cut and fill (mudstone plugs, described under facies A1c, are an example); (2) tabular channel bodies, displaying basal scour surfaces, intraformational lag conglomerates and epsilon cross-bedding (*e.g.* in the Scalby Formation on the southern side of Yons Nab (TA 085 840) and in the Saltwick Formation on the Whitby East Cliff (NZ 905 114)); and (3) complex channel bodies, encompassing all the major channel bodies found within the Ravenscar Group, which show either multilateral or stacked sandstone bodies (*e.g.* the meander belt sand on the foreshore of Burniston Wyke, labeled as facies A1a, and the Moor Grit at Hundale Point (TA 026 949), classified as facies A1b (Leeder & Nami 1979; Leeder & Alexander 1985; Alexander 1992a, b; Mjøs & Prestholm 1993). The following descriptions are based on examples of only the most common channel bodies found in the Ravenscar Group: for a fully comprehensive review of channel types (within the Saltwick and Scalby Formations), the reader is referred to Alexander (1992b).

Facies association A1a. Sandy, low-angle inclined stratification within lenticular bodies (meandering river point-bar)

This facies is characterized by erosive-based sequences with a basal lag, composed of trough cross-bedded sands which pass upwards into ripple-laminated finer sands with silt and clay alternations (typical of facies association A3: lake sediments), and finally into silts and clays penetrated by rootlets. In the southern exposures, the facies becomes progressively more heterolithic and bioturbated. Rip-up clasts, siderite pebbles and variously-sized wood fragments, together with a subordinate mix of other robust plant remains, are invariably found at the base of the channel bodies. Whilst the majority of the wood fragments are coalified, some charcoaled samples exist. The channels normally cut down into, and truncate, argillaceous overbank deposits, and similarly grade into overbank sediments in a lateral sense (A3-A5; lake, poorly-drained floodplain, or well-drained floodplain). Overall, there is much evidence for lateral accretion of the channel body. Frequently, levee and crevasse-splay sediments (facies A2; crevasse splay) can be traced from the margins of the channels (*e.g.* at the base of the

Gristhorpe Member, southern Yons Nab) and, more occasionally, mudstone lenses indicative of oxbow lake deposition are associated with the channels (A1c; mudstone plug). In this more overbank, better-drained environment, rootlets, *in situ Equisetum* and upright tree trunks can sometimes be found, for example at Iron Scar (Fig. 1.24, beds 18-19).

The facies is best displayed by the Long Nab Member on the foreshore between Long Nab and Scalby (TA 036 910) (Nami 1976), but there are many other examples of channel bodies showing evidence for lateral accretion (*e.g.* at the base of the Gristhorpe Member, to the south of Yons Nab). The Long Nab Member example incorporates low-angle, inclined stratification which consists of alterations of sandstone, siltstone and mudstone dipping transversely to the channel axis. In plan, the outcrop displays an arcuate bedding plane trace, highlighting the meandering and sinuous nature of the channels. Within thicker beds, planar lamination can be seen passing upwards into cross lamination. Plant debris is abundant and, in the upper parts of the facies, often includes delicate leaves and fructifications (*e.g.* the Scalby Ness Plant Bed: TA 037 911). Siderite nodules are found, and bioturbation occurs in more muddy beds indicating a marine influence on deposition.

Interpretation

Evidence gleaned from examination of the lithology, internal structure and plan of lateral accretion, together with associated facies, indicates that sediments of this type were deposited as part of a meander-belt complex. The inclined stratification so characteristic of this facies marks successive positions of subaqueous point-bar surfaces resulting from meander migration. Lateral migration may also explain the overall fining-upward trend seen in these deposits, although channel abandonment is another possible explanation. In this instance the upper, fine-grained member represents infilling of the channel by diminishing flow and perhaps later overbank flooding from an adjacent distributary channel. The increasing proportion of heterolithic and mud-grade sediment in southern areas of the basin probably reflects fluctuating and lower velocity flow, compared to more northern areas. The presence of a tidal influence upon deposition in southern areas is evinced by a higher mud content, trace-fossil assemblages, and the close association of facies ascribed to an estuarine environment of deposition (facies E1; tidal channel deposit). Overall, the form of the lateral accretion structures, which characterizes this facies, results from alterations in erosion and deposition, variation in sediment type, or fluctuations in sedimentation rate: truncation of individual beds may correspond to migration of the meander belt (Alexander 1992a).

Facies association A1b. Erosive-based, coarse-grained lenticular bodies (braided-river sediments)

Sediments of this type are less common than the facies described above. Represented by coarse-grained sandstone bodies displaying giant sets of trough cross-stratification and

multistorey channel fills (Leeder & Nami 1979), the base of the Scalby Formation (Moor Grit Member) at Hundale Point best represents these deposits. The low-sinuosity channel sequence cuts down sharply into the underlying Scarborough Formation by as much as 6m and is represented by an upward-fining succession from coarse-grained, mature sandstones, rich in coalified plant material including subordinate charcoal fragments, to progressively more silty, heterolithic sediments showing ripple trough cross-lamination and planar lamination. At the base of the channels, particularly within erosional troughs, derived siderite pebbles and disorientated logs, branches and twigs are often found. The margins of individual channel bodies are difficult to map in the vicinity of Hundale Point. The sequence at this locality reveals this facies passing upwards into argillaceous flood-plain facies of A4 (poorly-drained floodplain) and A5 (well-drained floodplain), which are in turn by superimposed meander belts, described by the point-bars of facies A1a. Overall, the facies displays evidence for vertical accretion, and very occasionally, sediments of this type occur in channel bodies dominated by lateral accretion (facies A1a).

Interpretation

This facies is interpreted as a braided-river system, on the basis of the sharp based, low-sinuosity, multistorey nature to the channels, which are predominantly composed of coarse-grained material (Leeder & Nami 1979). Furthermore, this evidence indicates that discharge in the channel was sporadic, containing a high proportion of bedload material. The fact that the margins of the channels are difficult to establish indicates that, in the region of Hundale Point at least, the channel bodies are laterally extensive and may coalesce with other channel body types (Leeder & Nami 1979; Fisher & Hancock 1985; Alexander 1992*b*).

Facies association A1c. Mudstone lenses (abandoned channels)

The nature of this association is characterized by its local development, lenticular form, and infilling by sediments typical of facies association A4. Exceptionally well-preserved plant debris are locally abundant, principally of leaves, stems, fructifications and variously sized wood fragments (*e.g.* Gristhorpe, TA 081 844 and Scalby Wyke Plant Beds, TA 030 328), particularly in the upper clay-rich portions of the lenses. Rare rootlets on the margins of these deposits provide the only evidence of *in situ* plant growth. The plant material occurs chaotically arranged and orientated parallel to bedding. The facies is characterized by structureless or crudely laminated sandy silt, of various shades of grey and brown, overlying a wide range of flood-plain facies: the boundary between the two is sharp and erosive based, or gradational with an upward-fining transition. Contorted bedding is also a common feature of the facies.

In the order of 10s of metres wide (with a maximum width of 60-100 m) and 2-4 metres thick, the deposits appear to be mostly vertically accreted and commonly succeeded by erosionally

based, coarser-grained beds such as sheet sandstones. The lenses are commonly sinuous in nature. This facies is most prominent when associated with other channel deposits, and most difficult to recognize when completely composed of mudstone and encased within argillaceous overbank deposits. Sediments of this facies can be distinguished from sequences deposited on lake beds by their more uniform thickness and laterally continuous nature.

Interpretation

The characteristic lenticular form and sharply erosive base, together with fine grain size and exceptionally well-preserved flora, suggests that the sediments were deposited in abandoned fluvial channels. It is probable that channel abandonment occurred when the active channel became blocked upstream by sediment during waning flow, creating an inactive channel in which fine-grained sediment settled out of suspension. More occasionally, the base of the facies is gradational and upward fining across the boundary, indicating that abandonment may have been gradual, perhaps by meander cut-off or avulsion (Alexander 1992*b*).

The common presence of exceptionally well-preserved and delicate plant material, indicates that deposition in the channels was rapid and perhaps poorly oxygenated. The inferred environment of deposition and overall character of this facies is reminiscent of the dark grey, organic-rich mudstones of facies association A4. The two facies are closely associated in the succession which forms the Gristhorpe Plant Bed: lenses of channel abandonment facies and poorly-drained flood-plain facies are juxtaposed laterally. Where the facies intergrade, it can be difficult to distinguish the two. Nevertheless, facies A4 can be identified on the basis of its general architecture (*i.e.* absence of an erosive base and its lateral continuity), comparatively heavy rooting and absence of a conspicuous clastic component.

Facies association A2. Sharp-bottomed, planar laminated silty sandstones (crevasse splays)

Facies association A2 is represented by sheet-like or lenticular, laterally extensive bodies predominantly composed of a well-sorted, medium to fine-grained sand containing little mica, which is occasionally interbedded with silty clay or sandy silt. The beds usually have a thickness of 0.5-1 m and extend over hundreds of metres. At several localities, the deposits can be traced to the margins of channel bodies (*e.g.* bed 22, Fig. 1.3, Yons Nab) and laterally the beds can be seen to thin and peter out into more argillaceous flood-plain facies. In areas where the facies extensively outcrops, successive sandy lobes can be seen prograding over flood-plain facies (*e.g.* Saltwick Formation, north of Hayburn Wyke: TA 010 977). Sedimentary structures most commonly include planar lamination, cross lamination, current ripples, contorted bedding, irregular horizontal mud drapes and laminae, but there are instances where the facies simply appears massive. The lower boundaries of the sheet sandstones are usually sharp and often erosive, truncating the beds below and frequently incorporating lithic fragments

as rip-up clasts in the basal portion. Loading and groove casts are fairly frequent, and at times can be used as palaeocurrent indicators (*e.g.* Cloughton Wyke: TA 021 955, beds 34 and 36, Fig. 1.15). Sheet sandstones are most prominent in the lower to middle part of the Gristhorpe Member.

At Yons Nab, the facies shows intense bioturbation which has destroyed the primary sedimentary structure of the beds: for example, *Diplocraterion* burrows pervade the sandstone resting on the Gristhorpe Plant Bed (bed 27, Fig. 1.3). Roots are frequently found in beds composed of this facies and stem casts of *Equisetum* often occur (*e.g.* *Equisetum* Bed, north of Hayburn Wyke (bed 11, Fig. 1.25); Cloughton Wyke (beds 36, 39; Fig. 1.15). Such rooting indicates colonisation of the sediment by vegetation, which often obscures the internal sedimentary structure, producing features consistent with a palaeosol. Scattered plant fragments occur within the beds but, with the exception of tough and robust leaves, are mostly fragmentary and indistinguishable. Sheet sandstones containing a robust and charcoaled flora occur in the upper Saltwick Formation at Hayburn Wyke (*e.g.* bed 3, log b, Fig. 1.31). Here the thin sands are intercalated with what have been termed coastal swamp sediments (facies L3) and, in part, are referred to as the Hayburn Wyke Plant Bed (TA 013 969). In the Burniston Footprint Bed located at Burniston Wyke, rare desiccation cracks and saurian footprints are associated with a sheet sandstone.

Interpretation

Beds of sandstone revealing these characteristics are likely to have been deposited as crevasse-splays. These deposits form during periods of excess fluvial discharge, causing breach of a river margin to allow sediment-laden waters to wash across the flood-plain (*e.g.* Elliot 1974, 1986; Fielding 1986). Thick crevasse-splay lobes may infill the interdistributary bay environment and are overlain by facies reflecting emergence or near emergence. Within the Ravenscar Group, the crevasse-splay sandstones can be found as single entities (A2), or as composite bodies consisting of several crevasse-splay sandstones (A2*) which may relate to deposition in a crevasse subdelta (Mjøs *et al.* 1993). An example of the latter occurs at a stratigraphic level corresponding to the lower and middle parts of the Gristhorpe Member, where channel sandstones are generally absent but a marine influence occasionally present: it is likely that these beds represent deposition from streams into standing lacustrine or lagoonal waters (Mjøs *et al.* 1993). Where sheet sandstones are stacked, periods of increased flood activity, possibly related to a fall in base level or perhaps seasonal effects, can be inferred (Knox *et al.* 1990). Crevasse-splay sandstones are frequently interbedded with flood-plain facies pertaining of facies A3 (lake sediments), A4 (poorly-drained floodplain) and A5 (well-drained floodplain), and less commonly are associated with facies L1 (brackish interdistributary bay) and L2 (high-energy interdistributary bay).

Facies association A3. Heterolithic sandstone and siltstone (lake sediments)

The predominantly silty mudstone lithology composing this facies contains subordinate amounts of thinly, and somewhat crudely, intercalated fine-grained sandstone and carbonaceous mudstone. Alternatively, parts of the facies may be represented by scattered siltstone lenses within a black, organic-rich clay. The facies is commonly laminated or more occasionally, where the sand component is reduced, structureless. Often, the lamination is disturbed by bioturbation. Small pieces of fragmentary plant debris occur on bedding planes. The units are usually less than a metre thick, level bedded, laterally impersistent and pass laterally into the fluvial sediments of facies association A1, the organic-rich mudstones of A4, or the silty mudstones of A5. Wave-ripple lamination, cross lamination and planar lamination are frequently found, as are bioturbation, carbonized rootlets and occasional body fossils (*e.g.* the freshwater bivalve *Unio kendalli*, near Whitby). Palynofacies studies (Hancock & Fisher 1981) have shown that sediments of this type frequently contain a brackish or marine microflora, especially in more southern parts of the basin: where this is the case, the facies grades into sediments similar in character to association L1 (brackish interdistributary-bay).

This facies usually forms part of a repetitive sequence of localized, small-scale, shallowing-upwards cycles. Best developed in the mid-portion of the Saltwick Formation north of Hayburn Wyke, the facies is often intercalated with sheet-sandstones (facies association A2), overlain by more argillaceous sediments containing roots and *in situ Equisetum* (facies association A5), and capped by plant-rich lignitic horizons. The cycles are in the order of 4-5 m thick. The sequential relationship of A2, A3, A5 is best shown in Fig. 1.25.

Interpretation

The presence of fine sand and silt laminae in siltstones and mudstones of this facies indicates water-sorting, perhaps within a freshwater lake or, less probably, under waning flow in a river channel. The occurrence of this facies some 3 m above the base of the Saltwick Formation, extending 4 km to the south-east of Whitby, provides the most extensive example. Here, sand and silt laminae are interbedded, and wave ripple-lamination is commonly found, unlike in some smaller, more restricted examples of this facies. Sediments of this type deposited in smaller and shallower freshwater pools on the floodplain tend to be thinner, display fewer sedimentary structures and show evidence for rapid aggradation. The development of these more ephemeral deposits is often cyclic, perhaps relating to seasonal flooding of the flood-basin. The erosive bases to some beds may have developed during these flooding events. The occurrence of a brackish and marine microflora suggests that this facies may be paralic, deposited on the landward side of the coast in shallow water susceptible to marine influence (Knox *et al.* 1990).

Facies association A4. Dark, organic-rich mudstone (poorly-drained areas of the floodplain)

This lithology is characterized by laterally extensive beds or lenses of dark grey to black mudstone. The most diagnostic features are the absence of a coarse clastic component and the abundance of organic matter, which ranges from finely-disseminated debris to well-preserved leaves, stems and fructifications. Wood in the form of logs, branches and twigs is commonly found, displaying shearing and distortion but no evidence of bacterial decay. Bioturbation is common at some horizons. Pyrite is ubiquitous and is usually associated with organic-rich layers, wood and roots. Siderite nodules and layers also occur. This facies commonly passes laterally or upwards into facies association A5: while these facies are grossly similar, they differ in the amount of organic matter, preservation of the plant remains, and presence of pedogenic features. Where the two facies intergrade, the resulting association forms units up to several metres thick. Instances of well-preserved plant material, however, tends to be more localized and forms only thin beds where these facies coalesce (*e.g. Solenites Plant Bed: TA 021 951*). To a lesser extent this facies passes laterally into the interdistributary bay deposits of L1 and L2, and the coastal marsh sediments of L3. These facies can, however, be separated on the basis of marine microplankton content, of which this example contains none.

A less common variety of this facies displays sediment which is brown to black in colour, friable, structureless and blocky in texture, displaying a dull vitreous lustre (*e.g. beds 5, base of 6 and 9, Fig. 1.34, High Hawsker: NZ 948 082*). The main differentiating factors between this and the more general description for the facies as a whole is its coaley texture, abundance of woody material showing varying degrees of compaction, and paucity of leaves and fructifications. In general character, this sub-facies is similar to that described as a lignite. In Yorkshire there are two principal types of lignite: those overlying rooted palaeosols and those overlying a genetically unrelated deposit. Where lignite overlies a palaeosol, the underlying sediment generally forms a thin bed and is composed of a light-coloured, bleached clay or a silty clay seatearth (*e.g. mid-way through the Saltwick Formation, Whitby West Cliff*). Carbonized roots usually penetrate the soil: they tend to be small and indicative of herbaceous plant growth, but more occasionally they are large and suggestive of tree growth (*e.g. bed 13, log c, Fig. 1.31; Hayburn Wyke at TA 0125 9690*). In contrast, lignites which rest on genetically unrelated sediments lack an underlying rooted horizon. The underlying sediments are variable in lithology, ranging from silty clays (*e.g. within the Gristhorpe Plant Bed*) to coarse sandstones (*e.g. at the base of the Saltwick Formation, High Hawsker*). In broad terms therefore, the abundance of wood and a commonly coaley texture distinguishes this sub-facies from the general description for A4.

Interpretation

The main factor influencing the character of these sediments is their deposition in pools of stagnant water on the flood-plain, where anaerobic conditions often prevailed: this is indicated by the ubiquitous presence of pyrite replacing stems, small roots and wood; the exceptional

preservation of plant material; and the apparent absence of microbiological activity in the fossil wood present. Furthermore, the common occurrence of shearing and distortion in the woody fragments — particularly in remains from the Gristhorpe Plant Bed — indicates that the wood was waterlogged for a period of time before fossilization occurred.

Abundant pyrite, siderite and organic matter, and absence of desiccation cracks and oxidized horizons, are all indicative of sedimentation in a waterlogged environment. Such conditions may have been created by fault movement to produce depressions on the floodplain, formed in abandoned channels, in topographic lows where the water-table intersected the ground surface, or in swampy areas of the coastal-plain. The homogeneity of the sediment suggests that there was not a great seasonal influence on deposition, unlike facies association A5 (well-drained floodplain). Instead, deposition may have been controlled by local subsidence or the propensity for differential compaction in the underlying sediments. The only possible seasonal control on the accumulation of this facies is in the introduction of logs and branches into the environment during times of flooding (*e.g.* thin woody beds within the Gristhorpe Plant Bed). Tree roots or stumps are not found *in situ* within this facies indicating that either they were not part of the immediate vegetation, the stagnant waters were slightly brackish inhibiting tree growth, or that post-depositional conditions were not conducive to their preservation.

Where the facies has a more coaley, wood-rich, lignitic appearance it is likely that it represents a peat. In the description of this sub-facies, peats associated with roots were distinguished from those which are not. It seems likely that the presence of roots can allow autochthonous peats (above rooted horizon) to be separated from allochthonous ones (no rooted horizon). In terms of the environment of deposition, autochthonous peats may represent those laid down in marshy or swampy areas, while allochthonous peats may relate to accumulation of plant debris in perhaps a lake setting. Of course, the dividing line between this sub-facies and the facies as a whole is somewhat vague. There are, however, field examples which show a clear separation of the two facies: within the Gristhorpe Plant Bed, both leaf-rich (*e.g.* bed 25, Fig. 1.3) and wood-rich (*e.g.* bed 24, Fig. 1.3) layers occur; the former typical of the general description for A4 and the latter characteristic of this lignitic sub-facies.

Facies association A5. Heavily-rooted silty mudstones (well-drained areas of the floodplain)

This facies consists of silts, silty mudstones and mudstones displaying a range of internal structures. The bedding is predominantly concordant or, very occasionally, undulose and rather erosive (*e.g.* bed 14, log b, Fig. 1.31 recorded at Hayburn Wyke: TA 0125 9690). The primary lamination of these beds tends to be disturbed to a varying degree, often showing complete homogenisation by animals and plants. In places, and on a small scale, the laminae are convoluted. In contrast, well-developed lamination or thin bedding is common and usually

found on a scale of a few millimetres. Within these normally graded, dark grey to brown laminae, small fragments of plant material occur. Roots are abundant and siderite nodules are common; less frequently, thin siderite bands are encountered. Rarely pyrite occurs, usually in association with rootlets and wood in more carbonaceous horizons. This facies may be internally rooted (*e.g.* Fig. 1.15 showing top of Gristhorpe Member at Cloughton Wyke), have roots descending into it from an overlying plant bed (*e.g.* bed 18, log a, Fig. 1.24: Sycharham Member at Iron Scar), or encompass the substrate from which roots penetrate into an underlying well-preserved palaeosol interval (*e.g.* bed 12, log c, Fig. 1.31: Saltwick Formation at Hayburn Wyke). Where this facies provides a rooting substrate, it begins to intergrade with the plant bed facies described above (A4).

The facies displays a range of colours including white, various shades of grey and brown, black, yellow and orange: the colouring is commonly patchy or mottled. The texture of this facies is often blocky and, in places, gritty: the gritty aspect to some beds is produced by coarser sand-grains within the mudstone or claystone matrix. X-ray diffraction analysis has revealed a clay mineral assemblage dominated by detrital kaolinite and illite in beds of this facies from the Cloughton and Scalby Formations (Lott & Humphreys 1992).

Within the bounds of this facies type, the sediments can be split roughly into two basic types. Some are lighter in colour indicating a low organic content, appear to be mottled, are often penetrated by roots and, more rarely, show desiccation cracks. In contrast, others are darker-coloured carbonaceous deposits, containing a restricted clastic component but ubiquitous fragmentary wood and plant debris. These more organic-rich beds are rather thin (in places only a few cms thick) and show little evidence for palaeosol development, indicating that they simply represent accumulated allochthonous plant material. These sediments intergrade with not only the dark, organic-rich mudstones of facies association A4, but where pyrite is common, also with the coastal marsh facies of L4.

Interpretation

The general absence of erosive features and graded nature of the primary lamination suggests a low-energy environment of deposition, perhaps by waning currents in a distal area of the floodplain. The common presence of roots argues for either emergent or very shallow-water conditions, and their occasional pseudomorphing by pyrite suggests relatively rapid mineralisation of the decaying roots. Furthermore, a marine influence during deposition can be inferred for those beds containing pyrite (Kantorowicz 1990). The rare presence of mud cracks provides evidence for emergent and desiccating conditions. More specifically, the combination of roots, siderite, colour mottling and a blocky texture are features commonly attributed to pedogenic processes. The rather limited, sporadic nature of the outcrop of this facies suggests that we may be seeing the erosional remnants of what were originally more extensive floodplain

deposits (Alexander & Gawthorpe 1993). Those palaeosols which reveal features characteristic of a more mature soil profile most likely developed during times when, or in areas where, there was little channel activity. For the most part, however, pedogenic features are poorly developed and the facies is simply represented by heavily rooted silty mudstones.

The conditions under which a single palaeosol developed can be neatly shown by the colouring of the sediment, as colour variability reflects Eh and pH conditions soon after deposition. Iron accounts for much of the colour mottling: in its reduced state iron colours the sediment greenish-brown, while in its oxidized state it imparts a yellow or orange colour. In contrast, greys and browns indicate the amount of organic matter contained within the sediment, which is best preserved in fine-grained, waterlogged sediments with a low Eh and little bacterial activity. Greys and browns are usually found in conjunction with greenish-brown colours produced by iron in its reduced state. Well-preserved plant material is often associated with these features indicative of reducing, low-oxygen conditions and high-organic matter content — this association highlights the transition of this facies with facies association A4 (poorly drained floodplain).

In the sediments suggestive of reducing conditions, siderite is a common diagenetic mineral. It is understood that siderite forms in sediments experiencing reducing pore-water conditions, usually in association with organic matter. The mineral is prolific as large concretions and beds of sphaerosiderite in the upper part of the Scalby Formation meander belt and overlying carbonaceous clay (at Burniston Wyke), and is interpreted as forming through precipitation from oxygen-deficient ground waters beneath a peaty soil, which at this locality is represented by the carbonaceous clay (Kantorowicz 1990).

The features listed above, therefore, provide valuable information for the interpretation of the development of palaeosols in the sequence. While siderite, pyrite, organic-rich layers and a greenish-brown and grey colouration attest to low oxygen levels in a waterlogged environment; in contrast, rooting, desiccation cracks and a yellow, orange and red colouration testify for emergent, oxidising conditions. Where these contrasting features are found in association or are interbedded, a fluctuating water table can be inferred. Frequently, sediments of this type is interbedded with the crevasse-splay sandstones of facies A2.

2.4.2 Estuarine facies

Facies E1. Bi-directional cross-bedded sandstones and siltstones (tidal-channel deposit)

Only two examples of this facies are recognized in the sequence, within the lower Gristhorpe Member at Osgodby Nab (Fig. 1.9: TA 065 864) and Long Nab Member, Burniston Wyke (Fig. 1.13). Features which are common to both examples include a sharp base, which in the Osgodby Nab instance appears to be erosive (an intraformational mud-clast conglomerate overlies the basal boundary), a lenticular form, tidally generated sedimentary structures, and marine trace fossils. The deposits at Osgodby Nab best display the features characteristic of this facies. Here the sediments comprise fine to medium-grained, moderately well-sorted, thinly-bedded sandstones and intercalated siltstones. Whereas the sandstone component tends to be laminated and somewhat flaggy, the siltstone beds show an intertidal flaser structure and occasional bioturbation. Additionally, there are rare instances of mud drapes cloaking sandy ripples. Planar laminated and structureless beds are less common. Small siderite nodules and layers are common within the more sandy beds. Small, disseminated plant fragments occur locally.

The most notable attribute of the facies at Osgodby Nab is the trough cross-bedding which exhibits bi-directional palaeocurrent orientations. Individual cross beds are in the order of 10s of cm thick and show an overall fining-upward trend; each shows an internal primary sedimentary dip of up to 18°. Two discontinuities occur within the deposit at Osgodby Nab, marked by a steeper inclination of the beds and, in places, a mud drape. Body fossils are very rare, and bioturbation is on the whole generally weak. However, burrows within the well sorted, ripple-drift laminated, fine-grained sandstone which forms the facies at Burniston Wyke are locally abundant and distinctive: most notably, *Ophiomorpha* is found at the base of the bed, together with prominent scour marks, gutter casts and desiccation cracks (Livera & Leeder 1981). The Long Nab Member example wedges out laterally and is enclosed within overbank deposits (typical of facies A5; well-drained floodplain)). The upper surface of the sand is penetrated by roots and, near its northern end, is downcut and scoured by a later channel (Rawson & Wright 1992).

Interpretation

An estuarine setting is suggested on the basis of the varied and commonly bi-polar palaeocurrents, the abundance of heterolithic facies, and the association of a marine suite of trace fossils with plant debris. Rapid and local facies variations, in a spatial and temporal sense, are a striking feature of the association. In the Osgodby Nab example, the sharp, erosive base to the channel body is immediately overlain by an intraformational conglomerate which grades upward into planar cross-bedded sands showing silt drapes on some of the foresets. The initial

downcutting and scouring of the channels reworked sediments from adjacent mud flats, incorporating the material into the basal portion of the sequence, which is today manifest as an intraformational conglomerate. Further erosion may have reworked mud drapes laid down during tidal deposition, producing more muddy clasts. Overlying sedimentary structures, which are dominated by bi-polar cross-bedding, flaser bedding, ripple-drift lamination and mud drapes, are suggestive of alterations in sediment transport conditions and a tidal influence upon deposition (Elliot 1986). This evidence is not indicative of a specific depositional environment, however, as such tidal influences could equally have been generated in a distributary mouth-bar as a tidal channel infilled by lateral accretion. Nevertheless, on the basis of a sharp basal boundary and fining-upward trend in this example a distinction can be made, and a tidal channel infilled by lateral accretion is proposed (Livera & Leeder 1981). The presence of *Ophiomorpha* supports this supposition, as it has been described from recent estuarine sediments (Frey *et al.* 1978) and from ancient estuarine channel sequences (*e.g.* Goldring *et al.* 1978). Where burrowing occurs, periodic stabilisation and colonisation of the bedforms during periods of weak current activity can be inferred. However, the general scarcity of bioturbation throughout the facies as a whole probably reflects reworking of the sediments by tidal currents.

Facies E2. Bioturbated, muddy sheet-sandstone (littoral sand)

Sediment classified under this facies type can be differentiated from facies association E1 on the basis of (1) the absence of a channelized form (or downcutting, lenticular nature), (2) the scarcity of bi-polar cross-bedded deposits, and (3) the lack of reactivation surfaces. Furthermore, this facies can be separated on the predominance of mud-grade sediment. Commonly, the facies forms a fairly laterally continuous sheet sand, which displays intense bioturbation: well-preserved burrows of *Skolithos* and *Rhizocorallium* occur. The basal boundary of these muddy, sheet sands is often sharp and sometimes erosive, and in places reveals a basal, thin, intraformational conglomerate. Within the body of the deposit, wavy flaser-bedding, ripple-drift lamination and cross-stratification are locally preserved. The facies is best displayed at the base of the Saltwick Formation in the Ravenscar area, where a 2 to 3 m thick, laterally continuous sandstone exists which contains bivalve debris, glauconite and, at the base, reworked lithic fragments from the underlying Dogger Formation (Ravenne *et al.* 1987).

Interpretation

The trace fossils associated with this facies indicate a marine origin, which is further constrained by the presence of wavy flaser-bedding, ripple-drift lamination and cross-stratification which relate to tidal processes. In combination, these features indicate an estuarine mode of deposition. The laterally continuous nature of the Ravenscar sandstone suggests the conditions under which this sand was deposited were fairly extensive, and not necessarily confined to a subtidal channel.

2.4.3 Lagoonal facies

Facies L1a. Structureless sandy siltstone (brackish interdistributary-bay)

These structureless sandy siltstones often form upward-coarsening sequences, from yellow or grey silty clay at the base to brown or grey silty fine sand at the top. Fragmentary and abraded plant and wood debris is a common constituent of this facies, but evidence for *in situ* growth is rare. Normally the sequence coarsens upward and at times thin sandstone beds occur at the top of individual cycles. Where the sediment becomes laminated, the deposit is described under a separate sub-facies outlined below. In both instances, individual sandy siltstone beds are sharp based and show weak bioturbation. Nodules or thin, impersistent beds of sideritic ironstone are common. This facies is well exposed in the Yons Nab Beds at Cloughton Wyke (beds 13, 14, Fig. 1.15), overlying the more bioturbated, heterolithic sands and silts at the base of the unit (beds 5-12, Fig. 1.15), categorized as facies L2: at this locality, the sediments contain a great deal of abraded plant debris (the Ginkgoalean Plant Bed: TA 081 844), and succeed a rooted horizon. Frequently this facies association succeeds M2 (*e.g.* Hayburn Wyke). Marine palynomorphs recorded from these sediments at Cloughton Wyke, include salinity-tolerant dinocysts, acritarchs, leiospheres and tasmanitids (Hancock & Fisher 1981).

Facies L1b. Laminated sandy siltstone (brackish interdistributary-bay)

In contrast to the sub-facies discussed above, sediment of this type displays mm-thick laminae or lenses of very fine sand or coarse silt within an overall sandy siltstone lithology. Again, this sub-facies coarsens upward. At the top of the Saltwick Formation at Hayburn Wyke, the facies passes from a grey, silty mudstone to a cross-bedded, medium-grained, buff-coloured sandstone (beds 15-20, Log b, Fig. 1.31). Occasional low-amplitude ripples occur, and small scattered siderite nodules and disseminated pyrite are common. Fragmentary plant remains are also found, and marine palynomorphs present (Hancock & Fisher 1981). This facies is usually overlain by the sand bars described under M2 (shoreface deposits), and at times the facies includes sheet sands which are attributable to A2 (crevasse splays): a lack of diagnostic marine characteristics and deficit of tidally generated sedimentary structures, differentiates these sheet sands from those identified as E2 (littoral sands). Where these sediments are intercalated with sheet-sand facies, a series of small-scale coarsening-upward sequences occur, on two distinct levels. Firstly, there are sequences which are on average 5-10 cm thick and commence with mudstone-siltstone beds including plant debris, and overlain by thin sheet sandstones (*e.g.* beds 3-4, log b, Fig. 1.31, Hayburn Wyke); the lagoonal facies described as L2, and indicative of higher energy conditions, are associated with this facies in the Hayburn Wyke locality.

Secondly, there are cycles on a 4-5 m scale where the laminated sandy silts are overlain and interbedded with sheet sandstone (A2) or sand-bar facies (M2).

Interpretation

The sub-facies L1a and L1b are associated on the basis of their marine palynomorph content, and their general character indicates deposition in a brackish interdistributary bay. Such areas of delta-plain are generally enclosed, shallow water environments which are quiet or even stagnant. The rare presence of ripples indicates mild agitation by perhaps locally generated wind-waves (Coleman & Gagliano 1965). This environment is, however, occasionally disturbed during flood periods as excess flow is diverted from nearby distributary channels: interbedded crevasse-splay and levee deposits form as a result (A2). Collectively, these facies infill the bay environment and provide a platform on which vegetation can grow.

Repeated infilling of the bay environment can produce a series of minor coarsening-upward cycles (5-10 cm scale) of mudstone and siltstone capped with sandstone (Elliot 1974). Cycles on a larger scale (4-5 m) vary in nature depending on their relative transgressive or regressive character. Within the top of the Saltwick and overlying Eller Beck Formations, cycles on this scale are found comprising lagoonal silty mudstones (L1 and L2) progressively overlain by shoreface sands (M2) within a transgressive regime. *In situ* tree stumps, rootlets and soft-sediment deformation at the top of the sand bars indicate shallow-water conditions or ephemeral emergence before renewed deepening (*e.g.* bed 12, Log c, Fig. 1.31). Conversely, the Yons Nab Beds exemplify a regressive passage from fine-grained prodelta facies upwards into a silty sandstone-dominated shoreline. Continued progradation resulted in a fluvial distributary channel truncating the sequence. Juxtaposition of these facies can be interpreted as a decrease in depositional energy and saline influence, as the marine embayment which the Millepore Bed section represents retreated.

Overall, these sediments are diagnosed on the basis on their structureless or laminated nature, stratigraphical position, and the presence of marine palynomorphs. However, an example of this facies at Cloughton Wyke is rather more ambiguous in character, as it incorporates fragmentary plant material and overlies a rooted horizon (bed 14, Fig. 1.15). Marine microfossils and a lack of pedogenic features do, however, allow easy distinction from the true palaeosols categorized by facies A5. Similarly, this facies also shares some aspects of its general character with the coastal marsh facies described by L3, but in the same way that it could be separated from A5, these lagoonal sediments can be discerned by the presence of roots and associated plant debris.

The structureless nature of L1a may be due to complete homogenization of the sediment by intense bioturbation: a common occurrence in sediments deposited in interdistributary bays

(Elliot 1986). In contrast, evidence for burrowing is absent in sub-facies L1b, and this lack of reworking and mixing of the sediment has allowed fine banding or 'varves' to be preserved. This lamination indicates sedimentation from suspension in quiet waters. To explain the paucity of bioturbation and lack of body fossils in sub-facies L1b, unfavourable pH, Eh or salinity conditions are suggested: the presence of pyrite, which normally requires anoxia for precipitation, supports this inference.

Facies L2. Weakly bioturbated, rippled, flaser and lenticular-bedded fine sandstone and siltstone (high-energy interdistributary bay)

Heterogeneous fine sand and silty clay compose this facies. The sandy component reveals ripples, planar-lamination and flaser bedding, which are in places disrupted by bioturbation, and locally abundant comminuted plant debris. In contrast the more argillaceous laminae display wavy and lenticular bedding. Within the facies, body fossils are common and, while patches of iron-staining are found, siderite nodules and layers are rare. A diverse marine palynomorph assemblage is contained within the deposit (Hancock & Fisher 1981).

Perhaps the best example of this facies represents the Yons Nab Beds at Cloughton Wyke (beds 5 to 12, Fig. 1.15). The facies succeeds the marine embayment facies at the top of the Millepore Bed (described by facies M8) and is dominated in the lower part by ripple-drift, cross-laminated sandstone. Upwards, the facies features flaser-bedded, shaley sandstone containing various bivalves including *Trigonia*, *Pecten* and *Ostrea* (Rawson & Wright 1992), which is in turn overlain by bioturbated, ripple-drift, cross-laminated sands penetrated by rootlets. Resting on this succession are the shaley, plant-rich deposits attributed to the lagoonal facies of L1a and b. Beds at the base of the Sycarham Member show comparable sedimentary features, including current ripples and wavy bedding. Thin, bioturbated, laterally continuous, rippled sandy horizons are intercalated with mudstone beds at this locality.

Interpretation

This facies is interpreted as representing deposition in a brackish interdistributary bay environment, during periods of high energy. The close lithological similarities with facies L1 (interdistributary bay), and their juxtaposed stratigraphic position, suggests that both L1 and L2 were laid down in comparable settings. Therefore, while an interdistributary bay environment can be diagnosed for both, the prevalence of current-generated sedimentary structures in this facies sets it apart from L1, and indicates that this facies was deposited during higher energy conditions. Where L1 succeeds L2 (at, for example, Cloughton Wyke), a decrease in depositional energy and saline influence can be implied. Frequently, barrier shoreface deposits (M2) overlie these lagoonal sediments; most notably in the Hayburn Wyke section.

Facies L3. Plant-rich, heterolithic sandstones, siltstones and mudstones (coastal marsh)

This facies is in general terms very similar to facies A4: both are predominantly argillaceous, organic-rich deposits containing exceptionally well-preserved plant material. What sets this facies apart, however, is the integral presence of marine microplankton (Hancock & Fisher 1981). Beds within the uppermost Saltwick Formation at Hayburn Wyke characterize the facies (beds 3 to 5, log b, Fig. 1.31), and reveal an interval of rapidly alternating thin sandstone, siltstone and mudstone beds. Within this succession the sandstones are sharp based and micaceous, incorporating charcoalfied wood and, notably, fertile fern fragments (of *Coniopteris hymenophylloides*). Soft-sedimentation deformation is apparent in these beds. Intercalated are dark-grey mudstones and brownish-grey siltstones which contain a variety of flora, including the remnants of the original leaf cuticle: *Equisetum* and *Czekanowskia* are especially prevalent (bed 5). Associated rootlets are rare.

Interpretation

The plant-rich nature of this heterolithic facies suggests that it represents a swampy, flood-plain environment. However, based on the presence of marine microplankton a saline aspect to the swamp can be inferred, suggesting that the depositional environment must have been accessible to sea water, perhaps in a coastal setting. On this evidence the facies is interpreted as a coastal marsh environment. In this setting, silt- and mud-dominated sediment was laid down, incorporating plant material washed in from nearby areas. The wholly allochthonous nature of this flora is supported by the absence of rooted horizons: the absence of *in situ* vegetation in this environment may relate to enhanced salinity levels. Nevertheless, from the exceptional preservation of the remains it is likely that the flora was not derived from too great a distance; perhaps from areas further inland represented by facies A5 (well-drained floodplain).

In comparison, the flora of the sandy intervals is rather more sorted, robust and fragmentary, indicating that it was transported over a greater distance prior to deposition. The sandstones within which the plants are incorporated bear a close resemblance to the crevasse-splay sandstones described under A2. Generally, this facies is associated with crevasse-splay sandstones (A2) and is often interbedded with the more lagoonal facies classified as L1 (*e.g.* within the top part of the Saltwick Formation).

2.4.4 Marine facies

Facies M1. Bioturbated, heterolithic sands and silts (siliciclastic embayment)

Bioturbated, heterolithic sandy silt deposits characterize this facies, of which individual beds (10-40 cm thick) may be uniform in grain-size throughout, fine-upward, or coarsen-upward. The silt and sand components of the facies exhibit particular sedimentary structures which help to characterize their mode of formation. The siltstones can be dark grey in colour and homogeneous, or display delicate laminations with the bedding picked out by carbonaceous layers. Ripple-drift bedding and scour- and-fill structures are commonly associated (*e.g.* within the Helwath Beck Member, Yons Nab: bed 34, Fig. 1.4). In contrast, the sandstones are more variable in form, displaying lenticular, wavy and flaser-bedding, and are very fine to medium-grained. Despite this variety of structures, beds showing simple current structures are rare. Shelly debris and bioturbation are common (*e.g.* basal Eller Beck Formation, Iron Scar: bed 2, Fig. 1.24).

The base of units composed of this facies tend to rest sharply upon underlying deposits. It is certain that these sediments most closely typify the Helwath Beck Member, which overlies beds of the uppermost Gristhorpe Member (facies A5). At Cloughton Wyke (beds 55-61, Fig. 1.15) and Yons Nab (bed 39, Fig. 1.3), where this facies most clearly outcrops, *Diplocraterion* and 'J'-shaped burrows penetrate from the base of this facies into the underlying Gristhorpe Member by depths of up to 20 cm. Interestingly, the palynomorphs derived from the top of the Gristhorpe Member and the Helwath Beck Member show similar miospore assemblages, despite their varied depositional setting (Hancock & Fisher 1981). The bivalve fauna of the facies is restricted and includes only three species (Gowland & Riding 1991), whereas the trace fossils are diverse throughout; including *Planolites*, *Diplocraterion*, *Arenicolites*, *Skolithos*, *Thalassinoides* and *Teichichnus*. The facies is intimately associated with the sediments described below (M2; shoreface deposits), which often succeed sediments of this type.

Interpretation

The generally sandy nature, paucity of simple current-produced structures, restricted bivalve fauna, and predominance of miospores, suggest that this facies was deposited in a siliciclastic embayment where fluctuating salinities prevailed. This finding is supported by the presence of a diverse trace-fossil community. Sedimentary structures produced by tidal processes are mostly absent and variation in wave energy with depth was most probably the main control on sedimentation. The Helwath Beck Member characterizes this facies and, at Cloughton Wyke where it best exposed, can be divided into two parts. The lower portion of the member is represented by this facies, and is dominated by heterolithic silts and sands, which reflect bay-floor sedimentation and wave-dominated subtidal shoal deposits respectively (Gowland &

Riding 1991). As these beds overlie rooted shales of the Gristhorpe Member which contain palynomorphs indicative of deposition in brackish lagoons (Hancock & Fisher 1981), it seems likely that they represent the gradual establishment of more open marine conditions and are not the product of a sharply transgressive regime. The 'J'-shaped burrows which occur at the base of the sequence, can be attributed to the burrowing activities of supratidal crabs during the early stages of the transgression (Gowland & Riding 1991).

Facies M2. Wave-rippled and hummocky cross-stratified sands (shoreface deposits)

These sediments can be distinguished from the facies described above on the basis of a greater quantity of sand displaying wave-rippled and/or hummocky cross-stratification, and a sharp-based, sheet-like nature. The facies can be clearly delineated from the heterolithic sediments summarized above at Cloughton Wyke, but at Yons Nab the junction is not as well marked. In the Scarborough Formation at Cloughton Wyke (beds 62-63, and 75, Fig. 1.15), the sedimentary structures apparent in the fine sand alter vertically, from medium- and large-scale megaripple cross-stratification to planar lamination and low-angle cross-stratified lamination (Gowland & Riding 1991). Wave-generated ripples are found locally. Overall the unit coarsens upward and, in the upper part of the Helwath Beck Member, pronounced scour marks occur (3m wide by 0.55 cm deep: Gowland & Riding 1991). The bivalve fauna and trace fossil assemblages are comparable to those found in facies M1. Small fragments of plant material, some of which is charcoalified, are often found scattered throughout. Substantial root systems penetrate the top of the beds at some localities (*e.g.* at Iron Scar; bed 12, Log a, Fig. 1.24).

There are several instances where this facies is closely associated with lagoonal sediments representing L1 or L2. Perhaps the most notable interbedded sequence is that found at the top of the Saltwick and overlying Eller Beck Formations at Hayburn Wyke. In this example, lagoonal facies are overlain by well-sorted, buff-coloured sandstones, showing sharp, undulose bases, minor soft-sediment deformation, small-scale cross-lamination and planar lamination.

Interpretation

These sandy, cross-stratified deposits, which commonly succeed the bay-fill sediments described as facies M1, are interpreted as storm sand-sheets on the basis of their sheet-like nature and the sedimentary structures they embody (Gowland & Riding 1991). The planar cross-stratification present at the top of this facies at Cloughton Wyke, indicates an upward increase in wave energy levels by virtue of a gradual shallowing. This sand body is interpreted to have formed through the landward advance of a wave-dominated coastal barrier, during the transgressive episode which the underlying heterolithic sands and silts are thought to represent. More specifically, this sand body is inferred to be a barrier shoreface deposit (Gowland &

Riding 1991). The *Diplocraterion* burrows which penetrate the top of the sand, closely resemble those produced by modern supratidal crabs (Allen & Curran 1974).

Facies M3. Coarsening-upward sandy limestone sequence (siliciclastic shelf shoal)

This facies includes an array of lithologies which, collectively, display a very limited selection of sedimentary structures, trace fossils and fauna. Lime mudstones, siltstones, carbonaceous siltstones, silty sandstones and sandstones characterize the sediment, the internal structures of which are often obliterated through intense bioturbation: *Teichichnus*, *Planolites* and *Thalassinoides* dominate the trace fossil assemblages. In places within the upper part of the facies, relict horizontal lamination, hummocky cross-stratification and wave-ripple cross-lamination are present: silt-grade sediment is commonly associated. The bivalve fauna is restricted throughout; highly comminuted bivalve debris is commonly found within localized pockets in the sediment (Gowland & Riding 1991). Similarly, the marine microplankton assemblage is also restricted (Hancock & Fisher 1981).

These deposits typify the Hundale Shale Member (beds 64-68, Fig. 1.15) and basal portion of the overlying Hundale Sandstone Member (beds 69-74, Fig. 1.15), found at Cloughton Wyke. This unit sharply rests upon the sand sheet sands forming the top of the Helwath Beck Member which constitute facies M2 (shoreface deposits). The facies described here is absent in the Yons Nab area, but present in the Ravenscar borehole (Fig. 1.38e). In the vicinity of Cloughton Wyke, the Hundale Shale broadly coarsens-upward and includes thin intercalated carbonate beds. The top of the Hundale Shale is composed of such a carbonate layer (beds 67-68, Fig. 1.15), which is a lime mudstone developed above a strongly bioturbated contact with the underlying silty sandstone sequence. Bivalves are more diverse in this bed than in the lower Hundale Sandstone, and are found together with echinoderm fragments, crinoids, serpulids, foraminifera and ostracodes (Gowland & Riding 1991). A very similar lime mudstone occurs at the top of the basal part of the overlying Hundale Sandstone Member. Here the mud rests on the wave-rippled top to a coarsening-upward unit of this facies, displaying *Thalassinoides* and *Chondrites*.

Interpretation

Despite the rarity of sedimentary structures preserved in this facies, the grain-size profile indicates a vertical increase in wave and/or current activity which may indicate shallowing towards the top of the section (Gowland & Riding 1991). Relict sedimentary structures at the base of the Hundale Sandstone (formerly referred to as the Crinoid Grit Member: Parsons 1977) indicate deposition under high energy conditions which, together with the presence of abundant silt and intense bioturbation, indicate that the facies may represent a storm-generated sand sheet. The range of fauna associated with these beds is consistent with a shallow marine environment

(McKerrow 1978), but given the restricted nature of the bivalve and marine microplankton communities it is likely that salinity levels were somewhat variable. *Thalassinoides*, and to a lesser extent *Teichichnus*, occur throughout the sequence seemingly irrespective of the inferred palaeosalinity level: this is also certainly true for their presence within the Scarborough Formation as a whole.

The Hundale Shale-Hundale Sandstone interval, which characterizes this facies, contains two coarsening-upward cycles capped by thin lime mudstone layers: layers which can be interpreted as the temporary retreat of the siliciclastic coastal system (Gowland & Riding 1991). The rather more diverse faunal communities which these lime mudstones contain, probably correspond to an increase in salinity and a more open-marine environment. Succeeding this facies is another siliciclastic deposit which contains a rather higher carbonate content: the sediments are described as facies M4 (mixed siliciclastic/carbonate shelf).

Facies M4. Cyclic bioturbated siltstones and sandy limestones (mixed siliciclastic/carbonate shelf)

Three, crude coarsening-upward cycles (in the order of 1 to 2 m in thickness) comprise this facies, displaying intensely bioturbated siltstones and sandy siltstones, overlain by mixed sandy and carbonate deposits. The intensity of bioturbation disturbs the sedimentary structures to such a degree that only horizontal lamination is preserved. Shelly remains are most abundant in the upper portions of the coarsening-upward cycles, but also increase in quantity over the vertical extent of the facies as a whole. *Teichichnus* and *Thalassinoides* are the most common trace fossils, in silty and sandy intervals respectively. *Skolithos* and *Rhizocorallium* are also present. The Spindle Thorn Limestone exemplifies this facies, which is best exposed at Cloughton Wyke (beds 76-79, Fig. 1.15). The facies rests upon a firmground capping the top of the underlying siliciclastic shelf shoal facies (facies M2). At Ravenscar, the unit is amalgamated with the Hundale Sandstone Member, and contains significantly more shelly material than at Cloughton Wyke.

Interpretation

Lithological and palaeontological features of this facies indicate deposition in a shallow-marine shelf setting, between a siliciclastic coastal system and an open carbonate shelf (Gowland & Riding 1991). The coarsening-upward cyclicity within the facies is consistent with shoreline progradation and ensuing regression. Concentrations of shelly material in the upper parts of the cycles, reflect a decrease in terrigenous supply and perhaps concomitant winnowing of the debris due to shallowing.

Facies M5. Black silty mudstone (muddy outer shelf)

Deposits described as facies M5 are characterized by a dark grey to black, argillaceous and carbonaceous silty mudstone; only rare trace fossils (mostly confined to a few shell-filled *Thalassinoides* burrows and horizontal burrows typical of *Planolites*: Gowland & Riding 1991); a restricted bivalve fauna which often form monospecific shelly seams; and levels of concretionary siderite, which contain uncrushed fossils including ammonites such as *Dorsetensia* and rarer *Stephanoceras* (Parsons 1977). The deposits are exemplified by the Ravenscar Shale Member at Cloughton Wyke (bed 80, Fig. 1.15: 8 m thick) and in the Ravenscar borehole (8.5 m thick), which succeeds the Spindle Thorn Limestone facies across a gradational and rapidly upward-fining contact. Approximately 3 m from the base of the member, grain sizes are at their finest and, in the vicinity of Ravenscar, the level is manifest as a firmground. Above this surface, the lithology becomes progressively coarser. Despite the variations in grain size, thin-section observations indicate that finely disseminated pyrite is abundant throughout the sediment (Lott & Humphreys 1992). Despite the restricted nature of the bivalve community, the selection of belemnites, ammonites and microplankton is diverse (Bate 1965; Parsons 1977).

Interpretation

The gradual fining-upward contact from the top of the Spindle Thorn Limestone (M3; siliciclastic shelf shoal) into the base of the Ravenscar Shale, is consistent with a deepening towards a muddy outer shelf environment. The facies represents the deepest-water sediments found in the Ravenscar Group, and the widespread regional distribution of the shale suggests it was deposited during a basin-wide event (Bate 1965). The deepening of the marine environment into the base of the Ravenscar Shale Member is matched by a decrease in carbonate content, as compared to the underlying Spindle Thorn Limestone. This change in lithology can be attributed to an increase in the input of terrigenous fine-grained sediment, which may have also influenced the variety and abundance of the bivalve community. Associated low oxygen levels, perhaps resulting from stratification of the shelf water column, may also have been a limiting factor in this respect (Gowland & Riding 1991). Subtle variations in grain size mark the maximum point of deepening, after which there is a progressive increase in grain size and diversification in faunal component. The facies grades upward into sideritic silty sandstones represented by facies association M6.

Facies M6. Sideritic silty sandstone (nearshore environment)

Perhaps the most diagnostic characteristic of this facies is the red-brown colouration, imparted by nodular and disseminated siderite on weathering. Within the bounds of this general description, the facies can be divided into three components: (1) a coarsening-upward interval composed of bioturbated siltstones and silty sandstones; (2) a sideritic siltstone; and (3) a

nodular siderite containing a diverse shelly fauna, including bivalves, echinoid and serpulid fragments. Despite the ubiquitous presence of siderite, the mineral is not thought to relate to depositional processes. Instead, Kantorowicz (1982) suggested that it relates to changes in pore-water characteristics associated with the superimposition of the fluvial Scalby Formation. The lower part of the facies which, as a whole, is typified by the White Nab Ironstone Member, forms a prominent coarsening-upward sequence with the underlying Ravenscar Shale. Overall, the facies has a somewhat rubbly weathered appearance (particularly at Hundale Point, beds 81-84, Fig. 1.15), which from thin-section analysis is understood to be due to intense bioturbation of the sediment (Gowland & Riding 1991): burrowing which includes *Thalassinoides* and *Teichichnus*. Drifted, coalified logs occur, and the bivalve community is restricted. However, ammonites, belemnites, gastropods, echinoderms and serpulids are also found (Bate 1965).

Interpretation

The general diversity of body fossils, despite the rather restricted nature of the bivalves, indicates an open shallow-marine shelf environment for this facies. The depositional setting reflects relatively shallow conditions compared to those of the underlying Ravenscar Shale, and the conformable contact which is present between the two members probably reflects shoreline progradation. Continued progradation is represented by the overlying Bogmire Gill Member, which is classified by facies association M7 (prograding sandy shoreface).

Facies M7. Wave-rippled silty sandstones, containing plant debris and marine trace fossils (prograding sandy shoreface)

The thickness of this facies largely reflects the extent of the downcutting by the overlying Moor Grit braided channels. Where preserved, the facies forms a single coarsening-upward sequence from micaceous sandy siltstone to fine-grained sandstone. In coastal regions the facies generally succeeds the White Nab Ironstone, but in more western provinces the sediments overlie the Ravenscar Shale. Sediment of this type is characterized by the Bogmire Gill Member. At Cloughton Wyke and in the vicinity of Scarborough South Cliff, the lower part of the facies forms a 1.5 to 2 m thick succession and is silt-dominated, containing siderite nodules and displaying evidence for bioturbation. The sediments resting upon this silty sequence comprise an intercalated sequence of coarse silt and fine sand, reworked by trace fossils including *Thalassinoides*, *Planolites*, *Skolithos* and *Teichichnus*. Within the siltstone component, finely disseminated plant remains occur. The succeeding beds are composed of sandstones showing medium-scale trough and tabular cross-stratification, and hummocky cross-stratification. Microplankton indicating a marine influence is present (Gowland & Riding 1991).

Interpretation

Based on the presence of wave-generated sedimentary structures (primarily hummocky cross-stratification), shallow-marine trace fossils, and evidence gleaned from the facies' stratigraphic position, a prograding sandy shoreface is implied. The facies represents the culmination of a regressive phase, which is in turn downcut and eroded by the braided channel facies (A1b) comprising the Moor Grit.

Facies M8. Cross-stratified sandy oolite (tidal sand belt)

Sediments constrained by this facies association show significant lateral variations in lithology and sedimentary structures as it is traced northwards. Despite this variation, the facies shows a sharp, erosive base in all localities where it outcrops. In general, the lithology can be described as a subarkosic arenite; however, in southern regions, the deposits typically consist of large-scale cross-bedded sets of calcareous sandstone and sandy oolite. At Yons Nab, the unit displays 'herring-bone' cross sets and cross-stratification with bi-polar palaeocurrents (beds 2-9, Fig. 1.3), suggesting that the transgression which led to deposition of these beds came from south and southwestern parts of the basin (Livera & Leeder 1981). Wave-ripple sets occur locally. Pockets of thin, laterally impersistent conglomeratic layers also occur. To the east of the Yons Nab outcrop, an erosion surface occurs suggesting formation of a shallow channel. The Yons Nab example typifies this facies.

Interpretation

In general terms, these sediments are inferred to represent shallow marine sand-waves, which, on the basis of the wave-generated sedimentary structures present, can be inferred to have had a marine origin. The absence of bioturbation suggests a generally high-energy environment, but thin, localized conglomeratic layers highlight low-energy pockets between the sand waves. A shallow channel at the top of the sequence at Yons Nab is infilled by large-scale, avalanche cross-sets indicative of deposition under tidal currents, and is associated with an increase in oolite content. This part of the succession can be interpreted as an oolite tidal shoal deposit (Livera & Leeder 1981). Succeeding this facies are lagoonal sediments characteristic of the Yons Nab Beds, and described by facies L1 and L2.

2.5 Sedimentary cycles in the Cleveland Basin

In an attempt to achieve a more accurate stratigraphic control on the siliciclastic and subordinate carbonate deposits which comprise the Ravenscar Group and underlying Dogger Formation, sequence stratigraphic concepts have been applied to outcrop exposures and sub-surface core data. This approach involves the identification of 'key surfaces' in the sedimentary sequence:

(1) sequence boundaries, (2) transgressive surfaces, and (3) maximum-flooding surfaces (Mitchum *et al.* 1977; Van Wagoner *et al.* 1988). Whilst the character of these surfaces may vary on a proximal to distal transect, in outcrop they are generally expressed as: (1) an erosional unconformity, associated with a basinward shift in facies; (2) juxtaposition of deep-water facies over shallow; and (3) stratigraphic condensation (Van Wagoner *et al.* 1988). To supplement the conclusions drawn from the arrangement of such surfaces in the succession, the relative position of particular sedimentary facies within the lithological cycles was investigated, as the organisation within cycles of certain facies may largely be related to relative sea-level change (*e.g.* Hallam 1978).

This approach has enabled several previous authors to recognize depositional sequences, of distinct orders of frequency and magnitude, in different basins across the UK. Hesselbo & Jenkyns (1997) applied the key-surfaces concept to the British Lower Jurassic, successfully recognizing a series of cycles on a variety of levels; similarly, Coe (1992, 1996) used the approach to elucidate the Portlandian of the Wessex Basin. Using this method, the present study has established the presence of two large-scale and six medium-scale lithological cycles in the Aalenian-Bathonian sequence of the Cleveland Basin: these, so-called second- and third-order cycles (Haq *et al.* 1988, Vail *et al.* 1991), are outlined in detail in the following section. Summary sedimentary logs for each of the six cycles are provided below (Figs. 2.1-2.6), showing their intra-basinal correlation. Lithological cycles also occur at a smaller scale (fourth-order) in the Ravenscar Group, but regional or even intra-basinal correlation of these cycles is not possible with the current biostratigraphic resolution. However, details of the character and the temporal arrangement of these small-scale sedimentary cycles is presented within the context of the medium-scale cycle descriptions, as they can highlight base-level or relative sea-level fluctuations.

The central aim of this part of the chapter is two-fold: firstly, to construct a stratigraphic frame of reference against which other sedimentary sequences can be compared (and floral remains can be constrained); and secondly, to establish the lateral continuity and areal extent of the sedimentary cycles and the associated key surfaces identified in the Cleveland Basin. A similar study of Lower Jurassic strata by Hesselbo & Jenkyns (1997) has shown that large-scale sedimentary cycles can be traced between UK onshore basins. For the Middle Jurassic interval, the authors (Hesselbo & Jenkyns 1995) postulated that large-scale sedimentary cycles developed synchronously in the Cleveland and Wessex Basins, and there was a reciprocal depositional relationship due to their proximal and distal settings. A further goal of this thesis is to resolve the pervasiveness of lithological cycles within the Cleveland Basin across the southern North Sea to coeval parts of Scandinavia (Chapter 3). For the remainder of this chapter, however, the sedimentary character and stratigraphic extent of lithological cycles identified on a medium- and large-scale in the Cleveland Basin are described.

2.5.1 Medium-scale cycles

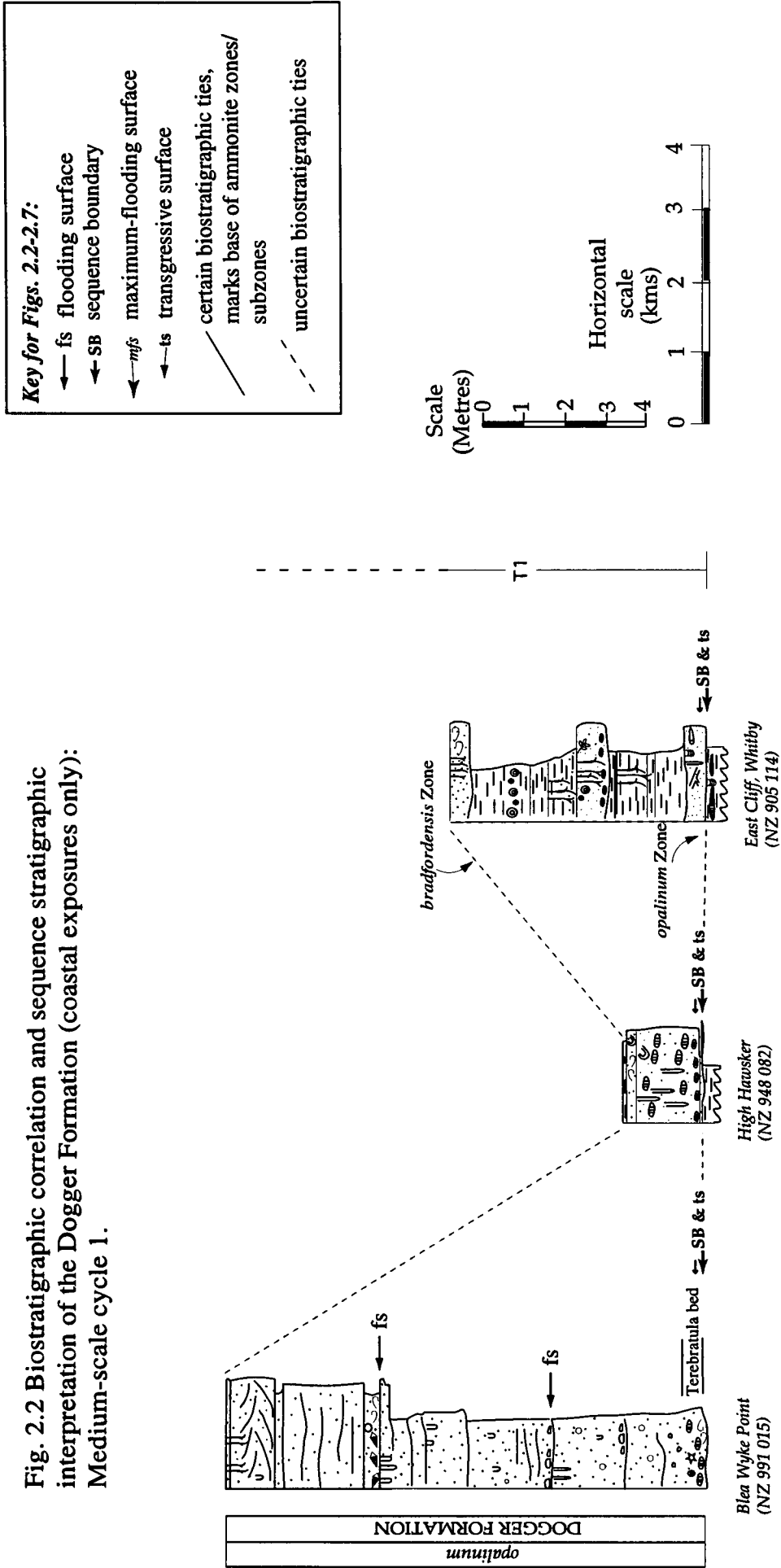
Cycle 1

Dogger Formation: Basal *opalinum* Zone to uppermost *murchisonae* Zone

The base of the Dogger Formation and Cycle 1 is marked by a major unconformity which is associated with a complex biostratigraphical gap. The nature of the contact with the underlying coarsening-upward late Toarcian succession varies regionally, both in appearance and in the duration of time that it represents. The most complete and best exposed section in the basin is that found at Blea Wyke, although the Upper Toarcian is restricted to the downthrown side of the syn-sedimentary Peak Fault where late Toarcian/early Aalenian erosion was less pronounced. The muddy siltstones and very fine sandstones of the underlying Blea Wyke Sandstone Formation are divisible into two coarsening-upward cycles (Knox 1984). The lower, grey-weathering cycle forms the Grey Sandstone Member, separated from the upper, yellow-weathering Yellow Sandstone Member by thin fossiliferous layers. The sandstones are heavily bioturbated and the fossils present include belemnites, *Lingula* and serpulids in the Grey Sandstone Member, and bivalves and brachiopods, similar to those found in the overlying Dogger Formation, and ammonites in the Yellow Sandstone Member (Rastall & Hemingway 1940; Dean 1954; Knox 1984).

The unconformity with the Middle Jurassic is marked by a concentration of brachiopods (the Terebratula Beds), derived phosphatized pebbles, a water-worn fauna (including ammonites of *striatulum* type; diagnostic of the Upper Toarcian), and a sharp increase in grain size to coarse sands and granules at the base of the Dogger Formation (Arkell 1933; Black 1934b; Rastall & Hemingway 1940; Dean 1954). The uppermost portion of the Yellow Sandstone displays abundant *Skolithos* and U-tubes of the *Arenicolites* type. The Upper Toarcian to Lower Aalenian therefore shows an overall shallowing trend, the Grey Sandstone and Yellow Sandstone cycles bringing into the basin progressively coarser sand, culminating in erosion at the Toarcian/Aalenian boundary. At this level the *aalensis* Subzone of the *levesquei* Zone is apparently missing (Parsons 1980; Knox 1984). Regionally, this erosion surface and biostratigraphic gap is even more pronounced, extending down into at least *falciferum*-Zone strata (Knox 1984). In localized areas of the Market Weighton High, the hiatus is accentuated where the formation rests on Hettangian sediments preserved in sub-Cretaceous syn-forms (Wright 1976).

The unconformable nature of this junction, across which there is a conspicuous change in lithology and pronounced basinward shift in facies, indicates that it formed as the result of erosional and non-depositional processes during relative sea-level fall. Consequently, it is



interpreted to be a sequence boundary. The stratigraphic separation recorded by the unconformity reduces southwards until it is simply marked by a correlative event with the Lower Estuarine Group resting upon the Northampton Sandstone Formation in the east Midlands (Horton 1977). Further afield in both the Hebrides and Wessex Basins, the uppermost *levesquei* Zone shows stratigraphic expansion as a consequence of increased volumes of sediments introduced into distal settings (Hesselbo & Jenkyns 1997). In a more regional context, the stratigraphic position and areal extent of this sequence boundary has stimulated much debate in recent years. Perhaps most notable is the work of Underhill & Partington (1993), who equated the unconformity or so-called 'Mid-Cimmerian event' with a significant change in coastal onlap and a significant fall in relative sea-level (Haq *et al.* 1987, 1988). Whilst this may be true, the age they assigned the stratigraphic break does not compare well with biostratigraphic information yielded by the Yorkshire succession. Rather than the *aalensis*-Subzone age constrained by Parsons (1980) and others, Underhill & Partington suggest an *opalinum/murchisonae* Zone stratigraphic gap.

The lateral discontinuity and lithological heterogeneity of the Dogger Formation was alluded to in a previous section (1.4, p.5). Briefly, the formation is divisible into two parts, differentiated on the basis of their integral ammonites. The lowermost *opalinum* Zone deposits, which are confined to central and eastern parts of the basin, can be clearly separated into two contrasting facies. This distinction is most obvious along the coast, between Ravenscar and Whitby. Overlying the basal *Terebratula* Bed at Ravenscar, the succession consists of sandstone and a sandy, sideritic, berthierine-rich oolite forming a 12 m thick unit. Within this unit there is evidence to suggest that deposition was cyclic and influenced by successive flooding events (Fig. 2.2). To the north at Whitby, however, the coeval section constitutes a mere 40 cm of ferruginous, sandy mudstone containing abundant phosphatized pebbles of Lower Jurassic shale. While these deposits collectively represent sedimentation in a well-oxygenated sea floor environment, at no more than 20 m depth (Hemingway 1974), the disparity in thickness and lithology of the unit highlights the variability in the local depositional setting. The expanded nature of the unit at Ravenscar indicates that there was only limited uplift and erosion (explaining why the contact between the Dogger and coarsening-upward late Toarcian strata appears to be gradational), in contrast to prolonged reworking and erosion at Whitby. The effect of these different facies was to bring the region close to sea level, either by erosion and reworking on the structural highs (*e.g.* Whitby), or by infilling of the lows (*e.g.* Ravenscar) created at the end of the Lower Jurassic by the development of a series of low-amplitude, open folds across the region (Hemingway 1974; Hancock & Fisher 1981).

The uppermost portion of the Dogger Formation is restricted to western and northern parts of the basin, where it oversteps the underlying (*opalinum* Zone) unit to rest directly on the Alum Shale. The formation consists of a conglomerate, limestone and ironstone succession, which

occupies the deepest parts of palaeovalleys and is in turn overlain by shales yielding *murchisonae*-Zone ammonites (Black 1934*b*). It is possible that the basal conglomerates, limestones and ironstones reflect a continuation of the transgressive phase first recorded by the *opalinum* Zone in central and eastern areas. To the east, there was extensive reworking of the *opalinum* Zone sediments during this time. Above this unit rests an upward-coarsening sequence of mudstone, siltstone and sandstone deposited during a regression. Therefore it would appear that the maximum-flooding surface was attained during reworking of the *opalinum*-Zone deposits and prior to deposition of the coarsening-upward facies; perhaps during the *scissum* Zone or overlying lower- to mid-*murchisonae* Zone. This date can, however, be made more precise by correlation with better-dated sections elsewhere in Britain. A tentative mid-*murchisonae* Zone age is implied, based upon age constraints imparted by the Yellow Conglomerate in Dorset, which is interpreted to be starvational in origin (Hesselbo & Jenkyns 1995); the occurrence of coeval thick shallow-water carbonates in the Worcester Graben; and an ammonite-rich (pertaining to the *murchisonae* Zone) limestone at the Dun Caan Shales/Bearreraig Sandstone boundary in the Hebrides (Graciansky *et al.* 1997).

The uppermost part of this facies frequently forms a rootlet bed for plants of the succeeding marshy deltaic environment, or alternatively, as in Westerdale near Guisborough, the sandstone may be deeply eroded by fluvial activity (Hemingway 1974). These features, which indicate that the region underwent a slow elevation of the depositional surface, are most common in western parts of the basin. Further east, marine deposition continued for a longer duration. However, the localized development of a thin coal throughout the basin highlights the possibility of subaerial erosion and uplift prior to deposition of the Saltwick Formation (Alexander 1989).

Cycle 2

Saltwick Formation: Basal *bradfordensis* Zone to uppermost *concavum* Zone

The Saltwick Formation, which represents Cycle 2, marks the initiation of deltaic deposition over marine Liassic and Dogger Formation sediments. The basal portion of the formation is largely eroded in western parts of the basin by later fluvio-deltaic channels, but along the coast scattered exposures can be found which display evidence of initial brackish-water sedimentation. These basal beds, which represent the transgressive portion of the cycle, rest upon a surface which may have a gradational or abrupt contact with the underlying Dogger Formation. The Hasty Bank locality reveals a somewhat gradational contact between marine shales of the Dogger Formation, and organic-rich clays and silts including a channel sandstone in the basal Saltwick Formation. Within these basal beds, marine algal microflora occur (tasmanitids and acritarchs: Muir 1964; Hill 1974*a*) and the leaf *Pachypteris papillosa* is found,

which Harris (1964) suggested grew in a salty setting either on mud flats or on the margins of tidal channels. On the basis of these findings, Hill & Shute (1975) implied that the Hasty Bank channel sandstone was of tidal origin.

A tidal influence upon deposition is, however, restricted to such north and western areas of the Cleveland Basin, as rapid delta progradation from the northeast limited marine influence in eastern areas, represented by the coastal exposures today (Knox 1973). In the region of Ravenscar, a 2-3 m thick muddy sandstone overlies an abrupt junction with the Dogger Formation, which is partly reworked and incorporated into this transgressive unit at the base of the Saltwick Formation. The deposit is laterally extensive and sheet-like, containing glauconite, bivalve debris and well-preserved burrows, and is interpreted as having been formed in estuarine conditions in the littoral zone (Fig. 1.38b). The local occurrence of wavy bedding and cross-stratification does, however, indicate that deposition at this locality was at times disposed to the influence of tidal processes (Eschard 1989).

Poor exposure of the lowermost Saltwick Formation hinders identification of the maximum-flooding surface in the field. However, the Ravenscar borehole (Fig. 2.3) has revealed a cemented horizon within a mudstone overlying the littoral sand-sheet, with which marine trace fossils including *Skolithos* and *Rhizocorallium* are associated. This surface is interpreted as a firmground and, on the basis of its condensed nature and position below lagoonal and swamp deposits, the maximum-flooding surface. Resting on this surface is the approximately 45 m thick regressive phase to Cycle 2, marked by a transition from lagoonal to delta-plain deposits. This contrast in the relative thicknesses of the transgressive and regressive phases, makes for a highly asymmetric cycle (Fig. 2.3). More specifically, at Ravenscar this vertical change is seen as an alteration from 3-4 m of muddy, bioturbated lagoonal and marsh sediments, to 41 m of argillaceous, overbank deposits in which isolated meandering channel bodies occur. In the succession, channel bodies are subordinate to the overbank deposits, indicating strong aggradation of the delta-plain. Despite the only loosely constrained biostratigraphy available for the Saltwick Formation (see Section 1.5.2, p.17), sections elsewhere in Britain which are thought to be approximately coeval also show progradational successions. Strongly progradational phases in the *concauum* Zone are indicated in the Hebrides (Morton & Hudson 1995) and in the Inferior Oolite of the Worcester Graben, which includes an unconformity at this stratigraphic level (Parsons 1980).

A tendency towards aggradation over progradation continued for the remaining portion of the regressive phase. This conclusion is drawn from evidence displayed by mid- to upper portions of the Saltwick Formation, most notably: (1) the increasing predominance of more isolated, mixed-load channels in poorly-drained, marsh deposits; (2) a greater quantity of allochthonous plant material enclosed within mudstones showing poor root foundations (*e.g.* the Hayburn

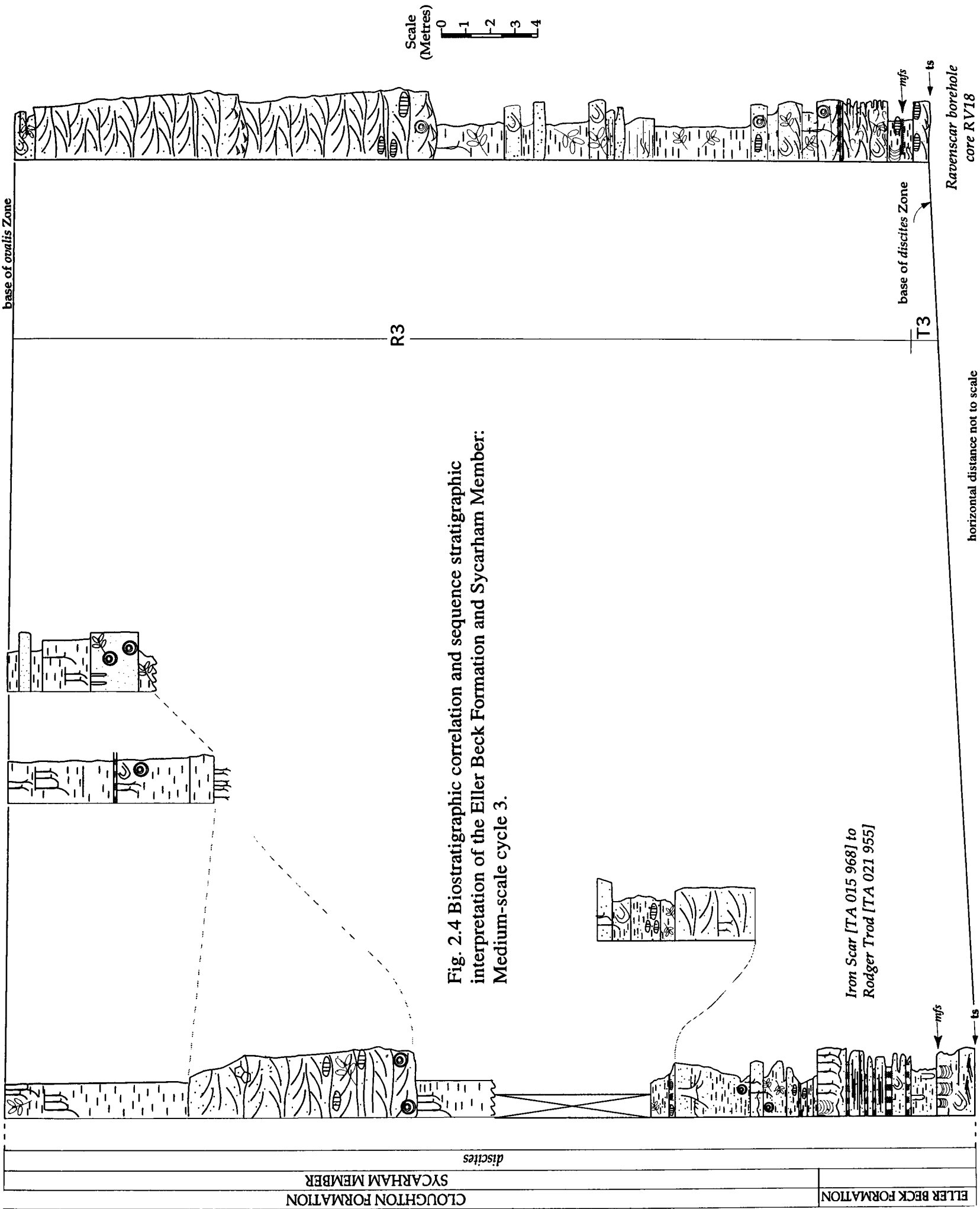
Wyke Plant Bed); (3) more soft-sediment deformation; (4) evidence for increasingly suboxic conditions; and (5) a greater diversity of marine microplankton (Hancock & Fisher 1981; Livera & Leeder 1981; Kantorowicz 1990). These vertical changes reflect gradual abandonment of the delta lobe, as a consequence of a slow rise in relative sea level and subsidence of the area due to sediment consolidation (Alexander 1986). This balance between accommodation rate and sediment supply is also manifest as a series of small-scale (fourth-order) coarsening-upward cycles, or parasequences (*sensu* Van Wagoner *et al.* 1988). The cycles consist of argillaceous crevasse-splay sandstones overlain by siltstones, leached clay and carbonaceous clays or low-grade coals, and reflect infilling of a shallow bay or lagoon situated close to the fluvial channel now forming the northern headland to Hayburn Wyke (Fig. 1.25) (Mjøs *et al.* 1993). At the top of the Cycle 2, distal saline swamps became established as a precursor for renewed fully marine deposition at the base of the Eller Beck Formation and Cycle 3.

Cycle 3

Eller Beck Formation and Sycarham Member: Basal to uppermost *discites* Zone

During the initial Eller Beck Formation transgression there was a change of lithofacies from non-marine or brackish sand, silt and mud to marine calcareous and ferruginous mud over the Cleveland Basin, with increasingly coarse clastics towards the south-west (Howardian Hills). The marine incursion caused reworking of the flat-lying delta-top marsh sediments (representing the uppermost Saltwick Formation), producing a laterally extensive, narrow siltstone-ironstone interval resting above a sharp and locally erosive transgressive surface. This surface, marking the 'Bajocian Transgression' of Arkell (1933, p.93), can be traced elsewhere in Britain to Dorset, Somerset, the Cotswolds and North Lincolnshire.

The transgression established an extensive low-energy saline bay across the basin, in which the siltstone-ironstone beds were laid down. In south-western areas of the basin the sequence is represented by a siltstone containing bivalves and scattered oolites, underlying a thin ironstone unit (Powell & Rathbone 1983), while in the vicinity of Ravenscar the section comprises a 1-m-thick argillaceous sand and silt layer deposited under the influence of wave and storm action (Eschard 1989). Similarly, the Iron Scar locality also reveals a silty sandstone, which contains disseminated shelly debris and displays bioturbation (bed 1, Fig. 1.24). Wavy-bedding, wave-ripple lamination and some lenticular bedding are common sedimentary structures, which are suggestive of a basin-wide bay environment, supported by the presence of a fine grain-size, absence of current-scour structures and preservation of an open marine fauna, including infaunal bivalves in their life position (Knox 1973). At the top of the siltstone-ironstone interval an approximately 20 cm thick, laterally continuous, intensely bioturbated horizon exists (including *Thalassinoides*, *Monocraterion*, *Diplocraterion* and *Rhizocorallium*), which is rich in



iron and siderite. The character of this bed suggests it was deposited during a period of reduced sedimentation, when faunal abundance and diversity reached a peak across the basin (producing a diverse trace-fossil assemblage): the resulting firmground, which is best displayed at Iron Scar and Ravenscar, is interpreted as the maximum-flooding surface (Fig. 2.4). From correlation to a better dated section in the Cotswolds, it is known that this surface reflects a lower *discites*-Zone age (see p.18).

The succeeding sediments thus represent the regressive phase, forming a highly asymmetric transgressive-regressive cycle; although not as extreme in character as the underlying cycles. This portion of the cycle comprises 40 m of strata, characterized by the remainder of the Eller Beck Formation and the overlying Sycarham Member. Resting on the transgressive siltstone-ironstone interval is a calcareous and non-calcareous mud and fine silt unit overlain by a lime mud, which, in south and south-west areas of the basin, contains a relatively diverse benthonic fauna (Powell & Rathbone 1983). The fauna is, however, comparatively restricted and less abundant than in the ironstone and limestone it is sandwiched between, indicating perhaps a brief return to a more brackish environment, an increased sedimentation rate, or an unfavourable substrate (Powell & Rathbone 1983). Similarly, marine palynomorph assemblages are also more restricted (Hancock & Fisher 1981).

In general terms, this calcareous limestone-mudstone sequence forms the base of a coarsening-upward succession. Initial progradation is marked by the deposition of non-calcareous mud and thin, wave-rippled sand lenses with *Diplocraterion* burrows. These sediments are overlain by a medium- to coarse-grained sandstone displaying large-scale cross-bedding, rootlets, and plant fragments; in places, erosive bases typical of fluvial or deltaic distributary channel sandstones cut into the top of the sand (*e.g.* in the Hambleton Hills area). In coastal regions, hummocky cross-stratification is frequently found in the lower portion of the sand, together with wave/current induced sedimentary structures. Shelly fragments and bioturbation are abundant. Near the top of the unit, low-angle, cross-bedding and current ripples become more common, which are in places disturbed by plant roots and the effects of soil formation (pedogenesis) (Fig. 1.24). Oxidized palynomorphs are also found (Hancock & Fisher 1981). Overall, the sandstone is interpreted as representing a prograding, wave-dominated littoral barrier, which became temporally emergent at the end of the progradation phase.

Along the coast, the Eller Beck Formation is succeeded by silty mudstones and fine sandstones deposited in a shallow lagoonal environment. The mudstone component, in particular, is intensely bioturbated and contains well-preserved trace fossils which locally disturb the lenticular bedding showing current ripples. The thin, bioturbated, argillaceous, sandy horizons are laterally continuous and display a combination of current-ripple bedding and wavy-bedding, perhaps representing washover fans (*cf.* Elliot 1986). The delta-plain sediments which rest on

these lagoonal deposits are characterized by small meandering channels and related crevasse splays, isolated within muddy overbank deposits. These sediments are particularly well displayed in the Iron Scar section, where plant-rich palaeosols, and homogeneous black or greenish-grey lacustrine and overbank mudstones containing abundant woody remains, occur (beds 14-19, log a, Fig. 1.24). Crevasse-splay sandstones and meandering channel sandstones displaying basal lags, point bars and mudstone plugs are intercalated (bed 1, log b, Fig. 1.24). The sediments are arranged in small-scale, coarsening-upward cycles, produced by delta aggradation.

In contrast, the succeeding deposits, representing the upper part of the cycle and the Sycharham Member, are composed of meandering channel-bodies (Fig. 2.4). In the Ravenscar area in particular, the channel bodies are amalgamated and comprise a thickness of up to 18 m (Eschard 1989). Laterally, however, the sandstones wedge out and, in the vicinity of Rodger Trod, constitute a thickness of only 10 m (bed 2, Fig. 1.22). Erosion surfaces overlain by pebbly horizons mark the base of separate channelling phases, of which at least three have been identified in the Ravenscar area by Eschard (1989). Towards the top of the trough cross-bedded and laterally-accreted channel sandstones, thin muddy plugs containing plant debris occur. This stacked channel sandstone sequence is characteristic of a decreased rate of relative sea-level rise and reduced accommodation space, leading to shoreline progradation. To the south of Yorkshire, this regressive phase is marked by the appearance of clastics within the Lincolnshire Limestone Formation (the Raventhorpe Member: Ashton 1975). If this influx of clastic material does indeed coincide in stratigraphical position with the most regressive part of the Sycharham Member (represented by the stacked channel bodies), then a more precise age can be obtained from the ammonite-bearing portions of the Lincolnshire Limestone. Comparison with the Hydraulic Limestone and Kirton Cementstones Member (Cope *et al.* 1980b, Fig. 4a) indicates an age slightly later than the mid-*discites* Zone for the regressive portion of Cycle 3 (see also p.19).

Cycle 4

Lebberston and Gristhorpe Members: Lower *ovalis* Zone to upper *sauzei* Zone

The uppermost overbank facies of the Sycharham Member are truncated and reworked by the shallow-marine facies of the Millepore Bed, forming the transgressive surface of Cycle 4. As in the preceding cases, the transgressive part of this cycle is strongly attenuated and represented by only a narrow interval of marine mudstones between Cloughton Wyke and Ravenscar to the north (Fig. 2.5). Whilst this basal junction is certainly undulose and erosive, most prominently at Ravenscar where several 1 m deep scours have been identified (Eschard 1989), there is no

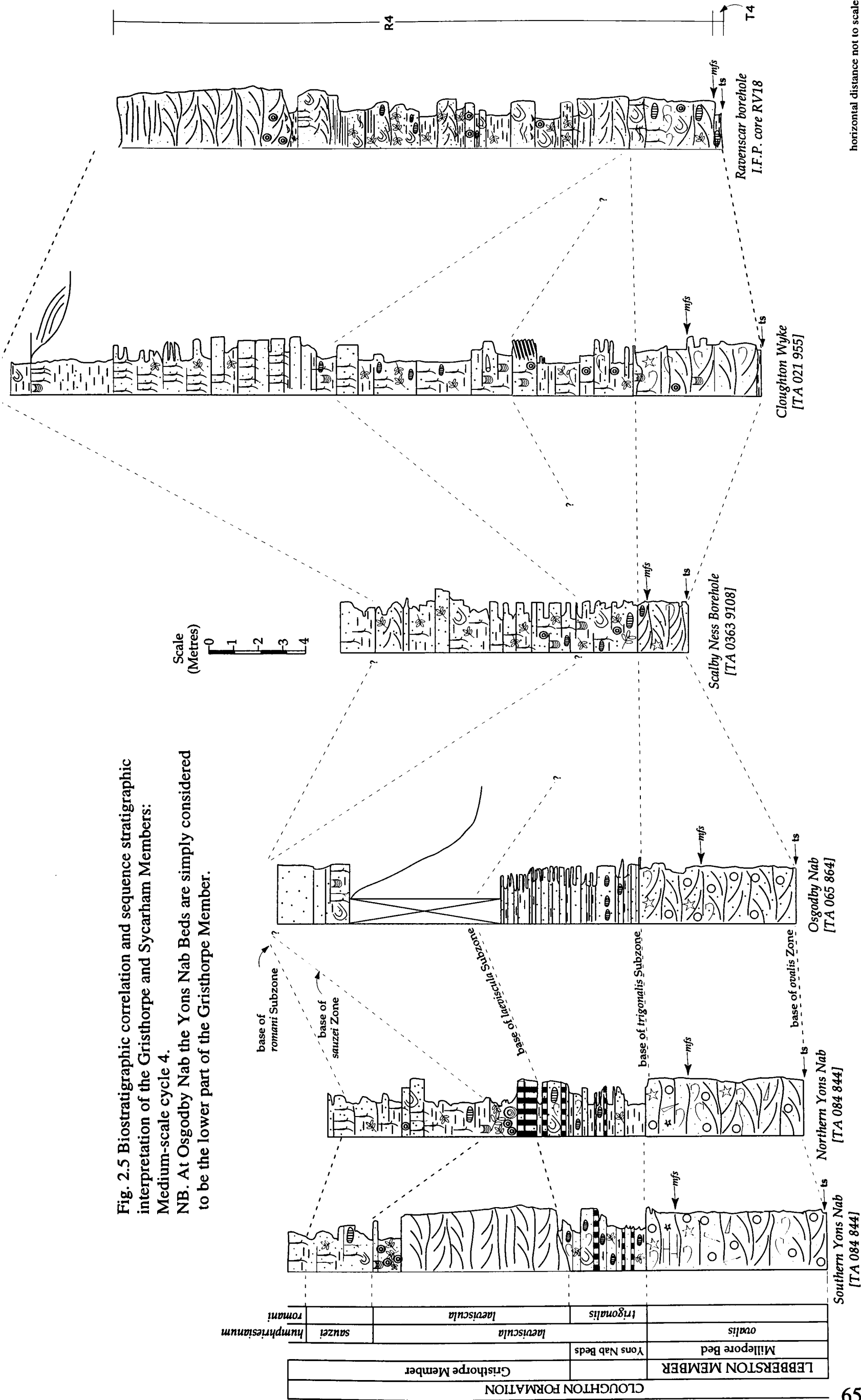
evidence for sub-aerial exposure (such as pedogenic features, rootlets *etc.*). This indicates that the erosional surface was probably generated by the processes of marine transgression.

Overlying this transgressive surface at Cloughton Wyke is a 25-cm-thick, dark-grey shale containing ostracod casts (Bate 1967), which thickens northwards to form a 1-m-thick marine mudstone at Ravenscar (Eschard 1989). This muddy interval is, however, absent in the region of Cayton Bay to the south, where a cross-bedded oolite rests disconformably upon the Sycarham Member. The most likely explanation for this lateral facies variation stems from a disparity in water depth across the basin, from shallow-marine and coastal settings in the south (Cayton Bay) to beach and lagoonal environments in the north (Cloughton Wyke-Ravenscar). In the vicinity of Whitby, the ferruginous facies which the Millepore Bed represents is more or less indistinguishable from a deltaic sandstone, indicating that the delta front was nearby (Bate 1967). Therefore, thinning of the Millepore Bed, as a whole, from south to north suggests the interval represents only a partial transgression in this region.

Tidal-flat deposits rest on these marine mudstones in the Ravenscar area, marking the beginning of the regressive phase. These tidal sediments overlie a nodular, iron-rich horizon which is interpreted as the point at which the maximum-flooding surface was attained. Further to the south at Cloughton Wyke, the marine mudstones are succeeded by shelly, calcareous sandstones and sandy limestones forming three coarsening-upward cycles (beds 5-10, Fig. 1.22). The fossiliferous and burrowed, iron-rich, cemented top to the second tier is interpreted as marking the surface of maximum flooding in this area. Southwards the surface can be traced without difficulty to a hardground at Osgodby Nab (top of bed 6, Fig. 1.9), developed in association with *Thalassinoides* and encrusted with serpulids, while at Yons Nab it is characterized by a horizon beneath an oolite tidal-shoal representing the upper 2 m of the Millepore Bed (top of bed 5, Fig. 1.3). A basal *laeviscula*-Zone age is indicated for this flooding surface, by the inferred upper age limit of the Millepore Bed (lowermost *laeviscula* Zone), and correlation of the flooding horizon with a known deepening event in south Humberside (the Kirton Shale Member: see Section 1.5.2, p.19).

In general terms, the onset of the regressive phase is highlighted in southern areas by cross-bedded, oolitic limestone containing diverse and abundant bivalve, echinoid and ostracod debris (Bate 1967), while a bioturbated, fine-grained calcareous sandstone marks the northern extent. Frequent hardgrounds associated with intense bioturbation are particularly common in these more northern areas, indicating periods of reduced sedimentation and hence condensation. In overall character, this maximum-flooding surface implies enhanced deepening, starvation and condensation in comparison to that of the previous cycle. In southern outcrops of the Millepore Bed, deposition occurred within a shallow-marine sand-belt dominated by tidal conditions,

Fig. 2.5 Biostratigraphic correlation and sequence stratigraphic interpretation of the Gristhorpe and Sycarham Members: Medium-scale cycle 4.
NB. At Osgodby Nab the Yons Nab Beds are simply considered to be the lower part of the Gristhorpe Member.



whereas to the north, the rather more siliciclastic sequence represents beach and littoral sedimentation.

Continued regression, from north to south, resulted in delta-plain sedimentation. The succession (the Yons Nab Beds) deposited during this early regressive phase thins dramatically northwards, where it passes laterally into non-marine beds at the base of lower Gristhorpe Member. In the Cayton Bay area, the beds coarsen-upward from fully marine fossiliferous shales to iron-rich, intercalated sands and silts deposited on the delta front: the succession is, however, composed of four, laterally restricted, small-scale coarsening-upward cycles indicating that the overall shallowing trend was pulsed. Whilst the beds are absent at Osgodby Nab (a topographic high at this time, which experienced non-deposition: Livera & Leeder 1981), the Cloughton Wyke to Petard Point section of the Yons Nab Beds represent a prograding sand-ridge passing over a lagoonal environment. The low level of bioturbation in this area suggests that wave energy was moderately high. However, the lack of associated washover sandstones with the minor tidal channel at Cloughton Wyke might suggest otherwise (bed 15, Fig. 1.15 displays neither a wave nor tidal influence). Evidence for the lagoonal setting continues northward, until beach deposits become increasingly dominant (particularly in the Petard Point-Ravenscar area).

In some regions, the lagoonal environment of deposition continued to influence deposition at the base of the Gristhorpe Member. This is particularly true in the vicinity of Cloughton Wyke where basal beds consist of dark grey to black shales containing thin coals and plant beds whose root foundation is poorly developed (*Solenites* Plant Bed), indicating that the plant material drifted into the lagoonal environment. Together with *Diplocraterion* burrows, small-scale cross-stratification including symmetrical ripple-marks are present in the succeeding coarsening-upward silt and fine-grained sand, indicating that a lagoonal environment remained in this area until mid-Gristhorpe Member times (*?laeviscula* Subzone) when delta-plain sedimentation began once again.

To the south at Yons Nab, lagoonal conditions disappeared more rapidly. The lowermost Gristhorpe Member is indeed bioturbated, but very sparsely compared to the marine and brackish beds below. A laterally accreted fluvial channel sandstone rests on the contact with the Yons Nab Beds and cuts down into the succession (bed 20, Fig. 1.4). Above, overbank and channel abandonment facies occur containing a diverse and abundant flora (the Gristhorpe Plant Bed). In all areas, thick rooty siltstones and crevasse-splay sandstones overlie the basal lagoonal deposits, forming the strictly regressive, upper Gristhorpe Member, of *sauzei*-Zone age (Cope *et al.* 1980b). Evidence for several brief marine incursions has, however, been found within this succession, usually evidenced by marine trace fossil assemblages in southern areas of the basin. One horizon in particular, which rests upon the Gristhorpe Plant Bed, is

very laterally continuous and has been identified from Cayton Bay in the south of the basin to Ravenscar in the north. While in other instances there is some question of whether these incursions were a product of minor sea-level rise or laterally shifting delta lobes, in this rather more extensive example there are associated dinoflagellates, leiospheres, acritarchs and syneresis cracks, indicating that the bed was deposited within a saline-bay environment (Hancock & Fisher 1981).

At the top of the Gristhorpe Member, a small channelized horizon yielding a typical point-bar palynofacies assemblage cuts into brackish vegetated swamps and lagoons (Fisher 1980; Hancock & Fisher 1981). Slumping is associated with these beds in the Yons Nab and Cloughton Wyke sections. From this evidence, the following can be deduced: (1) there was a small drop in relative sea level immediately before deposition of the Scarborough Formation, leading to formation of a minor discontinuity, a period of channelling, and perhaps initiation of unstable conditions from reduced or absent sedimentation; (2) despite this fall in relative sea-level there was still a saline influence upon deposition. The presence of evidence for brief marine incursions and marine palynomorph assemblages, and the predominance of mud-grade sediment over sand, indicates that the rates of aggradation were higher than those of the progradation, during this portion of the cycle at least. Furthermore, the vertical stacking of small-scale coarsening-upward cycles (or parasequences) suggests that accommodation rates balanced the rate of sediment supply in this setting (Eschard 1989).

Cycle 5

Scarborough Formation: *humphriesianum* Zone

Cycle 5 is represented by the Scarborough Formation which, unlike the preceding examples, consists of a well-developed transgressive phase up to 25 m thick (Fig. 2.6). The lower part of the depositional cycle encompasses three small-scale cycles, or parasequences, representing an overall deepening trend with brief regressive pulses superimposed. The contact with the underlying Gristhorpe Member is sharp, marking an abrupt junction between rooted siltstones below, and heterolithic siltstones and sandstones of a littoral barrier above. At the boundary, marine borings dominated by *Diplocraterion* and 'J'-shaped burrows penetrate the underlying strata (Fig. 1.8). The transgressive event which introduced renewed marine deposition across the region can be attributed to the abandonment and compactional subsidence of the Gristhorpe Member delta lobe, and a coincident rise in relative sea-level. The lateral equivalents of the Scarborough Formation thin southwards to a few metres over the northern margins of the Market Weight High, and are recognisable in the Lincolnshire area as a thin unit of marginal marine, fossiliferous, sandy mudstone, separating the Lincolnshire Limestone Formation from the Upper Estuarine Series (Bradshaw & Bate 1982).

The lowermost parasequence incorporates this initial transgressive phase, leading to the establishment of a laterally extensive brackish-marine embayment, which at Ravenscar and Cloughton Wyke shows ample evidence of an intertidal origin. The Ravenscar borehole reveals a sequence of black, organic-rich, marine mudstones, siltstones and sandstones resting upon a sharp and erosive transgressive surface; it is possible that the sandstone component of this unit was derived from the reworking of the uppermost Gristhorpe Member. In turn, the sequence coarsens-upward into argillaceous sandstones and intercalated fine-grained sandstones showing wave ripples. There is a perceptible fining in the uppermost part of the cycle and an increase in bioturbation (dominated by *Diplocraterion*), thought to relate to deposition of the unit as part of a prograding tidal sand flat (Livera & Leeder 1981). It is possible that any evidence of a subaerial exposure was removed by the subsequent transgression and subaqueous erosion at the base of the next parasequence.

Overall, the lowermost parasequence of Cycle 5 equates with the Helwath Beck Member. To the south at Cloughton Wyke, the parasequence is slightly thicker (7.6 m as opposed to 5 m at Ravenscar) and is in general represented by a coarsening-upward, delicately cross-bedded sandstone showing abundant marine trace fossils. A basal, 1 m thick interval of marine mudstone marks the initial transgressive phase at this locality, overlain by progressively coarser-grained silts and sands including numerous *Diplocraterion* burrows. An intensely balled-up sandstone resting on the mudstone interval in this area (Fig. 1.21), is interpreted to have been caused by an earthquake shock due to movement along the Peak Fault (Rawson & Wright 1992). The beds can be traced in outcrop all the way to Ravenscar. At Yons Nab, the lateral equivalent is thinner and preserves wedge, trough, and hummocky cross-stratification, but does not show evidence of bioturbation, indicating that deposition occurred in deeper water, perhaps in subtidal conditions.

The sharp and erosive base to the second parasequence is overlain by the Hundale Shale Member, which comprises silty sandstone passing upwards into muddy limestone, and represents the transgressive phase of this cycle. The representative sequence at Ravenscar is 4.5 m thick and consists of a fine-grained, flaggy sandstone containing *Pleuromya* sp., whereas at Cloughton Wyke the 2.6 m thick unit is composed of a dark-grey siltstone and medium-grained sandstone sequence which became progressively more lime-rich with time. The succeeding regressive phase, characterized by the Hundale Sandstone Member, is composed of a sandy, bioclastic limestone which gradually increases in terrigenous content upwards; the top of the cycle is marked by a bed rich in granules, crinoid ossicles, belemnites and shell debris. The trend towards a higher terrigenous content, together with temporal changes in the fauna and trace fossils, indicates a progressive decrease in water depth time (Farrow 1966). At the top of the Hundale Sandstone (and the second parasequence), a trace-fossil community dominated by

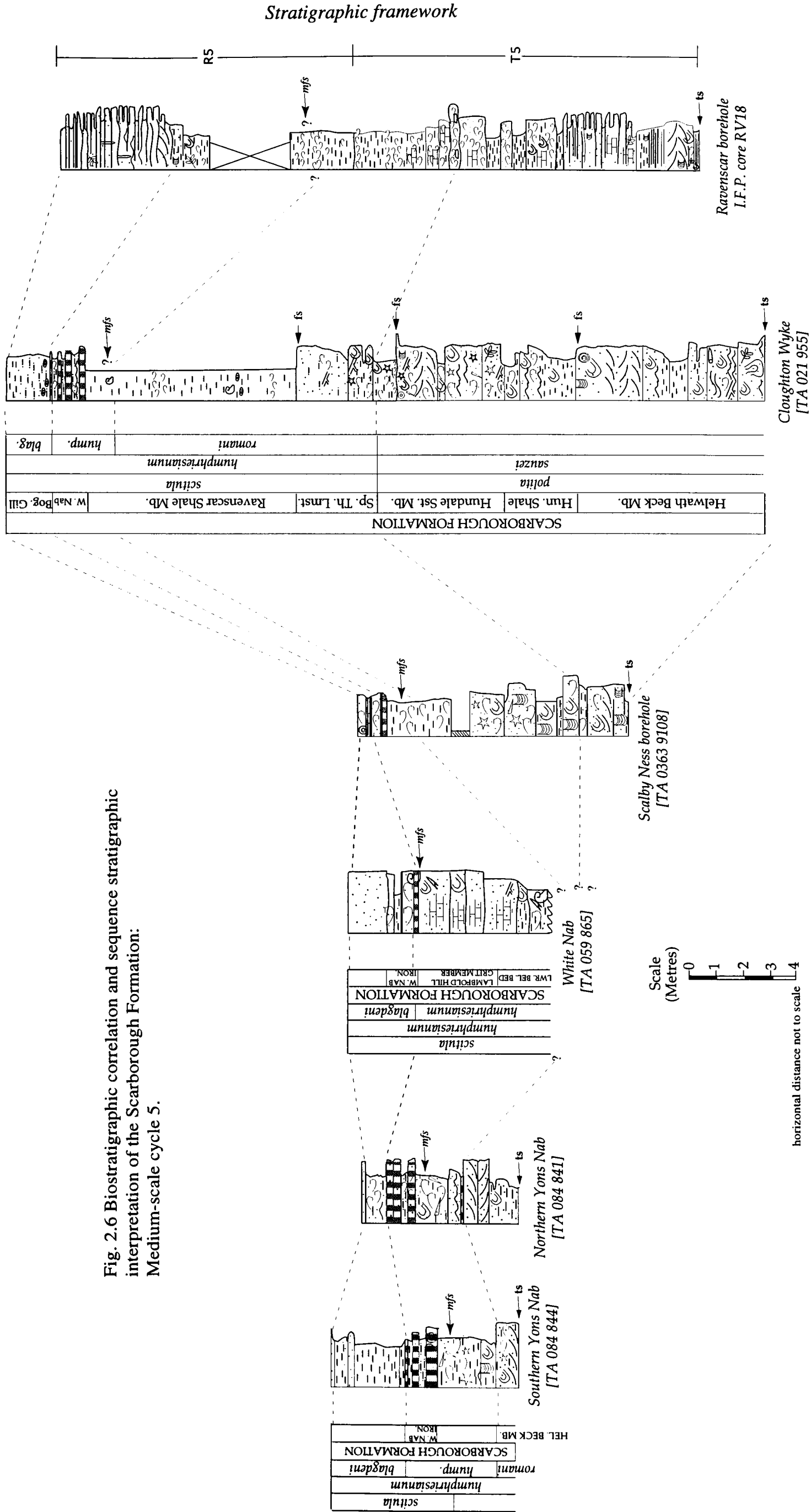


Fig. 2.6 Biostratigraphic correlation and sequence stratigraphic interpretation of the Scarborough Formation: Medium-scale cycle 5.

Rhizocorallium, *Teichichnus* and *Planolites* is cross-cut by large *Thalassinoides* and deep burrows of *Pleuromya*. These features suggest development of a firmground (Taylor & Gawthorpe 1993), which corresponds to a transgressive surface at the base of the third parasequence. There is no evidence for erosion at this level, indicating that the sea floor was beyond the reach of strong wave action.

At Cloughton Wyke, the parasequence can be resolved into three coarsening-upward cycles composed of intensely bioturbated siltstones and sandy siltstones, passing into mixed siliciclastic/carbonate deposits. The stacked nature of these cycles probably relates to successive phases of progradation and subsequent transgression. The contact with the overlying Ravenscar Shale Member is conformable, suggesting that there was a progressive increase in water depth until fully open-marine conditions became established. Above the basal 30 cm of the unit at Cloughton Wyke, the bivalve component is reduced to four species, and the trace-fossil assemblages are similarly restricted. Thus, palaeontological features indicate a deepening, which together with the concomitant increase in fine-grained material, indicate the presence of the maximum marine-flooding surface. Based on the associated ammonite fauna (Parsons 1980), this interval is thought to fall within the *humphriesianum* Subzone, of the *humphriesianum* Zone. Whilst the surface is difficult to pin-point at Cloughton Wyke the Ravenscar borehole reveals a firmground which likely corresponds to the maximum-flooding surface. At this time, marine conditions attained their maximum geographic extent: to the north of Whitby, littoral facies of the Spindle Thorn Limestone thicken markedly and overstep the Gristhorpe Member. However, to the south at Yons Nab the third parasequence is entirely absent, possibly as a result of syn-depositional movement along the Red Cliff Fault. Overall, the transgressive phase of this cycle comprises three landward migrating parasequences which culminated in a maximum-flooding surface; a flooding event of greater magnitude than those represented within the underlying medium-scale cycles.

Above the surface of maximum flooding, the sediments are regressive in character, forming a sequence up to 5 m in thickness. The unit, as a whole, represents shoreline progradation over a shallow, subtidal, muddy substrate. Thus, the upward-coarsening and decrease in marine body fossil communities indicates a shallowing trend, from quiet-water sedimentation to higher-energy conditions with only periodic bioturbation closer inshore. The succession culminates in a micaceous, sandy siltstone and fine-grained sandstone interval (the Bogmire Gill Member), which displays a range of wave- and current-generated sedimentary structures in the form of hummocky cross-stratification, symmetrical wave-ripples, together with medium-scale trough and tabular cross-stratification. Collectively, the succession has been previously interpreted as forming the wave-dominated sandy shoreface to the Scalby Formation delta lobe (Gowland & Riding 1991). However, bearing in mind the probable presence of a major stratigraphic gap

between the Scarborough and Scalby Formations, it is unlikely that the Bogmire Gill Member and Scalby Formation were contemporaneous.

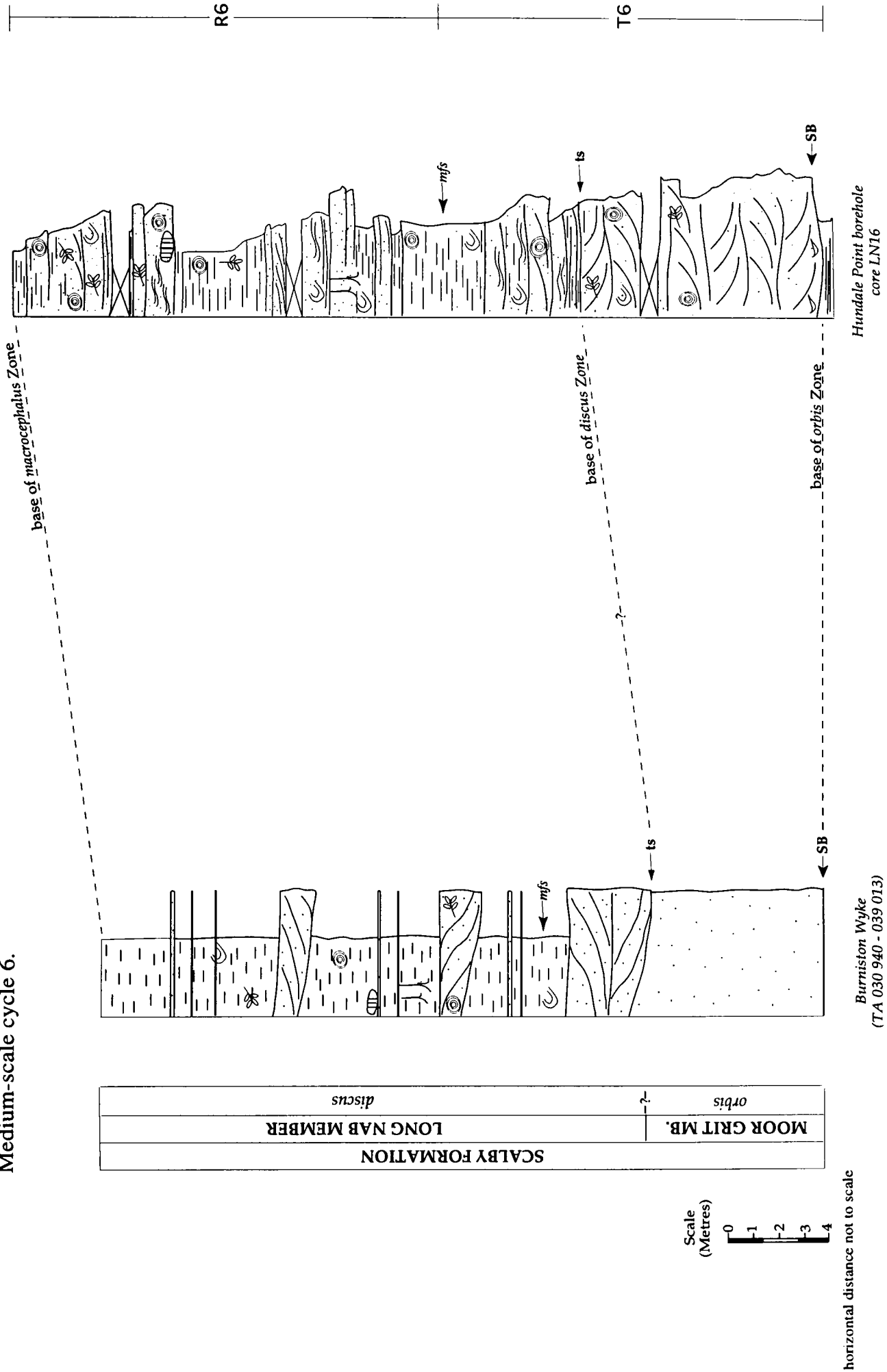
Cycle 6

Scalby Formation: *?orbis* to *discus* Zones

In localized areas across the Cleveland Basin, the uppermost littoral to sublittoral facies of the Scarborough Formation are downcut and eroded by the Scalby Formation (Moor Grit Member) braided-channel facies. At least 6 m of sediment is commonly removed, thus questioning the likelihood that the topmost Scarborough Formation and basal Scalby Formation were juxtaposed in terms of their contemporary palaeogeography. This regionally important surface has been interpreted as designating the floor of a palaeovalley which was eroded during a fall of relative sea-level (*e.g.* Nami & Leeder 1978), which, in view of current biostratigraphic interpretations, lasted a period spanning eight ammonites zones (see Section 1.5.2, p.20). The nature of this subaerially exposed surface provides the most convincing evidence in Yorkshire's Middle Jurassic succession for a prolonged period of erosion and non-deposition as, unlike the preceding cycles (apart from the base of Cycle 1), this depositional sequence preserves a conspicuous basinward shift in facies, and indicates a gradual denudation of the landscape through fluvial activity. The unconformity therefore is considered to be a sequence boundary.

The Moor Grit and lowermost Long Nab Members encompass a stepped rise in relative sea-level, during which the fluvial system retrograded and the palaeovalleys were infilled. The sequence comprises medium- to coarse-grained sandstones with giant sets of cross-stratification up to 8 m thick, overlain by a meander-belt sandstone sequence (Nami & Leeder 1978; Leeder & Nami 1979). Three multistorey channel-fill units have been recognized within the sequence as a whole (Eschard 1989), separated by intercalated mudstone partings bearing dinosaur footprints and desiccation cracks (particularly at Burniston Wyke). While the basal channel-fill consists of a low-sinuosity sand body deposited in a wholly fluvial environment, the succeeding channels reveal a progressively greater marine influence. The upper surface of the second sand-body (coinciding with the top of the Moor Grit Member) is sharp and appears to be erosive, and is overlain by a bioturbated mudstone containing clay drapes: the increase in marine influence, evidenced by these features, is interpreted to correspond to the landward expression of a transgressive surface. The overlying channel fill at the base of the Long Nab Member is a more argillaceous sandstone, consisting of a meander-belt composed of point-bars cross-cutting one another. Based upon the presence of marine palynomorphs (including acritarchs, leiospheres and a variety of dinoflagellate cysts: Hancock & Fisher 1981) within the overlying rooted, plant-rich shale, a saline swamp environment of deposition is envisaged. This interval marks

Fig. 2.7 Biostratigraphic correlation and sequence stratigraphic interpretation of the Scalby Formation: Medium-scale cycle 6.



the point of greatest marine influence on this otherwise wholly non-marine depositional sequence, and is the correlative extent of the maximum-flooding surface (Fig. 2.7) (Eschard 1989).

Within the overlying 40 m thick shale sequence, a number of channel sandstones occur which represent deposition in a range of meandering and low-sinuosity streams (Nami & Leeder 1978). The isolated channels characterize small distributaries which crossed the delta-plain, which, considering the predominance of clay over sand in the succession, must have been aggradational. The top of the Scalby Formation is abruptly overlain by the Cornbrash, which corresponds to a major marine transgression across the region.

In summary, the examination of key stratigraphic surfaces and their associated sedimentary packages in Yorkshire's Aalenian-Bathonian succession has revealed six medium-scale transgressive-regressive cycles. The stratigraphic range of each cycle equates to one or two ammonite zones: in reference to the levels of sedimentary cycle hierarchy devised and discussed by Haq *et al.* (1988) and Vail *et al.* (1991), these medium-scale depositional sequences correspond to third-order cycles and a 0.5 to 3 m.y. duration. Of the earlier inquiries into the range and extent of lithological cycles in the Ravenscar Group (*e.g.* Knox *et al.* 1990), the medium-scale cycles recognized by this study compare most favourably with the work of Eschard (1989), who identified five transgressive-regressive cycles in the succession. Whilst these cycles correspond well in stratigraphic position to those outlined by this study, the precise nature of these cycles differs for the following reasons. Firstly, because Eschard's work concentrates primarily on core data, while this investigation relies mainly upon field observations, the exact stratigraphic position of the bounding surfaces differs as a consequence of lateral facies variation and changes in stratal thickness. Secondly, the reevaluation and compilation of biostratigraphic information for this thesis has altered the apparent temporal extent of some formations and therefore cycles (*e.g.* the Scalby Formation, Cycle 6).

Examination of the temporal arrangement and changing character of these medium-scale cycles has elucidated two depositional cycles on a higher hierarchical level. These are described in more detail below.

2.5.2 Large-scale cycles

Using the same 'key surfaces' approach, two large-scale cycles have been recognized in the basin (3-10 m.y., second-order cycles of Haq *et al.* 1988; Vail *et al.* 1991). In these 100 m thick, stage-scale cycles, fluvial sandstones are relatively expanded and marine mudstones comparatively condensed. On the basis of gross grain-size differences through the sequence, the most proximal facies occur in the early Aalenian to early Bajocian (*opalinum* to *sauzei*

Zones) and late Bathonian (*orbis* and *discus* Zones). Conversely, the most distal sediments are recognized in the mid-Bajocian (*humphriesianum* Zone). The collation of such broad-scale facies interpretations with inferences drawn from the positioning of key stratigraphic surfaces, shows that the Aalenian-Bathonian interval in the Cleveland Basin comprises one entire large-scale cycle (*opalinum* to *humphriesianum* Zones) and one partial cycle (extending from the *orbis* Zone).

Two major unconformities, or sequence boundaries, mark the bases of the large-scale cycles. The basal Aalenian unconformity is sufficiently pronounced in character to allow its correlation both intra-and interbasinally. Within the Cleveland Basin, the hiatus commonly corresponds to the *aalensis* Subzone of the *levesquei* Zone, but in places extends down to *falciferum*-Zone strata. The overlying Dogger Formation can be traced with relative ease across the Market Weighton High (where it has been subsequently removed by intra-Bajocian erosion) to the Northampton Ironstone in Humberside, by the virtue of their strong faunal affinities (Cope *et al.* 1980*b*). Such are the similarities of these two units that it is probable they once formed a continuous deposit. South of the Market Weighton High, an erosional surface and stratigraphic gap exists which is comparable to that found in Yorkshire: however, because of a somewhat imprecise biostratigraphy, the exact duration of the hiatus is unknown. With distance southwards, the unconformity disappears and instead the horizon is expressed as a correlative conformity within the shallow marine Bridport Sands. Consideration of this sequence boundary and subsequent transgression in a regional context, suggests that the Cleveland to Wessex Basin lay on a proximal to distal transect: an inference compatible with sequence stratigraphic interpretations for the Jurassic previously made by Hesselbo & Jenkyns (1995, 1997).

The significant areal coverage of this sequence boundary alone might imply a sea-level fall of at least regional extent. This supposition is neatly supported by the character of the sequence boundary in the vicinity of Ravenscar. Here, the relationship between the unconformity and the major syn-sedimentary Peak Fault can be seen clearly (Black 1934*a*; Milsom & Rawson 1989). On the upthrown side of the fault, the stratigraphy is incomplete with the Dogger resting on the Alum Shale. Although the Blea Wyke Sandstone (Upper Toarcian) is preserved on the downthrown side, there is still a stratigraphic gap as the uppermost *levesquei* Zone is missing (Knox 1984). For these reasons, the movement of the Peak Fault alone cannot explain the development of the large-scale cyclicity, and a fall in relative sea-level is inferred (*e.g.* Hesselbo & Jenkyns 1997).

The overlying succession comprises a series of four medium-scale cycles which become progressively more transgressive in character with time. These cycles reflect pulsations in the overall deepening aspect of the large-scale cycle. Despite their transgressive nature, the

Stratigraphic framework

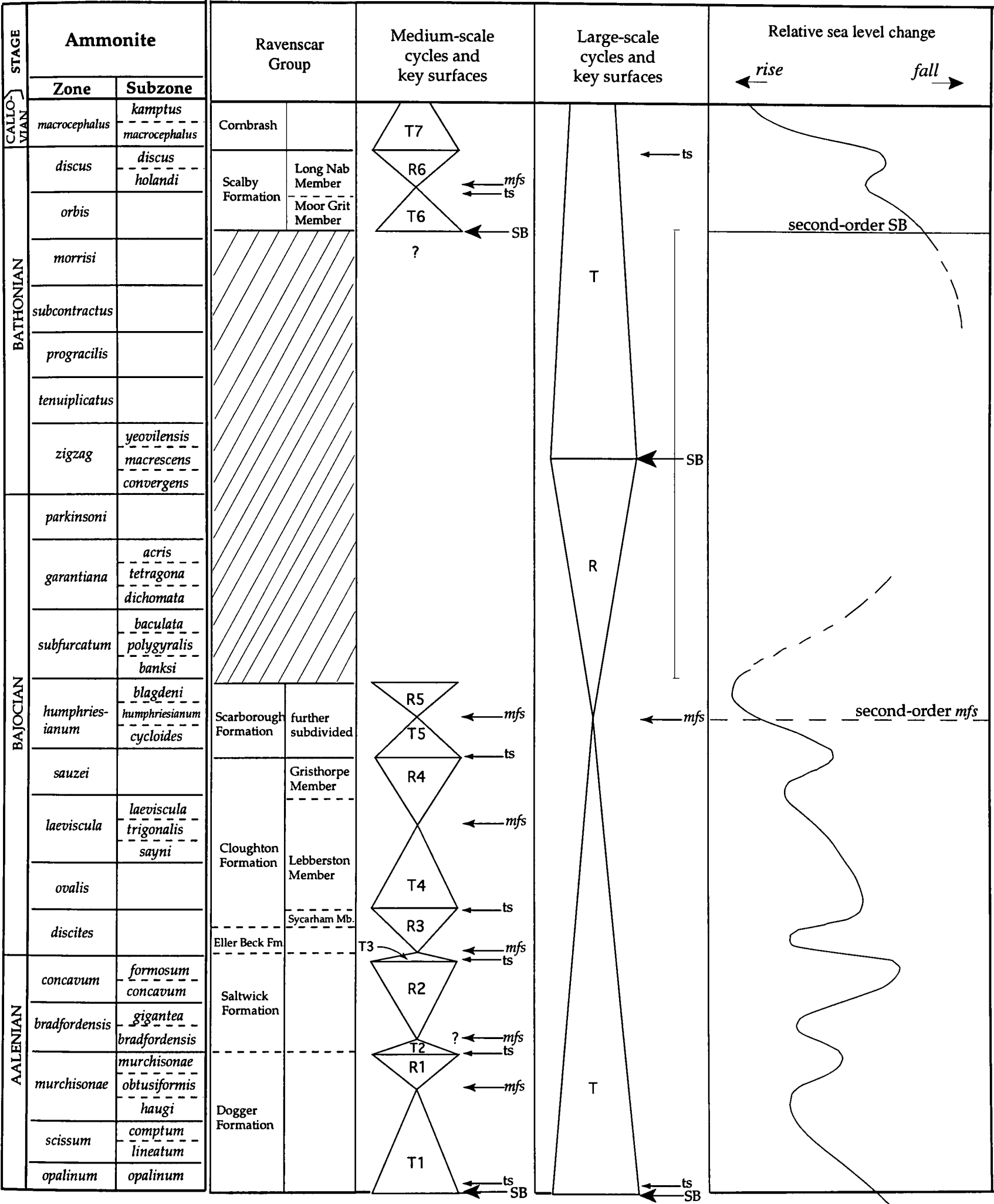


Fig. 2.8 Medium- and large-scale lithological cycles recognized in the Aalenian-Bathonian sequence of the Cleveland Basin. The relative sea level curve is with respect to the basement and assumes constant sediment supply (after Posamentier *et al.* 1988). An estimate of the dating error on the Bathonian sequence boundary is given.

medium-scale cycles are formed of thick fluvial successions, including only thin marine bands. The periodicity of these marine intercalations occurs on the third-order level, and relate to the *discites* (Eller Beck Formation; Cycle 3), and *ovalis* and *laeviscula* Zones (Lebberston Member; Cycle 4). The marine beds increase in thickness, duration and areal extent with time, until the point of maximum flooding was attained in the *humphriesianum* Subzone of the *humphriesianum* Zone (Scarborough Formation; Cycle 5). The predominantly deltaic mode of deposition, from Aalenian to late Bajocian times, is a reflection of the proximal setting of the Cleveland Basin. The resultant expanded sequence corresponds to a high sediment supply and increased accommodation space. In contrast, the coeval succession in Dorset reveals condensed, offshore marine strata, highlighting the basin's distal location (Hesselbo & Jenkyns 1997). The ability to correlate medium-scale cycles between the Cleveland and Wessex Basins indicates that local tectonics do not control their timing or formation. However, local tectonics do partially control the amount of accommodation space in which sediment can accumulate. This is demonstrated by thickening of individual sequences on the downthrown side of faults (e.g. the Dogger Formation adjacent to the Peak Fault, Blea Wyke; the Scarborough Formation across the Red Cliff Fault).

A further large-scale cycle overlies and downcuts the preceding depositional sequence. The sequence boundary forming the base to this cycle constitutes a major stratigraphic break representing the late Bajocian to mid-Bathonian (Leeder & Nami 1979; Lott & Humphreys 1992; Hogg 1994; Hesselbo & Jenkyns 1995). The unconformity can be recognized in areas of Humberside, but in Yorkshire is thought to be confined to the late Bajocian and early Bathonian (Cope *et al.* 1980*b*). With distance southwards evidence for a stratigraphic break is lost. Instead, the Dorset area reveals an expanded sandy sequence, corresponding to the Inferior Oolite, Fuller's Earth and Forest Marble. Overlying the Scalby Formation (Cycle 5), the base of the Cornbrash represents the cycle's transgressive surface.

2.6 Conclusions

The Middle Jurassic (Aalenian-Bathonian) can be subdivided into two large-scale ('second-order') lithological cycles, with durations of approximately 3-10 m.y., onto which six medium-scale cycles of relative sea-level are superimposed (Fig. 2.8). The sequence boundaries defining the large-scale cycles are determined on the basis of erosional unconformities or sedimentary facies successions indicative of reduced accommodation space in proximal areas. They are identified in the *aalensis* Subzone of the *levesquei* Zone (uppermost Toarcian), and spanning the *subfurcatum* to *morrisi* Zones (late Bajocian to early to mid-Bathonian). At this second-order level, a maximum-flooding surface is recognized within the *humphriesianum*

Subzone of the *humphriesianum* Zone on the basis of evidence for sediment starvation and a restricted faunal component. The expression of the maximum-flooding surfaces corresponding to the medium-scale cycles are not, however, as well defined. However, despite their frequent lateral variability and changing character, it is nevertheless possible to trace these flooding surfaces across the Cleveland Basin to adjacent basins. Hesselbo & Jenkyns (1995) noted that the Eller Beck Formation and Lebberton Member (*discites*, and *ovalis* and *laeviscula* Zones) can be correlated to levels of extreme condensation in Dorset: this finding may, therefore, suggest that there was at least some component of sea level controlling third-order cyclicity, rather than the influence of local tectonics alone. However, whether the medium-scale cycles can be securely traced to coeval sections in Scandinavia is more conjectural. The following chapter investigates the feasibility of stratigraphic correlation between Yorkshire and Scandinavia, on both second- and third-order levels. Based on these findings, inferences are made as to the controls on their formation.

Chapter 3

Chapter 3

Comparison of the Early and Middle Jurassic stratigraphy of Bornholm and Scania with Yorkshire

3.1 Introduction

This chapter aims to place the Ravenscar Group in a regional context. To achieve this objective, coeval plant-bearing fluvio-deltaic successions from parts of southern Scandinavia were chosen as a means for comparison. The Early and Middle Jurassic sequence from the Danish island of Bornholm comprises the major component of this study, complemented by information drawn from southern Swedish sections (Scania). Originally, these successions were selected for study because they are composed primarily of non-marine sediments intercalated with subordinate marine units, they contain diverse floral assemblages, and, until now, have not been compared in detail to the Yorkshire sequence. On this basis, fieldwork was undertaken in both regions and emphasis was placed on obtaining as detailed and complete a lithological succession as possible. This applied particularly to the Bornholm sections, as Scanian exposures of the relevant age were found to be few and of no great extent. Fieldwork also revealed that much of the plant-bearing sedimentary sequence of Early to Middle Jurassic age was poorly consolidated, thus hindering the collection of intact plant fossils. As a detailed examination of the plant remains at each locality could not be adequately accomplished in the time available, literature sources were referred to in order to gain an understanding of the Bornholm and Scania floras. Time constraints prevented these plant fossils being examined in as much detail as the Yorkshire flora (described in Chapters 4 and 5), but certainly given time similar analyses could be carried out.

3.2 Geological setting

Bornholm and Scania occupy a complex, fault-bounded zone within the Tornquist Line, which demarcates the stable Baltic Shield from the subsiding Danish Basin and Polish Trough. Both areas show incomplete evidence of deposition during Palaeozoic and

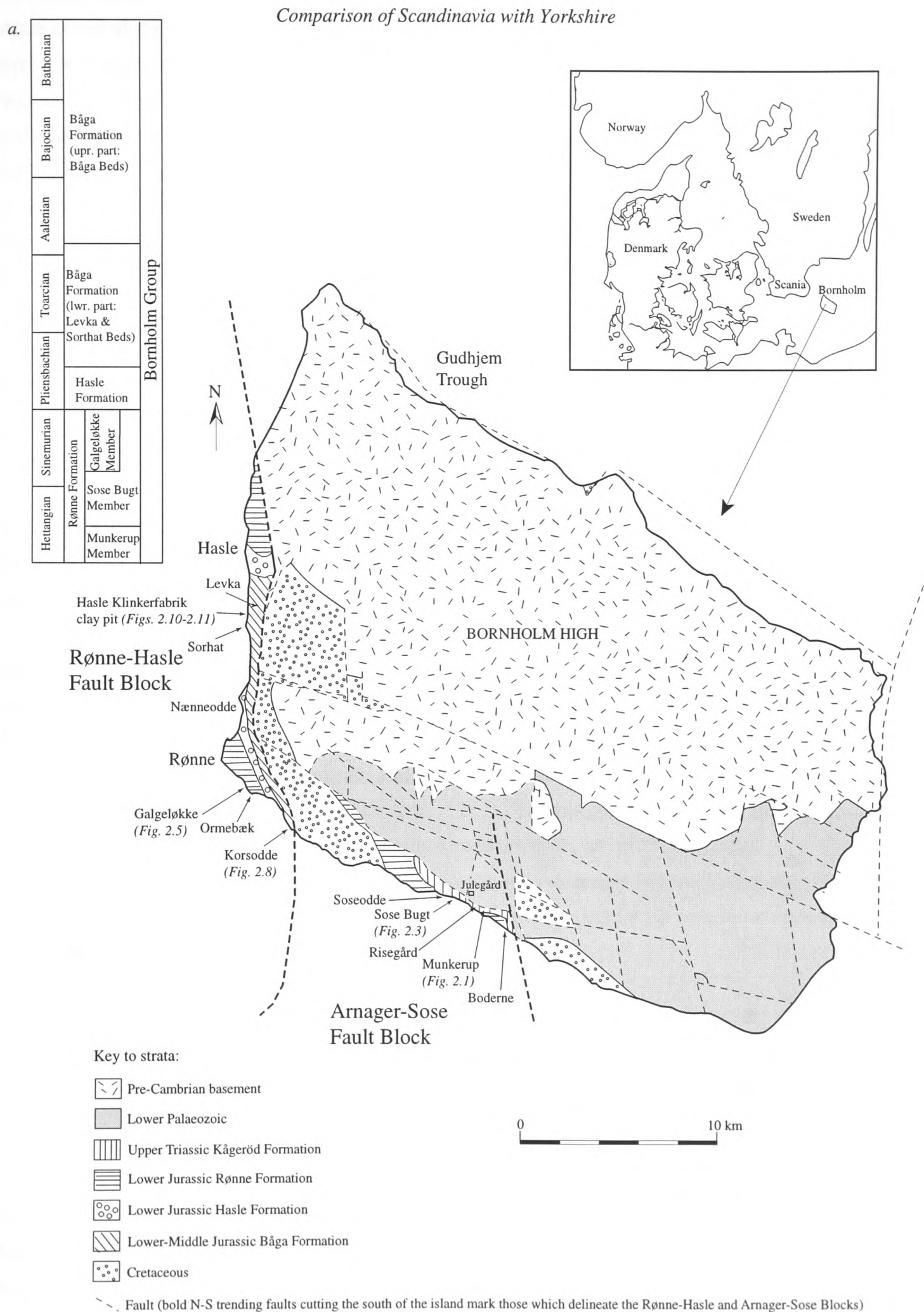


Fig. 3.1 Geological map of Bornholm (modified after Gry 1969; Koppelhus & Nielsen 1994).

The position of localities mentioned in the text are shown. Those sections recorded in the form of sedimentary logs are also indicated, which comprise Appendix 2.

In set a. provides a summary of the Bornholm Group nomenclature. Figs. 1.3-1.4 (Chapter 1) show a comparison with the stratigraphy of Yorkshire and Scania.

Mesozoic times into down-faulted blocks of Pre-Cambrian age. On Bornholm, Jurassic strata occur along the western and southwestern coasts whereas, in Scania, rocks of equivalent age mainly restricted to inland exposures and subordinate coastal outcrops in the region of Helsingborg. The Tornquist Line comprises a continuous fault zone from southeastern Europe to the central North Sea. The northern portion of this feature, termed the Sorgenfrei-Tornquist Zone, passes through Scania and the northeast of Bornholm, while to the southwest lies the Teisseyre-Tornquist Zone (EUGENO S-Working Group 1988). The two fault zones converge at the Rønne Graben, which straddles the west coast of Bornholm (Fig. 3.1). The Rønne Graben formed through transtensional wrench faulting, which affected large areas of the Sorgenfrei-Tornquist Zone during the late Carboniferous to early Permian (Vejbæk 1985; Liboriussen *et al.* 1987; Michelsen & Nielsen 1993). Mesozoic rocks subsequently accumulated in the graben, resulting in a fairly complete Triassic to Jurassic succession with thinner and less intact sections on adjacent upfaulted structures.

During Early and Middle Jurassic times on Bornholm, sediments were laid down within the confines of two principal fault blocks, with broadly similar tectonic histories and patterns of sediment accumulation: these are the Rønne-Hasle Block, which constitutes the easternmost part of the Rønne Graben, and the Arnager-Søse Block (Fig. 3.1). The eastern limit of Jurassic deposition on the Rønne-Hasle Block corresponds to a prominent north-south trending fault. There is evidence to suggest that the fault formed a substantial scarp during deposition of the Hasle and Båga Formations, as very angular pebbles of gneiss, quartz and feldspar occur in the former, and redeposited kaolinized granite boulders are present in the latter (Gry 1969; Gravesen *et al.* 1982). Overall, the strata of the Bornholm Group were primarily deposited in non-marine environments, are predominantly siliciclastic and are typically, though not exclusively, coarse grained. Late Cretaceous to early Tertiary basin inversion and uplift in the region of 1 km led to the pattern of outcrop we see today.

3.3 Comparison and correlation with the Yorkshire sequence

The Mesozoic succession of Bornholm represents sedimentary deposition from the late Triassic to the late Cretaceous unconformably onto rocks of Pre-Cambrian and Lower Palaeozoic age. Exposures are restricted to a few low coastal cliffs to the south and west of the island, and to some inland quarries. The Jurassic sequence is bounded by unconformities and consists of paralic deposits that are largely devoid of marine macrofossils except for a marine sandstone in the middle, which is used to subdivide the

succession into lower and upper lithostratigraphic parts. The marine unit, known as the Hasle Formation, is referable to the Early Pliensbachian *jamesoni* to *daveoi* ammonite zones, and is the only precisely dated interval. This lack of biostratigraphic information, combined with the fact that much of the paralic sequence is highly variable in a vertical and lateral sense, hinders reliable correlation and stratigraphic subdivision. Furthermore, comparison of sections is further impeded owing to the complicated tectonics of the island, scant marker beds, and the scattered and discontinuous nature of the exposures. As a result, the existing lithostratigraphic nomenclature is mainly informal and descriptive. Much of the current knowledge of the Jurassic stratigraphy is due to the work of Gry (1956, 1960, 1968, 1969), who subdivided the Aalenian-Bathonian sequence into the Lower Limnic, Marine and Upper Limnic Series. This scheme has, however, since been revised by Gravesen *et al.* (1982) to the Rønne, Hasle and Båga Formations, encompassed by the Bornholm Group (see Figs. 1.3-1.4, p.7-8).

The ages of the constituent units of the Bornholm Group are derived from a variety of sources. Until recently, much of the biostratigraphic information available for the Rønne Formation was obtained from age-diagnostic flora (yielding a “Rhaetic-Liassic” age: Grönwall & Milthers 1916; Harris 1937) and upper age limits imparted by the ammonite-bearing Hasle Formation. However, these methods have since been replaced by palynological studies (*e.g.* Koppelhus 1991; Koppelhus & Batten 1992; Koppelhus & Nielsen 1994), which provide a more accurate means to ascertaining the relative ages of the component members. Palynological investigations have also succeeded in disclosing a more precise age for the overlying Båga Formation, which was previously dated using megaspores alone (Gry 1969): dinoflagellate cysts and miospores have supplied a Late Pliensbachian to Bathonian age for the formation (Koppelhus & Nielsen 1994).

Palynological inquiries into the Early and Middle Jurassic of Scania have succeeded in producing an accurate biostratigraphy which eases correlation with the Bornholm sections (*e.g.* Guy 1971; Guy-Ohlson 1986, 1989). Studies of the Lower Jurassic interval (*e.g.* Pienkowski 1991*a, b*) have shown that in general terms the evolution of Scania closely mirrors that of Bornholm. Exposure of the relevant age are few and far between, requiring supplementary information to be gleaned from published descriptions of cores and outcrops that no longer exist. The most extensive example of Jurassic strata in Sweden occurs at Eriksdal, where the Roddinge and Mariedal Formations represent deposition through the Sinemurian to Bathonian. Other outcrops of the lower Hettangian (Lower Helsingborg Member) and the lower Sinemurian (Dösult Member) were also examined, in the region of Helsingborg and Höör.

Although the exact nature of the correlation of Bornholm and Scanian sequences with the Yorkshire succession is discussed in more detail below, it is appropriate at this juncture to refer back to the biostratigraphic charts illustrated in Chapter 1 (Figs. 1.3-1.4).

The goal of this section is to compare and contrast the stratigraphic development of Yorkshire with that of southern Scandinavia. The key-surfaces approach, defined in the previous chapter (p.52), is the method used to delineate the Scandinavian succession and assist a correlation with the Yorkshire sequence. A comparison is made between the Middle Jurassic sections using the stratigraphic framework constructed for the Ravenscar Group and described in Chapter 2. In contrast, the development of Scandinavia's Lower Jurassic interval is compared primarily to work carried out by Hesselbo & Jenkyns (1995, 1997) on Yorkshire's coeval section. In order to assess the lateral continuity of those lithological cycles found in the Early and Middle Jurassic succession, the stratigraphy of other sedimentary basins further afield are also taken into account. The paragraphs below describe the sedimentary character and stratigraphic extent of five entire large-scale (second-order) lithological cycles identified in the Early and Middle Jurassic succession, and explore the similarities of these cycles with those recognized in the Yorkshire sequence. Throughout this section, references are made to the sedimentary logs recorded on Bornholm and illustrated in Figs. 2.1-2.11, Appendix 2.

3.3.1 Large-scale scales

Cycle i

Munkerup and Sose Bugt Members: Basal *planorbis* Zone to mid-*semicostatum* Zone

The Munkerup Member marks the initiation of Early Jurassic deltaic deposition on Bornholm. The unit is found solely on the Arnager-Sose Block (Fig. 3.1) where the unit is only poorly exposed, particularly at its base. As a result, there is much speculation on the nature of the basal surface of the Munkerup Member and hence the Triassic/Jurassic boundary (*e.g.* Gravesen *et al.* 1982). Juxtaposition of the Munkerup Member against other, older units shows that its lower boundary may be either gradational or abrupt. At the Risegård locality, red and green variegated clays and sands of the Upper Triassic Risebæk Member have a gradational, although poorly exposed contact with the fluvial-dominated clays and sands of the overlying Munkerup Member. In the vicinity of Boderne the member is faulted against Lower Palaeozoic deposits, producing a contrastingly abrupt contact. Although little further information can be obtained from the Bornholm sections, comparison with coeval successions elsewhere is informative. Commonly, the Triassic/Jurassic boundary, and the base of Cycle i, represents a complex regional unconformity (*e.g.* Surlyk *et al.* 1995).

The extent of this unconformity can be traced across north-western Europe, but is most apparent (1) in Scania, where the Upper Rhaetic is missing leading to the Helsingborg Member of Hettangian age unconformably overlying the Middle Rhaetic Bjuv Member (Lund 1977; Sivhed 1984); (2) in northern Germany and Poland, where an unconformity can be recognized beneath Jurassic strata (Pienkowski 1991*a*) and; (3) in the Danish Basin, where an unconformity occurs of latest Rhaetic/basal Hettangian age (Surlyk *et al.* 1995). Poor exposure of the Hettangian portion of the Calcareous Shales in Yorkshire hinders its comparison with the Munkerup Member. Nevertheless, based on the frequently unconformable nature of this regionally important surface, and the presence of a pronounced change in facies across the boundary, a sequence boundary is interpreted. Resting upon this surface is a transgressive sequence of lower Hettangian age. Based on the London Platform sequence, the initial transgression can be constrained to the *planorbis* Zone, continuing into the *liasicus* Zone (Cope *et al.* 1980*a*). In Scania, the transgression is marked by the incoming of sandy marginal and deltaic sediments in the form of the Helsingborg and Döshult Members; similarly, rapid and widespread brackish-marine transgressions occur at the base of the Hettangian in Poland and southern Germany (Pienkowski 1991*a*). This gradual rise in Early Jurassic sea level affected most of NW Europe and the North Atlantic (Hallam 1988; Haq *et al.* 1988), and culminated in deposition of the fully marine Hasle Formation (Cycle iii of this study) (Michelsen 1978; Gravesen *et al.* 1982; Surlyk *et al.* 1990*a*). Cycle i probably represents a short-term transgressive-regressive pulse (Hettangian-early Sinemurian) superimposed on a longer-term transgression (Hettangian-Pliensbachian), which may relate to rifting episodes during the break-up of Pangaea (*e.g.* Wyatt 1986; Parkinson 1994).

Although the Munkerup Member is understood to have been laid down in a transgressive regime, the depositional environments which the deposit represents are wholly non-marine. Best displayed at the Munkerup locality (Fig. 3.1), the sequence comprises grey to black clays and subordinate sands forming a 20 m thick unit (Gry 1969). The lower part of the member comprises small-scale (fourth-order), coarsening-upward cycles, or parasequences (Fig. 2.1). Each cycle comprises a 1-2 m thick argillaceous unit capped by rootlet horizons and coals indicative of palaeosol development (Fig. 2.2). Within these coals, highly disseminated, finely divided, charcoalified plant material occurs. Overall, a lacustrine environment of deposition is inferred, based on the dominant lithology and the presence of a (albeit impoverished and poorly preserved) freshwater-bivalve assemblage (Koppelhus 1991). The occurrence of parasequences within the succession indicates that minor base-level fluctuations occurred during sedimentation of the Munkerup Member, which may reflect relative sea-level changes during the overall transgressive trend. The Munkerup Member is understood to represent the Hettangian, based on the presence of the so-called *Thaumatopteris* Flora (Harris 1937; Troedsson 1951, p.113), and occurrence of

palynomorphs indicative of the *Pinuspollenites-Trachsporites* Zone (Koppelhus 1991) (see Fig. 1.5, p.15). Age constraints imparted by the overlying Sose Bugt Member provide an upper Hettangian age-limit for the Munkerup Member (Gry 1969; Koppelhus 1991; Koppelhus & Batten 1992).

Transgressive conditions continued during deposition of much of the Sose Bugt Member. At the type section of Sose Bugt (Fig. 3.1), the exposed portion of the member is 26 m thick, but in reality the unit may exceed 40 m (Gravesen *et al.* 1982). The sequence extends slightly inland from the coastal type section and, based on similarities in stratigraphical position and lithological character, is also thought to be exposed just to the east of Ormebæk, west of Rønne (Gry 1969, Gravesen *et al.* 1982). The upper contact of the Sose Bugt Member and overlying Galgeløkke Member is poorly exposed, but crops out west of Sose Odde on the Arnager-Sose Block alone (Surlyk & Noe-Nygaard 1986). Here, the Sose Bugt Member ranges from the *bucklandi* Zone to mid-*semicostatum* Zone. On the Rønne Block where the Galgeløkke Member is absent, deposition of the Sose Bugt Member may have extended into late-Sinemurian times (*?raricostatum* Zone) (Koppelhus 1991). Thus, it is possible that the Galgeløkke Member and upper Sose Bugt Member are coeval. However, without better exposure and a clearer biostratigraphy, it is difficult to be more precise.

The Sose Bugt Member is dominated by alternating beds of grey laminated claystone and interlaminated claystone and siltstone, interbedded with cross-laminated fine-grained sandstone containing carbonaceous debris (Fig. 2.4) (Gravesen *et al.* 1982). Coalified wood, thin coal seams and rootlets are common constituents within palaeosols composing the unit (Arndorff 1993). A well-sorted, fine-grained, micaceous sandstone with abundant *Skolithos* and *Diplocraterion* is present in the middle part of the section, as an indication of the progressive importance of a marine influence. However, the establishment of marine conditions was pulsed, indicated in this part of the sequence by a fluvial channel erosively overlying these marine-influenced beds. Overall, a sparsely vegetated lower delta-plain across which marine waters occasionally flooded is envisaged (Koppelhus & Batten 1992). Near the top of the Sose Bugt exposure there is again evidence for an increase in marine influence: siltstone and claystone beds display wavy and flaser-bedding, contain thin iron-rich layers, and include numerous examples of *Diplocraterion* and *Planolites* (Fig. 2.4). One iron-rich horizon which is particularly heavily burrowed is a good candidate for the maximum-flooding surface (see Figs. 2.3 and 3.2). The occurrence of diagnostic miospores suggests an early Sinemurian age (*e.g.* Koppelhus 1991). More specifically, because the base of the overlying Galgeløkke Member is thought to correspond to the mid-*semicostatum* Zone (*e.g.* Gravesen *et al.* 1982), this flooding surface must be slightly older,

perhaps relating to the lower part of the *semicostatum* Zone (?*lyra* Subzone) (Fig. 3.2). The facies which rest upon the maximum-flooding surface are regressive in nature.

The stratigraphic extent of Cycle i represents the *planorbis* to mid-*semicostatum* Zones, forming a highly asymmetric transgressive-regressive cycle (Fig. 3.2). The character of this lithological cycle corresponds fairly well with an approximately coeval cycle on a second-order level identified in the Cleveland Basin by Hesselbo & Jenkyns (1997) (Fig. 3.2). Upon this cycle, third-scale cycles are superimposed (Hesselbo & Jenkyns 1995). Although clear evidence exists for smaller-scale relative sea-level fluctuations in Hettangian and Early Sinemurian strata on Bornholm (particularly in the Munkerp Member), the biostratigraphic resolution of the beds does not allow the stratigraphic extent of the cycles to be constrained. As a consequence there is (1) a difficulty in deciphering at what hierarchical level the cycles occur, and (2) an impedance of even local correlation of the cycles.

Cycle ii

Galgelokke Member: Mid-*semicostatum* Zone to the upper *raricostatum* Zone

The junction between the Sose Bugt and Galgeløkke Members is marked by a transition from shoreface deposits to tidal flat sediments (exposed to the west of Sose Odde). Although there is no evidence for erosion and downcutting, there is certainly a suggestion of a basinward shift in facies. A sequence boundary is interpreted of mid-*semicostatum* Zone age. The succession resting upon this surface is best exposed in the coastal cliffs forming the type locality at Galgeløkke, east of Rønne (Figs. 3.1, 2.6). The unit is only known to occur on the Rønne-Hasle Block, where in addition to the type locality, small exposures are found in the vicinity of Ormebæk and in the clay pits of Rønne Lervarefabrik. The thickness of the unit is quite variable: Gry (1969) determined a thickness of 150-210 m by measuring between a bed yielding the bivalve *Cardinia follini* near the top of the Sose Bugt Member, and the base of the Hasle Formation.

Although the basal part of the Galgelokke Member is not well exposed on Bornholm, the sedimentary succession which is exposed displays a regressive aspect (Fig. 2.5). At Galgelokke (Fig. 3.1), three basic portions comprise the sequence. The lower part is characterized by cross-laminated, fine-grained sandstone intercalated with wavy and flaser-bedded sandstones and claystones; at certain levels *Planolites* and *Skolithos* are locally abundant, serving as useful stratigraphic markers. Water-escape structures become increasingly common near the top of this lower unit and into the base of the middle unit. The middle unit comprises trough cross-bedded and herringbone cross-stratified sandstones

inferred to have been deposited in tidal channels (Fig. 2.6*b*): it is these tidal flat and tidal mouth-bar deposits which characterize the Galgeløkke Member as a whole (Sellwood 1972, 1975). The upper part of the member is composed of an accumulation of wavy and flaser-bedded siltstones which become progressively more carbonaceous upwards. A thin coal with rootlets penetrating the bed beneath is found at the top of the member, indicating palaeosol development (Arndorff 1993) (Fig. 2.7*b*).

A comparison with coeval sections elsewhere is instructive in the elucidation of this portion of Sinemurian stratigraphy. On the basis of diverse facies changes, it is well established that the *semicostatum* Zone was a time of major deepening in the British area (Hallam 1984; Haq *et al.* 1988). The upper *semicostatum* Zone is in turn interpretable as regressive, with a fall in relative sea-level continuing into the *obtusum* and *oxynotum* Zones (Pienkowski 1991*a*; Parkinson 1994; Hesselbo & Jenkyns 1997). Taking this information and applying it to the Bornholm sequence, it transpires that the character of Galgeløkke Member conforms well with these inferred relative sea-level fluctuations. From those parts of the Galgeløkke Member which are currently exposed on Bornholm, a mid-*semicostatum* Zone sequence boundary is known to occur at the base of the unit, and a regressive succession above, extending into the topmost-*raricostatum* Zone. What is rather more conjectural is the occurrence and stratigraphic extent of the intermediate transgressive phase, which, judging by the Yorkshire succession, may occur in the upper-*semicostatum* zone. Without further evidence it is difficult to be more specific, but on the basis of these comparisons a transgressive event near the base of this cycle is tentatively inferred (Fig. 3.2).

Cycle iii

Topmost Galgeløkke Member to Hasle Formation: upper *raricostatum* Zone to mid-*daveoi* Zone

The lowermost portion of Cycle iii currently exposed on Bornholm is the transgressive surface at the base of the Hasle Formation. However, evidence obtained from Yorkshire suggests that beneath this surface, at the base of the cycle, a sequence boundary may occur. Regression during the *obtusum* and *oxynotum* Zones in the Cleveland Basin resulted in the introduction of coarse, wave-scoured clastics, recorded by the Siliceous Shales, and the formation of a sequence boundary in the mid-*oxynotum* Zone (*simpsoni/oxynotum* subzonal boundary) (Hesselbo & Jenkyns 1997). Similarly, a lack of accommodation space in Late Sinemurian sections of Dorset and southern Germany has been highlighted by Parkinson (1994) and inferred to be the consequence of falling sea-level. Based on these comparisons, sequence boundary is provisionally placed within the uppermost part of the Galgeløkke Member (which at present is not exposed), of an approximate *raricostatum*-

Zone age (Fig. 3.2). This possibility is strengthened by the presence of the ?Tithonian-Lower Berriasian Homandshald Member immediately on top of the Galgelokke Member in the vicinity of Sose Odde: the Hasle and Båga Formations are entirely absent, indicating prolonged erosion and non-deposition (Gravesen *et al.* 1982).

The stratigraphy of the overlying Lower Pliensbachian Hasle Formation can be interpreted in terms of sea-level rise. The establishment of fully marine conditions on Bornholm is shown by a sequence of limonitic, coarse-grained siltstone and fine-grained sandstone lithologies laid down in an inner shelf environment, resulting in the formation of horizontal lamination, low-angled trough cross-bedding and hummocky cross-stratification (Fig. 2.7) (Gry 1969; Gravesen *et al.* 1982; Surlyk & Noe-Nygaard 1986). Thin lags comprising quartz pebbles and shelly material are present within the sandy sediments, and a rich marine fauna occurs, including over 60 species of brachiopods, bivalves and gastropods, with some belemnites, fish and plesiosaur remains (Forchhammer 1837; Malling & Grönwall 1909; Malling 1911, 1914, 1920; Höhne 1933). Abundant ammonites provide a *jamesoni-daveoi* Zone age (Gravesen *et al.* 1982).

In Scania, the marine transgression is represented by the Katslösa Member of the Rya Formation (Höhne 1933; Sivhed 1984); in Poland, the non-marine Radowo Beds pass into the marine Lobez Beds (Pienkowski 1991*b*); and in Eastern Greenland, the non-marine Kap Stewart Formation is overlain by the marine Neill Klint Formation (Surlyk 1990*a, b*; Dam & Surlyk 1992, 1993). In Yorkshire, the base of the Lower Pliensbachian (*taylori* Subzone, *jamesoni* Zone) is marked by organic-rich facies comprising the Pyritous Shales. The shales represent a second-order maximum-flooding surface in the earliest *jamesoni* Zone. With time, the Pliensbachian succession gradually became coarser until a maximum was reached in the *valdani* Subzone of the *ibex* Zone, where sand is fairly abundant and the sediments are referred to as the Ironstone Shales (Parkinson 1994). Following the deposition of this sandy interval, an abrupt fining occurred in the upper *ibex* Zone (*luridum* Subzone), succeeded by a progressive coarsening through the *daveoi* Zone (Hesselbo & Jenkyns 1995). As a result of this increase in grain size, the shallow-marine Staithes Sandstone was deposited during the *daveoi* and earliest *margaritatus* Zone. By comparison with the Yorkshire succession, a maximum-flooding surface is tentatively placed in the *taylori* Subzone of the *jamesoni* Zone in the Bornholm sequence. Above this surface rest comparatively regressive facies, which culminate in a sequence boundary at the base of the lower Båga Formation, corresponding to the mid-*daveoi* Zone. The placement of these key surfaces makes for a highly asymmetric cycle.

Cycle iv

Lower Båga Formation: mid-*davoei* Zone to uppermost *opalinum* Zone

The transition between the Hasle and Båga Formation is variable in character and may be locally conformable, marked simply by an upward predominance of non-marine sandstones, claystones and coal seams; may be disconformable; or as in the Boderne outlier, may be unconformable upon Silurian Shales (Gry 1969; Koppelhus & Batten 1992). The commonly erosive nature of this surface, and associated presence of a basinward shift in facies, suggests that the mid-*davoei* Zone might reflect a drop in relative sea-level and occurrence of a sequence boundary. Similarly, the transition in Yorkshire between the Ironstone Shale and Staithes Sandstone units (*davoei-margaritatus* Zones) is sharp and also interpreted as a sequence boundary, on a second-order level (Hesselbo & Jenkyns 1997).

The lower Båga Formation which represents Cycle iii comprises a sedimentary sequence laid down in a range of fluvial, lacustrine, estuarine and shoreface environments during Late Pliensbachian to Late Bathonian times (Koppelhus & Nielsen 1994). Before the lithostratigraphic revisions of Gravesen *et al.* (1982), the succession was originally known under the local names of the Levka and Sorthat Beds, which were applied to isolated exposures on minor fault-blocks: the Båga Beds relate to strata of Middle-Jurassic age (Malling 1920; Gry 1969). The great variability in facies types between these localized successions, difficulty in their correlation due to rapid lateral and vertical facies changes, and lack of biostratigraphic control, impeded the realization that the beds were actually closely related in both a stratigraphical and sedimentological sense. Work on the contained megaspores by Gry (1969) showed that the Levka and Sorthat Beds are approximately coeval, while the Båga Beds are slightly younger. This inference is supported by map evidence and similar lithologies (Gravesen *et al.* 1982).

The stratigraphic relationships of the beds are most clear on the western side of the island between Rønne and Hasle. In this area, the Båga Formation is separated into its constituent parts by two NW-SE trending faults which form a horst-like structure: to the north of the horst the Levka Beds occur, to the south the Sorthat Beds exist, and between the Båga Beds are found. Because these bed names further divide the Båga Formation into stratigraphic units displaying particular sedimentological or biostratigraphic characteristics, they are useful to refer to when making comparisons with the Yorkshire sequence. In simple terms, this apportionment of the Båga Formation relates not only to age and locality, but also to environment of deposition, as the contemporaneous Levka and Sorthat Beds indicate brackish-water deposition, and the Båga Beds suggest freshwater sedimentation. The subdivision of the Båga Formation therefore affords a higher resolution correlation with the

Cleveland Basin, and so in the following account, the Levka, Sorthat and Båga Beds are referred to where possible.

The Levka Beds comprise some 235 m of sediment which form the southeastern flank of a gentle anticlinal fold whose axis plunges to the southwest, and are bounded to the south and east by faults (Gry 1969). In the original description by Gry (1969), the 'Levka Beds' were assigned purely to an outcrop found to the south of Hasle in the region of Levka (Gry 1969, fig. 5). Poor exposure prevented a re-examination of this outcrop, however, so the section at Korsodde was recorded instead. As a result of the present study, and information gleaned from previous work (*e.g.* Koppelhus & Nielsen 1994), a relatively complete stratigraphic section of the beds has been established (Fig. 2.8*a-c*). Poor exposure over *c.* 8 m precluded the identification of the Hasle-Båga Formation boundary; the upper boundary of the Båga Formation is faulted against Upper Cretaceous sediments (Gry 1969). Above the unexposed basal section, an interval occurs which is characterized by channel sands (Fig. 2.9*b*); abandoned channel, lacustrine and lagoonal heterolithic sands and silts; and thin coals and rootlet horizons reflecting deposition in a swamp environment (Fig. 2.9*a*). It is likely that the heterolithic units were deposited by gradual infilling of coastal lakes and enclosed lagoons leading them to become vegetated and swampy, eventually forming palaeosols (Fig. 2.8*a, b*) (Koppelhus & Batten 1994). Commonly, the small-scale cycles are topped by lagoonal-brackish flooding events linked to base-level rises and relative sea-level fluctuations: these units correspond well in character and scale with the so-called fourth-order cycles found in Yorkshire, particularly in the Saltwick Formation at Hayburn Wyke.

In the context of the biostratigraphic scheme erected by Koppelhus & Nielsen (1994), the minor sea-level rises which caused the development of a distinct cyclicity culminated in shoreface deposition in the lower part of the Toarcian (Fig. 2.8*b*). The transition to marine-influenced deposition in this interval is well displayed by the Sorthat Beds in the Hasle Klinkerfabrik clay pit (Fig. 2.11). Here the beds attain a thickness of 41 m (broken by a section of non-exposure, 20-25 m thick), although regionally they are estimated to be 200 m thick (Gry 1969). The base of the Sorthat sequence comprises lagoons and tidal channels which have yielded dinocysts belonging to the *Mendicodinium reticulatum* Zone or *Luehndea spinosa* Zone (Koppelhus & Nielsen 1994). As we know the underlying Hasle Formation extends into the mid-part of the *daveoi* ammonite zone (Fig. 1.3, p.7), it is probable that this portion of the Båga Formation therefore represents the upper *daveoi* to *tenuicostatum* Zones. Above these sediments rest swamp and lake deposits cut by a ravinement surface, which is in turn succeeded by the shoreface sediments mentioned above: hummocky to swaley cross-stratified and wave-rippled sands prevail, including the

marine trace fossils *Diplocraterion*, *Teichichnus* and *Skolithos*. Overlying these shoreface sands are brackish-lagoon deposits.

In general, the character of this lower part of the Sorthat Beds indicates a gradual rise in relative sea-level during upper *daveoi* to *tenuicostatum*-Zone times (Late Pliensbachian to Early Toarcian). The Yorkshire section displays a gradual deepening over the same period until a maximum in the *falciferum* Zone was reached, when the Grey Shales and Mulgrave Shales were laid down (Hesselbo & Jenkyns 1997). Whilst the timing of the attainment of these transgressions differs slightly (the ?*tenuicostatum* Zone rather than *falciferum* Zone: Fig. 3.2, p.92), it is possible that both correspond to the same event. The relatively uplifted nature of the Rønne-Hasle Block during this period may explain why shoreface sediments were deposited on Bornholm, whilst deeper marine sediments accumulated in the Cleveland Basin. Resting upon these shoreface deposits are erosive-based fluvial channels of Aalenian age which removed the regressive portion of this cycle.

Cycle v

Upper Båga Formation: Basal *scissum* Zone to uppermost *morrisi* Zone

A major change in facies and a pebble-strewn, erosive surface marks the basal boundary of Cycle v and the advent of the upper part of the Båga Formation (Båga Beds). The lower portion of the formation at the Korsodde locality is composed of coarse-grained, cross-bedded sandstones containing pebbly layers; cobbles occur on scoured surfaces interpreted as channel bases (Fig. 2.8). Based upon the unconformable character of this junction, across which there is a conspicuous change in lithology and pronounced basinward shift in facies, a relative sea-level fall and sequence boundary is interpreted. The stratigraphic position of this surface points to the intra-Aalenian (e.g. Koppelhus & Nielsen 1994) which, despite being slightly younger in age (*opalinum/murchisonae* Zone as opposed to the *aalensis* Subzone, *levesquei* Zone), may correspond to the second-order sequence boundary found at the base of the Dogger Formation in Yorkshire (Cycle 1, described on p.54). Shoaling in the Late Toarcian and erosion at the Toarcian-Aalenian boundary have been recognized across Western Europe, contributing to the apparent pervasiveness of this sequence boundary.

Given the widespread occurrence of this sequence boundary, it seems unlikely that its genesis is linked solely to domal upwarping in the central North Sea area (e.g. Underhill & Partington 1993). Regressive facies in the Late Toarcian are widespread in basins across Western Europe, suggesting that there may have been alternative, more regional, control on sea level. Coarse siliciclastics were introduced into Yorkshire and Dorset, there was an

increase in siliciclastic mud supply in South Germany, and submarine fan systems prograded across the Lusitanian Basin in western Portugal (Parkinson 1994; Parkinson & Hines 1995). In the North Viking Graben the Lower Jurassic is commonly erosively overlain by proximal sediments of the Middle Jurassic Brent Group (Underhill & Partington 1993). Similarly, Scania reveals lowermost Aalenian sediments (Rya Formation) which are unconformably overlain by younger Aalenian to ?Bathonian non-marine deposits (Vihelmsfalt Formation) (Guy 1971; Norling 1972; Sivhed 1984). Others have related this unconformity and the underlying Lower Jurassic second-order cyclic motif to periods of rifting during the break-up of Pangaea (*e.g.* Wyatt 1986; Parkinson 1994). Superimposed is the influence of relatively local tectonics.

The overall difference in character between the upper non-marine Båga Beds and the lower brackish Levka-Sorthat Bed sequence is neatly shown by the presence of debris flows containing large cobbles and kaolinized granite boulders: whereas such flows are absent from the lower unit, they are commonplace in the upper part. The occurrence of these cobble beds has led previous workers to suggest that the crystalline granite basement was exposed along a fault scarp during deposition of the 190 m thick upper Båga Formation (Båga Beds), allowing kaolinized boulders to be eroded from, and incorporated into, deposits in adjacent basins (Gry 1969; Gravesen *et al.* 1982). The debris flows are found mainly in the upper portion of the Båga Bed sequence which, based on miospore evidence, is understood to fall within the top of the *Callialasporites-Perinopollenites* Zone, approximating to the Bathonian Stage (Koppelhus & Batten 1994). Unfortunately a more precise biostratigraphy is hampered by the long and overlapping ranges of the miospore species and, as a consequence, it is difficult to ascertain whether the non-marine Båga Beds represent continuous deposition over this interval, or encompass only parts of these stages. Nevertheless, from the character of the debris-flow sequence inferences can be made as to the general conditions of deposition. In order to expose the Pre-Cambrian crystalline basement there must have been a fall in relative sea-level, related to increased uplift or drop in eustatic sea-level, to allow removal of the Palaeozoic and early Mesozoic sedimentary cover.

A fall in relative sea-level of this magnitude during the Bathonian may not, however, be surprising given the presence of a significant second-order sequence boundary at this stratigraphic level in Yorkshire, the correlative conformity of which can be found in Dorset. Reasons for the comparatively ill-defined nature of the sea-level fall within the Båga Formation (compared to the distinct unconformity seen in Yorkshire), may include the complex interplay of tectonic controls in this area of southern Scandinavia: that is, perhaps rifting, North Sea domal activity, and block-faulting related to the Tornquist Line (*e.g.* Gravesen *et al.* 1982). As a result, whilst some areas of Bornholm did experience the uplift

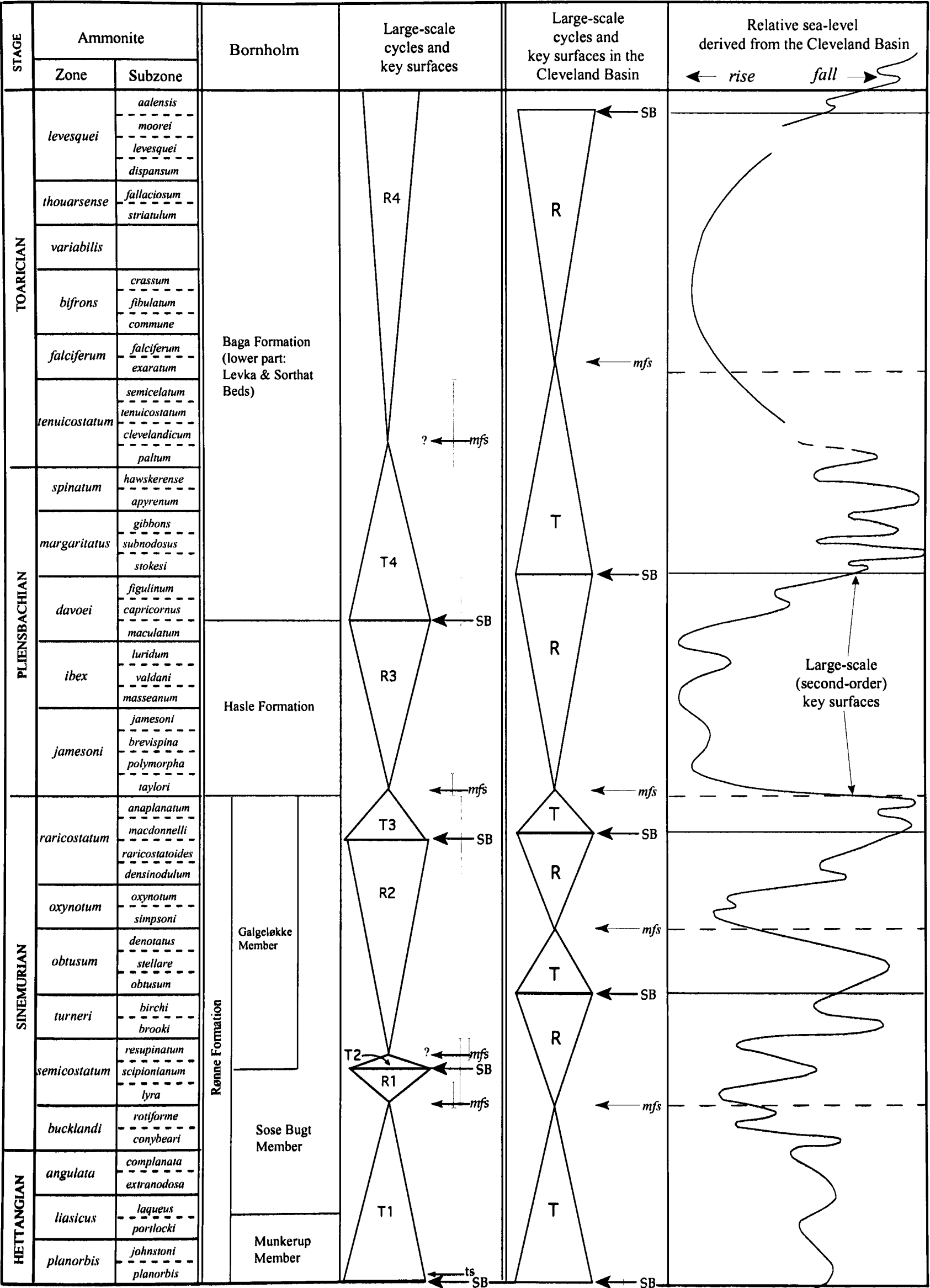


Fig. 3.2 Large-scale lithological cycles recognized in the Lower Jurassic (Hettangian-Toarcian) sequence of Bornholm. Large-scale cycles identified in Yorkshire have also been shown, together with a relative sea level curve applicable to the Cleveland Basin (after Hesselbo & Jenkyns 1997). The relative sea level curve is with respect to the basement and assumes constant sediment supply (after Posamentier *et al.* 1988). An estimate of the dating errors on the key surfaces is given (red for sequence boundaries; dark blue for maximum-flooding surfaces).

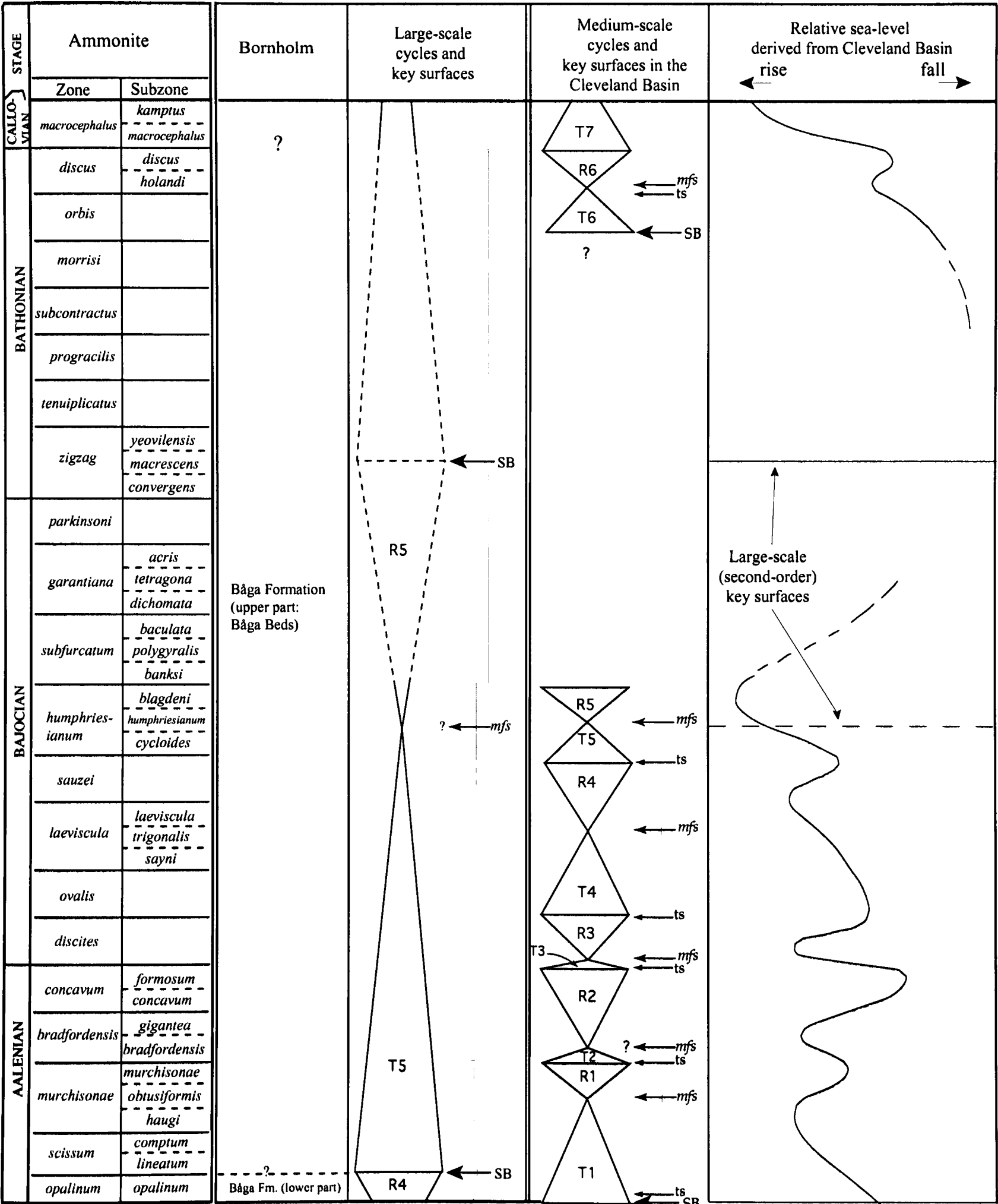


Fig. 3.3 Large-scale lithologic cycles recognized in the Middle Jurassic (Aalenian-Bathonian) sequence of Bornholm. The stratigraphic position of medium-scale lithologic cycles identified in the Cleveland Basin are also shown for comparison; the relative sea-level curve is that based upon the Yorkshire section (see Fig. 2.7). Note: position of the sequence boundary in the Bathonian on Bornholm is based purely on correlation with the Cleveland Basin. Whilst a Bathonian age is inferred from miospore evidence (Koppelhus & Nielsen 1994), a more precise biostratigraphy is not known. The relative sea level curve is with respect to the basement and assumes constant sediment supply (after Posamentier *et al.* 1988). An estimate of the dating errors on the key surfaces is given (red for sequence boundaries; dark blue for maximum-flooding surfaces).

and erosion seen in Yorkshire, other regions remained relatively subsident. In relation to the sedimentary sequence in question, the granite-bearing debris flows incorporated within the Båga Formation reflect uplift and erosion of the crystalline basement, and deposition in adjacent, down-faulted basins. If the correlation with the Yorkshire sequence is correct, then a second-order relative sea-level fall can be inferred to fall within the upper portion of Bornholm's Båga Formation.

Despite the success in identifying two sequence boundaries in the Båga Formation (which provide direct links with the Cleveland Basin), there is no clear evidence to indicate the presence of an intermediary second-order maximum-flooding surface to correspond to the *humphriesianum* Zone (Scarborough Formation) example located in Yorkshire. Several possibilities exist to explain the apparent absence of the surface, including (1) the removal of this portion of the stratigraphy through erosion; (2) the concealment of the flooding horizon by poor biostratigraphic control; and (3) the disguise of the flooding event in the non-marine environment which the Båga Beds represent. The probability that the maximum-flooding surface is absent because of the non-marine environment in which the succession was deposited is, however, diminished in light of evidence for several lacustrine flooding events in the Båga Beds. The intermittent establishment of lake conditions (every c.5-10 m: Fig. 2.8a-c) most likely relates to repeated rises in local base-level, probably corresponding to sea-level fluctuations on a fourth-order level. The common presence of pyrite in many of the coal seams lends support to the possibility that these lacustrine flooding surfaces reflect repeated increases in marine influence (Danielsen 1986; Petersen 1993). Therefore, it seems likely that the absence of the maximum-flooding surface is not by virtue of depositional environment, but instead as a consequence of erosion or low-resolution biostratigraphy. Thus, based on comparison with the Yorkshire sequence, in Fig. 3.3 a maximum-flooding surface is provisionally positioned within the *humphriesianum* Zone.

In summary, comparison of the Scandinavian sections with the Cleveland Basin succession has shown that a correlation can be made on the basis of second-order lithological cycles. In all, five second-order cycles have been identified in the Lower and Middle Jurassic sequence onto which smaller-scale cycles are superimposed. The most significant (second-order) transgressions occurred in the earliest Hettangian, mid-Sinemurian, earliest Pliensbachian, mid-Pliensbachian, and early Aalenian, whereas the most important regressions occurred at the basal Hettangian, the early Sinemurian, the mid-Pliensbachian, the late Toarcian, and the late Bathonian (Figs. 3.2-3.3). The medium-scale cycles so clearly visible in the Yorkshire Middle Jurassic section are more difficult to identify in the coeval section on Bornholm and in Scania, although their presence may well be concealed by the only long-ranging biostratigraphy available. Likewise, although fourth-order cycles

are well developed in the sequence, low-resolution biostratigraphy precludes their regional, and even local, correlation. Nevertheless, on a large-scale (second-order) level it is possible to correlate the Lower and Middle Jurassic sequence of Yorkshire with that of Bornholm. The ability to do this suggests that the controls on relative sea-level were at least regional. Figs. 3.2-3.3 show the key surfaces identified within the Lower and Middle Jurassic strata of the two areas, and compares the position and range of the inferred sea-level fluctuations with those disclosed for the Cleveland Basin.

3.4 Discussion and Conclusions

An investigation into the Lower and Middle Jurassic sequence on Bornholm has revealed a series of transgressions and regressions. A series of erosion surfaces, some more significant than others, characterize the succession, each followed by prolonged periods of sedimentation. The predominance of non-marine deposits through the Lower and Middle Jurassic interval suggests that Bornholm was relatively proximal to sediment source compared to the Cleveland Basin. The amount of accommodation space in the Bornholm area was therefore low and the frequency of marine incursions less than those affecting the Cleveland Basin. As a consequence of the lack of sufficiently different lithologies, cycles on a level higher than the second-order are difficult to identify. Sections of limited stratigraphic extent do show what are estimated to be fourth-order cycles (*e.g.* the 1-2 m scale cycles in the Munkerup Member), but poor biostratigraphic control hampers their correlation both intra- and interbasinally.

Five second-order cycles have been recognized in the Hettangian-Bathonian sequence of Bornholm. The stratigraphic position of these sea-level changes coincide well with those of the same magnitude in Yorkshire, suggesting that the stratigraphic framework constructed for the Lower (that of Hesselbo & Jenkyns 1997) and Middle Jurassic succession in the Cleveland Basin is viable in a regional context. Furthermore, the regional pervasiveness of these second-order cycles (across north-western Europe) suggests an element of common control. Strong arguments have been presented previously in favour of a regional stratigraphic forcing of sea level around the stage-frequency, that is second-order level. Compelling evidence has already been put forward in support of synchronous development of second-order cycles in the Cleveland and Wessex Basins (Hesselbo & Jenkyns 1997). Compilation of information drawn from a selection of Lower Jurassic basins in Western Europe also shows that correlation is possible on a second-order level (Parkinson 1994). Such cycles are understood to reflect rifting episodes in the break-up of Pangaea (Wyatt 1986). The affect of local tectonics upon these periods of rifting controlled the magnitude

of each regression and transgression: this would explain lateral changes in the expression of, for example, the intra-Bathonian regression.

The argument for a regional forcing mechanism becomes less compelling for the formation of higher frequency cycles. It was stated in the previous chapter (p.77) that comparable medium-scale (third-order) cycles are found in both the Cleveland and Wessex Basins, precluding the possibility that they might reflect a local tectonic control. Although third-order cycles were not recognized in the Bornholm sequence by this study, this is not to say that do not exist: poor biostratigraphic control, the predominantly non-marine lithology, and the discontinuous nature of many exposures are all factors which may shroud their presence. Causal mechanisms leading to the formation of third-order cycles, together with cycles on a higher level, could be either regional or global, and can be summarized by the following possibilities. The first possibility relates to eustatic changes in sea level caused by changes in ice volume. Currently, there is little documented evidence for permanent low latitude ice during the Jurassic (Hallam 1985), although Frakes & Francis (1988) have advanced an alternative view based on putative dropstone evidence; their findings providing evidence for late Mesozoic ice. Alternatively, glacio-eustatic sea-level changes may have also been caused by changes in the amount of mountain ice. However, in the Yorkshire area (which is inferred to fall within a warm-temperate biome: Ziegler *et al.* 1993), the actual affect of global ice volumes on sedimentary cycle formation is difficult to assess. Lastly, cycles on a very high frequency level in the British Jurassic have in the past been linked to climate changes related to Milankovitch cyclicity (*e.g.* Weedon 1987). On the scale of lithological cycles that we are dealing with in this study, however, it is unlikely that such a factor controlled their development. Without further work, it is difficult to clarify which one(s) of these generating mechanisms may have has an affect on the development of the third-order lithological cycles found by this study. An investigation of coeval strata in diverse geological settings may reveal the answer.

The principal result of the comparisons made in this chapter is that the stratigraphic development of the Yorkshire and Scandinavian basins were not independent of one another, but rather evolved concurrently. Yet, based on the present data, this statement is only true for development on a second-order level. Although the stratigraphic position of the second-order key surfaces in the Bornholm and Yorkshire successions are not perfectly synchronous, they are nevertheless in good accordance. To conclude, rifting relating to the fragmentation of Pangaea is inferred as the primary control on the formation of the second-order cycles, and local tectonics implied as the likely predominant controlling factor in the formation of higher-order cycles.

Chapter 4

Chapter 4

Palaeoclimatic and environmental interpretations based on the study of Lower and Middle Jurassic fossil wood from Yorkshire

4.1 Introduction

Growth rings in fossil woods provide valuable information for the interpretation of past climates, particularly when combined with sedimentological and other floral data. From the study of growth rings in modern trees, Fritts (1976) elucidated the environmental controls on tree growth, which provided a template with which to compare fossil growth rings. Growth-ring characteristics which are argued to be a function of climate, include their presence or absence, ring width, interannual variability of ring width, the presence of false rings, and ratio of earlywood to latewood (*e.g.* Fritts *et al.* 1965; Fritts 1976; Creber & Chaloner 1984*a*, 1985, 1987; Creber 1977; Francis 1983*a*, 1983*b*, 1984, 1986; Parrish & Spicer 1988; Chaloner & Creber 1990; Spicer & Parrish 1990; Ash & Creber 1992; Gregory 1992). Comparison of ancient examples to the growth response of modern trees with contemporaneous meteorological records was first employed in 1847. On the basis of a lack of rings in a sample of Palaeozoic wood, Unger (*in* Antevs 1925) inferred the tree had grown in an equable and seasonless climate. This same approach is commonly used today (*e.g.* Creber & Chaloner 1984*a*, 1984*b*, 1985, 1987; Jefferson 1982; Francis 1984, 1986; Ash & Creber 1992; Chapman & Smellie 1992; Gregory 1992; Kumagai *et al.* 1995) and forms the basis for this study.

Apart from noting the presence of growth rings, previous studies of wood from Yorkshire has been confined to their examination for the purposes of taxonomic classification (*e.g.* Holden 1913; Seward 1904, 1919). Fossil wood was first recognized in the Yorkshire Jurassic succession by Young & Bird in 1822, who noted the widespread presence of variously shaped and sized pieces of “petrified” stems, branches, twigs and roots. For the early part of the nineteenth century, the collections they made were surprisingly well-constrained stratigraphically: derived from the so-called “aluminous beds” located near the top of the Lower Jurassic, and sandstones, ironstones and doggers from the Middle Jurassic sequence.

Tate and Blake (1876) described the presence of fossil wood at various horizons in the Lower Jurassic, and Fox-Strangways (1892) went as far as to specify the *margaritatus* ammonite Zone in the Upper Pliensbachian as particularly wood-rich. Similarly, Kendall & Wroot (1924, p.402) highlighted the remains of a forest of trees of '*Dadoxylon*' type seated on a Dogger conglomerate at Whitby, which displays "roots which can be traced ramifying into shales of the Upper Lias."

Preservation of cellular structure and anatomical detail are sufficient in these fossil wood samples to enable measurement of the growth rings, as well as taxonomic identification. In the present study, numerous samples of fossil wood were collected from portions of allochthonous trunks, branches and twigs from the Cleveland Ironstone to Scalby Formation at localities shown in Fig. 4.1. A suite of previously unidentified specimens from the study area kindly loaned by the Yorkshire Museum, York, is also included in the study (samples are denoted by a 1994 or 1996 prefix). Sampling was undertaken in the context of the stratigraphic framework described in Chapter 2, resulting in an accurate, high-resolution record of permineralized and charcoaled wood in the Cleveland Basin. The study aims to identify the distributions of variously preserved fragments of wood within this framework, and moreover investigate the controls on the temporal changes found in the character of the growth rings for the purpose of determining palaeoclimatic change. The specimens collected for this study and marked with a 'J' prefix are lodged in the Oxford University Museum of Natural History; those preceded by the letters HSM are in the authors personal collection.

Currently, conditions during deposition of the Ravenscar Group are envisaged to have been warm and wet (*e.g.* Alexander 1992*b*; Rawson & Wright 1992). This study refines this otherwise empirical concept of palaeoclimatic conditions during the Late Pliensbachian to Late Bathonian in Yorkshire, using the record of short-term climatic changes manifest as growth rings in fossil wood. A glossary of terms used in wood anatomy and in this study is included at the back of this chapter (p.156-157).

4.2 Stratigraphic distribution and abundance

In the Cleveland Basin allochthonous fossil wood is found in beds of non-marine and marine origin lying parallel to bedding. It is ubiquitous as coalified remains, and occurs within discrete parts of the sequence as calcified, pyritized and charcoaled fragments. As fossilized wood is much more resistant to decay than leaves or fructifications, the information it contains has the potential to provide a more complete record of climate and environmental changes through time. Although it was not possible to conduct a quantitative measure of wood through the sequence in the time available, it was possible to monitor the relative

Palaeoclimatic inferences based on fossil wood

CALLO-STAGE VIAN	Ammonite		Yorkshire		Distribution of fossil wood collected for this study		
	Zone	Subzone					
BATHONIAN	macrocephalus	kamptus ----- macrocephalus	Cornbrash		⊙ Yons Nab (7) ⊙ Scalby Ness (1) ⊙ Hundale Point (2) ⊙ White Nab (4) ⊙ Scarborough South Cliff (4)		
	discus	discus ----- holandi	Scalby Formation	Long Nab Member			
	orbis			Moor Grit Member			
	morrissi						
	subcontractus						
	progracilis						
	tenuiplicatus						
	zigzag	yeovilensis ----- macrescens ----- convergens					
	parkinsoni	bomfordi ----- truelli					
	BAJOCIAN	garantiana				acris ----- tetragona ----- dichomata	
subfurcatum		baculata ----- polygyralis ----- banksi					
humphries- ianum		blagdeni ----- humphriesianum ----- cycloides	Scarborough Formation	further subdivided			
sauzei			Cloughton Formation	Gristhorpe Member	Lebberston Member		
laeviscula		laeviscula ----- trigonalis ----- sayni					
ovalis				Sycarham Mb			
discites				Eller Beck Fm.			
AALENIAN		concauum	formosum ----- concauum	Saltwick Formation		⊙ Hayburn Wyke (8) ⊙ High Hawsker (1) ⊙ Blea Wyke (8)	
		bradfordensis	gigantea ----- bradfordensis				
		murchisonae	murchisonae ----- obtusiformis ----- haugi	Dogger Formation			
	scissum	comptum ----- lineatum					
	opalinum	opalinum					
	PLIENS.	spinatum	hawskerense ----- apyrenum	Cleveland Ironstone	Kettleness		⊙ Staithes (3) ⊙ Hawsker Bottoms (6)
margaritatus		gibbons ----- subnodosus	Penny Nab				

Fig. 4.1 Stratigraphic distribution of fossil wood collected from the Ravenscar Group for the purposes of this study. For specific details of localities and bed numbers, see Table 4.3 and sedimentary logs in Appendix 1. The numbers in brackets correspond to the number of pieces of wood collected from each locality.

proportion. Before outlining the specific stratigraphic distribution of wood in Yorkshire, a brief description of the localities from which wood was observed and collected is presented here.

The Penny Nab Member forms the lower portion of the Cleveland Ironstone Formation and is exposed on the Yorkshire coast at Staithes (NZ 791 188), and between Hawsker Bottoms (NZ 942 083) and Castle Chamber (NZ 961 067). The unit comprises small-scale coarsening-upward cycles which are capped by berthierine-rich oolitic ironstones (Howard 1985; Young *et al.* 1990): from within these ironstones, moderately well-preserved calcified and pyritized samples were collected for study. Above, pyritized wood occurs scattered throughout the Grey Shale Member at Castle Chamber. Poor preservation of these samples prohibited their taxonomic identification, and as a consequence the wood collected from the Cleveland Ironstone Formation must form the basis of the Lower Jurassic data set. Although this material is supplemented by a set of Lower Jurassic wood specimens from the Yorkshire Museum, it is unfortunate that the provenance of these previously unidentified samples is no more precise than “Lias and M. Lias from near Whitby.” Despite this ambiguity, this study has established the implication of a Late Pliensbachian to Early Toarcian age, based on close anatomic similarities with samples examined as part of this study and taxa described in the literature. (Further details are given below in Section 4.5, p.132-136.)

The Lower Aalenian marine Dogger Formation at Blea Wyke (NZ 991 015) provided eight well-preserved calcified wood samples. The formation at this locality is composed of a sandy, sideritic, berthierine-oolite rich in fossils. At the base of the unit, fossil wood occurs within a winnowed accumulation of pebbles, siderite nodules, robust shelly fragments and derived ammonites. In the lowermost beds of the overlying non-marine Saltwick Formation, wood occurs predominantly within large channel sandstones. Collections were made from Whitby Long Bight (NZ 906 115) and High Hawsker (NZ 948 082), although much of the fossil wood was found to be poorly preserved (Fig. 1.34-1.35). Scarce fragments of charcoal also occur, disseminated through overbank deposits at Whitby Long Bight. Only a small amount of this charcoal is suitable for microscopic examination, however, as many of the specimens are wholly homogenized. Charcoal increases in abundance in the overlying, regressive part of the Saltwick Formation (Fig. 1.31), where it is restricted to channel sandstones and, towards the top of the formation, overbank deposits where it is particularly abundant. Of the numerous samples collected for this study, only nine were suitable for microscopic examination.

Wood is extremely rare in the marine Eller Beck Formation. It does, however, become more common in the overlying Sycarham Member that forms the regressive part of this cycle. On the whole, the wood obtained from the sequence is poorly preserved as charcoal or, most

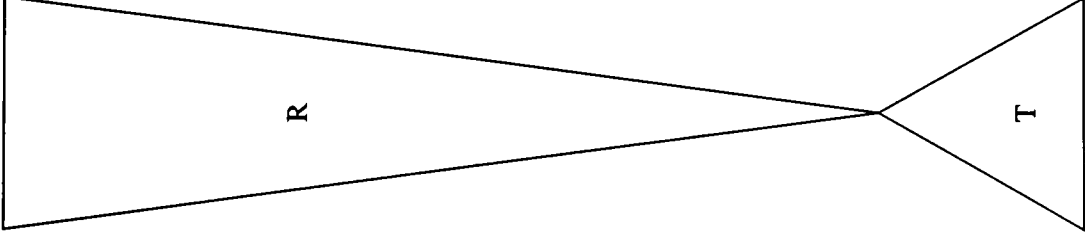
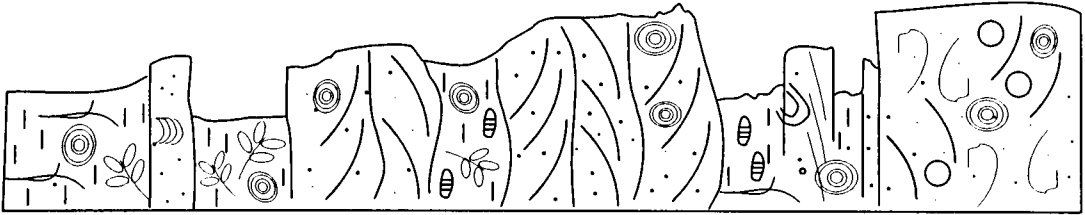
commonly, coal. In an environment which yields only small, badly preserved pieces of wood, it is interesting to note that during field work a tree stump was found *in situ*, in the basal portion of the member at Iron Scar (NZ 015 968); it was, unfortunately, too coalified to afford detailed examination (Pl. 4.1*a*). Above this interval, wood is not met with abundance until the Gristhorpe Member, where pyritized, coalified and charcoaled specimens occur. From wood-rich layers within the Gristhorpe Plant Bed, Cayton Bay (TA 081 844) (bed 24, Fig. 1.3), nineteen samples were recovered. Here, a great deal of coalified and pyritized wood exists parallel to bedding, often as large compressed trunks. Much of this wood is unusable for the purposes of growth-ring analysis because of its poor preservation state. However, pyritized cores at the centre of large coalified trunks do display some cellular structure. Smaller specimens composed entirely of pyrite were also collected and analysed. The dense concentration of logs, branches and twigs at two discrete horizons within the bed, most probably reflect crevasse-splaying from a nearby channel margin. Above this level, there are further accumulations of poorly preserved, homogenized, charcoaled wood in crevasse-splay sandstones (Pl. 4.1*b*).

At a locality between Cloughton Wyke and Hundale Point (TA 026 948), three small calcified wood fragments were collected from within the top part of the Helwath Beck Member, the lowermost unit of the marine Scarborough Formation (top of bed 63, Fig. 1.15). The sediment and trace-fossil assemblages here indicate a brackish, siliciclastic embayment into which small fragments of wood were washed: the presence of *Botryococcus* sp. and abundant gymnospermous pollen indicates a freshwater influence during deposition (Gowland & Riding 1991).

In contrast, abundant fossil wood in the overlying Scalby Formation is preserved as coalified or charcoaled fragments. Eleven charcoaled samples were collected from the basal portion of the Moor Grit Member, from localities ranging from Hundale Point in the north (TA 026 948) to White Nab in the south (TA 059 865). Eight further samples were collected from the Long Nab Member at Scalby Ness (TA 037 911) and Yons Nab (TA 081 844). Large coalified trunks and smaller, more fragmentary charcoaled branches and twigs are commonly entrained in the basal parts of the Moor Grit channel sandstones and in the meander-belt sandstone, crevasse-splay sandstones and overbank deposits composing the overlying Long Nab Member.

If we consider these wood-bearing localities in a stratigraphic sense, it is clear that the preservation state of the wood is broadly related to either facies type (for the pyritized and calcified samples) or stratigraphic interval (charcoaled fragments). In the following section the constraints on the preservation of woody remains are discussed in more detail, which

Fig. 4.2 Summary of depositional environments in which fossil wood occurs in the Cleveland Basin. A schematic log displays the main facies which incorporate wood fragments, against which the different preservation states are charted.

Sea-level cycle	Schematic log	Lithology	Facies	Woody remains	Preservation state
		Poorly bedded rooted mudstone, thin coaly beds and fragmentary plant debris.	Overbank	Small pieces of charcoal showing well preserved cellular structure. Large coalified logs, branches and twigs.	pyritized wood charcoalified & coalified wood calcified wood
	Sheet sandstone; marine trace fossils.	Crevasse-splay		Coalified and fragmentary wood.	
	Poorly consolidated claystone containing exceptionally preserved plant material.	Freshwater pond (sulphur derived from overlying unit)		Compressed logs; pyritized cores with coalified exteriors.	
	Fine to medium-grained cross-bedded sandstone.	Fluvial channel		Coalified and charcoalified wood fragments.	
	Mudstone containing iron nodules, plant remains.	Overbank		Coalified and charcoalified wood. Mostly small in size.	
	Fine to medium-grained cross-bedded sandstone.	Fluvial channel		Coalified wood of various shapes and sizes. Some charcoalified fragments.	
	Rooted mudstone.	Overbank		Coal and small pieces of charcoal.	
	Sheet sandstone.	Crevasse-splay		Coalified wood.	
	Homogeneous mudstone.	Overbank		Coalified wood.	
	Medium-grained, calcareous, cross-bedded sandstone containing ooids and shelly debris.	Tidal sand-belt		Fragments of branches and twigs: calcified, showing good preservation of cellular detail.	

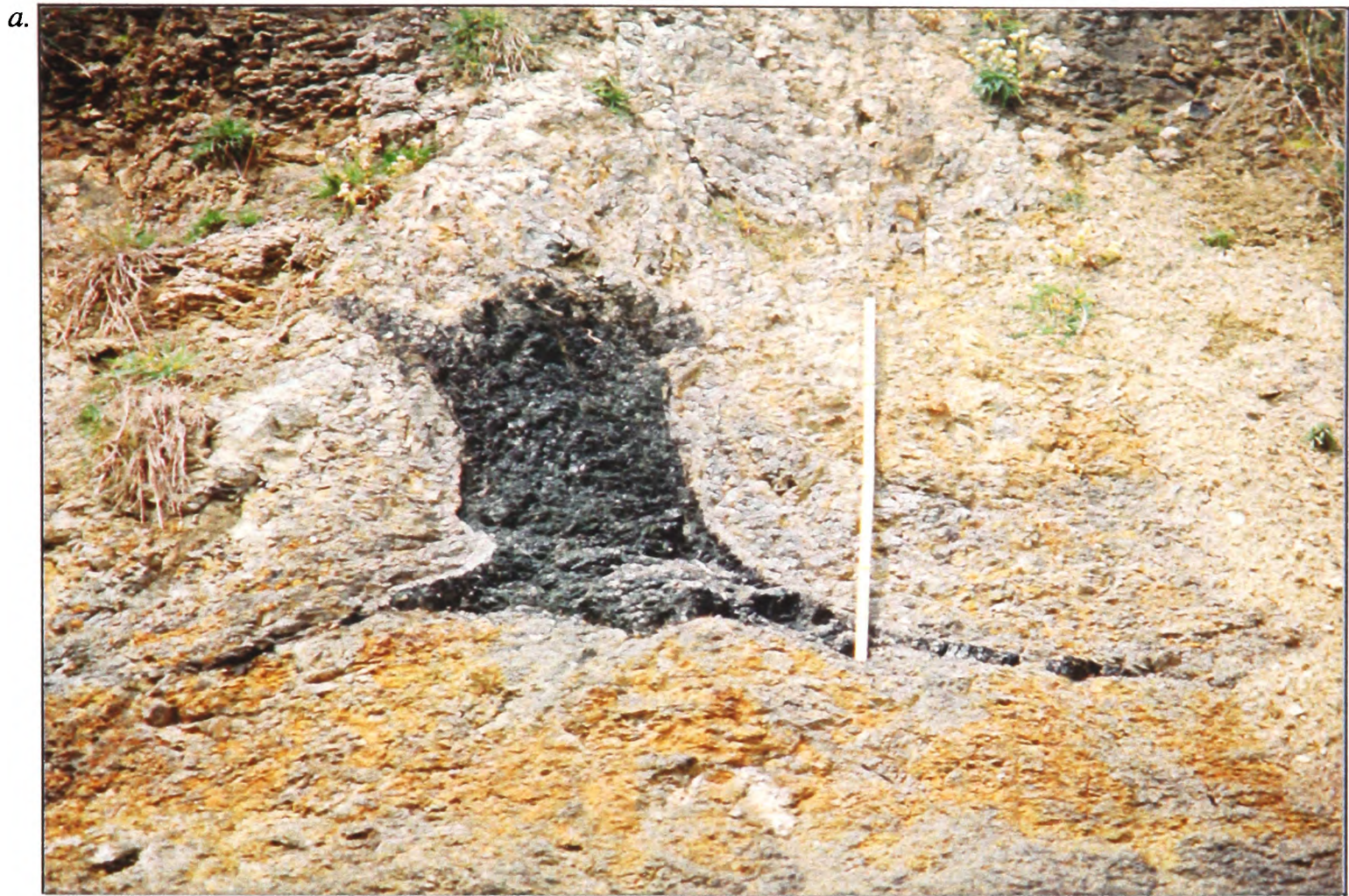


Plate 4.1 Fossil wood in the Ravenscar Group: examples of *in situ* and transported finds.

a. Basal portion of an *in situ*, coalified tree stump, showing roots splaying out horizontally. The tree is positioned within the lower Sycarham Member, Iron Scar (bed 18, log a, Fig. 1.24).

b. Fragmentary, charcoaled wood within a crevasse-splay sandstone in the mid-Gristhorpe Member, Yons Nab (the head of the hammer is resting upon the basal boundary of bed 29, Fig. 1.4).

adds considerably to the outline of the stratigraphic distribution provided here. Nevertheless it is pertinent at this point to summarize. Fig. 4.2 encapsulates the relationship of preservation state of the wood fragments to facies type and the stratigraphic interval.

Pyritized samples have the most restricted distribution, in beds of marine origin such as the Cleveland Ironstone and Dogger Formations where calcification is also common, and in beds deposited in the non-marine environment but under an ephemeral marine influence; the Gristhorpe Plant Bed, Cayton Bay exemplifies this case. Calcified wood is found in the Cleveland Ironstone, Dogger and Scarborough Formations alone, which represent transgressive portions of lithological cycles. An abundance of wood in transgressive deposits has been noted before (Plint & Pickerill 1985; Savrda 1991; Savrda *et al.* 1993) and explained by hydraulic concentration during a sea-level rise (Swift 1968; Nummedal & Swift 1987). Charcoalified wood occurs as small, brittle, well-preserved fragments of branches and twigs in the mid to late Saltwick Formation, mid to upper Sycharham Member, upper Gristhorpe Member, lower Moor Grit Member and within the overlying Long Nab Member. All of the above are regressive parts of the Ravenscar Group, with the exception of the Moor Grit which reflects a late transgressive phase of deposition. Possibilities as to why charcoal is found predominantly in regressive portions of the sequence are discussed in more detail below.

4.3 Preservation state

As indicated in the previous section, the nature of the woods' preservation directly impacts its analytical potential. The following text discusses the manner in which the wood is preserved and the implications this has on the environment of deposition. Despite the variability in preservation, the wood can be summarized by four main categories: (1) compressed logs, branches and twigs, composed of coal and lacking in cellular structure; (2) small specimens composed of pyrite showing evidence of shearing, cellular distortion and the effects of decay; (3) larger, robust specimens with well-preserved, clearly defined cell walls in a carbonate and subordinate silicate matrix; and (4) small fragments of charcoal which usually exhibit the best preserved cellular detail. In total 76 pieces of wood were examined, ranging in size from 0.8 to 9.5 cm in diameter and 1 to 22 cm in length. Table 4.3 (at the back of this chapter, p.158) lists the provenance, size, composition and preservation state of the wood samples identified.

4.3.1 Coalification

Isolated, coalified wood fragments are widespread in the non-marine beds composing the Ravenscar Group. Allochthonous coalified twigs, branches and logs lying parallel to bedding

are most common in channel sandstones, crevasse-splay sandstones and argillaceous overbank deposits. Only rare examples of *in situ* trunks were found during field work (*e.g.* Saltwick Formation, Hayburn Wyke (TA 981 971) and Sycarham Member, Iron Scar (NZ 015 968)). Coalified wood lacks cellular structure and is usually compressed, making it wholly unsuitable for microscopic examination.

4.3.2 Pyritization

Pyritization of wood most commonly occurs as the result of sulphate-reducing bacteria in fine-grained marine sediments where there is an adequate supply of sulphate (see reviews by Berner 1970, 1984; Goldhaber & Kaplan 1974; Allison 1990). While this scenario can be suggested for specimens from the marine Cleveland Ironstone Formation, for pyritized wood derived from an interval of the non-marine Gristhorpe Member a rather more careful examination of the containing sediments has been undertaken. Before going on to describe this particular locality, a brief résumé is presented outlining the process of pyritization in the context of the wood remains.

The process of pyritization is thought to occur in two stages (Kenrick & Edwards 1988): firstly aerobic decay between the time of death and permineralization, and secondly anaerobic decay during permineralization. The first stage involves bacterial decay which results in decomposition and release of carbon dioxide (Allison 1990). This process is then impeded by the progressive build-up of sediment, which acts as a barrier for oxygen replenishment and inhibits further aerobic decay. Cellulose and cell contents quickly decompose during this incipient stage of pyritization and form the substrate for the anaerobic sulphate-reducing bacteria rudiment in pyrite formation. As a result, the more slowly decaying lignin remains relatively intact. The bacteria then extract sulphate from overlying sediments and reduce it to sulphide (Canfield & Raiswell 1991). This in turn reacts with iron-bearing minerals formed by reduction during bacterial respiration from iron hydroxide in pore waters (Allison 1988). Iron monosulphide forms as a result, which reacts with sulphur obtained from inorganic reduction of hydrogen sulphide or else as a result of the activity of the sulphate-reducing bacteria (Berner 1970, 1984). This, at last, forms pyrite.

Studies of pyritized wood from the Eocene London Clay, Kent revealed that thin-walled earlywood cells of a growth ring have a lower lignin content than latewood cells, and are therefore more susceptible to decay (Allison 1988). The earlywood of the Yorkshire pyritized wood samples also display this bias, and are therefore usually degraded and replaced by pyrite (Pl. 4.2, figs. 3, 6). Latewood cells tend to be better preserved and retain their cell outlines (Pl. 4.2, fig. 4). Examination reveals that initial pyrite crystal growth began at the cell walls (where organic matter still exists) and continued into the lumen, similar to the manner

described by Canfield & Raiswell (1991). In turn, the lumen were then infilled with more massive pyrite crystals (Pl. 4.2, fig. 8): there are very few instances where lumen infilling has been only partial. Overall, the successive stages of pyritization displayed by the Yorkshire specimens is comparable to that of the London Clay wood samples, described by Poole (1993).

In a normal marine environment the key source of sulphur is sea-water sulphate, and iron minerals are present in abundance. Under these conditions, pyrite formation is chiefly limited by the supply of organic carbon (Berner & Raiswell 1983). During deposition of the shallow marine Cleveland Ironstone and Dogger Formations, wood provided the organic-carbon substrate used in the pyritization process. In freshwater environments, however, pyrite formation is instead curbed by the comparatively low sulphate concentration (Allison 1990). The presence of pyrite in the Gristhorpe Member at Cayton Bay (beds 23-26, Fig. 1.3), indicates that an abundant source of sulphate ions was available to initiate the pyritization process. Above the level of pyritization in the Gristhorpe Member there is evidence for several marine incursions: perhaps most significant is that which deposited a bed of sand which was penetrated by *Diplocraterion* burrows (bed 27, Fig. 1.3), immediately after the Gristhorpe Plant Bed interval had been laid down in a ponded environment on the flood-plain. The cycling of these marine waters through the underlying plant bed could have provided the necessary sulphate ions which, together with an abundant supply of organic carbon in the

EXPLANATION OF PLATE 4.2

Figs. 1-10 Range of preservation states.

Fig. 1, sample J.67951 (x 180); calcified wood showing irregular false ring and more continuous growth ring.

Fig. 2, sample J.67951(x 190); the common occurrence of pyrite infilling the lumen, indicates that this sample underwent a greater degree of secondary pyritization. Calcification occurred early on and replaced the cell walls. A hairline fracture running parallel to the ring boundaries is featured at the top of the photo.

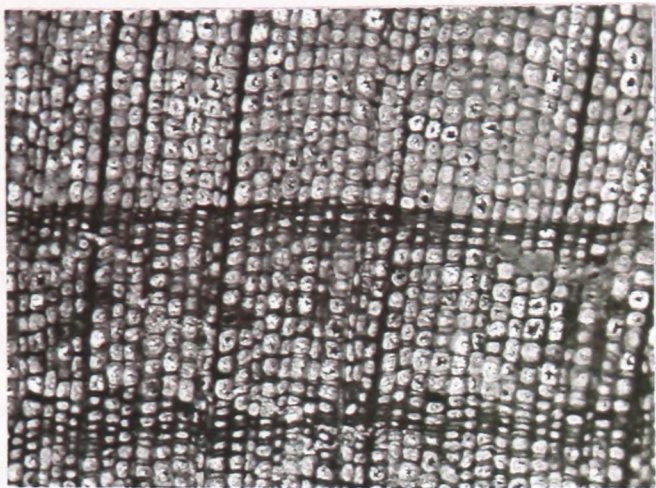
Fig. 3, sample 1996-166 (x 200); transverse plane displaying a growth-ring boundary, preserved by the process of calcification. The cell outlines remain intact suggesting that incipient calcification occurred soon after death. Following calcification, some lumen were infilled with pyrite.

Fig. 4, 1996-163 (x 190); earlywood cells fairly degraded and ragged in outline compared to the latewood cells, as a consequence of their lower lignin content. Partial infilling of the cells by pyrite occurs.

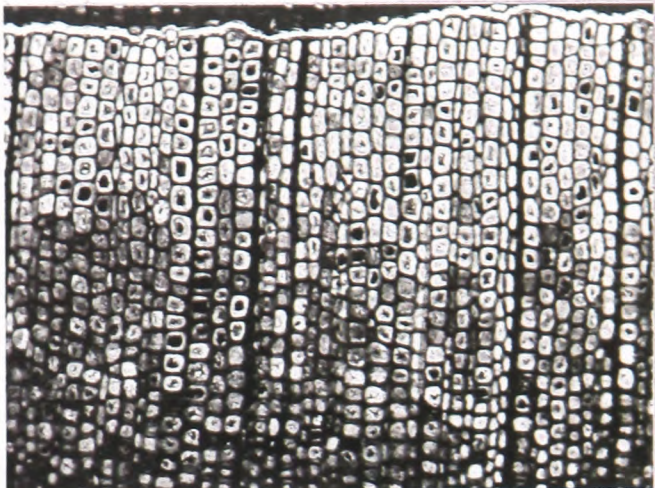
Figs. 5-6, these samples were collected from the Gristhorpe Plant Bed, Cayton Bay, but because of their poor preservation could not be identified. The samples are pyritized, display cellular degradation (fig. 3), distortion and shearing (fig. 4). This state of preservation is common in woods from this locality. Magnification x 170.

Figs. 7-8, sample J.67920 (x 150); these woods are preserved by pyrite. Fractures parallel to the growth rings are common in woods collected from the Gristhorpe Plant Bed, and have the potential to eliminate or obscure rings. An individual pyrite crystal can be seen in Fig. 8.

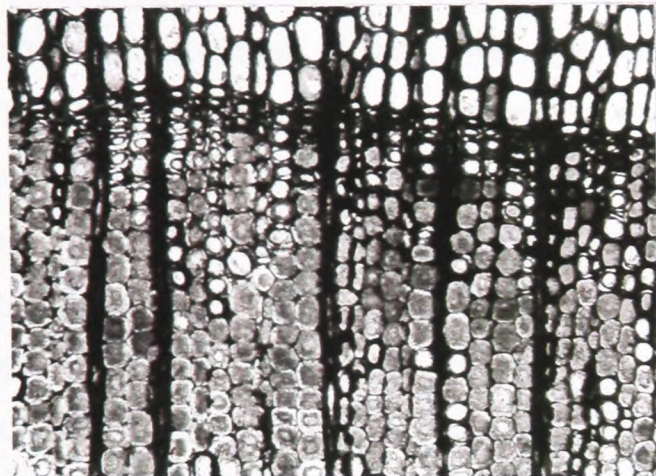
Figs. 9-10, sample J.67935 (x 90, x 170); this specimen is charcoaled and displays superb cellular preservation.



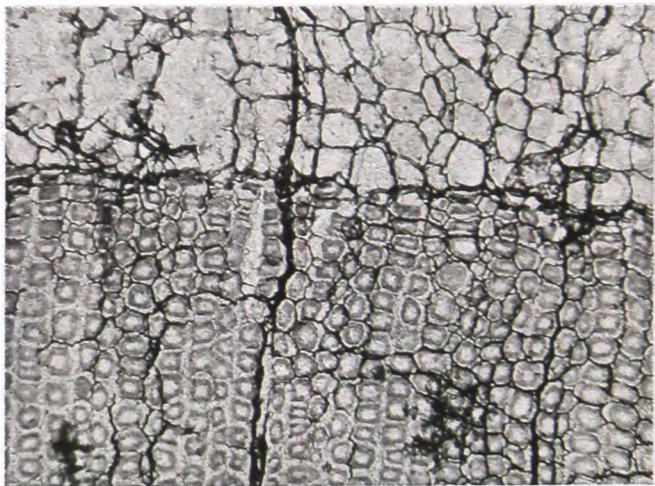
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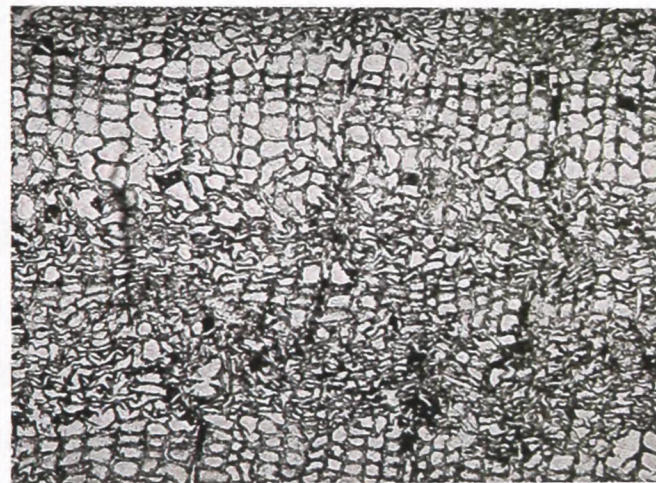
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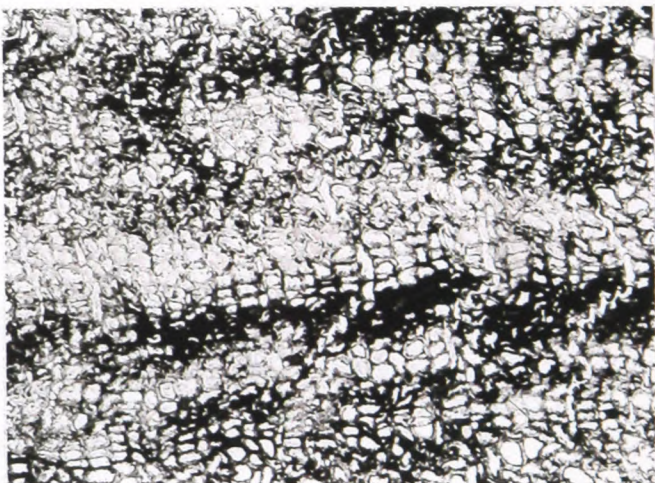
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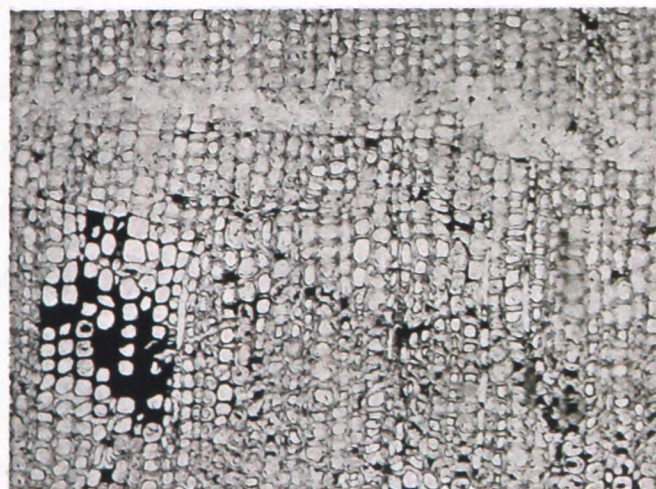
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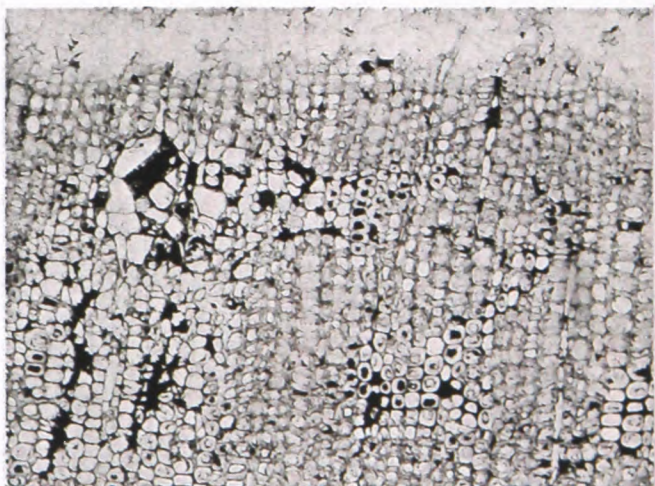
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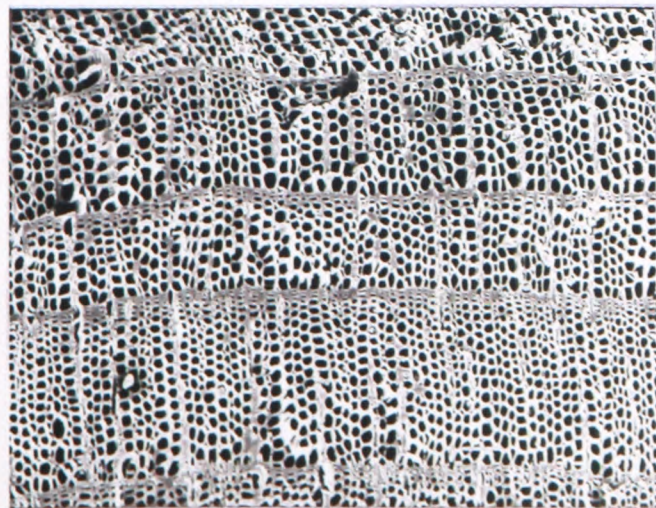
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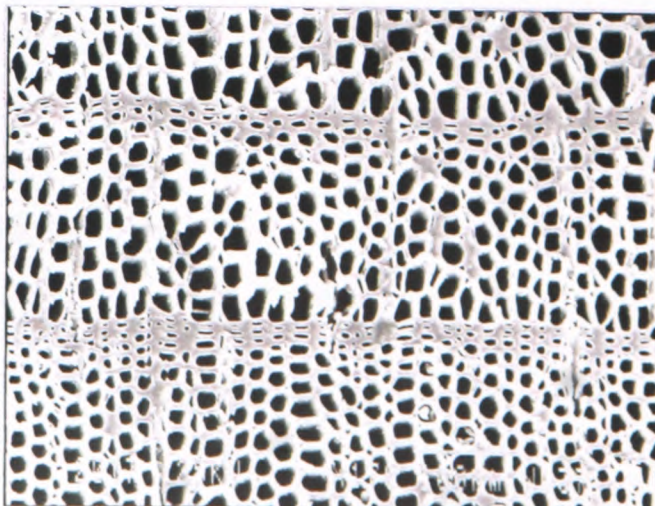
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form of decaying plant matter, would have supplied the required ingredients for pyrite formation. Although there is evidence for some decay of the original cellular structure, total degradation did not occur. The apparent absence of microbiological activity suggests that the environment may have been slightly anaerobic, as fungal attack and breakdown of wood occurs most rapidly in warm, moist and highly aerobic environments (Barghoorn 1952). For our purposes, therefore, an anaerobic environment provides the best conditions for the preservation of wood, as the oxygen required by most organisms responsible for decay is absent. Thus in the poorly drained, stagnant, shallow flood-plain basin which characterizes the depositional environment of the Gristhorpe Plant Bed, decay of the wood and flora was slowed by this restricted supply of oxygen. As the remains were progressively buried, compression was accommodated by the intercellular spaces while the cell walls remained largely unaltered. The process of coalification also began, which forced the volatile components from the cell walls. Introduction of sulphate ions into the system succeeded in terminating the coalification process and initiating pyritization. Compared to other diagenetic processes at work following deposition of the Ravenscar Group, pyritization is a relatively minor, late stage event (Kantorowicz 1984). Today, as a result of this process, remnants of the cellular structure exists only in small pieces of wood or at the centres of larger logs and branches.

4.3.3 Calcification

In this case, calcification is primarily concerned with the replacement of larger wood fragments by calcium carbonate in the marine environment, seen today in only the Cleveland Ironstone and Dogger Formations. It is thought this permineralization process frequently occurs before the stage of advanced decay, which therefore allows the preservation of detailed anatomical information (Schopf 1975). In marine settings, incipient calcification results from bicarbonate ions reacting with calcium ions to form calcite (Raiswell 1971, 1976).

Bicarbonate ions may concentrate on discrete pockets of decaying matter or on entire organic-rich beds (Allison 1988): the scattered nature of permineralized wood in these formations suggest that calcification was centred on the wood fragment.

There is little or no evidence in the form of fragmented and disrupted cell walls to indicate fungal attack, which suggests that post-mortem conditions were either unsuitable for microbiological activity of this kind or the process of calcification began soon after the death of the tree. For the most part, cells appear to be individually calcified leaving the cell outline intact: in some specimens this original organic matter is visible as orangey-brown to black material along the cell wall boundaries (Pl. 4.2, fig. 1). Based on microscopic observations, the process of calcification seems to have been two-fold; initially, tiny fibrous crystals developed, at right-angles to the cell wall; this was in turn followed by the formation of

individual crystals which infilled the cell lumen. Some samples display evidence of secondary pyritization (Pl. 4.2, fig. 2).

4.3.4 Charcoalification

Charcoal, or fusain, is concentrated in discrete portions of the sequence as black, opaque, brittle fragments displaying superb anatomical preservation (*e.g.* Pl. 4.2, figs. 9-10). The question of whether all black, charcoal-like fossil plant material is the product of pyrolysis by wildfire has a long history. Two theories exist regarding the origin of fusain in the geological record: based on its resemblance to modern charcoal, many consider fusain to be the chemically inert residual product of natural wildfire, which may have been initiated by spontaneous combustion, volcanic activity, meteorite fall, sparks due to rock fall, or most commonly, lightning strike (*e.g.* Harris 1958, 1981; Komarek 1972; Batten 1974; Scott & Collinson 1978; Cope 1980; Cope & Chaloner 1980, 1985; Scott 1989). The lightening theory is now widely held, but previously some believed that fusain could form by some biological process (Stopes 1919, 1935), such as wet oxidative decay at an early stage (Schopf 1975). Supporting this theory, there is one instance in the Yorkshire succession where progressive oxidation is thought to have produced fusain (Fisher & Hancock *in* Scott & Collinson 1978; Cope 1980). Noting *in situ* roots (possibly of *Equisetites*) which displayed no cellular structure, Fisher & Hancock postulated that the fusain was produced by inertinisation to form vitrinite, a once gelified and structurally homogeneous substance.

The reliability with which one can discriminate between fusain produced by pyrolysis of wood, and various forms of wood affected by different degrees of diagenesis, is open to conjecture (Cope 1980). However, over the years a number of criteria have been set to distinguish between the two. Cantrill (1919) judged three critical methods for distinguishing fusain from variously coalified woods: (1) its relative insolubility in oxidizing mixtures (*e.g.* nitric acid with chlorate); (2) its silky lustre; and (3) its black streak when rubbed on paper. Harris (1958) developed further this list of distinguishing characteristics and, based upon work dealing with charred leaves (Harris 1981), enumerated other attributes of fusain. McGinnes *et al.* (1974), however, state that the single most distinguishing feature of charcoalified wood is the homogenization of the cell wall, occurring when the middle lamellae of the cell walls, normally evident in the xylem cells, becomes indiscernible (Pl. 4.2, fig. 10). Chaloner (1989, table 2) summarizes the most notable characteristics of fusain and coalified wood, previously discussed in Cope & Chaloner (1985).

The tough nature of charcoal provides the best documentation of the occurrence of past fires in the stratigraphic record. In Yorkshire, the record of wildfire during the Middle Jurassic period is represented by charcoalified conifer wood, cycadophyte stems, *in situ* root systems

and compressed plant organs, such as the pinnules of the fern *Phlebopteris woodwardi* (Harris 1958, 1959). This evidence is essentially restricted to regressive phases in the Ravenscar Group: that is, the upper Saltwick Formation, parts of the Sycarham Member and Gristhorpe Member, and the Scalby Formation. As previously discussed in Chapter 2, these deposits correspond to five of the six, medium-scale cycles identified in the Ravenscar Group (the other refers to the wholly marine Scarborough Formation).

The ecological effect of these fires would have been significant, impacting not only on local sedimentation but also on the composition of the plant communities. Our level of understanding has been further heightened by studies of modern tropical swamps such as the Florida Everglades (Cypert 1972; Komarek 1972; McPherson *et al.* 1976; Cohen & Spackman 1977), which have revealed that fire is an important part of these environments. In these settings, vegetation experiences a burst of seasonal growth, usually triggered by rains, followed by seasonal drought ending with thunder storms, which produce lightning but not always rain. Extensive removal of vegetation by fire greatly increases erosion rates, particularly when fire is followed by torrential rain and winds. This results in both sediment and charcoal being transported into adjacent depositional sites. Forest fires are not confined to seasonally dry areas, but it is in such areas that their effects are most commonly seen. Therefore, the presence of charcoal in a sedimentary sequence probably reflects a seasonally wet and seasonally dry climate.

There are many ancient examples of wildfire which are inferred to have been initiated by a seasonal dry spell terminated by lightning and thunder storms. Evidence for fire in the English Wealden is one such example (Harris 1958), as is the Carboniferous Coal Measures (Scott 1978). Scott (1978) stressed the importance of forest fire in shaping the Coal Measures environment and attributed the apparently paradoxical presence of charred fossil wood devoid of growth rings to irregular short-lived periods of drought. Drought dried out the forest litter enough to allow fire to spread quickly, whilst the undersoil remained sufficiently moist not to effect wood growth.

Yet despite Harris' informative studies, surprisingly little work has been carried out on the palaeoecological effects of wildfire in the Yorkshire Jurassic. Perhaps the only relevant work is a recent account by Cope (1993), based on an investigation of charcoaled wood fragments from the Scalby Formation, Scalby Ness. Studies based on other regions during different time periods are nevertheless instructive for this investigation into the cause and affect of wildfire in Yorkshire.

4.4 Methods

For each sample, three mutually perpendicular planes of section were prepared (transverse, radial longitudinal and tangential longitudinal) (Fig. 4.3). The dimensions of the wood samples were first measured before being broken into small pieces of a convenient size. Only well-preserved portions of the wood were selected for further sectioning and microscopic investigation. The following account describes the techniques employed to prepare the 76 wood samples, depending on their manner of preservation.

4.4.1 Pyritized wood

With the exception of a small number of partially pyritized specimens from the Cleveland Ironstone Formation, this form of preservation typifies wood from the Gristhorpe Plant Bed, Cayton Bay. The brittle, crumbling, unstable nature of the specimens necessitated a balance between the most effective method in conservation and the most efficient means of preparing the samples for microscopic study. To prepare the three planes of section (Fig. 4.3), a rock saw was used to cut the samples into pieces of a manageable size. While the transverse section was left entire to show the maximum number of growth rings, longitudinal sections were trimmed to between 2 and 3 cm². In turn, the samples were coated with an epoxy resin to help fortify the wood during the final stages of preparation. Next, two alternative methods were employed depending on the state of preservation. The more stable specimens were simply thin-sectioned, whereas the more unstable or well-preserved samples were made into polished blocks in order to best preserve their cellular structure.

Polished blocks were made using a method described by Beck (1955). Kenrick & Edwards (1988) and Poole (1993) employed this method but with an additional late stage polish, which is also used in this study. After the three planes of section had been prepared, the samples were placed face down in small plastic beakers and covered completely with epoxy resin. This serves to stabilize and strengthen the samples enough to allow grinding. Specimens were ground on a glass plate with successively finer grades of carborundum powder in small amounts of water to produce highly-polished surfaces. The samples were washed with water and liquid detergent between grades, in a technique similar to that used by Collinson and Ribbins (1977).

Both the thin sections and polished surfaces of the blocks were studied using reflective light. Bright field illumination teamed with a monochromatic green filter gave the best results. Photographs were taken using 35 mm Ilford PanF and FP4 black and white film.

Palaeoclimatic inferences based on fossil wood

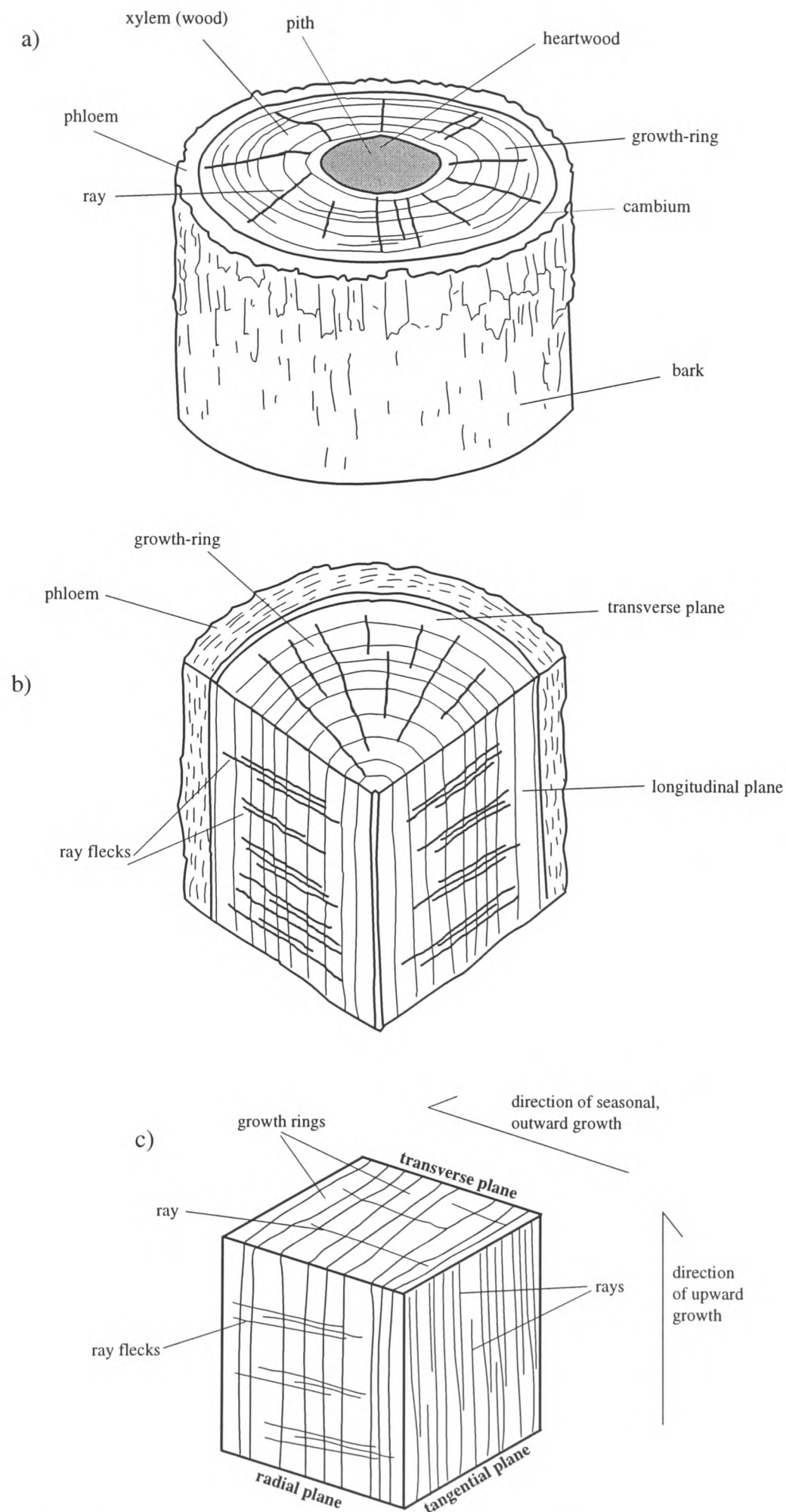


Fig. 4.3 a) Simplified structure of a cross-cut tree showing concentric growth-rings, cambium, bark, heartwood, pith and rays. This plane is the transverse section referred to in the text.

b) Schematic drawing of a tree stem split longitudinally along the rays. This is the radial longitudinal section; the transverse longitudinal section is at right angles to the radial plane. After Barefoot & Hankins (1982).

c) Schematic drawing of a block of wood showing three mutually perpendicular planes which fully demonstrate the anatomy of the sample.

4.4.2 Calcified wood

Calcified wood makes up a large percentage of the Cleveland Ironstone Formation material and all of the Dogger Formation collection. Some of these calcified samples also contain scattered patches of pyrite. Calcified specimens are the largest, most resistant and sturdy of the wood samples and exhibit the longest overall ring sequences. The three planes of section were produced by cutting the samples with a rock saw. The transverse section was prepared by cutting the wood into approximately 1 cm thick slices, while the longitudinal sections were simply cut into manageable sized pieces, usually 2 to 3 cm long. Thin sections were then made in the usual way and mounted in Canada Balsam for examination under the light microscope. Some cleanly fractured samples were examined by SEM for additional microscopic detail.

4.4.3 Charcoalified wood

Of the charcoalified material collected for examination, only samples from the Saltwick and Scalby Formations were suitable for microscopic study. Unlike the calcified and pyritized wood samples, fusain displays empty cell lumen and pit chambers, an absence of the original cellular structure, and homogenized cell walls. There is no evidence for microbiological decay in these samples. In the laboratory, the small, brittle, often cubic fragments of charcoal were first placed in a sonic bath for up to one minute to remove loose dust particles, and then split using a sharp, single tap with a hammer and chisel. Charcoal tends to split along the length of the wood grain, and it was only with some difficulty that clean fractured transverse surfaces were obtained.

The samples were mounted on aluminium stubs for SEM examination. They were first cleaned with acetone and then an epoxy-adhesive was applied to secure the specimens because of their relatively large size. Next, the samples were gold-sputter coated on a Polaron E5000 coating unit to a thickness of 28 nm (280 Å). Specimens were viewed using a Jeol 840A SEM at the Department of Earth Sciences, University of Oxford; a working voltage of 25kv and a working distance of 25 mm obtained the best results. Micrographs showing longitudinal and transverse sections were taken on Ilford FP4 120 format black and white film.

4.4.4 Storage of specimens

To help prevent decay, the wood samples were stored in an air-tight upright chest desiccator with silica gel following examination. Particular care was taken of the pyritized material as it is most susceptible to decomposition, and may even undergo complete disintegration in humid environments (Rixon 1976; Cornish 1987). Although storage in a fluid such as

silicon oil will hinder decay (Collinson 1987), this method was not applied in this study as the oil can otherwise obscure the finer details of the wood anatomy.

4.5 Systematic descriptions

The classification of fossil gymnospermous wood has been reconsidered several times, becoming increasingly complicated with each revision (*e.g.* Seward 1919; Kräusel 1949). The difficulty of classification is exacerbated by the inherent variability of fine anatomical details (even within a single piece of fossil wood: *e.g.* Bailey & Faull, 1934), and the necessity of excellent preservation for successful identification. Kräusel's key (1949) forms the basis for the identifications below, supported by the taxonomic descriptions of Seward (1904, 1919) and Holden (1913) which are based chiefly on wood fragments from Yorkshire.

After detailed anatomical investigation and comparison (identifiable features of the longitudinal planes are outlined in Table 4.4, p.161; for full details see Tables 3.41-3.46), Appendix 3), the wood specimens were assigned to five genera of Mesozoic coniferous wood. In two cases, samples have been identified to a species level. Detailed anatomical descriptions of each wood type and the salient features of the genera to which they are assigned are given below and summarized in Table 4.1, p.137. Table 4.3 (p.158) lists the specimen identifications.

Family CUPRESSACEAE

Form-genus CUPRESSINOXYLON Goeppert, 1850

- 1850 *Cupressinoxylon* Goeppert, p.196
- 1870 *Cupressinoxylon* Kraus in Schimper, p.374, pl. 74, figs. 1-4
- 1905 *Cupressinoxylon* Goeppert; Gothan, p.39
- 1919 *Cupressinoxylon* Goeppert; Seward, p.186-199, fig. 715

Type species. *Cupressinoxylon subaequale* Goeppert, 1850, Tertiary in age (p.202, pl. 27, figs. 1-5). Of the species of *Cupressinoxylon* described by Goeppert this particular species is the most adequately illustrated, and on this basis Andrews (1970) subsequently designated it as the holotype.

Diagnosis. Annual rings distinct and often narrow, parenchymatous cells abundant, scattered throughout rings, recognisable by dark cell contents in transverse section (Seward 1919, p.186).

Bordered pits on tracheids circular, can be in contact or separate, if in more than one row, opposite. Pits of cupressoid-type, typified by apertures inclined to horizontal plane and contained within pit border. Cross-field pits contain single or several small pits, which have broadly elliptical apertures inclined from horizontal. Rays uniseriate, usually fairly short (Kräusel 1949); can also be biseriate.

Discussion. Overall, the characters of *Cupressinoxylon* listed above denote a wood similar to *Cedroxylon*, except in the greater abundance of axial parenchyma in both the earlywood and latewood of rings. Some believe the character of the rays provides a more satisfactory distinction between the two genera (Seward 1919, p.187). The taxon *Cupressinoxylon* is composite, containing the representatives of various living groups, and as a consequence is very large (Stopes 1915, p.168).

Occurrence. Jurassic to Recent, world-wide (*cf.* Seward 1919).

Cupressinoxylon spp.

(Pl. 4.3, figs. 1-10; Fig. 4.4A-D)

Description. Growth rings distinct, usually with abrupt earlywood-latewood transition and narrow latewood zone composed of two to four cells; false rings often present (39% of the specimens) (Pl. 4.3, figs. 1-2). Tracheids square to rectangular in cross-section, with length:width (L:W) ratio of 1.12 in earlywood cells, and 0.68 in latewood cells. On average 415 cells occur per mm² in the earlywood portion of each ring. Axial parenchyma scattered and widespread within rings.

Bordered pits on radial walls of tracheids mainly uniseriate and spaced or, more occasionally, in contact. Subordinate biseriately arranged pits in adjacent rows either alternate or opposite in arrangement (Fig. 4.4A-B). Bordered pits typically 15µm in diameter, pit apertures usually rounded or elliptical, approximately 5µm in diameter. Cross-field pits fairly small (10µm), oval, with oblique apertures of cupressoid type, contained within the pit border (Pl. 4.3, fig. 8). One to two pits generally occur within cross-field, and on occasion even more (Fig. 4.4C).

Rays, seen in the tangential longitudinal section, typically uniseriate, up to 22 cells high (Fig. 4.4D). A small group of specimens from the Gristhorpe Member show an unusually high proportion (50-90%) of biseriate rays comprising 2-23 cells (Pl. 4.3, fig. 10).

Discussion. In this study, fossil wood with this structure was most commonly found, comprising 62% of all identifiable wood samples. However, considering the variability of anatomical detail within the group, it is quite possible that the genus contains more than one species: those samples usually displaying frequent biseriate rays are one such example of where this may be true. The most distinctive features of this wood, as a whole, are abundant, scattered parenchyma cells throughout the well defined, narrow growth-rings; a narrow latewood-zone; cupressoid

cross-field pits; and spaced or contiguous pitting on the tracheid walls (Pl. 4.3, figs. 5-6). The pits are circular in outline, and when touching only slightly compressed — pits with polygonal outlines typical of araucarian wood are not found.

The state of preservation is not always good in the pyritized and calcified examples, but is excellent in the charcoalfied samples. Although the charcoalfied woods reveal minute details helpful for identifying the samples, direct measurements were not taken from these specimens because of the inherent uncertainty of the amount of shrinkage that fusain is known to exhibit (~30% compared to calcified examples).

Wood displaying these features is therefore assigned to the form-genus *Cupressinoxylon* on the basis of dispersed axial parenchyma, absence of resin canals, variable arrangement of tracheid pits, and presence of cupressoid cross-field pits. In the past, these features were thought collectively to represent woods of the extant Cupressaceae and Taxodiaceae (Seward 1919), but more recently (due to improved microscope techniques), minute diagnostic features have been recognized which separate the two families. For example, dentate ingrowths on the horizontal walls of the axial parenchyma (not found in these fossils) and taxodioid pits both characterize *Taxodioxyton*, of the family Taxodiaceae, alone (Barefoot & Hankins 1982). Exceptional preservation in some specimens has allowed *Taxodioxyton* to be recognized in this wood collection; which is described in detail below. Interestingly, leafy shoots identified as *Elatides* have repeatedly been found with *Cupressinoxylon* in the Yorkshire succession. It has been stated, however, that the character of this shoot shows a greater consistency with living Taxodiaceae, than Cupressaceae (Harris 1979, p.66).

Taken alone, some features of *Cupressinoxylon* can be characteristic of other genera. For example, the presence of ubiquitous axial parenchyma is also a common feature of the Podocarpaceae, and the related fossil wood *Podocarpoxylon*, but in this genus it is not a diagnostic feature. *Podocarpoxylon* was not found in this study but has been identified in Yorkshire in the past: a sample collected from a locality in the vicinity of Scarborough was identified as such by Holden (1913).

The mixed arrangement of tracheid pits found in this wood is intermediate in character between araucaroid and pinoid wood. This character is reminiscent of many Mesozoic woods including those of the Cupressaceae, Podocarpaceae and Pinaceae (Seward 1919). Holden (1913, p.537) used this arrangement of pits, together with scattered axial parenchyma and absence of cressulae, to erect the new genus *Paracupressinoxylon*. *Paracupressinoxylon cedroides* Holden, 1913 was introduced for material specifically located on the Yorkshire coast and has many similarities with the samples under consideration here. In these samples, pits are restricted to the radial walls of the medullary rays and cressulae are absent, but this may be a reflection of the varied preservation state. It is possible that some of these woods may be *P. cedroides*, but without the presence of the full suite of diagnostic characters, they must simply be placed in the form-genus *Cupressinoxylon*.

Occurrence. Late Pliensbachian to Late Bathonian: Cleveland Ironstone to Scalby Formations, Yorkshire.

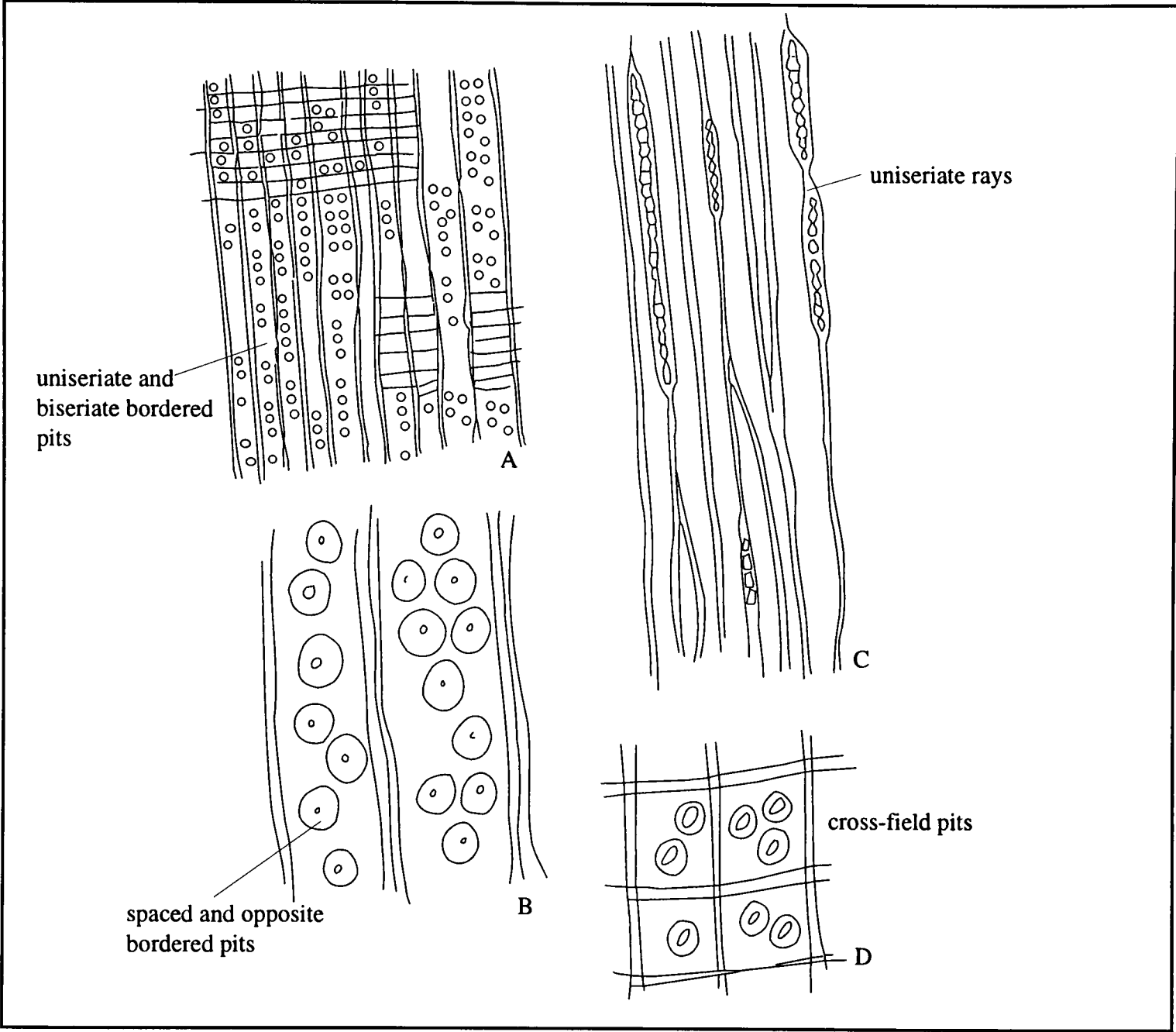
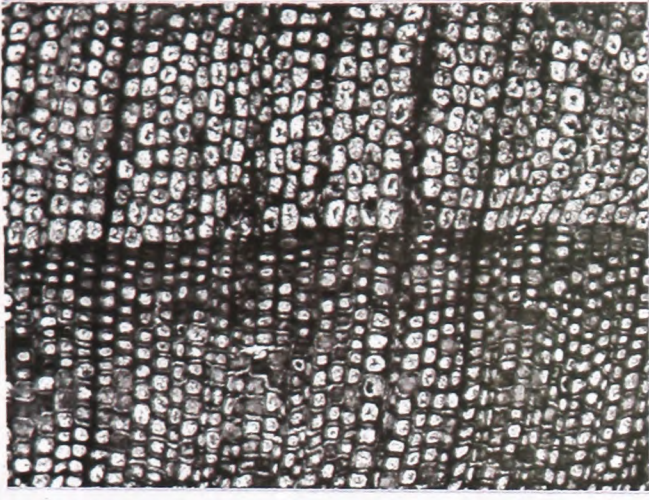


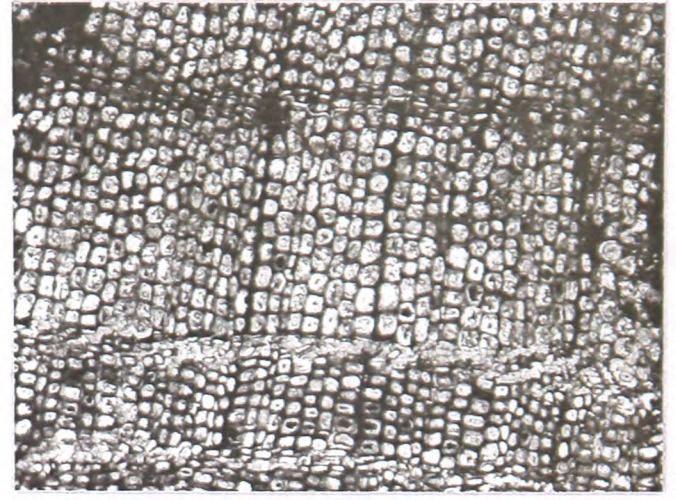
Fig. 4.4 *Cupressinoxylon* Goeppert.
A. Radial section, x 90. Showing arrangement of bordered on pits on the tracheids. Pits mainly uniseriate and spaced, some biseriate and either opposite or alternate. B. Radial section, x 300. Uniseriate and biseriate pits on the radial wall.
C Tangential section, x 100. Uniseriate rays up to 23 cells high.
D. Cross-field showing up to three cupressoid pits. x 110.

EXPLANATION OF PLATE 4.3

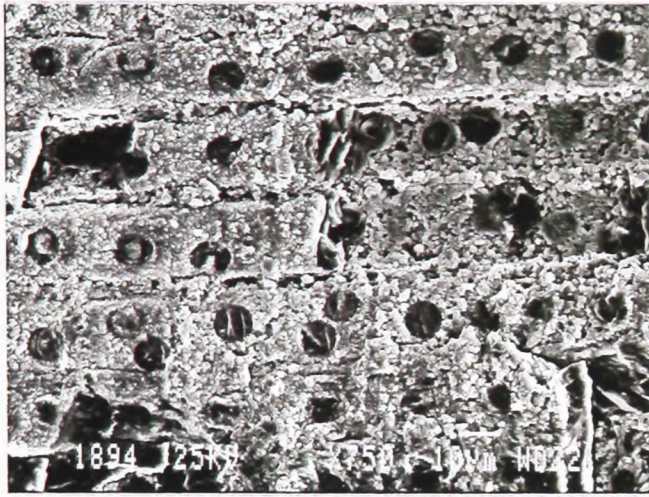
Figs. 1-10 *Cupressinoxylon* Goeppert.
Figs. 1, sample J.67952 (x 150); transverse section illustrating a growth-ring boundary. In this specimen the transition from the earlywood to latewood is fairly indistinct; the latewood zone appears to comprise 5 cells on average. Axial parenchyma is scattered and widespread in both the late- and earlywood.
Fig. 2, sample J.67952 (x 150); transverse section showing growth-ring boundary and false ring.
Figs. 3-4, sample J.67926 (x 750 and x 1100); showing one to two cupressoid pits per cross-field.
Figs. 5-8, samples J.67912 (x 350), J.67947 (x 350 and x 370), J.67896 (x 1400); bordered pits mainly uniseriate and spaced, but more occasionally in contact (fig. 5). Biseriate pitting is shown in fig. 6, where the pits are arranged in an opposite and alternate manner.
Fig. 7 displays the pit border.
Figs. 9-10, sample J.67924 (x 140); uniseriate rays — can be found up to 22 cells high.
All samples are pyritized, with the exception of those displayed in figs. 1-2 which are also partly calcified and fig. 8 which is charcoaled.



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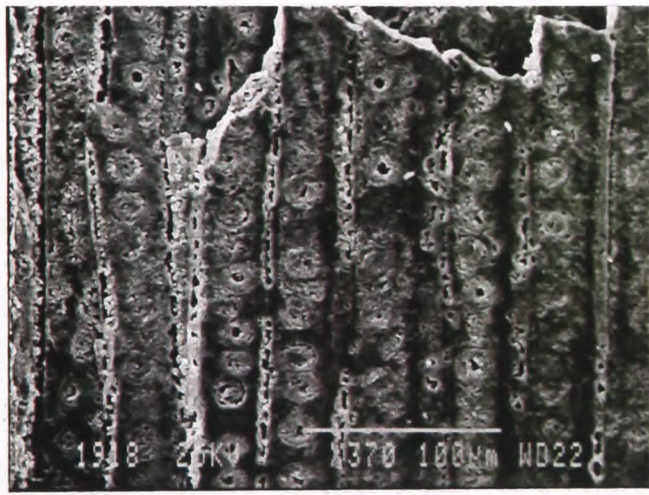
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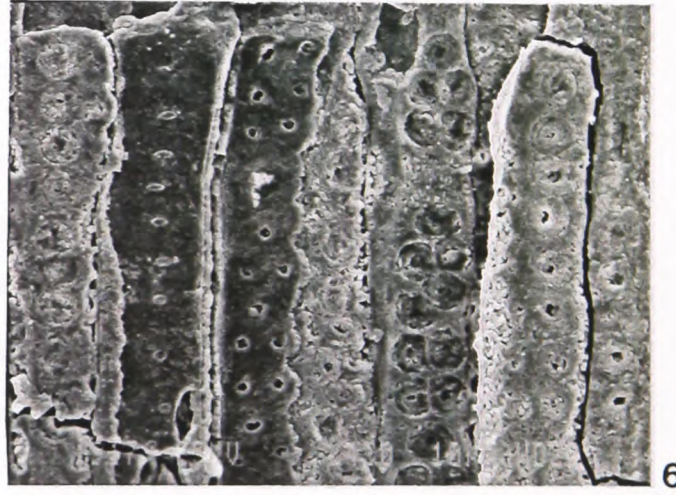
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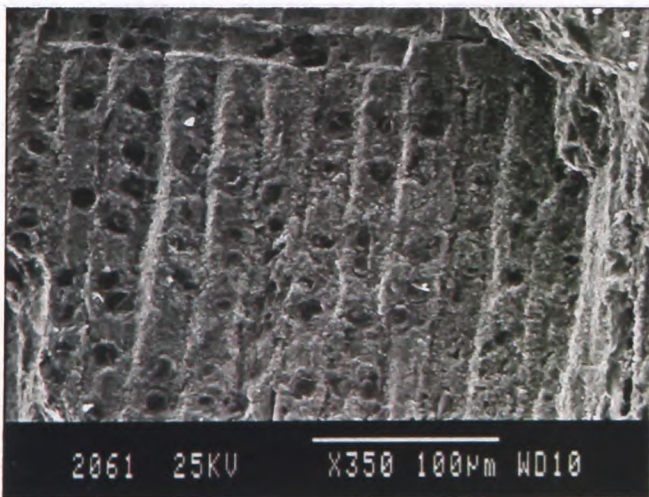
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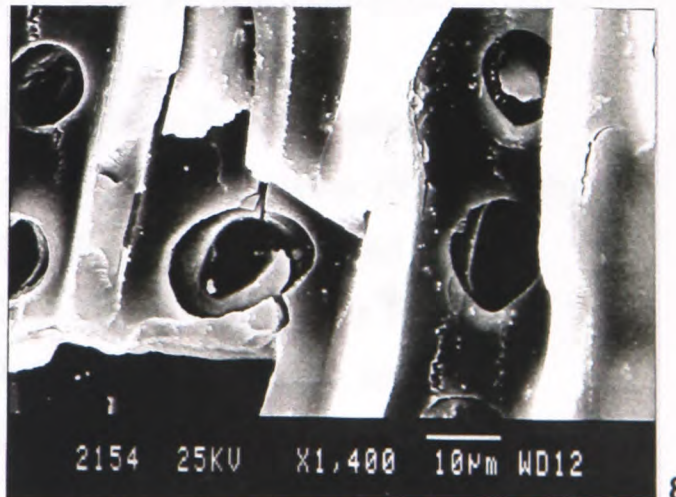
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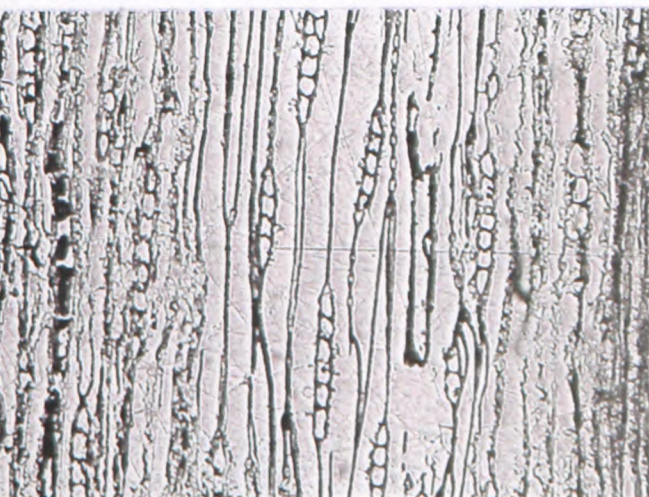
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Family TAXODIACEAE

Genus TAXODIOXYLON Hartig, 1848

1848 *Taxodioxydon* Hartig, p.169

1905 *Taxodioxydon* Hartig; Gothan, p.168

Type species. *Taxodioxydon goepperti* Hartig, 1848 (p.169), by original designation.

Diagnosis. Annual rings distinct, containing scattered axial parenchyma. Bordered pits on tracheid radial walls mainly uniseriate, either spaced or touching. Can also be in double rows, opposite and touching, sometimes alternate and compressed. Bordered pit diameters of 18µm and pit apertures of 6µm common. Pits of taxodioid type (apertures horizontal). Cross-fields exhibit one to four pits, with average diameters of 14µm. Rays uniseriate, 3-12 cells high.

Occurrence. Jurassic to Recent in Europe (Seward 1919; Philippe 1994a).

Taxodioxydon spp.

(Pl. 4.4, figs. 1-8; Fig. 4.5A-D)

Description. Specimens of this wood type make up only 4% of the collection. A transverse section is not preserved in any of the samples, but because of the superb preservation of the longitudinal planes (in charcoal or carbonate), detailed features of the anatomy can still be observed. Taxodioid cross-field pitting is the most distinctive feature of this wood, and is usually the primary feature used to distinguish this genus from *Cupressinoxylon* (Seward 1919). The pits are large — oval to circular in outline — and have apertures which are horizontally oriented and wider than the border (Fig. 4.5A). Tracheid pits are commonly uniseriate, but where biseriate may be araucarian in nature (Fig. 4.5B; Pl. 4.4, figs. 5-7).

Discussion. The style of cross-field pitting alone diagnoses this wood as *Taxodioxydon*.

Taxodiaceous wood usually has between one and five pits per cross-field (Greguss 1972), often arranged in horizontal rows. The pits are often fairly large, simple and bordered, and with elliptical apertures oriented in the horizontal plane. One to four cross-field pits are found in this group of specimens (Pl. 4.4, figs. 3-4), and in some instances the horizontally inclined apertures can be seen clearly (Pl. 4.4, fig. 2). The features of these samples fit well with the standard descriptions given for taxodiaceous wood.

Collectively, taxodioid pitting, smooth medullary ray cell walls, cressulae, common axial parenchyma, and the tendency of bordered pits on the radial walls to arrange themselves in one or two rows, are characteristic features of *Taxodioxydon* and the extant families Araucariaceae and Taxodiaceae (Seward 1919; Kräusel 1949). In members of the Araucariaceae, pitting on the radial walls is such that, when multiseriate, the pits are alternate and abutting with hexagonal borders. This feature is mostly absent from the fossils under consideration here, although

localized areas of araucarian-type pitting can be found (*e.g.* J.67950). This mixed type of pitting has been noted in taxodiaceous woods before: an investigation of Lower Jurassic wood from France by Philippe (1994*a*), revealed both Araucarian and non-Araucarian pitting in *Prototaxodioxylon romanensis* Philippe, 1994*b* and *Prototaxodioxylon* sp.

Although there is some uncertainty over the related conifer foliage, both male and female cones of *Elatides williamsonii* and *Pagiophyllum* have been tentatively associated with taxodiaceous wood in the Yorkshire succession (Harris 1943).

Occurrence. Late Pliensbachian Cleveland Ironstone Formation to Late Bathonian Scalby Formation, Yorkshire.

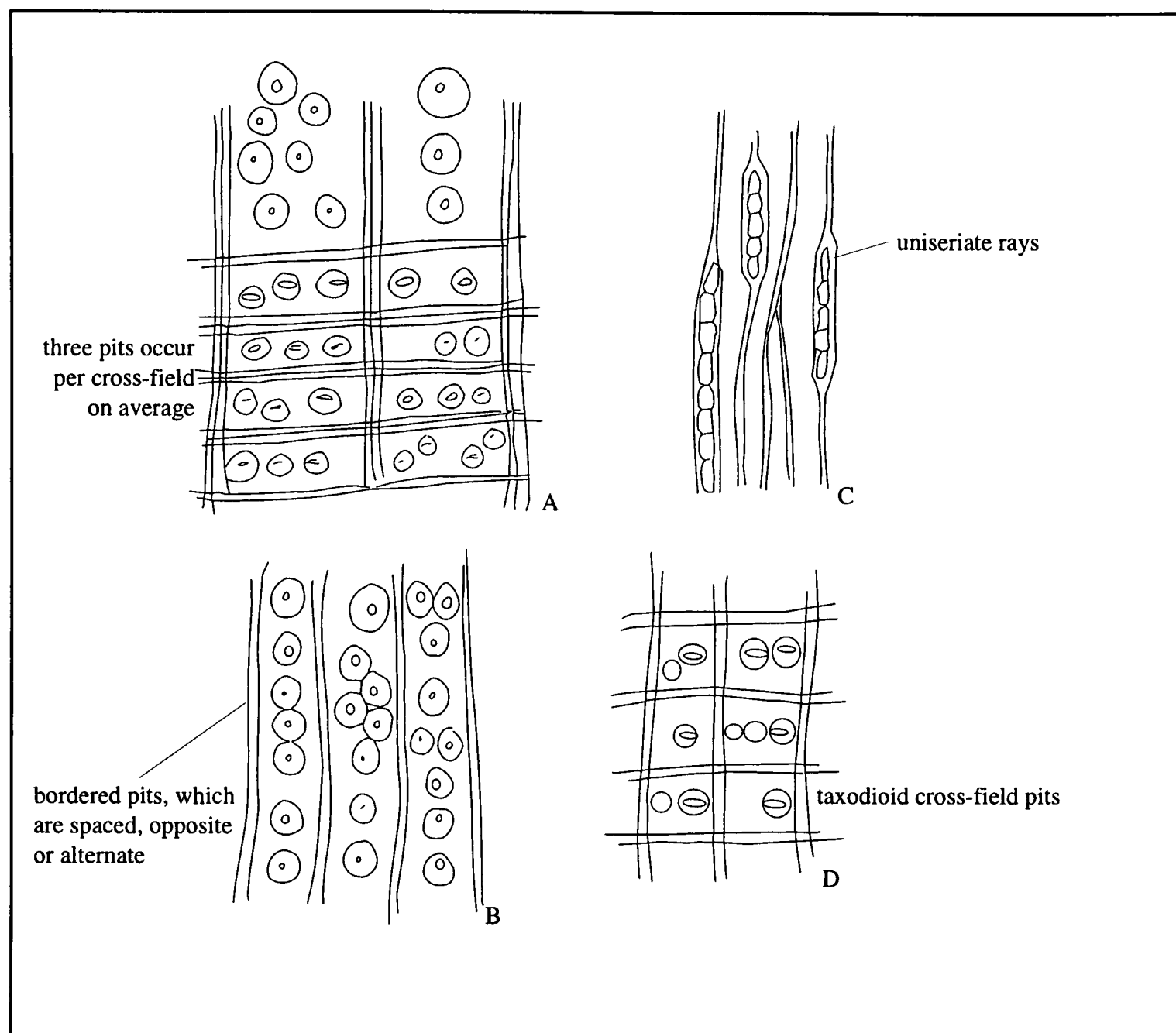


Fig. 4.5 *Taxodioxyylon* Hartig.

A. Radial section, x 280. Cross-fields showing up to three taxodioid pits per field. Bordered pits on the tracheid walls are mainly uniseriate and spaced.

B. Radial section, x 270. Bordered pits on radial walls of tracheids. Pits mostly uniseriate and either spaced or touching. When biseriate, pits can be opposite and touching, or alternate and slightly compressed.

C. Tangential section, x 100. Uniseriate rays up to 12 cells high.

D. Detail of cross-fields showing on average two taxodioid pits per field. x 260.

EXPLANATION OF PLATE 4.4

Figs. 1-8 *Taxodioxyylon* Hartig.

Fig. 1-4 samples J.67940 (x 430 and x 1800), J.67950 (x 700, x 450); showing arrangement of the cross-field pits.

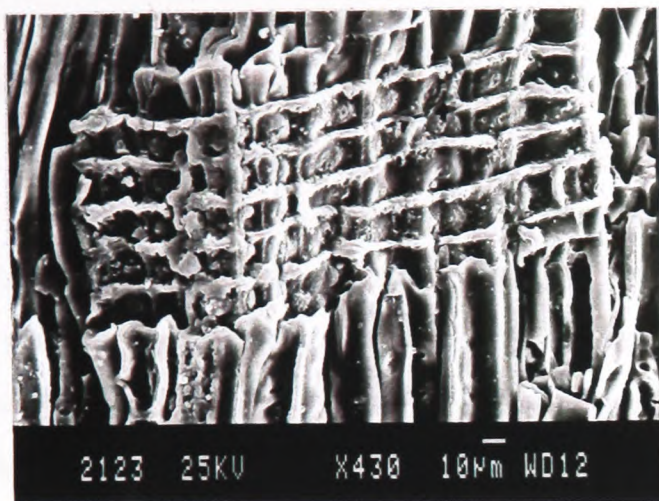
Figs. 1-2 display single well-developed taxodioid pits in each field; fig. 3 one to two pits. Fig. 4 exhibits one to four circular pits per cross-field, arranged in horizontal rows.

Figs. 5-7, sample J.67950 (x 180, x 170, x 400); bordered pits uniseriate and either spaced or touching. Occasionally pits are biseriate and display an Araucarian character (fig. 6).

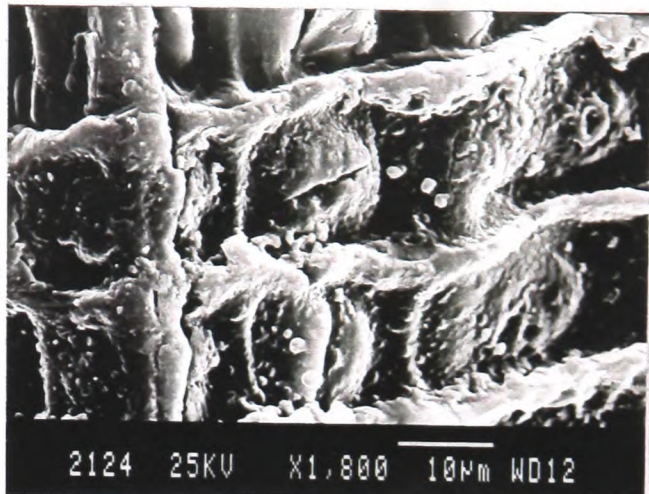
Fig. 8, sample J.67950 (x 140); rays uniseriate and 3-12 cells high.

Samples exhibited by figs. 1-2 are charcoalified, while the remaining samples are pyritized.

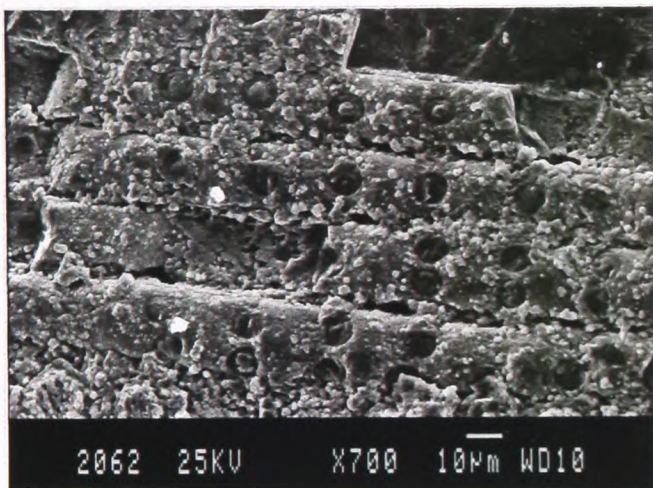
Plate 4.4



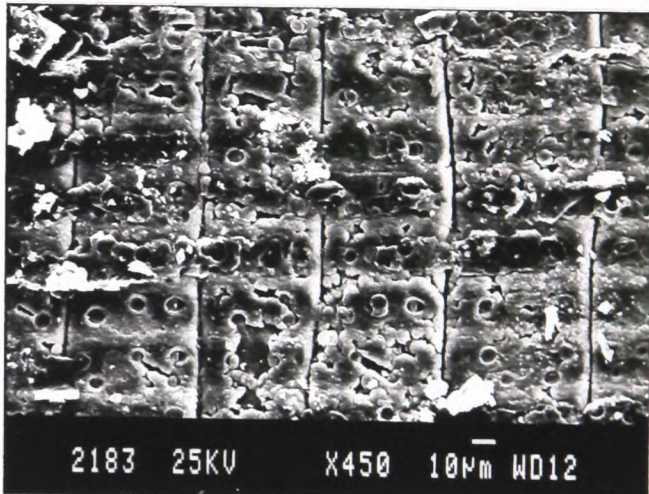
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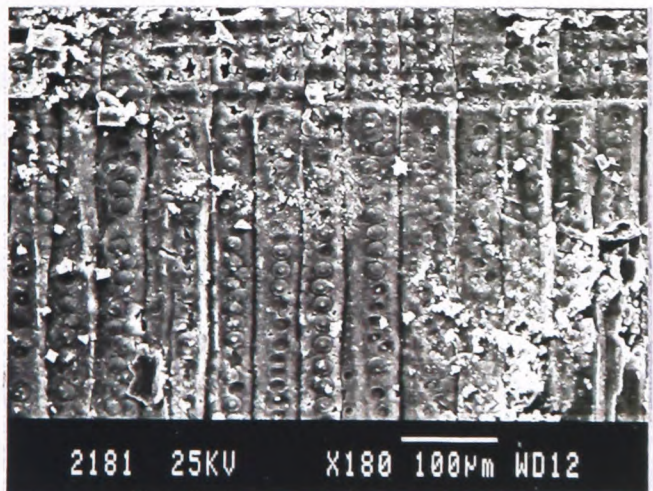
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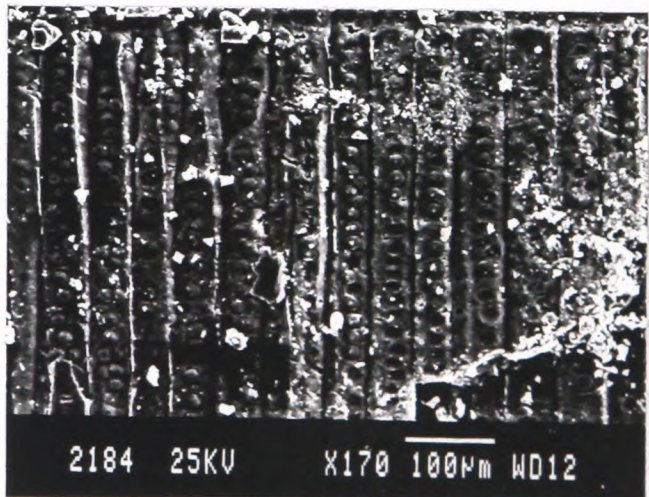
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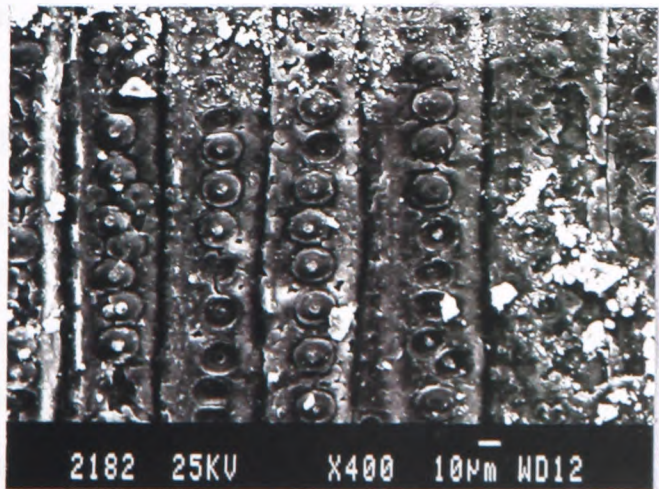
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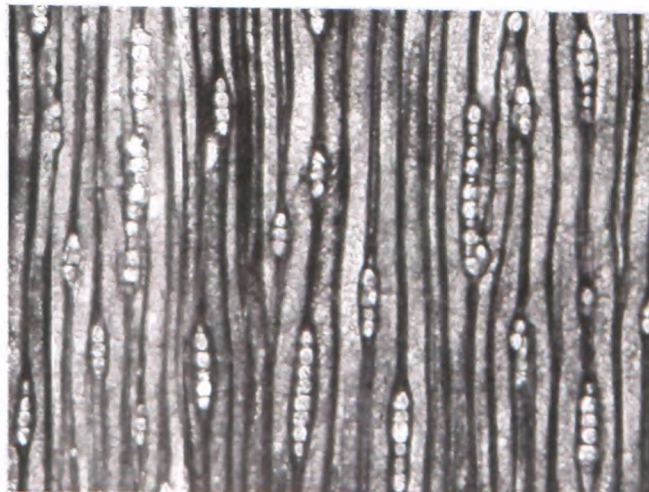
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8

Family TAXODIACEAE

Genus XENOXYLON Gothan, 1905

1905 *Xenoxylon* Gothan, p.38

Type species. *Xenoxylon latiporosum* (Cramer) Gothan, 1905 (p.38), by original designation.

Diagnosis. Tracheid pits large, generally flattened above and below, often transversely oriented. Cross-field pits contain single large pit. Rays uniseriate.

Discussion. *Xenoxylon* is described by Seward (1919, p.242) as being a generalized type and one of the most homogeneous wood genera. Anatomically, the genus exhibits features shared by the Araucariaceae and Taxaceae: it is characterized by very large bordered pits on the tracheids, which are oblate and extended laterally, with one simple pit per cross-field and an absence of resin canals (Kräusel 1949; Müller-Stoll 1951). The combination of these features is unknown outside this genus (Philippe & Thevenard 1996). Despite this apparent homogeneity of the genera, some species show a mixed type of tracheidal pitting on the radial walls, and some are typically Araucarian (Gothan 1905).

Occurrence. *Xenoxylon*'s distribution is circum-polar and confined to high-latitudes in the Triassic, expanding towards the equator during the Jurassic and the late Cretaceous (Philippe & Thevenard 1996).

Xenoxylon phyllocladoides Gothan, 1906

(Pl. 4.5, figs. 1-10; Fig. 4.6A-D)

1906 *Xenoxylon phyllocladoides* Gothan, p.454, fig. 4

1910 *Xenoxylon phyllocladoides* Gothan, p.36, pl. 6. figs. 9, 10, etc.

1904 *Cupressinoxylon barberi* Seward, p.60, pl. 7, figs. 1, 4, 9

1919 *Xenoxylon phyllocladoides* Gothan; Seward 1919, p.241, fig. 730

Type species. *Xenoxylon phyllocladoides* Gothan, 1906 from the Bathonian of Poland (Gothan 1906, p.454, fig. 4), by original designation.

Diagnosis. Bordered pits large, occasionally compressed and elongate in transverse plane.

Description. Growth rings are distinct, and the earlywood-latewood transition is fairly abrupt. False rings are rare and axial parenchyma is absent. Tracheid cells are quite square in cross-section, and have a earlywood cell L:W ratio of 1.09 and a latewood cell L:W of 0.72. In the earlywood part of the ring, an average of 317 cells occur per mm². Bordered pits on the tracheid walls are large (up to 28µm in diameter) and fenestrate, often appearing square in outline. The bordered pits are transversely oriented and usually remote or, more rarely, touching and flattened (Fig. 4.6A; Pl. 4.5, fig. 7-8). When in more than a single row they tend to be arranged oppositely, sometimes alternately. A single, large (7-14µm) pit commonly

occurs in each cross-field (Fig. 4.6C; Pl. 4.5, figs. 1-3), or more rarely there are two pits. Rays are uniseriate and 2-16 cells high, often appearing oval in tangential section (Fig. 4.6D).

Discussion. Fossil wood of this type comprises only 7% of the identified wood samples and is preserved as either calcified or charcoalified fragments. The samples correspond well to the general descriptions for *Xenoxylon*, in that single, large cross-field pits occur, and large, sometimes partially compressed, contiguous uniseriate bordered are present. Although the systematic position of *Xenoxylon* is unclear, it could be the wood of *Podozamites*, *Baiera* or, on the basis of their palaeogeographic distribution, *Sciadopitys* (Nathorst 1897; Arnold 1953; Bailey 1953). A relationship with the leafy conifer shoot *Elatides* has also been suggested (Nathorst 1897; Seward 1919, p.239).

Comparison with known species of *Xenoxylon* has shown that the woods can be identified to a species level. The nature of the bordered pits provides the most secure means of separating the species: for example, whereas *Xenoxylon latiporosum* Gothan, 1910 displays vertically flattened and transversely oriented pits, *Xenoxylon phyllocladoides* rarely reveals this extreme compression (Pl. 4.5, figs. 7-8). Previously, both species have been identified in the Yorkshire succession: *X. latiporosum* a short distance north of Robin Hood's Bay (Holden 1913, p.536), and *X. phyllocladoides* from more widespread localities, leading Holden (1913, p.535) suggest that the species comprised "the greater part of the lignite from Scarborough", from the "Oolite" succession (which presumably equates to the Middle Jurassic sequence). Because the specimens under consideration here only very occasionally show extreme compression of the bordered pits, it is likely that the woods represent *X. phyllocladoides*.

Occurrence. Late Pliensbachian Cleveland Ironstone Formation to Late Bathonian Scalby Formation, Yorkshire.

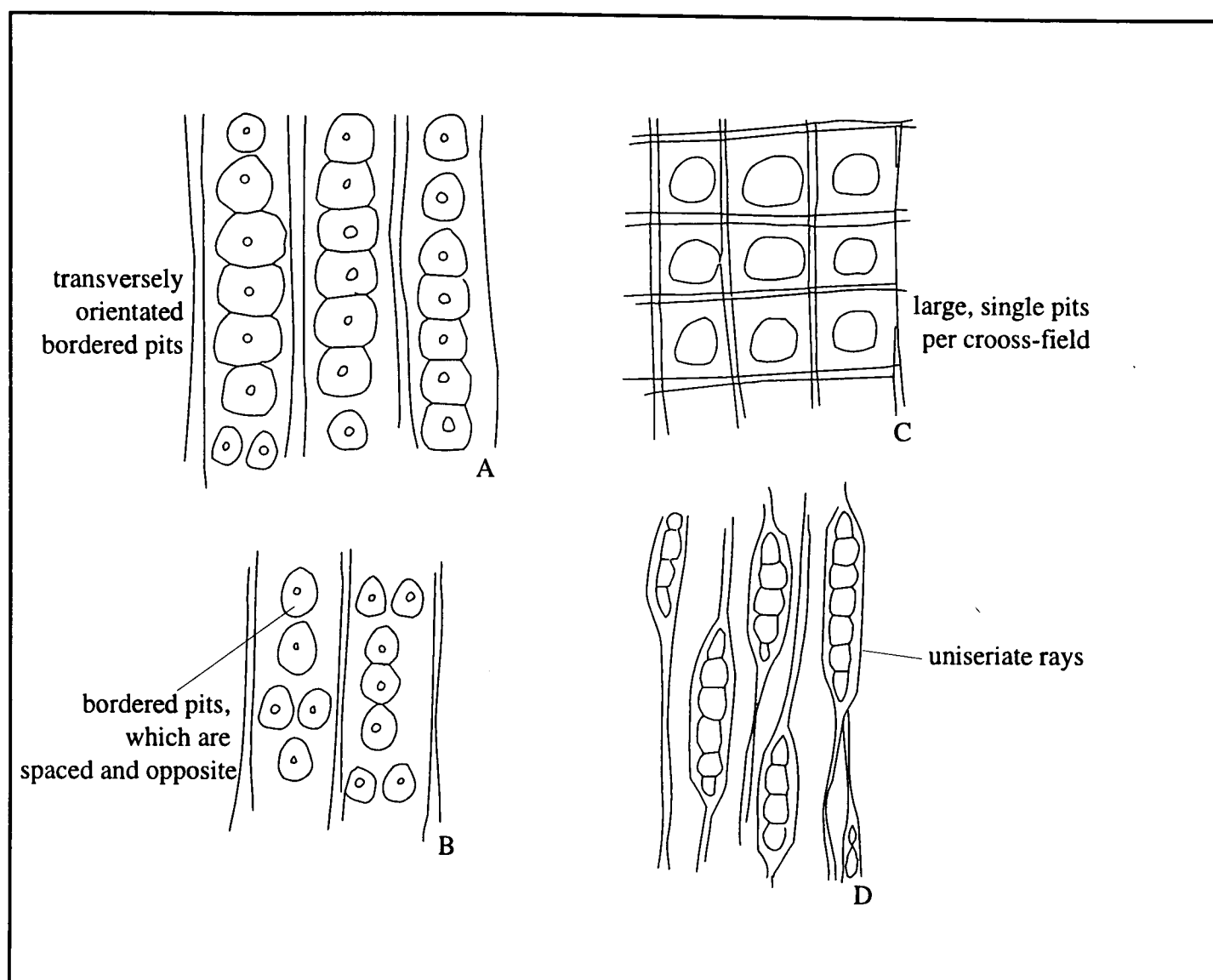


Fig. 4.6 *Xenoxylon phyllocladoides* Gothan.

A. Radial section, x 290. Bordered pits on the radial walls which are large, touching and transversely oriented

B. Localized areas of biseriate pits occur, where the pits are oppositely arranged. x260.

C. Cross-fields showing a single large pit per field, x 290.

D. Tangential section, x 100. Uniseriate rays up to 16 cells high.

EXPLANATION OF PLATE 4.5

Figs. 1-10 *Xenoxylon phyllocladoides* Gothan.

Figs. 1-3, samples J.67956, HSM93BW3, J.67935; showing single, large (7-14 μ m), window-like pits in each cross-field.

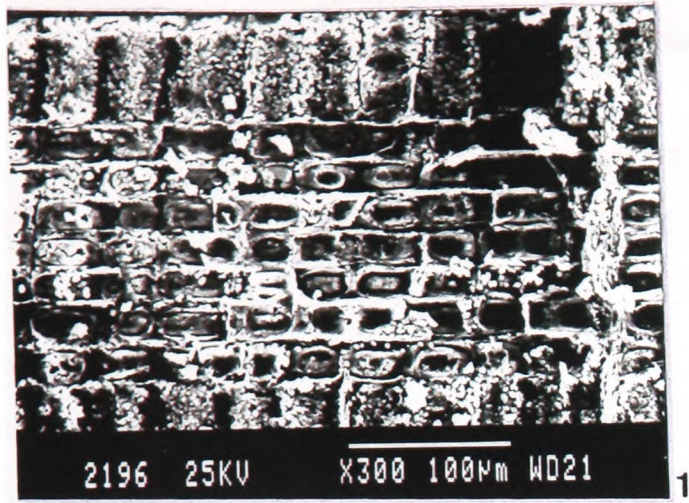
Fig. 1 magnified by x 300, fig. 2 x 450, fig. 3 x 400.

Figs. 4-9, samples J.67935 (magnified x 400), J.67951 (x 200 and x 200), J.67952 (x 500, x 700), J.67935 (x 1700);

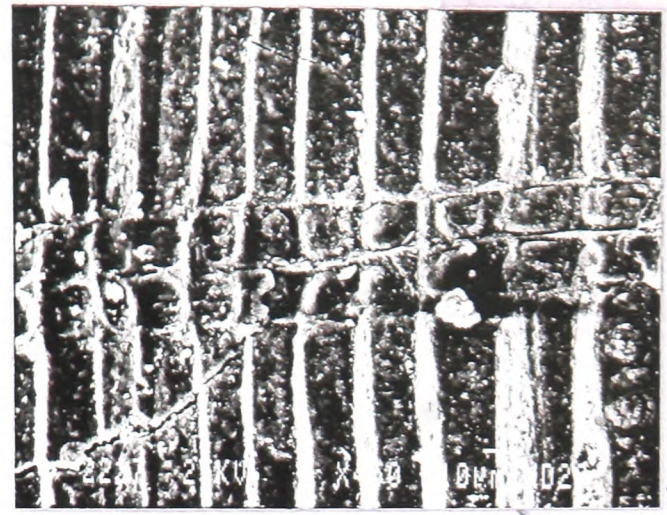
illustrating the bordered pits on the radial tracheid walls. The pits are large (up to 28 μ m in diameter) and usually remote (e.g. figs. 4, 9), but where they are contiguous, they are flattened in the horizontal plane. Figs. 7-8 best display the flattening and elongation which diagnoses this taxon. Note: in Figs. 7-8 the tracheids are oriented from left to right across the page.

Fig. 10, sample J.67935 (x 200); rays are uniseriate and 2-16 cells high.

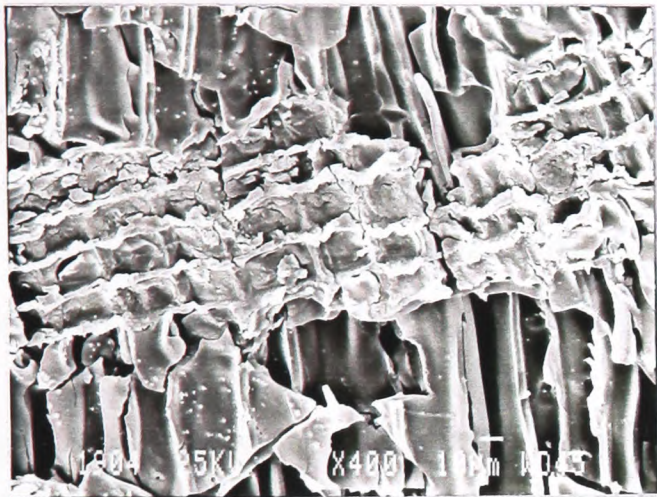
Samples illustrated in Figs. 1, 2, 5, 6 & 7 are partly calcified and pyritized, while the remaining specimens are charcoalified.



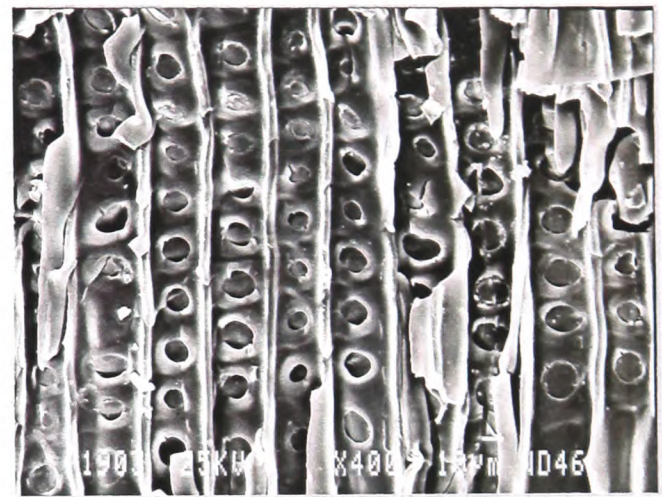
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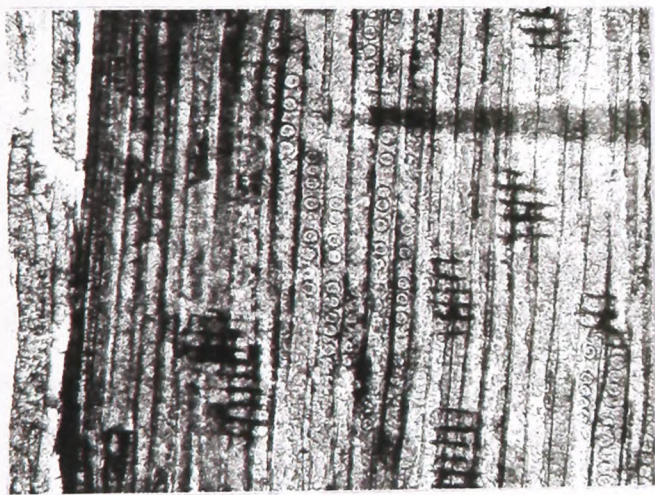
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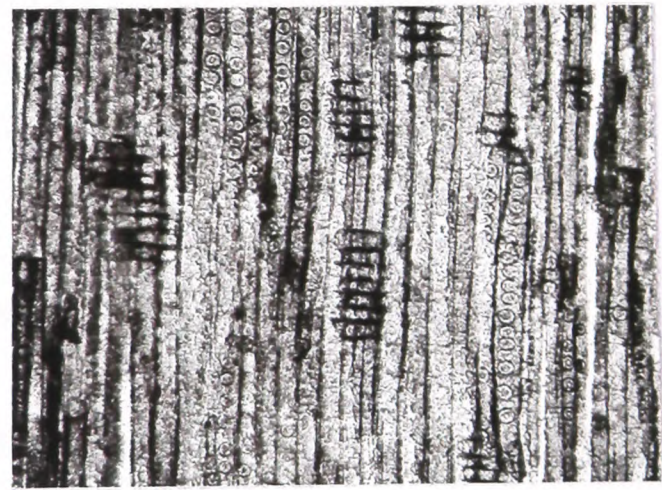
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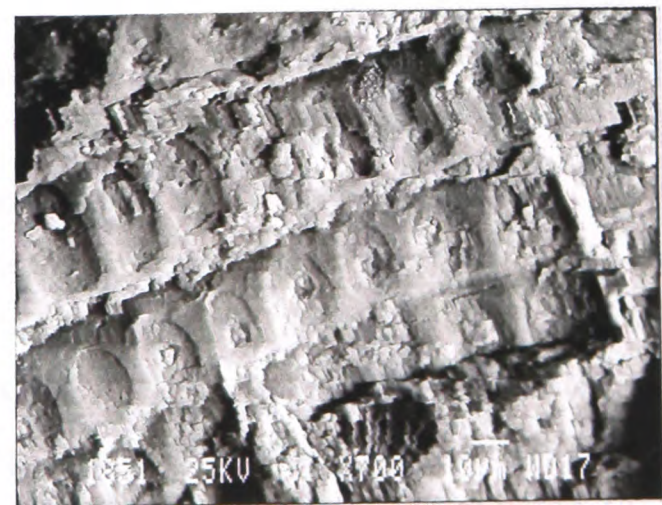
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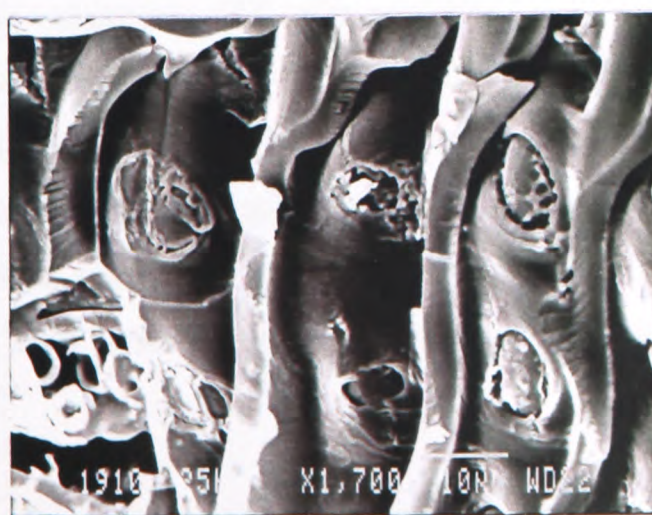
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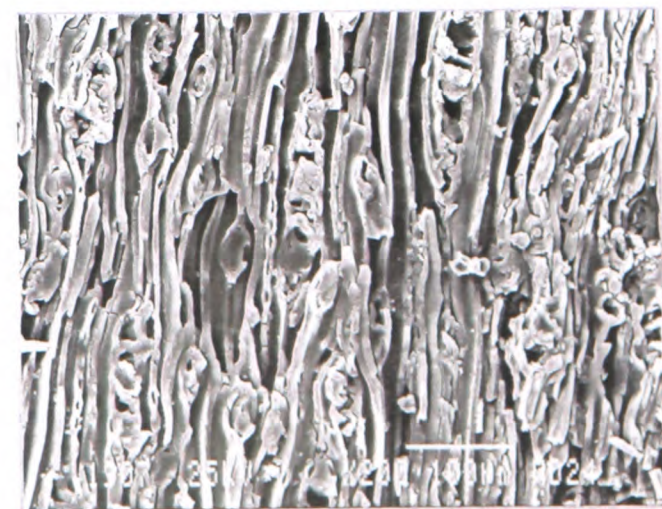
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8



9



10

Family ABIETINEAE

Genus CEDROXYLON Kraus, 1870

- 1850 *Cupressinoxylon* Goeppert, p.196
1870 *Cedroxylon* Kraus in Schimper, p.370, pl. 74, figs. 5, 6
1890 *Cedroxylon* Schenk in Schimper & Schenk, p.862
1905 *Cedroxylon* Gothan, p.102

Type species. Andrews (1970) designated *Cedroxylon withami* Kraus, 1870 (in Schimper 1870, p.370) from the Carboniferous of England as the type species.

Diagnosis. Axial parenchyma, if present, confined to latewood. Bordered pits often contiguous and flattened, can be uniseriate or biseriate. Cross-fields contain 1-6 or, rarely, more pits. Rays uniseriate.

Discussion. The genus *Cedroxylon* was introduced for fossil wood agreeing with *Cupressinoxylon* in the arrangement of tracheidal pits and in the absence of resin canals, but differing in the occurrence of the axial parenchyma: whereas *Cedroxylon* contains parenchyma in the latewood of the rings only (see Fig. 4.11, p.143), it is widespread in *Cupressinoxylon* (Seward 1919, p.213). Nevertheless, the separation of these two genera is not always an easy matter, since they resemble each other very closely in many ways. Other characteristic features of *Cedroxylon* include circular and separate (and if in more than one row, opposite) bordered pits (Seward 1919; Kräusel 1949). However, in some species of *Cedroxylon*, araucarian-type alternate and hexagonal pitting occurs.

Occurrence. ?Triassic to Recent in Europe (cf. Seward 1919).

Cedroxylon spp.

(Pl. 4.6, figs. 1-10; Fig. 4.7A-D)

Description. Growth rings are well defined, the transition from earlywood to latewood gradual (Pl. 4.6, fig. 1). The latewood is wide and composed of as many as ten cells, but more commonly eight cells. False rings are present in about half of the specimens, and up to 70% of the rings within a single wood fragment may be affected. Axial parenchyma is present, but is confined to the latewood (Fig. 4.7A). Tracheid cells are large and square in cross-section, with a earlywood L:W ratio of 1.12 and latewood L:W ratio of 0.63. On average the earlywood part to each ring comprises 465 cells per mm².

Pits on the radial walls of the tracheids are bordered, and can be uniseriate or biseriate and opposite (Fig. 4.7B). On occasion, both uniseriate and biseriate pits can be seen in a single tracheid, and in these samples the double pits become more alternate. The pits generally abut, are sometimes partially compressed, and are 9 to 14µm in diameter. The apertures are 4µm in diameter. Two styles of cross-field pitting are found in this group: specimens with on average

two small (7µm diameter), circular, cupressoid pits (Fig. 4.7D; Pl. 4.6, fig. 3); and specimens with 4-8 rounded pits per field which are opposite in arrangement (Fig. 4.7C; Pl. 4.6, fig. 8-9). Rays are between 2-18 cells high and always uniseriate (Pl. 4.6, fig. 10).

Discussion. Fossil wood displaying these characteristics constitute 13% of the identified specimens collected for this study, which are preserved as calcified and charcoalfied remains. *Abiocalis*, the genus used for structurally preserved stems exhibiting features similar to modern *Abies*, is thought to be related to wood of this type in the Yorkshire sequence (Seward 1919; Taylor & Taylor 1993).

The features which distinguish this wood include a wide latewood zone containing axial parenchyma; uniseriate and contiguous, or biseriate and alternate pitting on the tracheid walls; the common presence of dense pitting in the cross-fields; and tall rays. The presence of araucarian pitting is found in several of the collected specimens, which, interestingly, have a similar arrangement to localized occurrences of this type of pitting in *Cedroxylon hornei* Seward & Bancroft, 1913 from the Late Jurassic of Scotland.

An additional feature of the collected specimens displaying araucarian pitting are the presence of 4-8 pits in each cross-field, arranged in horizontal lines. Although this group is rather different from the general description given for *Cedroxylon*, these woods have been assigned to this form-genus after careful consideration. This judgement is based on the occasional presence of local araucarian pitting, in addition to cited examples of one to six pits occurring per cross-field in *Cedroxylon* (Seward 1919, p.214; Kräusel 1949). Of the previously identified Yorkshire taxa, this wood is in fact most similar to *Metacedroxylon araucarioides* Holden, 1913, collected from the Lias of Robin Hood's Bay and the 'Oolite' of Whitby and Scarborough. However, because the transverse plane is not preserved in any of the four collected samples demonstrating this anatomy, their identification has not been ascertained beyond the generic level.

Occurrence. Aalenian Dogger Formation to Bathonian Scalby Formation, Yorkshire.

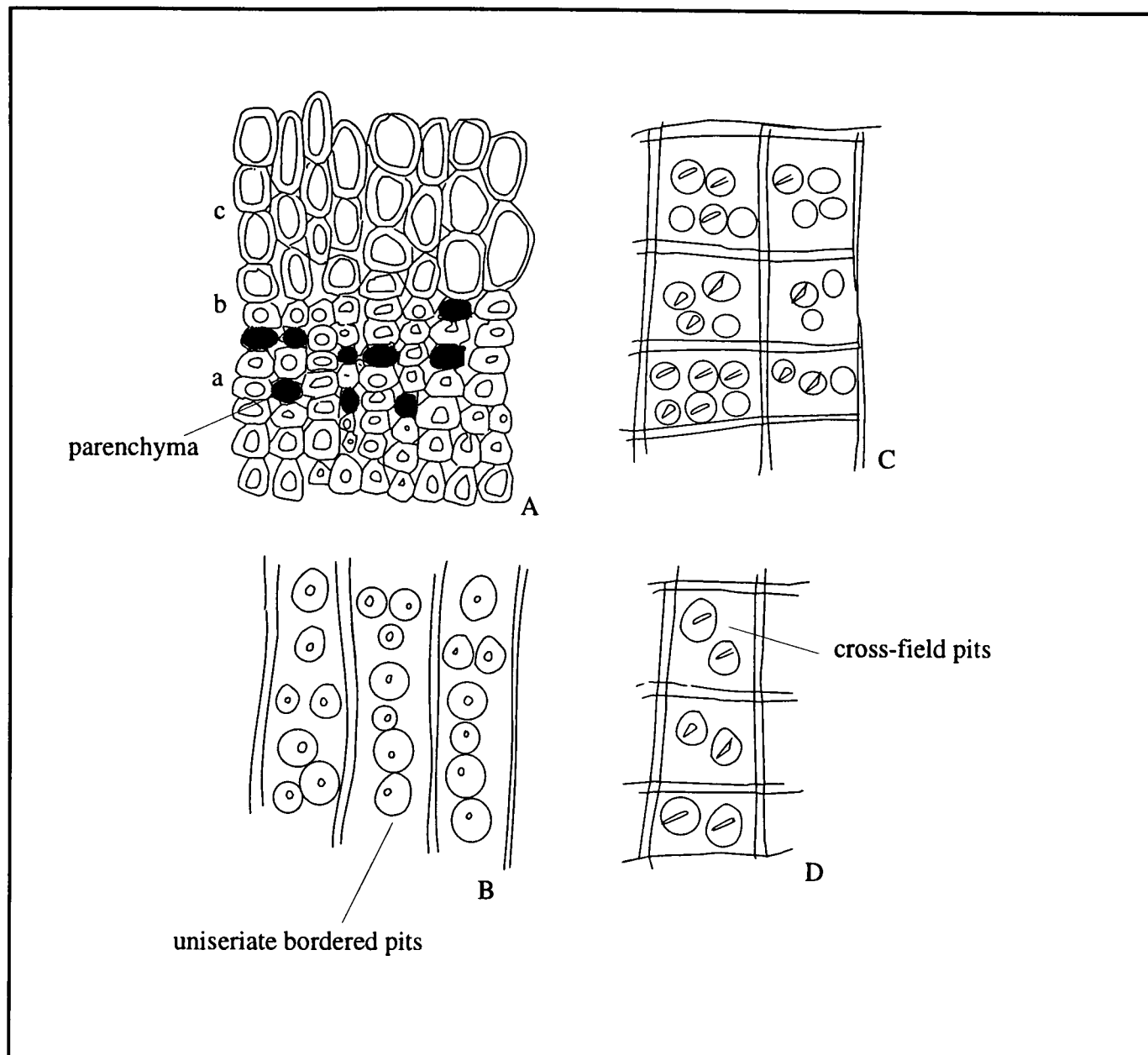


Fig. 4.7 *Cedroxylon Kraus*.

A. Transverse section, x 90. a, latewood zone of a growth ring including parenchymatous cells; b, ring boundary; c, earlywood.

B. Radial section, x 260. Showing arrangement of bordered pits. Uniseriate pitting is most common. Biseriate pits which are opposite or alternate also occur.

C. Cross-fields showing between four and eight cupressoid pits per field, x 100. The pits are opposite in arrangement.

D. Cross-fields containing on average two cupressoid pits. x 100.

EXPLANATION OF PLATE 4.6

Figs. 1-10 *Cedroxylon Gothan*.

Figs. 1-2, samples J.67945 (x 150); exhibiting growth-ring boundaries. In both examples, axial parenchyma can mainly be seen in the latewood. Fig. 2 displays a false ring, ~3 cells wide, in the early part of the earlywood zone.

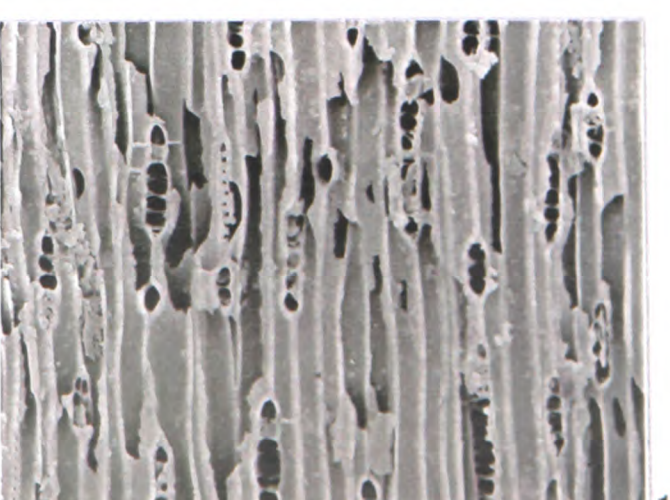
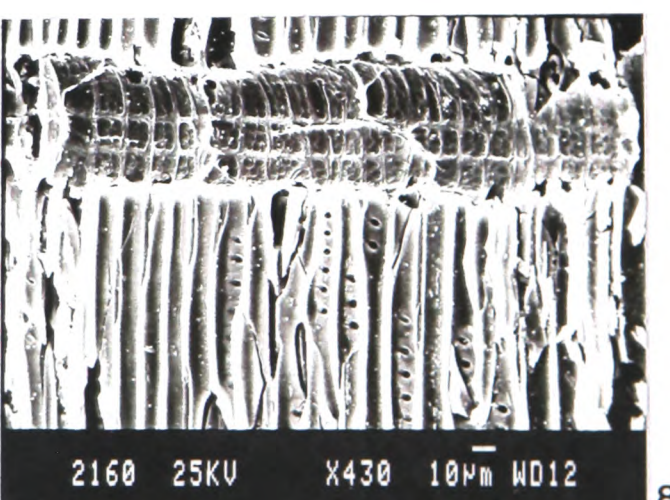
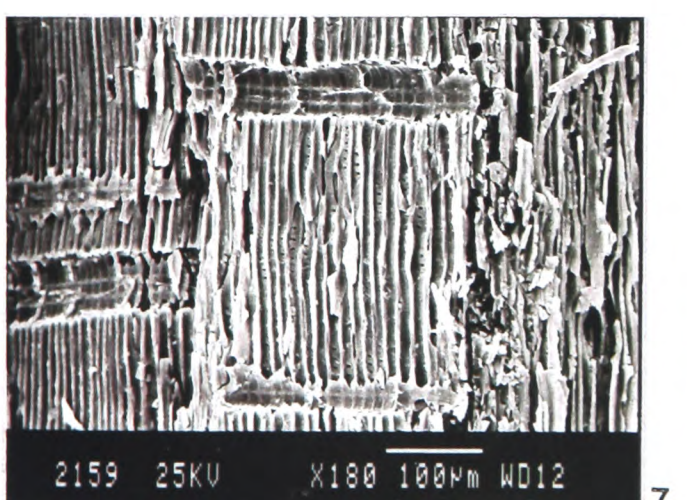
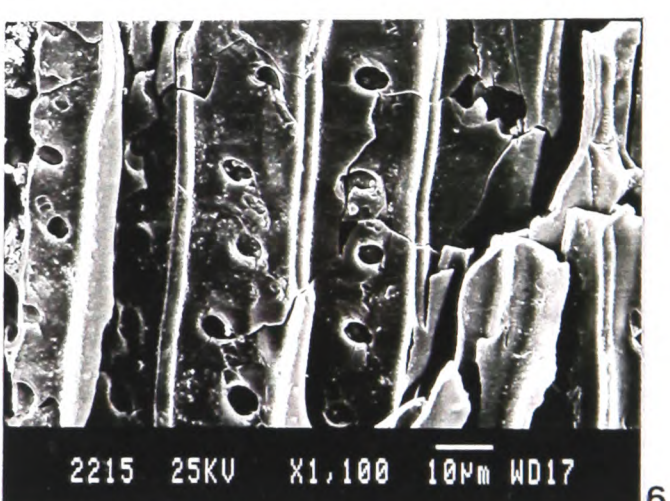
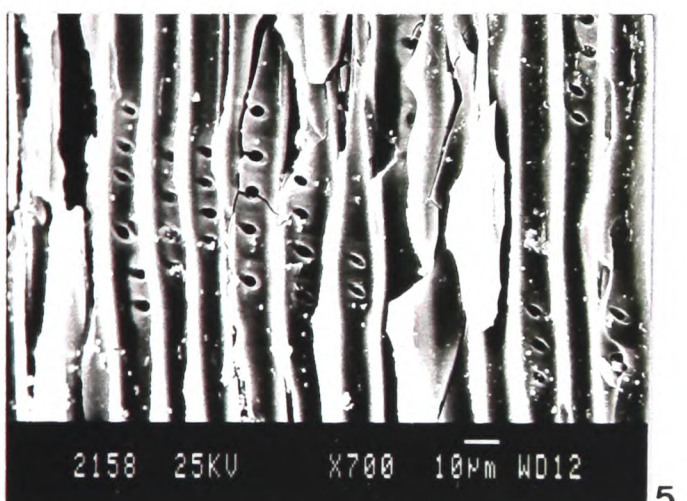
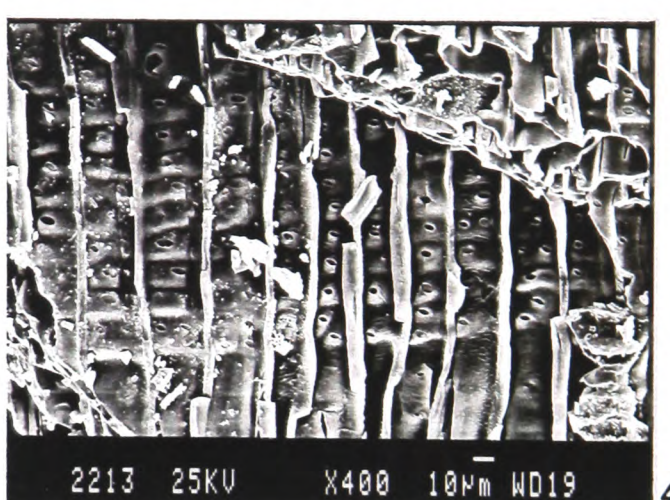
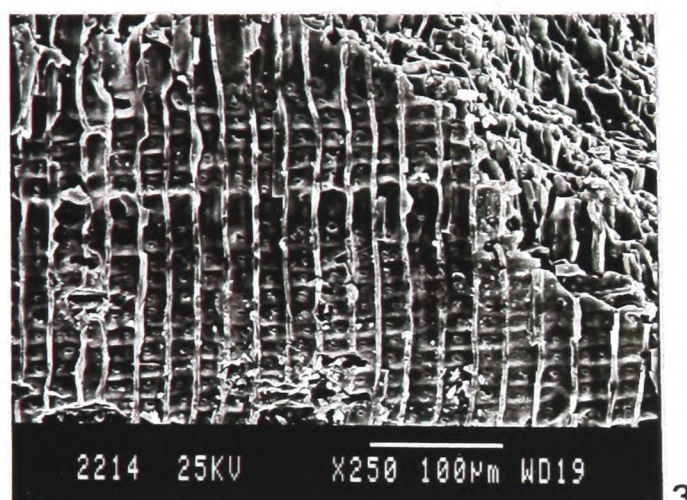
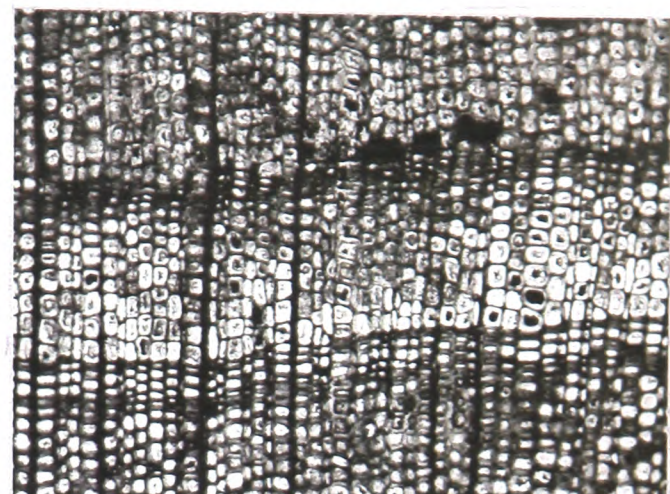
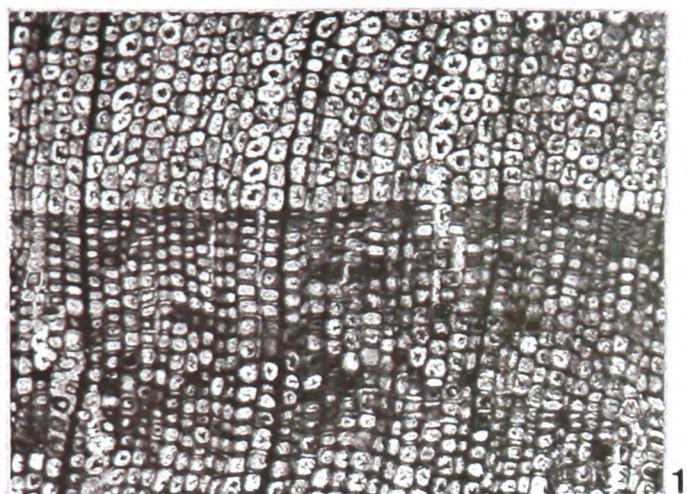
Figs. 3-6, sample J.67938 (x 250, x 400, x 700, x 1100); displays the character of the radial longitudinal wall. On average two, small, cupressoid pits occur per cross-field.

Bordered pits are uniseriate or biseriate and opposite (fig. 4).

Figs. 7-9, sample J.67895 (x 180, x 430, x 750); displaying four to eight rounded pits per field which are opposite in arrangement.

Fig. 10, sample J.67895 (x 150); uniseriate rays which can be up to 18 cells high.

Samples illustrated in figs. 1-2 are pyritized, while those in figs. 3-8 are charcoalified.



Family ARAUCARIACEAE

Genus ARAUCARIOXYLON Kraus, 1870

1870 *Araucarioxylon* Kraus in Schimper, p.380, pl. 74, figs. 9, 10

Type species. *Araucarioxylon carbonaceum* Witham, 1833 was subsequently designated by Andrews (1970) as the type species.

Diagnosis. Bordered pits on radial walls of tracheids, if uniseriate flattened above and below, when in two or more rows alternate and polygonal. Between 1-15 pits in cross-fields. Rays uniseriate, rarely double. Axial parenchyma absent or rare.

Discussion. Perhaps the most diagnostic characteristic of *Araucarioxylon* is the presence of alternating, compressed, and mutually hexagonally compressed bordered pits on the radial walls (Kraus in Schimper 1872). Additionally, smooth medullary rays walls and numerous, small pits within each cross-field are typical features of the genera. Resin canals and crassulae are usually absent (Holden 1913; Kräusel 1949), whilst axial parenchyma is present and growth rings well marked (Seward 1904). Rays simple, uniseriate and numerous (Stopes 1914).

Occurrence. Widespread in Europe, North America and Asia from Palaeozoic to mid-Tertiary times (Stopes 1915; Seward 1919).

Araucarioxylon lindlei (Witham) Seward

(Pl. 4.7, figs. 1-8; Fig. 4.8A-E)

1833 *Peuce lindleiana* Witham, p.58, pl. 9, figs. 1-5, pl. 15, figs. 1-3

1904 *Araucarioxylon lindlei* (Witham); Seward, p.56, pls. 6, 7

Type species. *Peuce lindleiana* Witham, 1833 (p.58, pl. 9, figs. 1-5, pl. 15, figs. 1-3) from the Lias of the Whitby area. However, the species has more recently been redescribed and renamed as *Araucarioxylon lindlei* (Witham) Seward, 1904.

Diagnosis. Bordered pits show an assortment of araucarian and non-araucarian characters.

Description. Growth rings are usually well marked and the transition to the latewood abrupt: 7-9 cells typically comprise the zone. More occasionally ring boundaries are indistinct, with a gradual transition from the earlywood to latewood. False rings are absent. The earlywood tracheids are square to rectangular in cross-section and the L:W ratio is on average 1.03. Latewood cell L:W is 0.8. Between 619 and 648 cells occur per mm². Axial parenchyma is rare and resin canals are absent.

Bordered pits on the radial walls of the tracheids are commonly biseriate, alternate, polygonal and usually contiguous; more rarely the pits are arranged in three or more rows and rather compressed (Pl. 4.7, fig. 3-6; Fig. 4.8 B,C). On the exceptional occasion when uniseriate pits are found, the pits retain their polygonal outline. Therefore the style of pitting is typically

araucarian, but some localized non-araucarian pitting is also found. The pits are 16µm in diameter and have an aperture of 4µm. Up to four cupressoid pits occur per cross-field, which are 12µm in diameter.

Rays are uniseriate and 2-15 cells deep (Pl. 4.7, fig. 8, Fig. 4.8A). On average five tracheids occur between each ray. Occasional, widely-separated pores occur on the tangential walls between rays.

Discussion. Wood specimens showing this anatomy are from the Yorkshire Museum and form only 5% of the collection. The material is mostly calcified, with localized patches of pyrite. These samples are characterized by biseriate, alternate, compressed and hexagonal bordered pits, which are of araucarian type. Several small pits occur per cross-field, axial parenchyma is rare and resin canals are absent.

The samples in question correspond well with this general description and are therefore assigned to *Araucarioxylon*. However, a comparative study with known species of *Araucarioxylon* reveals that, based upon the occasional non-araucarian pitting on the tracheids and rare pores on the tangential walls, *A. lindlei* can be identified. Seward (1904, p.56) noted that the wood has 1-3 rows of bordered pits on the tracheid walls; the pits are usually positioned in two contiguous rows, alternately disposed and polygonal in shape; occasionally three rows of pits occur, or more rarely a single row. Generally, the samples in question agree well with Seward's diagnosis.

Perhaps one of the most unusual features of these specimens is the presence of mixed araucarian and non-araucarian pitting on the tracheid walls. Subsequent to Seward's descriptions, Stopes (1916) highlighted the importance of this characteristic in coniferous wood of Middle Cretaceous age from New Zealand. Based on the striking combination of araucarian and non-araucarian attributes, Stopes (1916, p.119) introduced the genus *Planoxylon*, which encompasses *A. lindlei*. Stopes stressed that non-araucarian pitting (*i.e.* single rows of adjacent or isolated pits) is essentially confined to the tracheids of the latewood in this species. In this study, however, non-araucarian pitting is more scattered in its occurrence, suggesting that these samples are more characteristic of *A. lindlei* than *Planoxylon*. For these reasons, the samples are named as such.

As mentioned above, previously *A. lindlei* has been identified from the Lias of the Whitby area (Seward 1904). This is the only cited example of the species in the Yorkshire Jurassic, and has helped in identifying the provenance of these museum specimens which were previously known only to be of "Lias or M. Lias [age] from near Whitby." The Lias in this area is composed of the Mulgrave Shale and Alum Shale Members, which form a combined total of 45 m of strata. Wood was collected from this outcrop of the Mulgrave Shale Member during field work for this thesis, but unfortunately its poor preservation prohibited further examination. It is possible that the samples of *A. lindlei* collected by Seward (1904) may correlate with the stratigraphic interval from which these samples were collected, giving them a

possible Pliensbachian age. Unfortunately, however, it is impossible to infer a more precise age without further evidence.

Lastly, it is useful to note that wood of this type is associated with the conifer shoot *Brachyphyllum mamillare* and the female cone *Araucarites phillipsii* (Harris 1979); these floral elements are common members of the Yorkshire flora, present in the overlying Aalenian-Bathonian strata.

Occurrence. Lias or Middle Lias age: ?Cleveland Ironstone Formation.

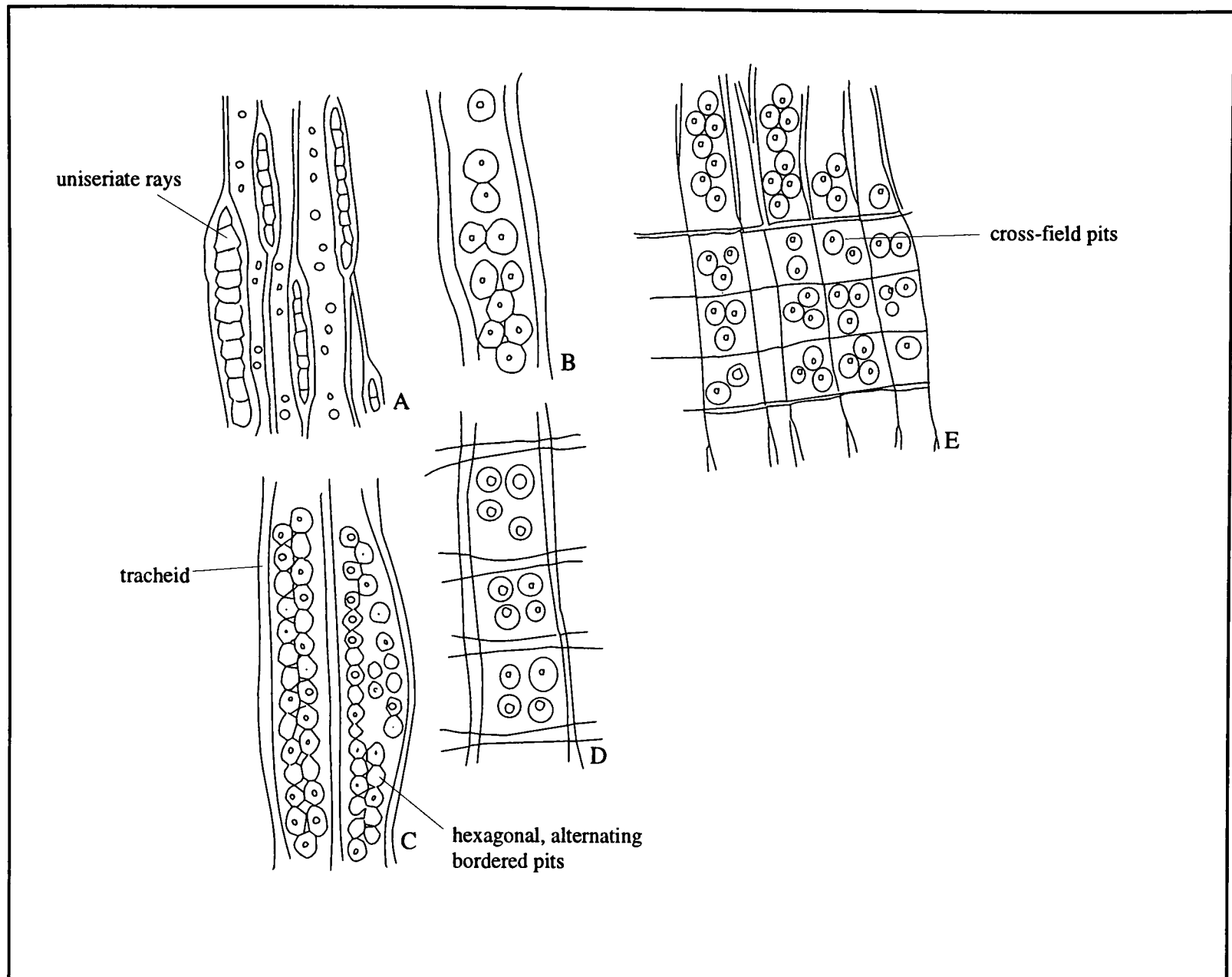


Fig. 4.8 *Araucarioxylon lindleyi* (Witham) Seward

- A. Tangential section, x 90. Rays are uniseriate and up to 15 cells high. Widely spaced pores occur on walls between rays.
- B. Radial section, x 90. Bordered pits are contiguous, biseriate, alternate and polygonal in outline.
- C. Radial section, x 150. In places uniseriate pitting is found, together with biseriate and opposite pits.
- D. Cross-fields showing up to four cupressoid pits, x 100.
- E. Radial section, 90. Showing up to four pits per cross-field, and biseriate and alternate pits on the tracheid walls.

EXPLANATION OF PLATE 7

Figs. 1-8 *Araucarioxylon lindleyi* (Witham) Seward

Figs. 1-2, sample 1996-163 (~x 120, x 200); fig. 1 one displays an entire growth-ring and fig. 2 exhibits an enlargement of the latewood zone and ring boundary. There is an apparently gradual transition to the latewood, which is usually wide. Ring boundaries are distinct.

Fig. 3-6, sample 1996-166 (~x 200); showing the arrangement of the bordered pits on the radial walls of the tracheids. The pits are commonly contiguous, biseriate, alternate and polygonal. In fig. 6 the pits are arranged in three rows on the tracheids.

Figs. 7-8, samples 1994 1799-46 (x 130), 1996-163 (x 140); uniseriate rays, up to 15 cells high.

All samples are calcified, with exception of that shown in fig. 7 which is pyritized.

Plate 4.7

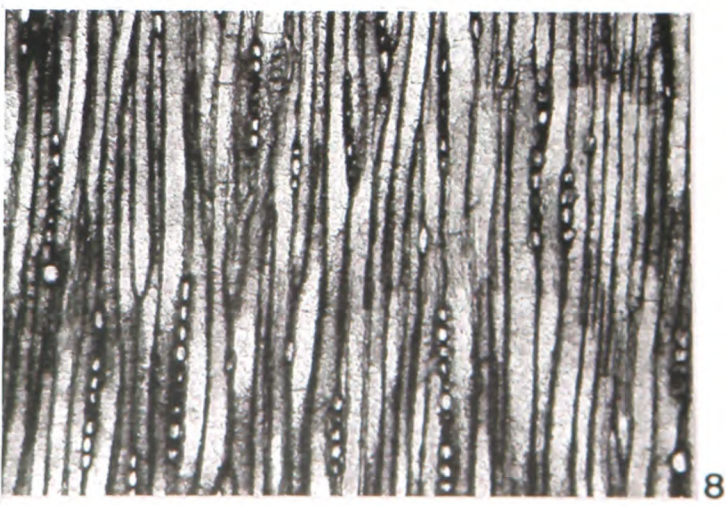
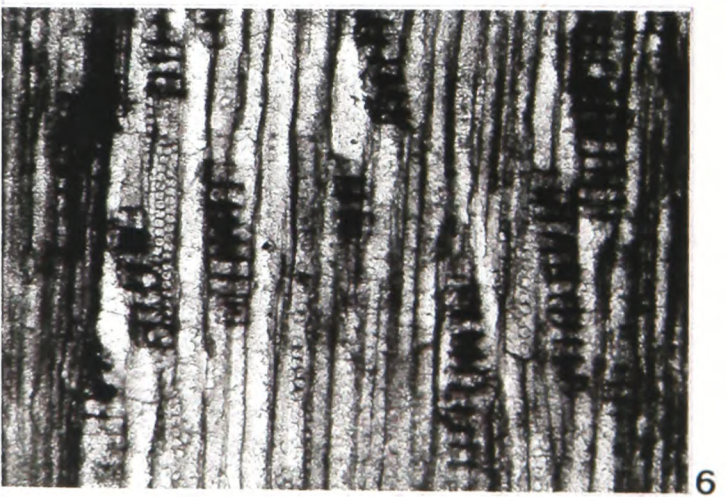
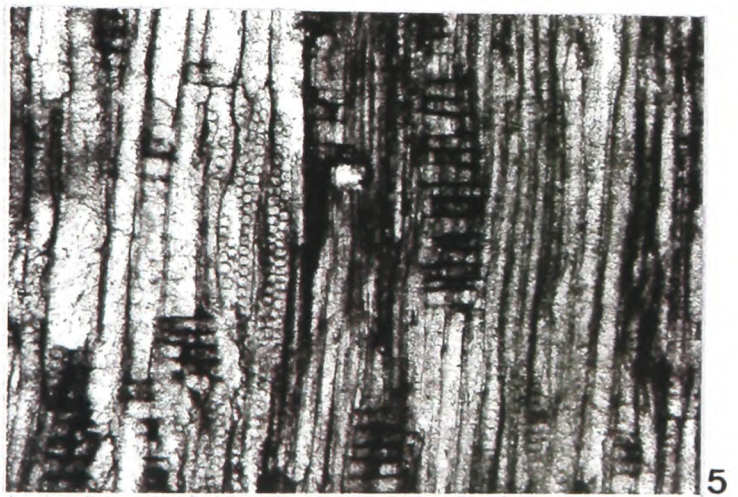
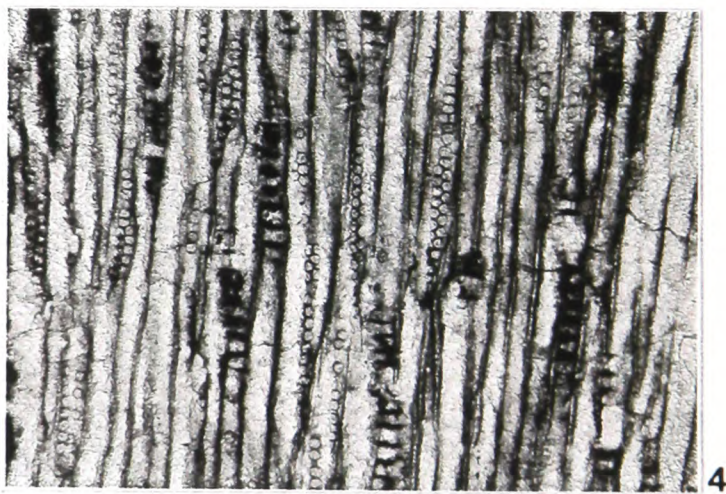
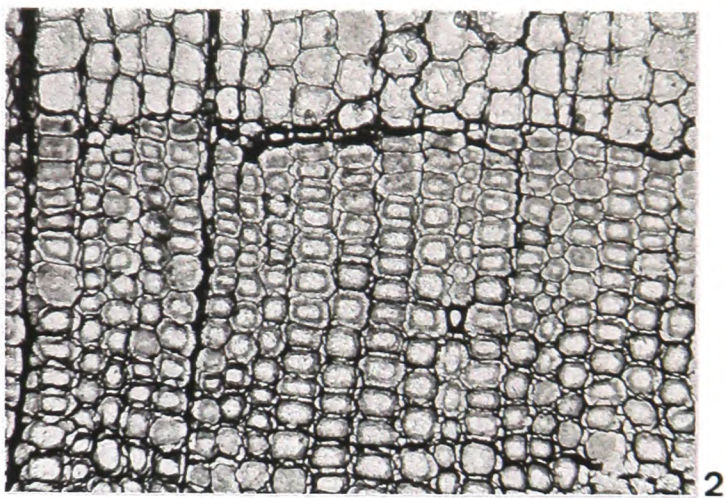
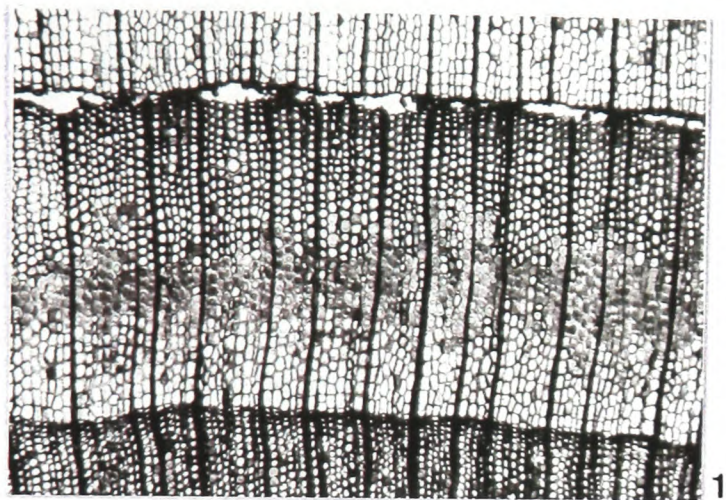


Table 4.1 Summary table to show key features of Yorkshire wood taxa.

GROUP	NON-ARAUCARIAN			
	ARAUCARIAN			
GENERA	<i>Araucarioxylon lindlei</i>	<i>Cupressinoxylon</i> spp.	<i>Taxodioxylon</i> spp.	<i>Cedroxylon</i> spp.
GROWTH RINGS	Well marked growth rings. Transition from earlywood to latewood abrupt, with 7-9 cells forming the latewood zone. False rings absent.	Ring boundaries distinct, with a distinct earlywood-latewood transition; only 2-4 latewood cells per ring. False rings present.	Distinct ring boundaries, with abrupt transition from earlywood to latewood. Latewood composed of 2-4 cells.	Growth rings are distinct and the transition from earlywood to latewood is gradual. Latewood composed of as many as 11 cells. False rings present.
AXIAL PARENCHYMA	Parenchyma is absent.	Widespread parenchyma conspicuous in the transverse plane. Can occur frequently or infrequently.	Some parenchyma observed.	Parenchyma confined to the latewood.
VASCULAR RAYS	Rays uniseriate and 2-15 cells high.	Predominantly uniseriate, 2-22 cells in height, with subordinate biseriate examples, 2-23 cells high.	Uniseriate, 3-12 cells in height.	Rays 2-18 cells high and always uniseriate.
BORDERED PITS ON TRACHEID WALLS	Pits are commonly biseriate, alternate, polygonal and contiguous. More rarely pits are found in up to three rows and compressed.	Tracheary pits circular, spaced and sometimes in contact, mainly arranged uniseriately. Biseriate rows of pits occur more occasionally and are arranged alternately or oppositely.	Predominantly uniseriate. Pits are spaced and slightly elongate in the transverse plane.	Pits are uniseriate, or biseriate and opposite. Occasionally both uniseriate and biseriate pits occur in a single tracheid. Pits generally touching, at times squashed.
CROSS-FIELD PITS	Up to 4 cupressoid pits per cross-field.	Single or several small cupressoid pits per cross-field (7-15µm diameter).	Single taxodioid pit per cross-field (14µm).	Small, circular, cupressoid pits; usually 2 per cross-field (7-9µm).
STRATIGRAPHIC RANGE	?Upper Pliensbachian to lower Toarcian	Cleveland Ironstone to Scalby Formations	Saltwick Formation	Dogger Formation
				Cleveland Ironstone to Scalby Formation

4.6 Growth-ring analysis

4.6.1 Measured characteristics of the growth rings

Before investigating features of growth rings which provide climatic or environmental information, it is pertinent to explain the fundamental nature of tree growth: the trunks, branches and larger roots of a tree consist largely of secondary xylem (or wood) formed by the active division of a layer of cells called the vascular cambium (Creber & Chaloner 1984*a*). As a result of this activity, the cambium is displaced in an ever outward direction. In tropical, equatorial regions where favourable conditions for growth exist year round, activity in the cambium is constant (Creber 1977). In trees growing in mainly temperate latitudes, however, growth is not constant throughout the year because of unfavourable conditions occurring on a seasonal basis which encourage a tree to undergo a period of dormancy. This cessation in growth results in the appearance of tree rings, visible in cross section. Cells are thin walled and achieve a greater radial diameter early in the growth season; later as growth begins to slow, small, dark-coloured, thick-walled cells are produced. The resulting concentric band is called a growth ring and is composed of earlywood and latewood respectively (Fig. 4.9, p.139; Pl. 4.2, fig. 10, p.107).

The presence or absence of growth rings, the mean or maximum ring width, the variability of ring width (mean sensitivity), the proportion of latewood to earlywood, and the presence of false rings are thought to be indicators of climate, and have been used to help identify climatic fluctuations (Creber 1977). In this study, these same features were used to make palaeoclimatic inferences from the Yorkshire wood specimens. Before determining and interpreting the palaeoclimatic signature of the woods it was, however, necessary to identify other factors that might have had an effect on growth, such as taxonomic diversity, and damage by insects and fungi. The position of a tree during life (*e.g.* in a river valley or on a slope) can exert a considerable effect on resultant wood structure, and ideally should also be constrained. However, the allochthonous nature of the wood samples comprising this dataset obviated any possibility of such inquiry.

Of the 76 samples examined, only 39 yielded good cellular preservation in the transverse plane and measurable growth rings. An inherent problem due to the small size of the wood samples are short ring-sequences, which range from 2 to 30 rings, with an overall average of 9 rings per sample. While it is accepted that those sequences preserving a greater number of rings reflect interseasonal growth most accurately, examination of rings series comprising more than 20 rings alone would seriously limit this study (only 9% of the dataset contain sequences

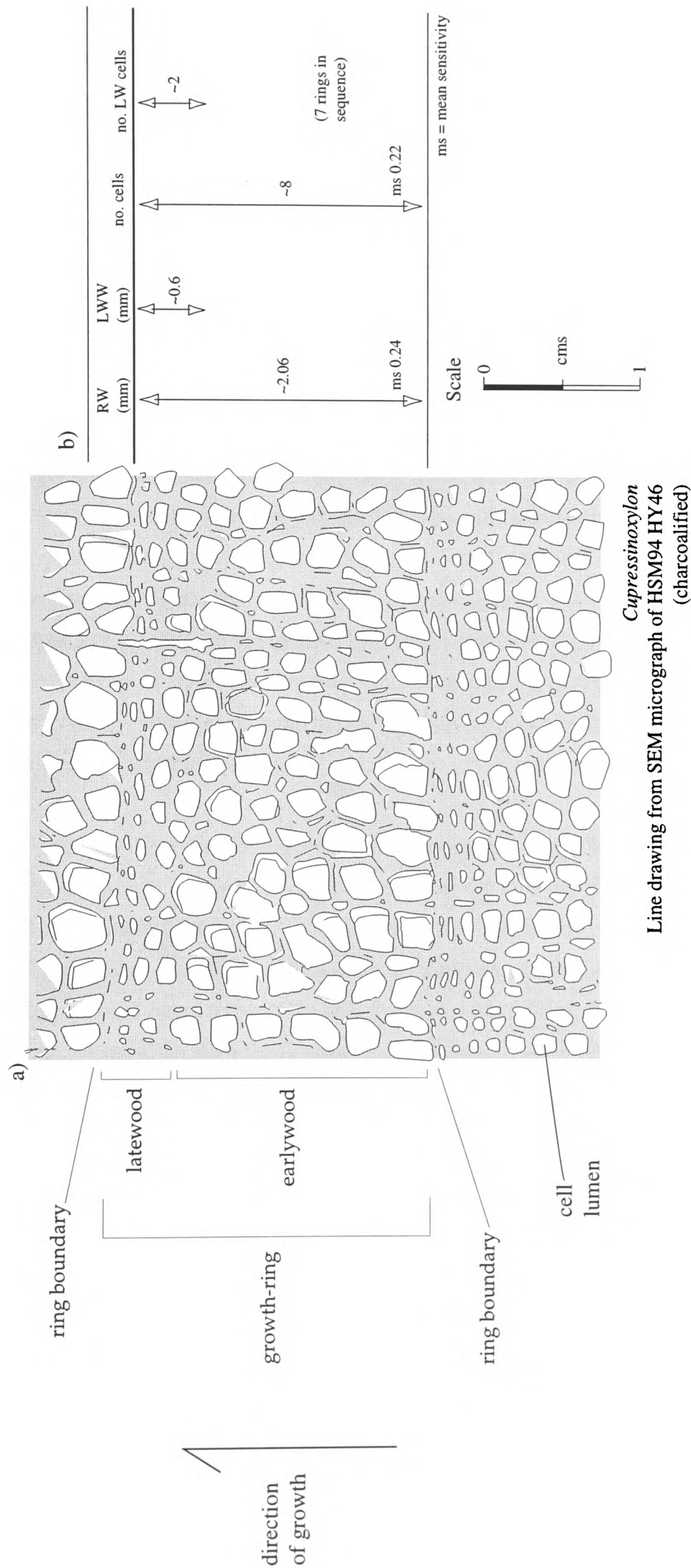


Fig. 4.9 Features of the transverse section.

a) Growth ring terminology. This illustration highlights a single growth ring, composed of earlywood and latewood. Earlywood is characterized by large, thin-walled, window-like cells, and the latewood by smaller, thick-walled latewood cells. Taking a present-day example of wood growing in a temperate climate zone, earlywood equates to spring and summer tree growth, while the latewood marks a slowing in growth. A cessation in growth is represented by a ring boundary.

b) Growth ring measurements for ring analysis. These are the most important features of the transverse section from which climatic or environmental information can be gleaned.

which exceed 20 rings). For this reason, samples consisting of fairly short ring series were also incorporated into the study, and interpretations were weighted accordingly. The following paragraphs describe those characteristics of the growth rings which were measured for the purposes of deriving palaeoclimatic information. (Full details of the results obtained from growth-ring analysis are given in Tables 3.1-3.40, Appendix 3.)

Ring width

Ring width basically expresses the biological productivity of a tree for a given year. It is perhaps the most useful indicator of growth, as generally the wider the ring, the longer the growing season or the faster the growth (Fritts 1976). Seasonal growth is understood to be primarily controlled by the geographical area over which a species is distributed, soil conditions and solar insolation, which are in turn affected by factors such as site conditions (*i.e.* relating to slope, aspect, factors of the hydrological regime) and differences in climatic tolerance between species (Fritts 1976). The activity of the vascular cambium in laying down a year's growth increment is controlled primarily by growth substances (plant hormones) being produced in the young leaves and shoots at the crown of the tree (Creber & Chaloner 1984*a*). The transition to latewood growth near the end of the season is governed by ambient temperature, water availability, atmospheric humidity, nutrient supply and light (Creber & Chaloner 1984*a*). Many of these factors vary on a seasonal basis, interacting with each other and the inherent growth potential of a particular species to produce a situation of some complexity (Creber & Chaloner 1985).

In modern trees, growth rings are often referred to as annual rings, as one increment of growth is added each year. While this is likely true for the Yorkshire Jurassic wood specimens, such an assumption cannot be tested by cross-matching ring series between coeval trees, as it can for modern examples. However, in support of annual ring growth, it has been observed that non-annual rings tend to be less distinct with diffuse boundaries (Jefferson 1982); a feature incompatible with the Yorkshire samples. Two methods were employed to record ring width and the earlywood and latewood components. Measurements were first taken directly from scaled photographs. Next, the number of cells comprising each ring were counted: three measurements were taken for each ring and the results averaged (see Fig. 4.9, p.139). The standard deviation (*i.e.* the measurement of the total variation in ring widths about the mean, or distance from the mean in which 65% of the measurements fall) of each ring series was also calculated for the purpose of ascertaining the variability of growing conditions during the life-time of the tree. A ring series of variable width produces a high standard deviation value which may be explained by a period of climatic fluctuation or environmental perturbation during the growth of a tree, or indicate that the tree grew at the limits of its climatic tolerance, or on the periphery of a forest (Fritts 1976). In contrast, a ring sequence of constant width gives a low standard deviation value, which can be explained by

uniform growing conditions, produced during a period of climatic stability, or position of the tree within a forest interior.

Although standard deviation can be a useful gauge of the variability of past growing conditions, it can produce spurious results if applied to a series of rings of constant width showing only occasional variation in ring width. Such a series could indicate forest disturbance (local factors such as soil conditions, shading by a larger tree, death of a larger tree to create space, fire and storm damage), rather than climatic change. Instead, a year-to-year based calculation called mean sensitivity can be used, which accounts for the presence of atypical rings within a ring series: the method of calculating this variable is described in the following section.

A clear picture of how a wood fragment related to its parent tree can help to increase the validity of palaeoclimatic information is drawn from ring-width analysis. It is important to distinguish between wood derived from aerial axes or subterranean roots, as disparate parts of a tree may express productivity differently (Weaver *et al.* 1997). For this reason, an attempt was made in this study to assess the origin of each sample. Although few of the ring series demonstrate an absolute position within the parent tree, as pith/xylem or xylem/phloem boundaries are uncommon in the majority of the samples, it is possible to assess a specimen's origin and relative maturity by studying the degree of curvature of the rings (J. L. Chapman pers. comm.). That is, while inner rings of a trunk are curved, outer rings are more flat (Francis 1984). The importance of identifying the relative maturity of a ring series is highlighted in the work of Fritts (1976), who stressed that as the circumference of a tree increases and the growth rate declines, there will be a concomitant decrease in ring width: a factor which could lead to spurious palaeoclimatic and palaeoenvironmental interpretations. Furthermore, ascertaining a specimen's place of origin can eradicate problems of interpretation resulting from compaction and contortion of growth rings in basal trunk sections or on the underside of branches.

Similarly, the preservation state of a fossil wood can also affect the ease with which palaeoclimatic data can be gleaned. Many of the specimens analysed in this study, particularly those composed of pyrite, have suffered the effects of distortion and fracturing (Pl. 4.2, figs. 5-8, p.107). In the examination of deformed specimens, distorted rings were traced laterally to an unaffected area where successive measurements could be made. Distorted areas of cells, found particularly in the earlywood, are common features thought to be related to waterlogging or desiccation (Pl. 4.2, fig. 6) (Jefferson 1982; Francis 1984; Creber & Chaloner 1985; Parrish & Spicer 1988). Particular attention was also paid to the occurrence of concentric hairline fractures which run parallel to the growth rings and can obscure or eliminate one or more rings (Pl. 4.2, fig. 2).

Mean Sensitivity

Annual sensitivity is a measure of the similarity between adjacent pairs of growth rings, and mean sensitivity is the average of these values for each wood specimen (Fritts 1976; Creber 1977). Mean sensitivity is calculated using the following equation:

$$ms = 1 / n - 1 \sum_{t=1}^{t=n-1} | (2(x_{t+1} - x_t)) / (x_{t+1} + x_t) |$$

where x_t is the ring width for a given year (t), x_{t+1} is the width of the adjacent ring, and n is the total number of rings in the sequence. For every pair of adjacent rings the mean width is calculated, allowing the variability between consecutive rings to be assessed. By definition, the mean sensitivity of a tree may vary between 0 and 2, the former representing no annual variation, and the latter, great yearly variation. These are, however, extremes rarely encountered in nature. The value of 0.3 is used to split populations (Fritts *et al.* 1965): while a value <0.3 distinguishes 'complacent' trees which are interpreted to have either little response to climate change or alternately indicate climatic stability, a value >0.3 suggests 'sensitivity' to climatic variation (Creber 1977). In very broad terms, a sensitive result may indicate the tree was growing near the edge of its climatic tolerance, or in temperate or boreal regions where climatic conditions fluctuate yearly. In contrast, a complacent tree suggests growth in a non-seasonal, tropical area (Creber & Chaloner 1985).

The calculation does have its limitations, however. For example, a complacent result may not only suggest a tree's growing in the sub-tropics, but also perhaps a tree's growing in a forest interior sheltered from high winds, extremes of temperature, and fluctuations in soil moisture. Wide rings with little or no definition between early- and latewood can be a product of both situations. Similarly, a tree's sensitivity can also be influenced by factors such as waterlogging, which can impede growth (Fritts 1976). Therefore the mean sensitivity calculation should not be used as a sole means to assess past climatic change, as position of growth (*e.g.* altitude, aspect, drainage), disturbance during growth (fire, insect attack) and the taxonomic identity of the tree, can all affect the nature of growth and a tree's tolerance to changing or unfavourable conditions. These factors, in effect, dampen the climate signal: as a result mean sensitivity is perhaps a more accurate reflection of palaeoecological conditions, than palaeoclimatic change.

Latewood

The timing of precipitation during the growing season, temperature at the end of the season, and shorter day lengths related to growth in high latitudes, are all factors which are ascribed to initiation of latewood formation (Fritts 1976; Parrish & Spicer 1988). The sharpness of the transition from earlywood to latewood indicates the rate at which the growing conditions

Palaeoclimatic inferences based on fossil wood

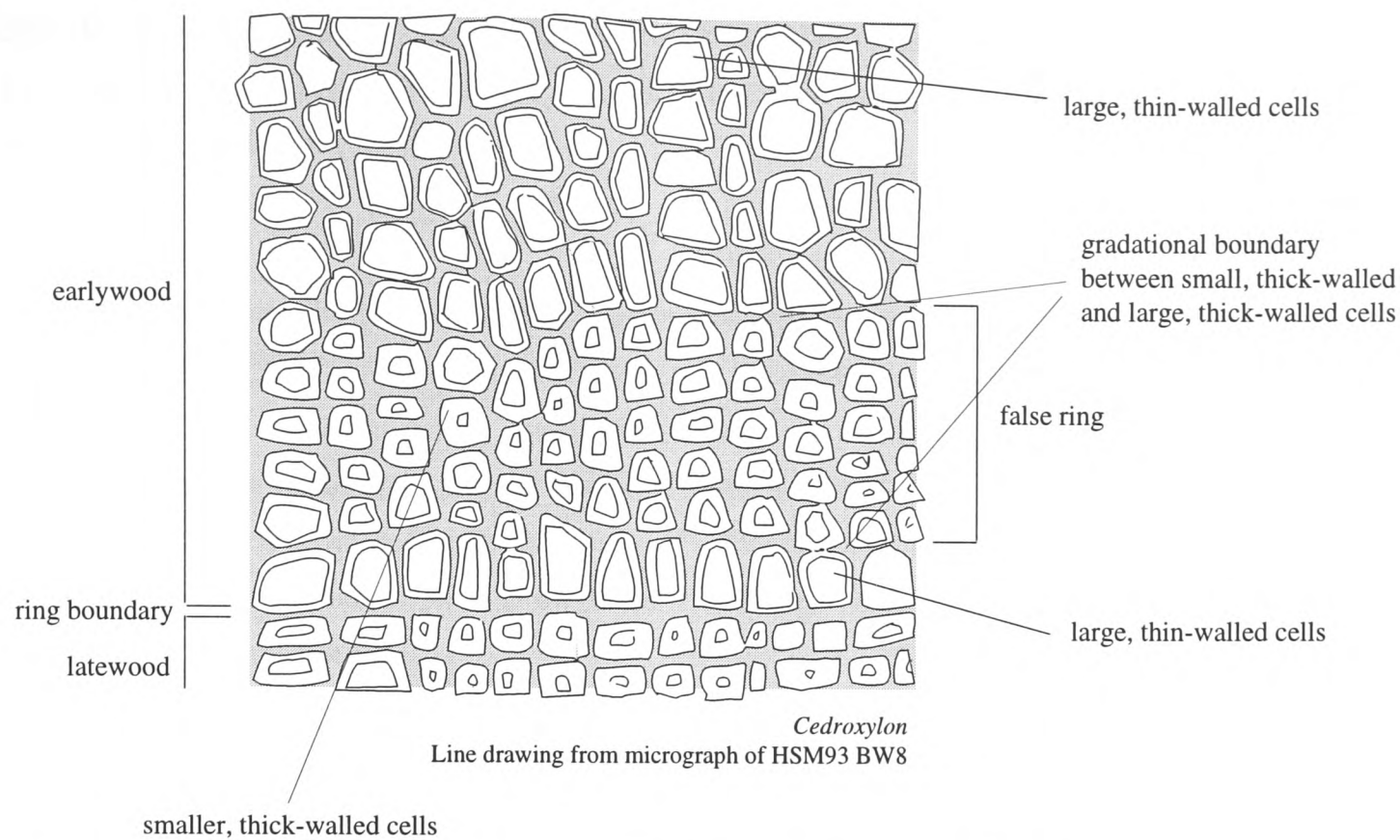


Fig. 4.10 False ring. A false ring is characterized by a gradual diminution of cell size, followed by a return to normal cell size; they can be irregular and discontinuous. False rings can be attributed to, for example, drought, freezing or insect attack during the growing season causing growth to temporarily slow or shut down (Fritts 1976). Location of a tree during growth can also affect development of false rings: for example, a tree growing in a forest interior is unlikely to form false rings, due to the amelioration of local climate by shelter from the surrounding trees (Fritts *et al.* 1965).

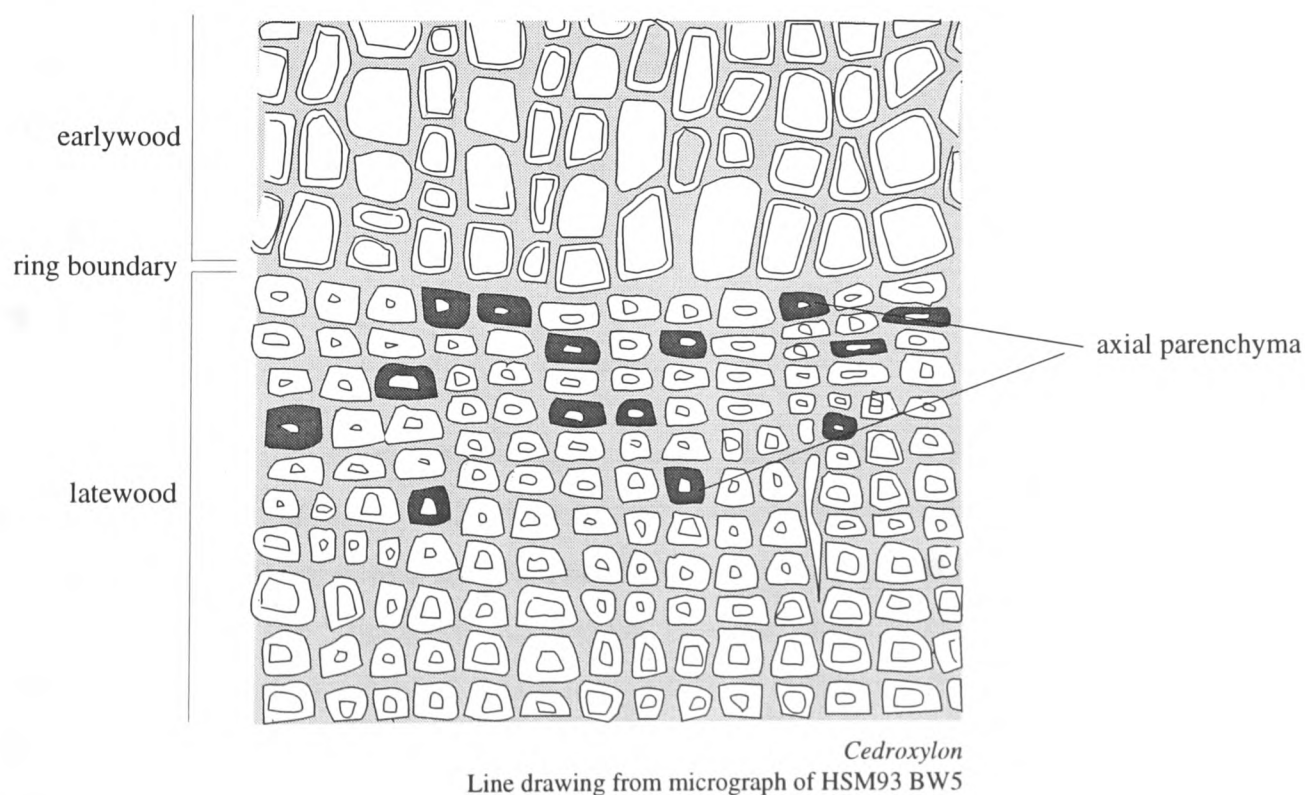


Fig. 4.11 Axial parenchyma dispersed within the latewood of *Cedroxylon*: this feature is a diagnostic feature of the taxon. Parenchyma is a tissue composed of cells that are typically oblong or square in shape and have simple pits. Parenchyma is primarily concerned with the storage and distribution of food materials.

deteriorated, while the resultant width of the latewood reflects how long the tree continued to produce cells under inauspicious conditions before finally shutting down for the season. In recording the latewood, its width was measured, its constituent cells counted and measured ('intra-ring cell analysis' is described by Creber & Francis, in press), and the ratio of earlywood to latewood was calculated.

False rings

False rings may be caused by factors affecting an individual tree, or by general climatic conditions affecting all trees. Although there are many intraseasonal environmental fluctuations which can cause false ring development, they can be summarized as drought, flooding and waterlogging of roots (Spicer 1990), freezing (Glock 1951), insect attack to foliage and herbivory (Creber & Chaloner 1984*a, b*). The position of a tree during growth can also influence their formation, as, for example, false rings rarely form in forest interiors where conditions are ameliorated.

False rings are represented by a gradual diminution of cell size to form thicker-walled 'latewood' cells, followed by a gradual return to thinner-walled earlywood cells (Fig. 4.10). They can be either very dark and more prominent than the annual rings, or much fainter. As a consequence, a false ring may be easily mistaken for latewood and a ring boundary. However, it is possible to distinguish them by a gradual change in cell diameter and cell wall thickness, and also by their irregular and discontinuous form (Pl. 4.2, fig. 1, p.107; Pl. 4.3, fig. 2, p.119). False rings are recorded in the wood collection: each ring was arbitrarily divided into three portions roughly corresponding to the early, middle and late stages of growth in a year and the presence and number of false rings were recorded for each of these divisions. Lastly, the number of affected rings of a sample was calculated and expressed as a percentage of the total rings.

4.7 Results

Growth-ring analysis indicates a markedly seasonal climate during Pliensbachian to Bathonian times in the Yorkshire area, with low to moderate interseasonal variation in wood production. Mean ring-widths for individual samples are in the range of 0.37-4.64 mm, and the broadest ring examined within the Yorkshire wood collection measures 4.64 mm (Table 4.2*a*). While some 38% of the ring series have a mean ring-width of >2 mm — indicating a long growing season, favourable conditions for growth, or both (Fritts 1976) — there are no rings with a width of greater than 5 mm in the collection. Rings of this width are considered to indicate rapid and sustained growth (Parrish & Spicer 1990). Overall, the widest rings are found in

Table 4.2a Growth-ring data.

KEY RW: ring width; s.d.: standard deviation; LW: latewood. Underlining denotes max. and min. values for entire growth-ring series.

Strat. Unit	Specimen Number	Taxa	No. rings	RW (mm)	s.d. (RW)	RW (cells)	s.d. (cells)	LW (cells)	s.d. (LW)
Scalby Formation	J.67907	?	21	1.85	0.77	<u>10</u>	3.42	3	0.76
	J.67904	<i>Xenoxylon phyllocladoides</i>	5	0.55	0.18	15	1.48	3	0.75
	J.67903	<i>Cupressinoxylon</i>	11	0.41	0.20	17	8.27	3	0.83
	HSM94 YNMA	<i>Cupressinoxylon</i>	5	0.63	0.35	24	13.38	4	1.02
	J.67901	<i>Cupressinoxylon</i>	12	<u>0.37</u>	0.09	13	1.54	3	0.72
	mean values:			0.76	0.32	16	5.62	3	0.82
Gristhorpe Member	J.67934	<i>Cupressinoxylon</i>	5	1.05	0.68	63	37.58	3	0.89
	J.67933	?	4	2.40	0.63	111	26.48	4	0.43
	J.67928	<i>Cupressinoxylon</i>	9	2.07	0.58	98	25.10	5	0.96
	J.67926	<i>Cupressinoxylon</i>	4	<u>4.64</u> †	0.47	<u>190</u>	21.58	13	2.35
	J.67925	?	3	1.89	0.25	51	13.02	5	0.47
	J.67924	<i>Cupressinoxylon</i>	3	3.80	0.62	97	18.46	4	0.47
	J.67921	<i>Cupressinoxylon</i>	4	2.83	0.26	83	6.12	4	0.43
	J.67920	<i>Cupressinoxylon</i>	8	1.86	0.57	85	19.82	3	0.33
	J.67919	<i>Cupressinoxylon</i>	3	3.85	0.21	97	9.29	6	0.94
	J.67918	?	3	3.00	0.41	82	9.55	4	0.47
	J.67917	?	8	2.58	0.25	68	8.06	5	0.78
	J.67916	<i>Cupressinoxylon</i>	3	1.86	0.19	85	0	3	0.94
	J.67915	<i>Cupressinoxylon</i>	4	3.62	0.90	107	16.62	8	1.12
	J.67913	<i>Cupressinoxylon</i>	8	2.60	0.25	68	8.06	5	0.78
	mean values:			2.72	0.45	92	15.70	5	0.81
Saltwick Formation	J.67936	<i>Cupressinoxylon</i>	7	2.73	0.70	11	2.71	2	0.45
	J.67937	<i>Cupressinoxylon</i>	6	2.41	0.46	11	1.50	3	0.5
	mean values:			2.57	0.58	11	2.11	3	0.48
Dogger Formation	J.67947	<i>Xenoxylon phyllocladoides</i>	15	1.10	0.32	53	15.15	11	2.98
	J.67946	<i>Cedroxylon</i>	18	1.79	0.64	39	11.79	9	1.54
	J.67945	<i>Cedroxylon</i>	22	1.30	0.39	57	16.32	5	1.37
	J.67944	<i>Cedroxylon</i>	30	1.41	0.86	47	22.99	6	2.65
	J.67943	<i>Cedroxylon</i>	11	1.30	0.33	42	10.75	10	2.21
	mean values:			1.38	0.51	48	15.40	8	2.15
Cleveland Ironstone Formation	J.67953	<i>Cupressinoxylon</i>	2	2.61	0.38	71	8.50	2	0.5
	J.67952	<i>Cupressinoxylon</i>	17	0.72	0.32	30	9.68	6	2.06
	J.67951	<i>Xenoxylon phyllocladoides</i>	17	1.65	0.59	x	x	x	x
	J.67955	<i>Cupressinoxylon</i>	7	1.01	0.05	49	7.24	3	0.45
	J.67954	<i>Cupressinoxylon</i>	8	x	x	35	15.65	3	0.48
	J.67949	?	9	x	x	30	13.92	3	0.74
	J.67956	<i>Xenoxylon phyllocladoides</i>	9	x	x	37	14.39	3	0.89
	J.67950	<i>Taxodioxygen</i>	6	x	x	57	15.55	3	0.79
	mean values:			1.50	0.34	44	12.13	3	0.84
Yorkshire Museum Specimens	1996-163	<i>Araucarioxylon</i>	12	1.49	0.29	43	7.07	9	2.15
	1996-164	<i>Xenoxylon</i>	7	3.50	0.81	100	29.34	6	2.75
	1996-165	<i>Araucarioxylon</i>	13	1.62	0.42	41	13.74	7	1.55
	1996-166	<i>Araucarioxylon</i>	14	1.71	0.57	58	20.16	8	2.10
	mean values:			2.08	0.52	61	17.58	8	2.12

Table 4.2b Growth-ring data, continued.

KEY RW: ring width; AS : annual sensitivity; *ms* : mean sensitivity. Underlining denotes max. and min. values for entire growth-ring series.

Specimen Number	Min. AS (RW)	Max. AS (RW)	ms (RW)	% 'complacent'	Min. AS (cells)	Max. AS (cells)	ms (cells)	% 'complacent'
J.67907	0	0.67	0.27	55	0	0.77	0.26	65
J.67904	0.12	0.73	0.33	50	0.13	0.19	0.11	100
J.67903	0	0.97	0.41	60	0	0.98	0.36	60
HSM94 YNMA	0.03	0.33	<u>0.55</u>	25	0	0.17	<u>0.52</u>	50
J.67901	0.33	1.31	0.16	73	0.21	1.21	0.12	91
mean values:			<u>0.34</u>				0.27	
J.67934	0.07	0.72	0.30	50	0.09	0.85	0.32	50
J.67933	0.13	0.67	0.29	33	0.13	0.67	0.25	67
J.67928	0.07	0.86	0.48	38	0.00	0.83	0.41	38
J.67926	0.11	0.25	0.13	33	0.12	0.27	0.14	100
J.67925	0.22	0.32	0.15	100	0.50	0.61	0.37	0
J.67924	0.26	0.4	0.22	50	0.14	0.44	0.19	50
J.67921	0.09	0.11	0.08	100	0.07	0.24	0.10	100
J.67920	0.07	0.55	0.32	43	0.06	0.51	0.23	43
J.67919	0.06	0.06	0.04	100	0.06	0.22	0.09	100
J.67918	0.31	0.35	0.33	0	0.09	0.13	<u>0.07</u>	100
J.67917	0.08	0.22	0.10	100	0.02	0.26	<u>0.07</u>	100
J.67916	0.07	0.26	0.11	100	x	x	x	x
J.67915	0.09	0.5	0.19	66	0.02	0.31	0.12	67
J.67913	0.08	0.22	0.12	100	0.05	0.26	0.18	100
mean values:			<u>0.20</u>				0.20	
J.67936	0.6	0.45	0.24	50	0.12	0.52	0.22	67
J.67937	0.13	0.52	0.22	60	0.00	0.40	0.12	80
mean values:			<u>0.23</u>				0.17	
J.67947	0.01	1.05	0.43	36	0.05	0.88	0.43	36
J.67946	0.03	0.56	0.26	47	0.02	0.62	0.29	41
J.67945	0	0.67	0.30	57	0.09	0.74	0.44	52
J.67944	0	1.09	0.36	48	0.04	1.00	0.41	45
J.67943	0	0.43	0.24	60	0.00	0.35	0.17	80
mean values:			<u>0.32</u>				0.35	
J.67953	0.29	0.29	0.15	100	0.24	0.24	0.12	100
J.67952	0.02	0.81	0.28	44	0.03	0.98	0.36	38
J.67951	0	1.43	0.33	56	x	x	x	x
J.67955	0.03	0.09	<u>0.04</u>	100	0.02	0.49	0.19	83
J.67954	x	x	x	x	0.04	0.77	0.38	57
J.67949	x	x	x	x	0	0.73	0.34	38
J.67956	x	x	x	x	0.06	0.82	0.37	60
J.67950	x	x	x	x	0.06	0.82	0.35	50
mean values:			<u>0.20</u>				0.30	
1996-163	0	0.39	0.14	82	0	0.43	0.15	91
1996-164	0.09	0.48	0.26	33	0.01	0.54	0.26	50
1996-165	0.04	0.54	0.15	90	0.06	0.42	0.21	92
1996-166	0	1	0.19	69	0.02	0.43	0.2	100
mean values:			<u>0.19</u>				0.21	

Table 4.2c Growth-ring data, continued.

Strat. Unit	Specimen Number	Taxa	Position and instances of false rings:			% of rings containing false rings
			early	middle	late	
Scalby Formation	J.67907	?	2	2	0	9
	J.67904	<i>Xenoxylon phyllocladoides</i>	0	0	0	0
	J.67903	<i>Cupressinoxylon</i>	0	0	1	9
	HSM94 YNMA	<i>Cupressinoxylon</i>	1	3	1	40
	J.67901	<i>Cupressinoxylon</i>	0	0	1	8
	mean values:		27%	46%	27%	20%
Gristhorpe Member	J.67934	<i>Cupressinoxylon</i>	2	3	0	60
	J.67933	?	0	1	0	25
	J.67928	<i>Cupressinoxylon</i>	0	0	0	0
	J.67926	<i>Cupressinoxylon</i>	0	0	0	0
	J.67925	?	0	1	1	33
	J.67924	<i>Cupressinoxylon</i>	0	0	0	0
	J.67921	<i>Cupressinoxylon</i>	0	3	0	50
	J.67920	<i>Cupressinoxylon</i>	1	2	0	25
	J.67919	<i>Cupressinoxylon</i>	2	1	0	66
	J.67918	?	1	0	0	33
	J.67917	?	3	0	0	38
	J.67916	<i>Cupressinoxylon</i>	0	0	0	0
	J.67915	<i>Cupressinoxylon</i>	0	0	0	0
	J.67913	<i>Cupressinoxylon</i>	3	0	0	0
	mean values:		50%	46%	4%	52%
Saltwick Formation	J.67936	<i>Cupressinoxylon</i>	0	0	0	0
	J.67937	<i>Cupressinoxylon</i>	0	0	0	0
	mean values:		0	0	0	0%
Dogger Formation	J.67947	<i>Xenoxylon phyllocladoides</i>	1	0	0	7
	J.67946	<i>Cedroxylon</i>	0	0	0	0
	J.67945	<i>Cedroxylon</i>	5	16	2	50
	J.67944	<i>Cedroxylon</i>	6	17	3	70
	J.67943	<i>Cedroxylon</i>	0	0	0	0
	mean values:		24%	66%	10%	35%
Cleveland Ironstone Formation	J.67953	<i>Cupressinoxylon</i>	0	0	0	0
	J.67952	<i>Cupressinoxylon</i>	2	2	2	29
	J.67951	<i>Xenoxylon phyllocladoides</i>	x	x	x	x
	J.67955	<i>Cupressinoxylon</i>	1	0	0	14
	J.67954	<i>Cupressinoxylon</i>	2	2	2	38
	J.67949	?	x	x	x	x
	J.67956	<i>Xenoxylon phyllocladoides</i>	x	x	x	x
	J.67950	<i>Taxodioxylon</i>	x	x	x	x
	mean values:		38%	31%	31%	41%
Yorkshire Museum Specimens	1996-163	<i>Araucarioxylon</i>	0	0	0	0
	1996-164	<i>Xenoxylon</i>	2	2	1	57
	1996-165	<i>Araucarioxylon</i>	0	0	0	0
	1996-166	<i>Araucarioxylon</i>	0	3	0	21
	mean values:		25%	63%	12%	17%

Table 4.2d Ring-width values for ring sequences of varying length.

length of ring sequence	average ring width	average ms
<10	2.69 mm	0.36
11 to 15	0.79 mm	0.31
16 to 20	1.39 mm	0.29
21 to 25	1.41 mm	0.36
overall average	1.78 mm	0.26

woods collected from the Saltwick Formation and Gristhorpe Member, whereas narrow rings typify samples from the Scalby Formation. Narrow rings, especially those <1 mm (15% of specimens), suggest that seasonal growth was limited. In general, the relative width of the growth rings is more or less equivalent to the number of cells per ring: samples from the Gristhorpe Member have the highest number of cells at 92 on average, whereas the Scalby Formation displays wood containing a mean of only 16 cells (Table 4.2a).

The variation in ring width is, therefore, principally a function of cell number rather than cell diameter, and indicates that the rate of cell division varied on a year-to-year basis, or that the length of the growing season was variable. Annual sensitivity values for the Yorkshire woods generally fall into the complacent field, suggesting little interseasonal perturbation in growing conditions (the wood collection has an average mean sensitivity of 0.27: Table 4.2a). In some samples, however, several highly variable ring couplets exist within individual ring series, producing high annual sensitivity values that skew the mean sensitivity result towards the sensitive field (>0.3). That is, within the generally 'complacent' dataset, some 63% of specimens have annual sensitivity values in excess of 0.3, highlighting sporadic seasons of high or low growth rates (Table 4.2a). These findings indicate that although growth was mostly uniform, adverse growing conditions occasionally occurred which produced one or more rings of variable width. The opposite relationship was found for the Late Jurassic of southern England by Francis (1984), who identified periods of complacency in the predominantly sensitive Purbeck trees. The lack of a discernible pattern or regularity to the fluctuations in annual sensitivity found in the present wood collection indicates that variations in local conditions may have been the cause. This being the case, it may be true that mean sensitivity is indeed a better indication of palaeoecological conditions, than palaeoclimatic change.

It has been suggested by previous authors (*e.g.* Fritts 1974; Jefferson 1982), that growth character may differ between taxonomically disparate woods, and, therefore, there may be anatomical variation between trees growing in comparable environmental and climatic settings. The results from this study indicate only a limited correlation between genotype and growth-ring character, however. When ring width and standard deviation in the wood collection are compared (characteristics which are believed to be strongly controlled by a tree's genetic make-up), there does not appear to be any significant correlation with species type. Whilst this finding may be true of this dataset of limited size, it is however in contrast to the observations of Fritts *et al.* (1965), who found large differences in mean sensitivity and standard deviation between species.

Each season's growth consists mostly of uniform-sized earlywood cells with just two to four smaller cells comprising the latewood. A small amount of latewood is a common feature in

woods from the Saltwick Formation, Gristhorpe Member and Scalby Formation, and is associated with a sharp transition from the earlywood. The sharpness of the boundary may relate to a rapid deterioration in growth at the end of the season, which may relate to cool temperatures or lack of rainfall: shorter day lengths at high latitudes can be ruled out as Yorkshire lay at approximately 35°N during the Middle Jurassic (*e.g.* Ziegler *et al.* 1993). Among the Yorkshire wood collection, several samples display a contrastingly wide latewood zone and a more gradual transition from the earlywood. These specimens are primarily from the Cleveland Ironstone Formation (including specimens from the Yorkshire museum which are inferred to be of this age) and the Dogger Formation. One explanation for a wide latewood zone in modern trees, is the presence of greater rainfall late in the growing season (Fritts 1976): an interpretation which may be applied to these fossil woods. Overall, between 3% and 21% of a single ring is composed of latewood.

The woods show many false rings. The number of false rings within an annual increment varies considerably in the wood collection however, as some seasons have no false rings, while others have up to four. Although woods of the Saltwick Formation are devoid of false rings, the very small sample size (2 specimens) questions their inclusion in the results. Disregarding these woods, between 17 and 52% of specimens include false rings. The false rings are not grouped in particular zones of the growth ring (*i.e.* early, middle, late portions), but tend to occur throughout (Table 4.2c). Similarly, they are as common in woods consisting of narrow growth-rings of variable width (Scalby Formation woods), as in woods with wide rings of constant width (from the Gristhorpe Member). Their ubiquitous presence is reminiscent of false rings found in woods from ancient and modern semiarid and Mediterranean climates (Francis 1984). In such regions, false rings are produced by water shortages during the season, and the resultant ring width controlled by annual drought. In light of the growth-ring analysis results as a whole, it is proposed that the Yorkshire woods may have undergone similar water restrictions during life: as evidenced by narrow rings, sensitive mean sensitivity values and presence of false rings. Given the abundant nature of false rings in the samples and what we understand of the climatic conditions of the time, we can safely rule out insect attack and freezing as cause for their formation.

Comparison of the different growth-ring characters shows that there is a correlation between anatomical features interpreted to represent particular growing conditions. For example, there appears to be reciprocal relationship between ring width and latewood width within a single stratigraphic unit. Specimens from the Scalby Formation exemplify this case, as all woods have narrow rings and narrow latewood zones. In contrast, however, the development of false rings and rings of variable width (which often produce sensitive annual sensitivity results) seems to have been rather more aberrant. Overall, this pattern of occurrence suggests that climate may have been the dominant control on the length of the growing season

(affecting ring width, latewood growth), which was periodically superimposed by local site conditions that affected intraseasonal growth, including false ring formation.

In summary, growth-ring analysis indicates a distinctly seasonal climate with low to moderate interseasonal variation in growth. Significant intraseasonal influences on wood production are implicit in the abundance of false rings. Whilst factors such as (1) the variation in growth-ring characteristics, within and between specimens; (2) the difficulty in distinguishing a sample's origin on the parent tree; and (3) absence of *in situ* fossil woods, hamper a quantitative palaeoclimatic study, the information gleaned from this analysis nevertheless significantly enhances our previous knowledge of climatic conditions during the Yorkshire Jurassic. Salient conclusions drawn from this analysis are commented upon below.

4.8 Discussion

Perhaps the most secure palaeoclimatic inference we can draw from this study is the presence of a pronounced seasonality during Late Pliensbachian to Late Bathonian times in the Yorkshire area. Of course, evidence attained from growth-ring analysis does not stand alone in indicating seasonal variation, as there are several features of the sedimentological and floral record which provide congruent evidence. On the basis of swamp and pond deposits, freshwater bivalves, authigenic siderites, kaolinite-rich muds, ferns and other species that require abundant moisture, fungal attack of plant material, and the sheer size of the logs that are preserved, it is inferred that water was in plentiful supply for at least part of the year. However, clearly defined growth rings, pollen with windborne dispersal, abundant charcoal, and signs in the floral record of seasonal deciduousness in certain ginkgophytes and cycadophytes, indicate that a distinct dry season existed. A post-mortem feature known as checking, which appears as elongate slits on tracheid walls, is found in 9% of the samples (predominantly from the Scalby Formation, but also single samples from the Dogger and Saltwick Formations), provides persuasive evidence for desiccation of the wood. Furthermore, evidence in the sedimentary record for flooding episodes, crevassing, abandonment of distributary channels by avulsion, and variations in lake sedimentation probably related to run-off, indicates seasonal variations in water supply. Although the Cleveland Basin probably experienced annual periods of water shortage, evaporite formation and development of desiccation cracks (for example) were inhibited — most probably by the proximity of the sea which tempered the climate.

Based on the evidence presented above, it is proposed that the seasons were chiefly controlled by water supply. This suggestion is compatible with previous interpretations, based upon

alternative sources of evidence, which indicate that in general terms seasonality during the Middle Jurassic interval was predominantly controlled by precipitation levels, and not temperature fluctuations (*e.g.* Stahl & Jordan 1969; Hallam 1984; Kutzbach & Gallimore 1989; Dubiel *et al.* 1991). Furthermore, growth-ring analysis has shown that the seasonal dry spell was accentuated in the Bathonian Scalby Formation, as evidenced by narrow rings of variable width, sharp earlywood-latewood transition, wide latewood and abundant false rings. The possibility of stressed growing conditions in the Bathonian concurs with work by Hudson (1968) and Wright (1985) who, from the examination of growth bands in mollusc shells, concluded that the climate during the Bathonian experienced strong seasonal fluctuations. More recently, this supposition has been embellished upon by Hendry & Kalin (1997) following isotopic analysis of Bathonian mollusc shells from eastern England. They imply a seasonal, moderately humid, 'Mediterranean'-type climate in the Bathonian: conditions not unlike those envisaged by Francis (1983, 1984) for the Purbeck of southern England.

The somewhat aberrant occurrence of false rings was remarked upon in the previous section. Based upon their presence in both narrow and wide growth rings (which are understood to reflect length of the growing season), it is suggested that false ring formation is a reflection of local, site conditions. Previous authors have indicated that many of the Yorkshire conifers grew on well-drained, upland areas adjacent to the delta-plain (Chaloner 1958; Harris 1966, 1979). If, in such areas, the water-table was at the limit of root penetration, then growth would quickly cease during (both inter- and intraseasonal) periods of drought. The narrow rings and abundance of false rings in woods from the Scalby Formation indicate that they may derived from such an upland area. Conversely, samples from the Gristhorpe Member are indicative of growth on slightly elevated areas of the flood-plain itself, where water was in plentiful supply (so that growth could continue for a greater part of the year, producing wide rings). False rings are also common in the Gristhorpe fossil wood, but they may perhaps be suggestive of waterlogging, rather than drought.

In order to clarify the significance of these growth-ring features, it is useful to consider the woods in a stratigraphic sense:

Cleveland Ironstone Formation

The ring series comprising the calcified and partially pyritized wood specimens from this unit fall below the average ring width for the Yorkshire woods, and exhibit one of the lowest standard deviations for the entire collection. This relative uniformity in ring width is mirrored by a particularly low, or 'complacent', mean sensitivity. Therefore, although it would appear that the growing season during the Pliensbachian was comparatively short, the conditions that governed annual growth were fairly constant. The transition from the earlywood to latewood

is fairly abrupt, implying that growth at the end of the season rapidly shut down and ceased. Despite the inferred constancy of yearly growth, false rings are fairly common, indicating that there were periodic water-shortages. It is possible that these samples represent growth in upland, well-drained areas adjacent to the flood-plain, where apart from periodic water-shortages, the environment was largely stable. A wide range of wood genera occur at this stratigraphic level.

The Yorkshire Museum specimens are derived from roughly this same stratigraphic level. The rings comprising these woods are wider than average, and of a fairly constant width, while the transition to the wide latewood zone is gradual. False rings are present in all but two of the specimens. Overall the samples indicate a more favourable growing environment than those woods collected during fieldwork for this study, perhaps as an indication of the position of growth.

Dogger Formation

Specimens derived from this unit display the longest overall ring sequences in this study. The rings themselves are typically of below average width and more narrow than those described from the Cleveland Ironstone Formation. In contrast, however, the standard deviation of these ring series is greater than those from the Cleveland Ironstone Formation. This indicates a shorter growing season of variable length which is also demonstrated by a relatively high mean sensitivity value: these specimens, together with the samples from the Scalby Formation, form the only 'sensitive' mean sensitivity values for the wood collection. Limited growth is also highlighted by abundant false rings, which are at their most common in wood samples of this unit. Given the character of these samples, it seems likely that these specimens grew in upland areas where soils were well drained and the water-table fell within the limit of root penetration.

These features provide tangible evidence for a brief and relatively unstable growing season during the Early Aalenian, but the latewood of these specimens complicates the interpretation somewhat. Rather than the rapid termination of growth inferred for the samples from the Cleveland Ironstone Formation, these specimens commonly show a gradual passage to latewood growth and a wide latewood zone. As noted in the previous section, this feature is present in samples of both *X. phyllocladoides* and *Cedroxylon*, and so cannot easily be explained by genotype alone. Superimposition of climatic deterioration on species tolerance is, however, a distinct possibility.

Saltwick Formation

Unfortunately, the number of samples from this unit preserving a transverse section is small, which hinders palaeoclimatic interpretation for the Late Aalenian. Both charcoalified samples

reveal wider than average ring widths showing little intra-annual variability, complying with the 'complacent' mean sensitivity value calculated. The apparent amelioration of growing conditions, compared to the woods from underlying units, is further supported by the absence of false rings and a narrow latewood zone. Although these results should most probably be disregarded statistically, it is interesting to note that growth rings in woods from the overlying Gristhorpe Member are similar.

Gristhorpe Member

Ring series comprising these pyritized wood samples are wide and of a relatively constant width, producing the lowest group of mean sensitivity values for the entire wood collection. This indicates that growth was not significantly or periodically limited over the course of the growing season. A commonly narrow latewood zone suggests that growth shut-down fairly rapidly at the end of the season. The occurrence of a small number of specimens with a wide latewood zone most probably show some degree of genetic overprint. Despite the apparently favourable conditions for growth, the common development of false rings in the early- to mid-portion of the rings suggests that periods existed when growth was temporarily impeded. It seems likely that samples from this unit were derived from trees growing on slightly elevated areas of the flood-plain where water was in plentiful supply: as a result local site conditions may mask the original climate signal.

Scalby Formation

The growth rings forming woods from the Scalby Formation are particularly narrow and of variable width; yielding the most 'sensitive' mean sensitivity value for the whole Yorkshire wood collection. The growing season was therefore short and not favourable for plant growth, and was constrained by limiting factors dominated by water supply (supported by the presence of false rings). In addition, the latewood is exceptionally wide, forming at least 20% of the entire ring width, which attests to a gradual deterioration in growing conditions from an earlier point in the season compared to the older woods. Implicit in the features of these growth rings is a comparatively stressed growing environment, one which has been highlighted by previous researchers using other floral evidence: some suggesting that an increase in aridity occurred in the Bathonian (*e.g.* Vakhrameev 1991; Boulter & Windle 1993). Here it is suggested that the seasons became accented, prolonging the annual dry spell.

4.9 Conclusion

The ease with which climatic information can be retrieved from growth rings depends on the influence of local conditions during growth. It is certain that small-scale environmental perturbations are expressed in the rings but unfortunately the allochthonous nature of the

samples makes separation of these features from a climatic signal difficult. However, in combination with sedimentological, stratigraphical, and other floral data, inferences can be made on the particular conditions of growth.

If we first consider the position of growth, calcified, pyritized and charcoalified samples derived from the Cleveland Ironstone Formation, Dogger Formation, Scalby Formation and Yorkshire Museum may represent a range of conifers growing in well-drained, upland areas. The far-traveled nature of these specimens is indicated by their presence in coarse-grained, distributary channel sandstones and marine sediments. These woods show a high incidence of narrow ring-series and false rings, indicating that a limited water supply restricted growth. It is proposed that in such upland areas the conditions of growth were stable (low mean sensitivity values) during the Early Jurassic, but became more unsettled with time. The harshest climatic conditions are expressed in wood samples from the Bathonian Scalby Formation.

Although results from the Saltwick Formation should be treated with caution given the limited sample size, these charcoalified woods reveal similar features to the pyritized specimens derived from the Gristhorpe Member. In contrast to the woods described above, these specimens reveal wide rings of relatively constant width reflected in a low mean sensitivity value. While the incorporation of these samples into crevasse-splay sandstones highlights a degree of transportation prior to deposition, the growth rings indicate that the trees may have grown in areas where growth could persist for a greater part of the year; perhaps on slightly elevated areas of the flood-plain. In such a setting false rings could equally have developed through waterlogging or drought.

Of course, the effect of climatic changes are superimposed on the nature of the site conditions. Earlier in the chapter, the coincidence of charcoal in regressive parts of the sequence was highlighted. It appears that during regressive episodes, vegetation dried out sufficiently during the dry season to allow forest fires to become easily initiated by lightning or electrical storms at the start of the wet season. In light of this, we might reasonably assume that the effect of regression on the climate was to accentuate the seasonality, reducing rainfall and lengthening the dry season. This limiting effect on growth is best displayed by woods from the Scalby Formation, which is compatible with the 'Mediterranean' palaeoclimate during the Bathonian envisaged by Hendry & Kalin (1997). The reverse of this hypothesis, in times of transgression, is difficult to test because rising sea-level may not so much ameliorate the climate as inundate more environmentally stable, forested areas inland: in both cases, wood revealing growth rings indicative of favourable conditions of growth will become incorporated into the sequence.

Therefore, if regression does indeed accentuate seasonality by reducing water supply, perhaps the effects are most apparent in woods from the Scalby Formation because they are superimposed on a climatic deterioration towards drier conditions. A change in the composition of the Yorkshire flora into the Bathonian has been noted before (Couper 1958; Florin 1958), and ascribed to an increase in aridity (Boulter & Windle 1993). Clearly, to elucidate fully the climatic conditions it is necessary to consider these results within the context of the entire floral database. The following chapter investigates temporal fluctuations in the Yorkshire plant megafossils and assesses their palaeoclimatic significance.

Based on the evidence presented above, a picture of a seasonal climate with an annual dry spell emerges in which tree growth was sensitive to variations in climatic conditions; the character of the growing season appears to have been accentuated during regressive phases. Periodically, the trees were subject to brief unfavourable periods of drought, or some other form of water stress, which commonly caused the formation of false rings. The high frequency of false rings indicates that periods of water stress were fairly common. Furthermore, narrow latewood-zones are commonplace indicating an abrupt end to the growing season and onset of more hostile conditions. The overall 'complacent' mean sensitivity results indicate that the trees grew within the limits of their natural geographic range, but a high incidence of 'sensitive' annual sensitivity values suggests that at times the trees were exposed to adverse growing conditions, most probably as a result of local fluctuations in the hydrological regime.

4.10 Glossary of terms used in wood anatomy

Based on Barefoot & Hankins (1982), with contributions from Fritts (1976).

Araucarian pitting - Bordered pits which are alternate in position, abut and have hexagonal borders.

Bars of sanio - Former name for crassulae; see below.

Cambium - The actively dividing layer of cells that lies between, and gives rise to, secondary xylem and phloem.

Cambium initial - Individual cell of the cambium.

Crassula(e) - Cellulose thickenings across the tracheids: appear as white lines between the pits in the fossil wood.

Cross-field - Formed by the walls of a ray cell and an axial tracheid as seen in radial section.

Cupressoid pits - Bordered pits showing an aperture which is inclined from the horizontal position.

Earlywood - Wood growth early in the growing season: characterized by large, thin-walled, window-like cells.

False ring - Characterized by a gradual diminution of cell size, followed by a return to normal cell size; they can be irregular and/or discontinuous. Can be attributed to drought, freezing or insect attack causing growth to temporarily slow or shut down.

Fusiform initial - Cambial initial giving rise to an axial element of xylem or phloem; it is spindle-shaped.

Growth ring - A layer of wood produced during a single growing season. A ring can usually, particularly in woods of temperate zones, be divided into earlywood and latewood.

Heartwood - Inner layers of wood containing no living cells and in which the reserve materials (e.g. starch) have been converted into heartwood substances.

Latewood - Wood growth late in the growing season: characterized by small, thick-walled cells.

Lumen - The cell cavity.

Medullary ray - See ray.

Parenchyma - Tissue comprised of oblong or square-shaped cells which have simple pits. Primarily concerned with the storage and distribution of food materials.

Parenchyma, axial - Parenchyma cells derived from fusiform cambial initials. Axial parenchyma appears as dark oblong or square cells, conspicuous in the transverse plane.

Phloem - Primary food conducting tissue of vascular plants. Separated from the secondary xylem by the cambium from which it was derived.

Pith - Central core of stem comprised of mainly parenchyma or soft tissue.

Pit - A recess in the secondary wall of a cell, together with its external closing membrane; open internally to the lumen.

Pit, aperture - The opening or mouth of a pit.

Pit, bordered - A pit in which the membrane is overarched by the secondary cell wall.

Ray - Ribbon-like cells extending radially from xylem to phloem.

Secondary xylem - Wood produced by the vascular cambium, immediately beneath the bark.

Taxodioid pits - Bordered pits which contain apertures which are horizontal in position, parallel to the transverse section of the tree.

Tracheary element - Principal water conducting element of the xylem; mostly vessels and tracheids.

Tracheid - Imperforate wood cell with bordered pits to adjacent tracheids. Their main function is to provide mechanical strength by adhering to one another.

Wood - The principal strengthening and water-conducting tissue of stems and roots.

Characterized by presence of tracheary elements. Synonymous with xylem.

Xylem - See wood.

Table 4.3a List of identified wood samples from the Lower and Middle Jurassic of Yorkshire.

N.B. With the exception of samples from the Cleveland Ironstone Formation, where the bed numbers of Howard (1985) are used, all other samples are related to the bed numbers and figures of sedimentary logs compiled for this study. Wood sample diameters relate to the transverse section. For every specimen, details of preserved and examined faces are denoted by the letter Y (Tr.S= transverse plane studied only; L.S.= longitudinal planes only; 3 planes= all 3 planes).

STAGE	STRATIGRAPHIC UNIT		BED NUMBER	AMMONITE ZONE	SAMPLE NUMBER	LOCALITY	SIZE (diameter)	COMPOSITION	3 planes	Tr.S only	L.S only	TAXA
BATHONIAN	Scalby Formation	Long Nab Member	(Scalby Ness p.b.)	<i>?orbis</i> Zone	J.67895	Scalby Ness	1.5 cm	All specimens are charcoallified			Y	<i>Cedroxylon</i>
			52, Fig. 1.4		J.67900	Yons Nab	1.2 cm				Y	<i>Cupressinoxylon</i>
			52, Fig. 1.4		HSM94 YN47	Yons Nab	1.4 cm				Y	<i>Cupressinoxylon</i>
			52, Fig. 1.4		HSM94 YNMA	Yons Nab	1.7 cm				Y	<i>Cupressinoxylon</i>
			52, Fig. 1.4		J.67901	Yons Nab	1.7 cm					<i>Cupressinoxylon</i>
			52, Fig. 1.4		J.67902	Yons Nab	1.4 cm				Y	<i>Cupressinoxylon</i>
			52, Fig. 1.4		J.67903	Yons Nab	1.8 cm		Y			<i>Cupressinoxylon</i>
			52, Fig. 1.4		J.67904	Yons Nab	1.5 cm		Y			<i>X. phyllocladioides</i>
			13, Fig. 1.10		HSM94 WN18a	White Nab	1.2 cm				Y	<i>Cupressinoxylon</i>
			13, Fig. 1.10		J.67896	White Nab	1.3 cm			Y		<i>?</i>
	Moor Grit Member		13, Fig. 1.10	<i>?discus</i> Zone	J.6789	White Nab	1.1 cm		Y			<i>Cupressinoxylon</i>
			13, Fig. 1.10		J.67898	White Nab	1.4 cm		Y			<i>Cupressinoxylon</i>
			13, Fig. 1.10		J.67899	White Nab	1.4 cm		Y			<i>Cupressinoxylon</i>
			13, Fig. 1.10		J.67905	Scar. South Cliff	1.8 cm		Y			<i>Cupressinoxylon</i>
			13, Fig. 1.10		J.67906	Scar. South Cliff	1.6 cm					<i>Cupressinoxylon</i>
			13, Fig. 1.10		J.67907	Scar. South Cliff	1.7 cm		Y			<i>?</i>
			13, Fig. 1.10		HSM94 SSC1	Scar. South Cliff	1.7 cm			Y	Y	<i>Cupressinoxylon</i>
BAJOCIAN	Scarborough Formation	Helwath Beck Member	63, Fig. 1.15	<i>sauzei</i> Zone	J.67910	Cloughton Wyke	1.2 cm	Calcified			Y	<i>Cupressinoxylon</i>
			63, Fig. 1.15		J.67911	Cloughton Wyke	1 cm	Calcified			Y	<i>Cupressinoxylon</i>
			63, Fig. 1.15		J.67912	Cloughton Wyke	1.4 cm	Calcified			Y	<i>Cupressinoxylon</i>
	Cloughton Formation	Gristhorpe Member	50, Fig. 1.15	<i>sauzei</i> Zone	HSM93 CW10	Cloughton Wyke	1.3 cm	Calcified			Y	<i>Cupressinoxylon</i>
			24, Fig. 1.15		J.67913		2.4 cm	Pyritised		Y		<i>Cupressinoxylon</i>
			24, Fig. 1.15		J.67914		1.6 cm	Pyritised			Y	<i>Cupressinoxylon</i>
			24, Fig. 1.15		J.67915	all samples	0.8 cm	Pyritised		Y		<i>Cupressinoxylon</i>
			24, Fig. 1.15		J.67916	collected from	1.4 cm	Pyritised		Y		<i>?</i>
			24, Fig. 1.15		J.67917	the Gristhorpe	3 cm	Pyritised		Y		<i>?</i>

Table 4.3 continued.

PLIENSBACHIAN	Cleveland Ironstone Formation	Penny Nab Member	27 28 28 34 34 34 34 34 37	<i>margaritatus</i> Zone	J.67948	Staithes	3.7 cm	Pyrite			Y	<i>Taxodiooxylon</i> ?
					J.67949	Hawsker Bottoms	4.3 cm	Pyrite		Y		<i>Taxodiooxylon</i>
					J.67950	Staithes	8 cm	Pyrite		Y		<i>X. phyllocladioides</i>
					J.67951	Hawsker Bottoms	5.5 cm	Pyritised & calcified		Y		<i>Cupressinoxylon</i>
					J.67952	Hawsker Bottoms	4 cm	Pyrite		Y		<i>Cupressinoxylon</i>
					J.67953	Hawsker Bottoms	2.2 cm	Pyrite		Y		<i>Cupressinoxylon</i>
					J.67954	Hawsker Bottoms	3.1 cm	Pyrite		Y		<i>Cupressinoxylon</i>
					J.67955	Hawsker Bottoms	4.1 cm	Pyrite		Y		<i>X. phyllocladioides</i>
					J.67956	Staithes	2.9 cm	Pyrite			Y	

Table 4.3b Yorkshire Museum Specimens.

M. Lias Lias Lias Lias Lias		1994 1799-46	nr. Whitby	2 cm	Pyrite		Y	<i>Araucarioxylon</i>
		1996-163	nr. Whitby	6.7 cm	Calcified	Y		<i>Araucarioxylon</i>
		1996-164	nr. Whitby	9.5 cm	Calcified	Y		<i>Xenoxylon</i>
		1996-165	nr. Whitby	6 cm	Calcified	Y		<i>Araucarioxylon</i>
		1996-166	nr. Whitby	5.4 cm	Calcified	Y		<i>Araucarioxylon</i>

Table 4.4a Summary of data from the radial and tangential longitudinal planes.
Missing data reflects poor preservation of the sample.

Specimen Number	Cross-field pits			Rays			
	pit diameter (µm)	max. no. pits	mean no. pits	% uniseriate rays	min. cell no.	max. cell no.	% biseriate rays
J.67895	6	10	6	100	3	8	0
J.67897	9	1	1	100	7	13	0
HSM94 WN18a	7	4	3	80	3	11	20
J.67899	9	1	1	100	5	22	0
J.67900	9	2	1	100	6	20	0
HSM93 YN47	10	1	1	100	6	20	0
J.67901	10	1	1	100	2	10	0
J.67902	11	1	1	100	3	16	0
J.67903	9	1	1	100	3	12	0
J.67904	10	1	1	100	2	11	0
J.67905	9	1	1	100	1	5	0
J.67906	10	2	2	100	2	8	0
HSM93 SSC1	11	1	1	100	1	7	0
J.67908	12	1	1	100	1	7	0
J.67909	14	1	1	100	2	9	0
J.67910	10	1	1	100	4	8	0
J.67911	9	1	1	100	2	10	0
J.67912	10	1	1	100	2	10	0
J.67932				90	4	14	10
J.67931				50	6	14	50
J.67930				80	2	7	20
J.67923				80	3	13	20
J.67924				90	2	10	10
J.67921				100	2	12	0
J.67914				90	2	16	10
J.67929	9	4	3	50	7	20	50
J.67928	10	1	1	90	2	9	10
J.67927	9	2	1	80	7	11	20
J.67926	10	2	1	50	2	22	50
HSM95 CW10	9	2	1	100	3	9	0
J.67940	14	1	1	100	3	12	0
HSM93 HY2	13	1	1	100	6	12	0
J.67930	15	1	1	100	4	13	0
HSM93 HYB	15	1	1	100	3	8	0
HSM93 HY45	12	4	4	100	3	5	0
J.67939	13	1	1	100	2	7	0
J.67935	12	1	1	100	1	7	0
HSM93 BW2	7	1	1	100	2	12	0
HSM93 BW3	8	1	1	100	2	9	
J.67947	7	2	1	100	3	10	0
J.67943	7	2	1	100	3	13	0
J.67942	9	2	1	100	3	13	0
J.67953				100	2	6	0
J.67952				100	3	7	0
J.67951	14	1	1	100	3	7	0
J.67954	13	1	1	100	3	8	0
J.67956	14	1	1	100	3	6	0
J.67950	13	4	3	100	3	8	0
1994 1799-16	12	3	2	100	3	13	0
1996-163	12	4	3	100	2	12	0
1996-164	14	1	1	100	2	12	0
1996-165	13	3	2	100	3	15	0
1996-166	12	3	2	100	4	11	0

Table 4.4b Summary of data from the radial and tangential longitudinal planes.

Specimen Number	Bordered pits							
	pit diameter (µm)	aperture diameter (µm)	uniseriate pits (%)	biseriate pits (%)	triseriate pits (%)	Pit character: spaced/touching	round/ hexagonal	If biseriate, opposite/alternate
J.67895	10		100	0	0	spaced	round	x
J.67897	14	6	100	0	0	spaced	round	x
HSM94 WN18a	15	5	100	0	0	touching	round	x
J.67899	22	8	100	0	0	spaced	round	x
J.67900	18	4	100	0	0	touching	round	x
HSM93 YN47	17	4	100	0	0	touching	round	x
J.67901	16		10	0		touching	round	x
J.67902	18		100	0	0	touching	round	x
J.67903	17		100	0	0	touching	round	x
J.67904	16		100	0	0	spaced	round	x
J.67905	11	6	100	0	0	spaced	round	x
J.67906	12		100	0	0	touching	round	x
HSM93 SSC1	15	4	100	0	0	touching	round	x
J.67908	14	5	100	0	0	spaced	round	x
J.67909	13	3	100	0	0	spaced	round	x
J.67910	15		100	0	0	spaced	round	x
J.67911	12	3	100	0	0	spaced	round	x
J.67912	11		100	0	0	touching	round	x
J.67932								
J.67931								
J.67930								
J.67923								
J.67924								
J.67921								
J.67914								
J.67929	15	4	50	50	(rare)	touching	round	alt + opp
J.67928	13		60	40	0	spaced + touching	round	alt
J.67927	12		50	50	0	touching	round	alt
J.67926	12	2	50	50	0	touching	round	alt
HSM95 CW10	15	5	100	0	0	spaced	round	x
J.67940	18	6	90	10	0	spaced + touching	round	alt
HSM93 HY2	19	6	100	0	0	spaced	round	x
J.67930	18	8	100	0	0	spaced	round	x
HSM93 HYB	17	6	100	0	0	spaced	round	x
HSM93 HY45	14		100	0	0	spaced	round	x
J.67939	17		100	0	0	spaced	round	x
J.67935	15		100	0	0	spaced	round	x
HSM93 BW2	12		100	0	0	spaced	round	x
HSM93 BW3	14		100	0	0	spaced	round	x
J.67947	18	4	50	40	10	spaced + touching	round	alt + opp
J.67943	14		50	50	0	spaced	round	x
J.67942	14		50	50	0	spaced	round	x
J.67953								
J.67952			50	50	0	touching	round	alt
J.67951	28	9	100	0	0		round	
J.67954	24	7	100	0	0		round	
J.67956	22	9	90	10	0	touching		alt + opp
J.67950	21	6	90	10	0	touching	round	alt + opp
1994 1799-16	15	3	0	100	0	touching	hexagonal	alt
1996-163	16	4	0	100	0	touching	hexagonal	alt
1996-164	28	8	100	0	0	spaced + touching	round	x
1996-165	17	3	0	75	25	touching	hexagonal	alt
1996-166	18	4	0	100	0	touching	hexagonal	alt

Chapter 5

Chapter 5

Stratigraphic distribution of the Yorkshire flora

5.1 Introduction

This investigation of the Yorkshire flora's distribution has two primary components. Firstly, a brief review is presented of previous attempts at classifying the plant beds in terms of their depositional environment, floral components and degree of fragmentation. These studies are discussed in light of the findings from this thesis, as an understanding of the taphonomic processes at work during the deposition of the Yorkshire flora is of paramount importance in the analysis of its temporal distribution as a measure of palaeoclimatic change. The temporal distribution of the flora forms the second part of this chapter. This particular study subjects the plant remains to a multivariate statistical analysis in order to determine the validity of previous investigations which have revealed a fluctuation in the flora with time. The data challenge Harris' conclusion that the flora displays no significant vertical stratigraphic variations.

5.2 Discussion of previous work investigating the distribution of the flora

Two alternative approaches have been employed in attempting to identify the palaeoecological controls on plant growth during the Middle Jurassic in Yorkshire. One is concerned with classification of the plant assemblages by type (*i.e.* in terms of composition, degree of fragmentation, inferred depositional environment), while the other investigates the temporal distribution of the flora.

5.2.1 Classification of the plant beds

The first attempt to classify the Yorkshire plant beds in a sedimentological context was carried out by Black (1929) who, based chiefly on plant beds exposed in the cliffs at Scalby and Burniston, concluded that there are two main kinds of plant bed in Yorkshire:

1) 'Drifted' (allochthonous) plant beds. These assemblages are distinctly sorted and dominated by robust, thick-cuticled leaves such as ginkgophytes. The lithology of the beds is typically coarse-grained and associated with distributary channels or sheet sandstones, such as the Scalby Wyke Plant Bed.

2) '*In situ*' (autochthonous) plant beds. These beds are poorly sorted and as a consequence both robust and delicate leaves occur together. These assemblages are typically found in fine-grained sediments deposited in lakes and swamps in the flood-plain environment, such as in the Gristhorpe Plant Bed.

Harris (1952*a*) refined Black's basic classification using information from all Yorkshire plant beds known to him at the time; he divided the plant assemblages into four main types: 1) those with excellent (that is, well-preserved) leaves, 2) coal seams, 3) root beds and 4) dispersed fragments. Harris (1952*a*, 1953) considered the beds within a depositional context, allowing him to arrange the accumulations into the five types listed below to which have been added observations made by Hill (1974*a*) and this study. In Harris' scheme, the term *in situ* is restricted to beds whose plants are strictly in the position of growth: this point was stressed by Harris (1952*a*) because, although there are examples of exceptionally well-preserved plant assemblages in Yorkshire (*e.g.* the Gristhorpe Plant Bed), a truly autochthonous origin cannot be proven in the absence of roots and stems.

Harris' scheme:

1. Beds where plants are preserved in position of growth; upright stems and roots are usually all that remain of the original plant. For example, the '*Equisetum* Beds' at the foot of Beast Cliff, north of Hayburn Wyke, and 5.5 m above base of Sycarham Member, Iron Scar.
2. Fine-grained sediments deposited in freshwater lagoons and abandoned channels; fructifications found with leaves and stems, such as the Hasty Bank section and Gristhorpe Plant Bed. Note that Black (1929) ascribed these beds to his *in situ* category.
3. Distributary channels infilled by fine sand, containing a flora similar to that of type 2 albeit with slightly more water-abraded material. Exemplified by the Whitby Long Bight Plant Bed.
4. Channel deposits of fine to coarse sand, containing a drifted flora. Water-worn material is prevalent and fragments of charcoal common. Intergrades with type 3. Examples are the Millepore Bed and the plant beds in the Scalby Formation at Yons Nab and Scalby Wyke.
5. Redeposited plant beds consisting almost entirely of material with thick cuticles: such as the Bilsdale Tripsdale Todd Intake Plant Bed and Westerdale Stockdale Beck waterfall bed.

5.2.2 Discussion

Black's concept of a two-fold classification for the plant beds of Yorkshire is based upon the assumption that plant fossils behave like sedimentary particles: *i.e.* because drifted floras are more fragmented and sorted than *in situ* ones, it is assumed that they have been transported further before deposition and therefore represent a more inland source. If this is true, taking Black's idea a step further, it is clear from field observations that drifted floras are mainly associated with coarse-grained sediments, and *in situ* floras with fine-grained deposits. Hill (1974a) rationalized this correspondence by assuming the Yorkshire Jurassic delta behaved in the same way as modern systems, in that sediment of a coarser grain-size is deposited in proximity to the inland source where flow velocity is high, and the finer sediment downstream where the river is more tranquil. It then follows that plant fossils contained within the coarser-grained deposits were derived from further inland and had been comminuted beyond recognition by the time they reached the lower parts of the delta-plain, allowing plants growing locally to be preferentially represented (*i.e.* the *in situ* flora).

While the notion of an inland flora (drifted) versus delta flora (*in situ*) is the conventional interpretation, there is no evidence that drifted floras grew on upland hills alone. Moreover, modern deltas expose several zones of vegetation, indicating that the 'drifted' and '*in situ*' floras could simply represent two zones of the delta vegetation growing relatively close together. Hill (1974a) suggested that the *in situ* flora may have grown on low swampy areas of the floodplain, while the drifted flora occupied slightly higher, better drained regions. Therefore, while the two floras grew in relatively close proximity, the contrast in ecological conditions imposed by variations in water supply was sufficient to create these rather different floras. Hill (1974a) inferred that the common occurrence of lowland *in situ* floras in the succession can be explained by their position of growth along swampy margins of laterally migrating distributary channels: only when the delta subsided and the channels migrated across previously stable land did drifted floras become incorporated into the depositional sequence.

A similar scenario was suggested by Harris (1966) to explain the favoured representation of inland floras in some stratigraphic intervals. Within the otherwise barren, coarse-grained, channel sandstones of the Moor Grit Member (Scalby Formation), thin but laterally extensive plant beds occur containing abundant conifers and presumed taxads (first described by Florin in 1958). Harris (1966) suggested that subsidence of the delta and concomitant relative sea-level rise would have drowned lower areas of the delta-plain and its constituent flora, allowing the preservation of plants from higher levels of the delta.

Although these conclusions may be, in broad terms, correct, their validity may be questioned in light of field observations noted during work for this thesis. Firstly, Black's scheme assumes

that the floral assemblages are exclusively drifted or *in situ*, which they clearly are not: in fact there are several examples of single plant beds in Yorkshire (*e.g.* the Gristhorpe Plant Bed; beds 23-26, Fig. 1.3) which, when traced laterally, display features of both types of floral assemblage. Although Black (1929) offered the Gristhorpe Plant Bed as an example of an *in situ* plant bed, roots and stems in the position of growth have not been found, suggesting that the remains could have been transported, even if only over a short distance (Harris 1952a). However, even where roots are associated with an assemblage, there may still be a drifted component to the flora. Secondly, by the simple nature of Black's classification, a drifted deposit must represent all plant accumulations thought not to be in the position of growth: this is a somewhat vague bracket to describe what in reality are a range of assemblages that have travelled over different distances. In fact, transportation of a plant organ is commonly variable between species and also between sites: for example, while *Equisetum columnare* occurs *in situ* at Hasty Bank, Iron Scar and north of Hayburn Wyke, at other localities (such as Hayburn Wyke and Cloughton Wyke) it has a disarticulated, drifted appearance. From such points, it may therefore be concluded that, although Black's concept of drifting is essentially correct, the term should ideally be applied to the plant bed in question only in varying degrees of severity.

Yet even the refined classification of Harris (1952a), which stipulates that *in situ* beds must display roots and upright stems, and divides drifted assemblages into four common types, does not account for all possibilities. Of course, this is not surprising considering the unique character of many assemblages in terms of their taxonomic diversity, species abundance, degree of fragmentation and leaf physiognomy. The effect of a taphonomic bias upon the original vegetation varies from one depositional environment to another as a product of the sedimentary regime, including matrix type, climate, the hydrological properties of a leaf species and its resistance to degradation and microbial attack. For these reasons, appropriate care must be taken when making palaeoclimatic or other environmental inferences from transported floral remains.

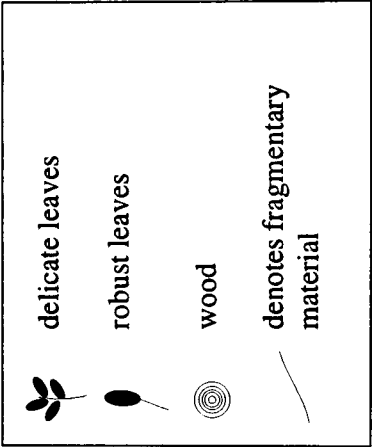
5.2.3 A new classification scheme

Table 5.1 presents a summary of the sedimentary facies in which plant remains are found in the Ravenscar Group. In contrast to Harris' classification, which is based chiefly on the content and degree of fragmentation of the flora itself, this summary considers the flora primarily in terms of the sedimentary facies in which it is contained. This scheme is based upon the facies analysis described in Chapter 2: in this instance, however, more information is provided regarding the flora's preservation state and field examples of where such assemblages can be found.

Unlike the schemes of Black and Harris, the classification does not distinguish purely autochthonous and allochthonous assemblages. The reason for this amalgamation rests on the fact that these two types of assemblage are usually found together. The lower part of the

Facies	Floral preservation	Description	Example	Correspondence to the work of Harris —	
				insitu	Black drifted
Variable sand bodies (A1): (a) channel lag	  	Fragmentary, highly sorted assemblages, dominated by wood of various sizes. Best preserved in braided, vertically accreted channels.	Channel at base of Saltwick Formation, east Whitby.		✓
(b) upper part of point bar	  	Diverse, well-preserved, unsorted plant remains.	Scalby Ness Plant Bed, Scalby Ness.		✓
(c) upper portion of channel body	  	Finely disseminated plant fragments, upper parts are also rooted. Some <i>in situ Equisetum</i> .	Top of Channel 'X', Saltwick Formation, Hayburn Wyke; beds 1-5, Fig. 1.28.		✓
Crevasse-splays (A2)	  	Robust, fragmentary plant remains. Substantial root systems and <i>in situ Equisetum</i> .	Mid-Gristhorpe Member, Yons Nab (beds 31-33, Fig. 1.3) Sandstone tiers, Gristhorpe Mb, Cloughton Wyke (beds 34-39, Fig. 1.15).	✓	✓
Interbedded crevasse-splays and flood-plain facies (A2, A4/A5)	  	Mix of robust remains in the crevasse splays and more delicate, unsorted plants in the flood-plain deposits.	Hayburn Wyke Plant Bed (beds 1-5, log b, Fig. 1.31).		✓
Freshwater lake (A3)	  	Mix of well preserved leaves, stems and wood. <i>In situ Equisetum</i> and rootlets commonly found.	Base of Saltwick Formation, Whitby area.		✓
Ponds on flood-plain (A4) & abandoned channels	  	Plant remains occur as exceptionally preserved pockets within flood-plain deposits. Wood is pyritised.	Gristhorpe (beds 23-26, Fig. 1.3), Hasty Bank, <i>Solenites</i> (bed 22, Fig. 1.15) & Scalby Wyke Plant Beds.		✓
Interchannel deposits (A5)	  	Plant material is often poorly preserved and fragmentary. <i>In situ</i> roots and <i>Equisetum</i> common.	Lowermost Sycarham Member, Iron Scar (beds 13-15, Fig. 1.24).	✓	✓
Back-barrier lagoon (L1)	  	Highly abraded flora, dominated by robust taxa and wood.	Ginkgoalean Plant Bed, Cloughton Wyke (bed 14, Fig. 1.15).		✓
Coastal marsh (L3)	  	Charcoalified wood and leaflets common in sandy parts of this facies, while well preserved leaves are common in the silty beds.	Top of Saltwick Formation, Hayburn Wyke, (bed 5, log b, Fig. 1.31).	✓	✓
Various open marine facies (M1-M7)	  	Plant material is uncommon, well sorted, abraded and highly fragmentary.	Scarborough Formation, Cloughton Wyke.		✓
Sandy shoreface (M2)	  	Heavy rooting at the top of this facies. Some fragmentary plant remains.	Top of Saltwick Formation, Hayburn Wyke, (bed 12, log a, Fig. 1.31); <i>Nilsonia</i> Bed (bed 16, Fig. 1.15).		✓
Shallow marine sand belt (M8)	  	Plant material is uncommon, well sorted, abraded and highly fragmentary.	Millepore Bed, Cloughton Wyke (beds 5-10, Fig. 1.15)		✓

Table 5.1 Sedimentary facies in which plant material is found in the Ravenscar Group. Chapter 2 provides further details of the sedimentary facies.



Sycarham Member at Iron Scar illustrates this point, as *in situ Equisetum* penetrates a palaeosol in which poorly preserved, fragmentary plant remains are found. In either of the previous classification schemes these floras would have been separated into *in situ* and drifted components. This classification does not 'shoe-horn' the floral assemblages into a small number of plant-bed types conceived by the fragmentation of the plant remains, but instead relies foremost on the recognition of the sedimentary facies, within which a variety of species and preservation states may be found.

5.3 Changes in the distribution of the flora

In Harris' opinion (Harris 1952*b*, p.209), the flora is more or less evenly distributed spatially across the Yorkshire area, and furthermore does not display a fine stratigraphic zonation which could be useful for correlation purposes. He did, however, find a distinct floral character to each of the Deltaic Series subdivisions, which was evident as a change in the frequency of individual species through the succession (excluding those rare species whose range and frequency are poorly understood). Harris created five floral groups from this work which he believed had zonal significance. With the addition of a sixth group by Van Konijnenburg-Van Cittert (1971), the groups are listed below:

1. Species spanning the whole succession without a striking change in abundance, for example, *Brachyphyllum mamillare* and *Coniopteris hymenophylloides*.
2. Species common in the lower formations but lacking in the uppermost Scalby Formation, including *Equisetum columnare*.
3. Species such as *Pachypteris papillosa* which appear to be confined to the Dogger and/or Saltwick Formations.
4. Species common in the Saltwick Formation which are rare or absent in the Cloughton Formation, only to become common again in the Scalby Formation. For example, *Pseudoctenis oleosa*, *Ptilophyllum pectinoides*, *Baiera furcata*, and *Pachypteris lanceolata*.
5. Species common in the Cloughton Formation, but which are practically absent from the underlying and overlying formations. These include *Ptilophyllum pecten* with male *Weltrichia pecten* and the female *Williamsonia leckenbyi*.
6. Species such as *Ginkgo huttoni* and *Czekanowskia blackii*, characteristic of the Scalby Formation, but rare or absent from other beds.

According to Harris (1952*b*, p.207) his results indicate a “fluctuation and return in the flora”, as the Saltwick and Scalby Formations are characterized by the relative abundance of one species, and the two members of the Cloughton Formation by the relative abundance of another. In terms of the floral groups listed above, groups 1, 2, 3 and 6 are typical of a gradually changing flora through time, and groups 4 and 5 imply a fluctuation and subsequent restoration of the flora. Van Konijnenberg-Van Cittert (1971) added the sixth category to Harris’ five floral groups in light of the large proportion of unique species contained within the Scalby Formation. This tripartite division of the Ravenscar Group flora into assemblages which typify the Saltwick, Cloughton and Scalby Formations, concurs with the findings of Fox-Strangways (1892) who published the first outline to the general stratigraphic relations of the Yorkshire flora. Despite exposing a temporal fluctuation in the flora, Harris (1952*b*) concluded that in light of the apparently equal numbers of xeromorphic to delicate leaves through the succession, the flora should be treated as a single entity.

5.4 Testing Harris’ zonation

Since the work of Harris (1952*b*), several palaeobotanists have attempted to reproduce this temporal fluctuation in the flora using particular macrofossil groups or palynological data. Florin (1958, p.379) investigated the distribution of the ‘taxad-conifer complex’ of the flora and discovered closer similarities between the “Lower and Middle Deltaics”, than between the “Lower and Upper Deltaics” as Harris (1952*b*) had found. That is, it appeared that the flora of the Sycharham Member was comparable to that of the Saltwick Formation and Gristhorpe Member, while the Scalby Formation contained a high percentage of species quite unlike the flora of the underlying units. Florin interpreted this zonation as reflecting a gradually changing flora through time.

In a similar vein, Couper (1958) studied the occurrence and distribution of dispersed spores and pollen grains in the Middle Jurassic strata. He found the spore and pollen assemblages from the Scalby Formation could be readily separated from the Saltwick and Cloughton Formations, warranting a ‘separation’ in accordance with Florin. In fact, Couper found the Scalby Formation assemblages to be so distinct that he was able to recognize cognate assemblages in coeval British sections, leading him to postulate that the “Upper Deltaic [Scalby Formation] flora may have a definite stratigraphic value.” Furthermore, Couper (1958, p.96) detected a change in araucarian versus pinaceous remains through the Jurassic succession. While araucarian plants, represented by *Araucarites australis* and related forms characterized by *Classopollis torosus*, predominate over ‘pinaceous’ plants in the Saltwick and Cloughton Formations, this position is reversed in

the Scalby Formation and into the Upper Jurassic. At the end of the Jurassic (especially in the Purbeck Beds), *Classopollis* pollen resumed the dominant role for a short period before becoming very rare or absent again in the Early Cretaceous (Wealden). Couper offers no explanation as to the cause of these fluctuations, but other researchers such as Vakhrameev (*e.g.* 1982, Fig. 2; 1991, p.22) have related the presence of *Classopollis* to arid conditions.

Temporal variation in recovered Mesozoic palynomorphs was also noted by Boulter & Windle (1993) in their collation of palynological data from England and Sweden. On the basis of this work they were able to infer three distinct floral communities: Mesozoic gymnosperms in the Aalenian, fern prairies in the Bajocian, and coniferous forest in the Late Bathonian. They suggest that the change in the flora with time may be a product of climatic change towards more arid conditions, in which the humidity-loving Mesozoic gymnosperms disappeared, thus providing a niche for the conifers.

5.5 A multivariate approach to understanding the temporal distribution of the Yorkshire flora

5.5.1 Introduction

The concept that plants may reflect changes in their environment and therefore are useful palaeoclimatic tools is well established (*e.g.* Seward 1892). Studies of modern vegetation have revealed that in response to competition from their neighbours, plants are forced to develop a close relationship with the environment in which they grow in order to maximize their photosynthetic capability. We see the effects of this competition as a suite of morphological characters which reflect the climatic conditions in which they live. Leaves best display these characters and therefore carry the strongest climatic signal (Spicer 1989). In the fossil record, however, such a signal may have been dampened by the effects of transport, burial and diagenetic alteration. While the possibility of a taphonomic bias is inherent in any study concerned with floral (or faunal) assemblages, it is understood that due to the relatively delicate nature of leaves (compared to more durable spores and pollen grains or fossil wood) they rarely travel great distances from their origin and they are seldom reworked once deposited (Spicer & Wolfe 1987). For these reasons, leaves are both good indicators of a relatively local environment and have the potential to yield a high-resolution climate signal.

In an attempt to examine the putative link between floral remains and climate, until recently two alternative methodologies have been employed. The floristic approach operates on the assumption that a fossil plant's 'Nearest Living Relative' (NLR) can provide useful

environmental information in reconstructing a flora's environment of growth (Axelrod 1957, 1965; Axelrod & Bailey 1976). On a very general level, the NLR procedure shows that the Pinaceae are indicative of more temperate conditions than other conifers; the Cheirolepdiaceae are suggestive of warm climatic conditions disposed to intermittent arid periods; and the Caytoniales are characteristic of sub-tropical climates (*e.g.* Vakhrameev 1991). However, on a more detailed taxonomic level the basic tenets to the floristic approach are considered to be flawed, as they rely on the assumption that the environmental preferences of a taxonomic group remain constant over time; an assumption which in turn implies evolutionary stasis (Wolfe & Schorn 1989). Although these assumptions may be legitimate for diverse modern groups such as the palms (which are uniformly sensitive to frost: Wing & Greenwood 1993), many comparative examples exist to demonstrate the unsuitability of the NLR method. For instance, the genus *Ginkgo* was widely distributed in the Mesozoic compared to its presently restricted distribution in southeastern China (Tralau 1968). It was previously thought that the suitability of the NLR approach was further undermined by the unknown affect the advent of the angiosperms may have had on the relationship between non-angiosperms and climate (Hughes 1994). However, other work by Spicer *et al.* (1993) has shown that the evolution of the angiosperms did not greatly disturb the relationship between non-angiosperms and climate.

Developed in the early part of this century, the second, physiognomic, approach concentrates on identifying the link between leaf physiognomy and climate (Bailey & Sinnott 1915, 1916). Its main premise assumes that physiognomic adaptations occur repeatedly in unrelated species responding to the same environmental constraints. This method is independent of the undetermined relationship between modern and ancient plants, which forms the basis to the NLR approach and hence is considered to be most reliable for extracting climatic information from plant fossils.

Unlike the angiosperms which display physiognomic characters quantifiable in terms of climate (*e.g.* Wolfe 1979, 1993; Spicer 1990), non-angiosperms (*e.g.* ferns, pteridosperms, cycadophytes and conifers) as yet provide only qualitative climatic data. Early attempts to glean climatic information from non-angiosperms concentrated on the determination of broad phytogeographic patterns thought to relate to climatic zones. Many of these studies have since been criticized for their highly subjective use of data, reliance on only a few key taxa, and poorly constrained stratigraphic frameworks (*e.g.* Krassilov 1981). More recently, many palaeoclimatic studies using floral databases have turned to a multivariate statistical approach known as Correspondence Analysis (CA), which has been widely used by plant ecologists. CA allows the data to be portrayed in two-dimensional plots of either localities or taxa, permitting the patterns observed to be easily compared (Hill 1973, 1979). The ordination plots gained from this method contain a scatter of data points which represent the

species (or genera) comprising the flora in question: the first two axes produced by CA between them represent ~70% of the variation within the dataset. It is understood that in these plots similar entities are close by and dissimilar entities are far apart (Gauch 1982). From CA we can therefore resolve the significance between various elements of the floral assemblages and ascertain spatial or temporal divisions in the flora.

The ability of this technique to display phytogeographic patterns has been proven in several exploratory analyses — including study of Permian (Ziegler 1990), early Mesozoic (Ziegler *et al.* 1993, 1996) and Cretaceous floral data matrices (Spicer *et al.* 1993) — and has shown that the taxonomy of plant remains at a generic level reflects morphology and thus physiognomy. These analyses determine that there is also a correlation with climate. A climatic signal is most apparent when only leaf or leafy shoot genera are analysed as these are known to display the strongest physiognomic relationship to climate (Spicer & Thomas 1986; Spicer *et al.* 1993; Ziegler *et al.* 1993).

In order to better minimize taxonomic inconsistencies between previous studies, work is usually conducted at a higher taxonomic level which ensures a more standardized approach to identifications. This avoids problems of morphological variability of foliar organs, uncertainty of the relation of foliar organs to each other, and the subjectivity in assigning foliar organs to species. However, because of the comparatively good preservation of the Yorkshire flora (including identifiable features of the cuticle and reproductive structures) the likelihood of these inconsistencies affecting taxonomic identifications is diminished. Also, at the generic level the problem of species endemism is avoided.

In general terms, it is understood that certain characteristics of leaves correspond to particular palaeoclimatic conditions (Ziegler *et al.* 1993). The most obvious palaeoclimatically significant morphological differences between leaves include size (microphyllous or macrophyllous) and shape (broad or narrow), which can be combined with features such as cuticle thickness, character of the stomata and presence of papillae. Previous studies have shown that taxa displaying similar morphological features tend to group together in ordination plots (*e.g.* Spicer *et al.* 1993; Ziegler *et al.* 1996). The development of small leaves with thick cuticles, for example, is most probably in response to low moisture availability and relatively high temperatures, producing a high evaporative stress.

The following study employs CA in order to examine whether the fluctuation and temporal change in the Yorkshire flora found by previous palaeobotanists is reproducible and therefore conclusive, by subjecting the plant remains to a modern statistical treatment. While this is not the first endeavour to retrieve a climatic signal from the Middle Jurassic flora, it is the first rigorous quantitative attempt.

5.5.2 Floral data assembly and method of analysis

Floral lists were compiled for taxa of individual stratigraphic units from two sources: primarily from taxonomic information accessible in the literature, and also from data collected during fieldwork for this thesis. The lists incorporate pteridophyte, cycadophyte, coniferophyte and ginkgophyte leaves (fructifications are omitted), obtained chiefly from Fox-Strangways (1892), Seward (1900, 1904), Black (1929), Harris (1961-1980), Hill (1974*a, b*, 1987), Hill & Van Konijnenburg-Van Cittert (1973), Spicer & Hill (1979), Hill *et al.* (1985) and Van Konijnenburg-Van Cittert (1975, 1987, 1996). Three separate matrices were created from this dataset: Firstly, a data matrix was constructed for simple generic presence or absence through nine stratigraphic units comprising the Middle Jurassic interval. The results from this aspect of the analysis form the foundation to this study, as taxonomy of plants at a generic level is understood to reflect morphology from which climatic information can most accurately be recovered. This assumption is based upon climatically defined biomes created for the present day by Walter (1985). These biomes were defined on the basis of seasonal aspects of temperature and precipitation gained from about 8000 meteorological stations around the world. By comparing a fossil flora to the template of physiognomic characters which define Walter's biomes, several authors have successfully obtained palaeoclimatic information (*e.g.* Ziegler *et al.* 1993, 1996).

Secondly, a matrix composed of taxa at a specific level was assembled, to test the validity of results gained from analysis of the genera and investigate the degree of taxonomic inconsistency in the assignment of plant organs to species. Any inconsistency was not, however, thought to be great because of the exceptional preservation of the plant remains and its examination by essentially one worker (Tom Harris). Lastly, in light of possible taphonomic biases in the floras, the simple generic data matrix was adjusted to account for individual plant beds with known depositional environments. This last approach provides an opportunity to test and refine the climatic information obtained from simple generic CA. All these lists were then subjected to a multivariate statistical analysis (CA) which demonstrates the correlation of foliar physiognomy with time during the Middle Jurassic interval.

The stratigraphic units which constrain the floral lists relate primarily to the component formations and, where relevant, members of the Ravenscar Group. Additionally, because a small group of species is known to be confined to the very base of the Saltwick Formation and top of the Scalby Formation, these units have further been divided in two, at a level corresponding to roughly the mid-point of the formations — the lack of a precise stratigraphic control in the palaeobotanical literature allows only this otherwise arbitrary

division. A total of nine stratigraphic units results, within which 57 genera and 158 species were examined.

In order to investigate changes in the floral composition of individual assemblages through the sequence, it was originally hoped that all plant beds previously recognized in Yorkshire could be included in the revised data matrix. However, a lack of stratigraphic and geographic constraint in some of the published sources frustrated this particular goal. The best alternative therefore incorporates eleven of the so-called 'classic' plant beds which span the temporal extent of the Ravenscar Group and reveal the diverse and abundant flora which has always been of great interest to palaeobotanists. As a result, they are referred to in a consistent manner, and their approximate position in the stratigraphy and geographical location is well known (unlike some of the smaller more obscure plant accumulations). It has to be acknowledged that inability to include all known plant beds produces a bias in itself, but was the only course open under these circumstances.

5.6 Results and discussion

Ordination plots of the three principal axes for both stratigraphic units and taxa were generated for the genera, species and plant bed analyses. It is clear from examination of the stratigraphic unit plots (Figs. 5.1 and 5.4) that the principal axis (axis 1) shows a general correlation with time. In the taxonomic plots this axis displays an overall physiognomic trend from broad-leafed, thin-cuticled taxa towards more small-leafed forms showing xeromorphic characteristics. This change in physiognomy complements the conclusions drawn from growth-ring analysis in the previous chapter (p.155), as both datasets indicate a trend towards a seasonally dry climate in the Bathonian. However, as the plots generated by CA could equally reflect an enhanced taphonomic bias or an increased marine influence, the following paragraphs explore the validity of each possibility in reference to the ordination results. A series of plots has been prepared to portray these findings (Figs. 5.1-5.7), which form the basis for a discussion of the results below. The data points comprising these plots may represent a single taxon, or several taxa, depending on the closeness of the correspondence between genera. For the sake of clarity, only the most common or climatically significant taxa are referred to in the text: full floral lists are included in Appendix 4 (Tables 4.1-4.5).

5.6.1 Yorkshire plant genera

The polarity of broad- to small-leaved taxa is most apparent in the plots generated from the analysis of the flora at a generic level. The taxa plot (Fig. 5.2) demonstrates a distinct separation of genera along axis 1 (which accounts for 33.1% of the variance), from broad-leaved ferns on the left (including *Marattia*, *Hausmannia* and *Clathropteris*) to xeromorphic cycadophytes (such as *Zamites* and *Otozamites*) and small-leaved coniferophytes (including *Brachyphyllum* and *Pagiophyllum*) to the right. Broad-leaved, possibly deciduous cycadophytes (*Nilsonia*, *Pterophyllum* and *Ctenis*), ginkgophytes (*Ginkgo*, *Baiera*, *Sphenobaiera*, *Czekanowskia*) and coniferophytes (*Elatides* and *Elatocladus*) are intermediate between the two. The distinct separation of the fern *Marattia* and the conifer shoot *Pagiophyllum*, for example, suggests that these taxa rarely co-occur. While axis 2 appears to display little variation in taxa from the Saltwick and Cloughton Formations, it does seem to account for more variance in genera from the Scalby Formation and the three marine units.

A similar discontinuity exists in the complementary plot of sites (Fig. 5.1). A trend is evident from left to right along axis 1 of sequential, non-marine stages of the Ravenscar Group: from the Saltwick to the Scalby Formations inclusive. Interestingly, the marine units (Lebberston Member and Eller Beck and Scarborough Formations) are not positioned where one might otherwise expect in this temporal trend and instead occur very close to the Scalby Formation. Possible explanations for this pattern are explored below.

Superposition of the site and the genus plots (Fig. 5.3) shows a high degree of correspondence between fern-dominated vegetation and the Saltwick Formation (left of axis 1) and mixed macrophyllous cycadophytes and ginkgophytes and the Cloughton Formation (mid-point of axis 1). There is a considerable degree of overlap between the genera characterizing the Saltwick and Cloughton Formations, indicating that the floral assemblages from these units are not exclusive, but instead represent a subtle alteration with time from a fern-dominated, to a mixed macrophyllous, flora. While there is less of a correspondence between the microphyllous, xeromorphic genera and units of the Scalby Formation (to the right of axis 1 and higher on axis 2), there is nevertheless an association with the floral elements of the Cloughton Formation, which is also shared to a certain extent with the marine units. The coniferophytes neatly display this apparent morphological trend towards microphyllous taxa: long-leaved and relatively thin-cuticled *Elatides* and *Elatocladus* represent the coniferophyte component of the Cloughton Formation (mid-point of axis 1), which are supplanted by thicker-cuticled, commonly succulent, smaller-leaved taxa such as *Brachyphyllum*, *Pagiophyllum*, *Pityocladus*, *Bilsdalea* and *Geinitzia* in the Scalby Formation (right of axis 1).

Distribution of the Yorkshire flora

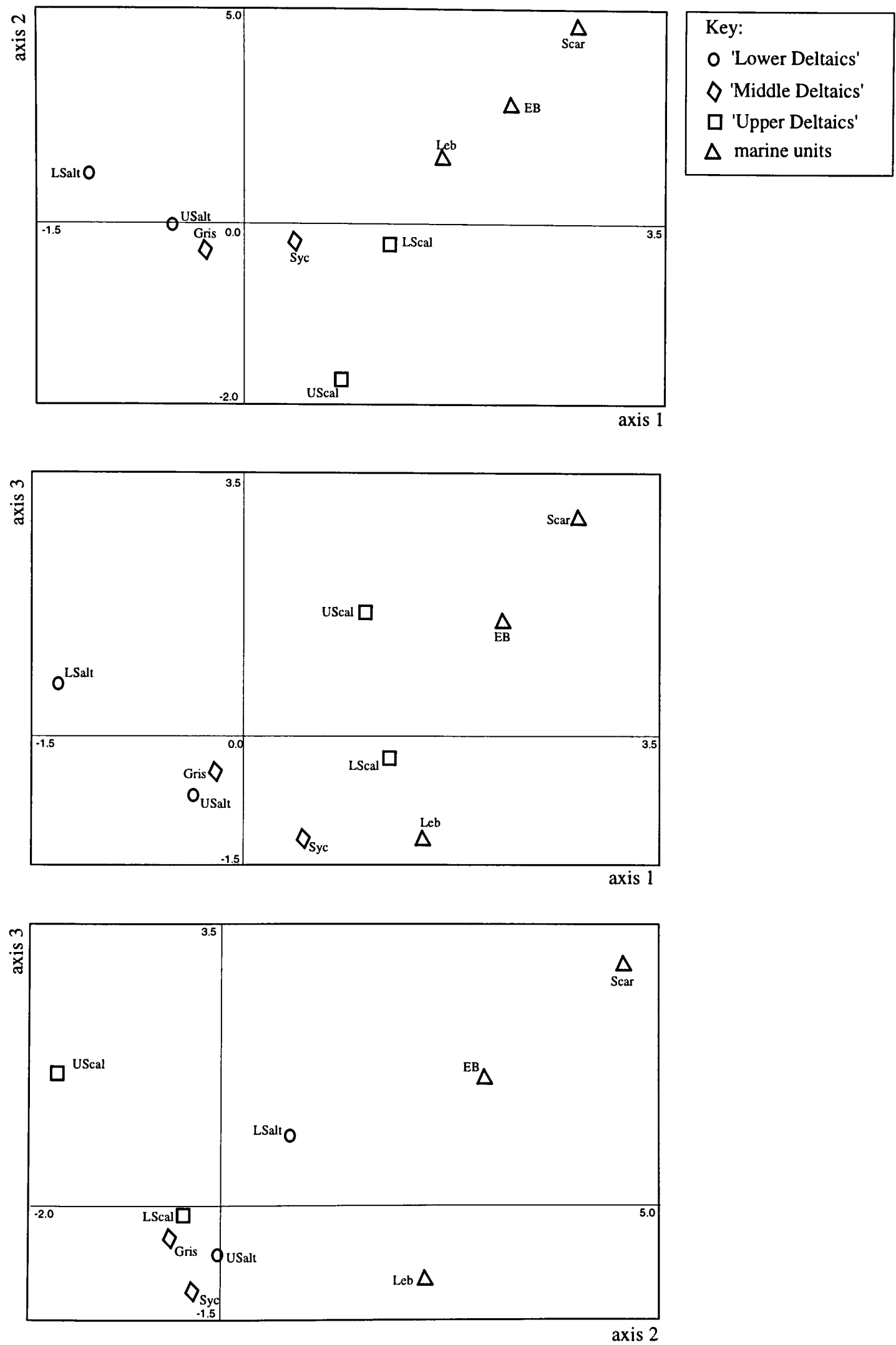


Fig. 5.1 Correspondence analysis (CA) site plot for the Yorkshire plant genera.
Key to plotted data: LSalt, Lower Saltwick Fm.; USalt, Upper Saltwick Fm.; Syc, Sycarham Mb.; Gris, Gristhorpe Mb.; LScal, Lower Scalby Fm.; UScal, Upper Scalby Fm.; EB, Eller Beck Fm.; Leb, Lebberston Mb.; Scar, Scarborough Fm.

Distribution of the Yorkshire flora

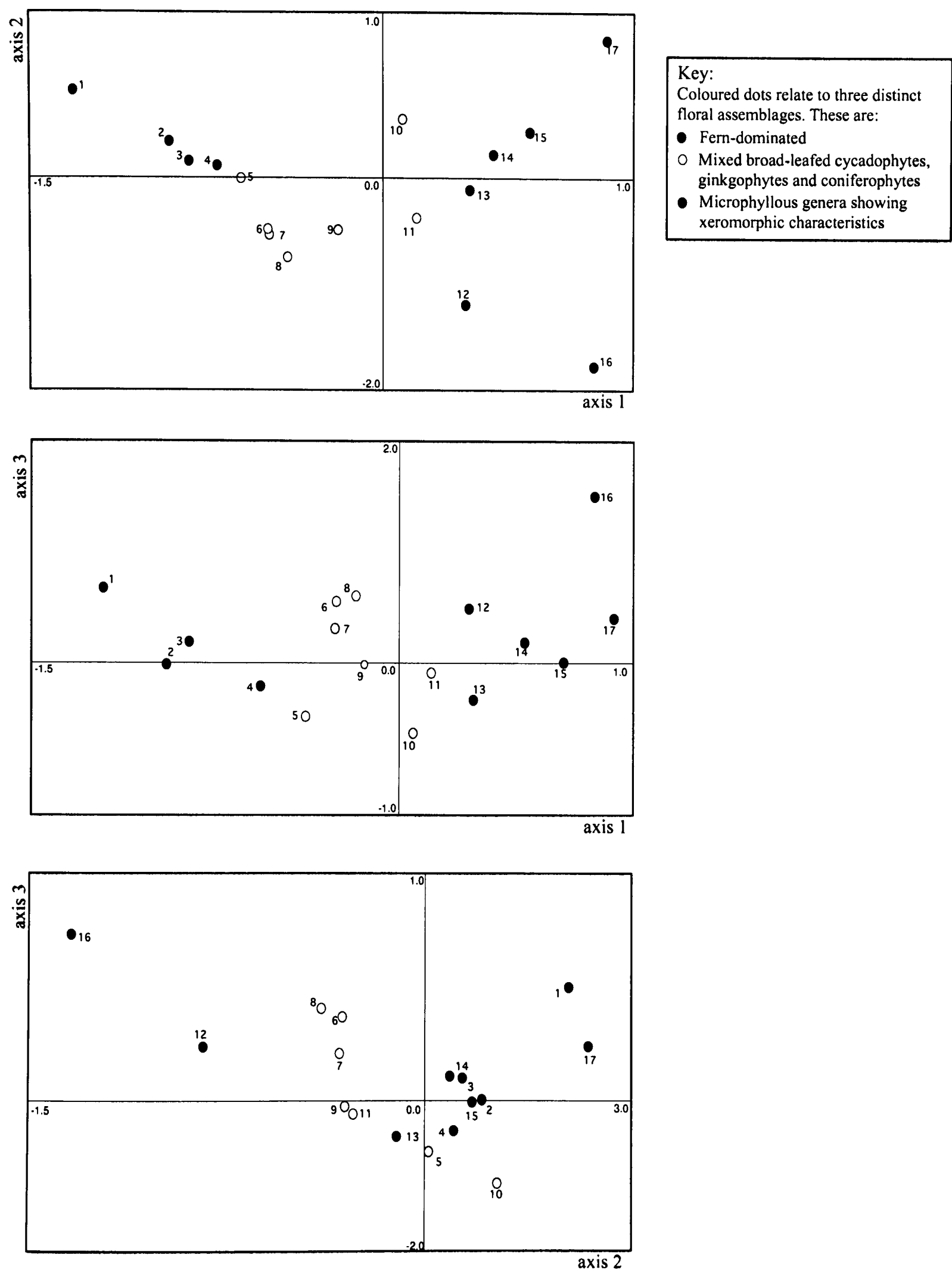


Fig. 5.2 CA genus plot for Yorkshire plant genera
For clarity only key genera are listed below; see Table 4.3, Appendix 4 for full listing: 1, *Marattia*; 2, *Clathropteris*; 3, *Deltolepis*; 4, *Cladophlebis*; 5, *Elatocladus*; 6, *Pseudotorellia*; 7, *Eboracia*; 8, *Elatides*; 9, *Nilsonia*; 10, *Anomozamites*; 11, *Baiera*; 12, *Cyparissidium*; 13, *Otozamites*; 14, *Ctenozamites*; 15, *Zamites*; 16, *Pityocladus*; 17, *Brachyphyllum*.

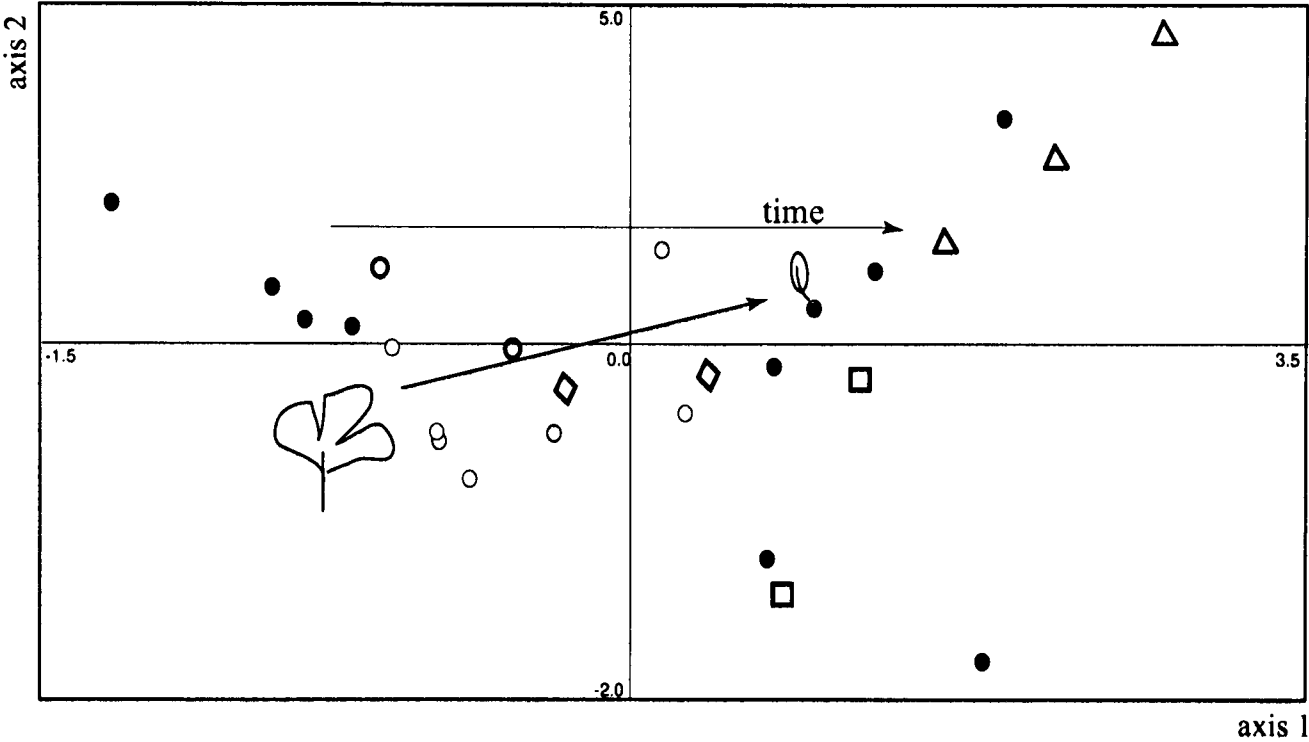


Fig. 5.3 Combined CA genus and site plots for Yorkshire plant genera.
The aim of this plot is to highlight morphological and time trends displayed by the data.

- Key:
-  Macrophyllous taxa
 -  Microphyllous taxa

The apparent juxtaposition of thick-cuticled, microphyllous taxa and marine units of the group (see Fig. 5.1) attests to a high degree of taphonomic sorting before deposition resulting in the preferred preservation of more robust genera. Significantly, the Leebberston Member contains the most diverse flora including ginkgophytes, cycadophytes and coniferophytes, which explains its intermediate position between the Cloughton and Scalby Formations (Fig. 5.1). The flora of the Eller Beck and particularly the Scarborough Formations comprise a more restricted coniferophyte-dominated flora and, as a result, show a greater degree of similarity with the Scalby Formation. This finding highlights the importance of analysing the physiognomic features of plant remains within a sedimentological context, because microphyllous, thick-cuticled leaves could equally reflect the efficacy of a taphonomic bias as a xeromorphic adaptation. In this case, however, the predominance of microphyllous taxa is interpreted to be related to taphonomy; that is, sorting in the marine realm.

This discussion brings us back to the three possibilities outlined at the start of this section (p.174), which may explain the scatter of data we see in the ordination plots. As for the marine units, a taphonomic bias could also explain the propensity towards microphyllous taxa showing xeromorphic characteristics in the Scalby Formation. It was suggested in the introductory paragraph that the predominance of microphyllous genera in this formation could represent an increased taphonomic effect; perhaps controlled by greater precipitation to enhance transportation and sorting. In a dynamic environment such as a delta, taphonomy certainly plays a key role in dictating the composition of the plant assemblages and thus cannot be sensibly excluded as a potential control — particularly given the allochthonous nature of this flora. However, considering the range of depositional environments in which these taxa occur (from channel sandstones to floodplain mudstones), if a taphonomic bias does indeed exist, it must be present to a varying degree and some assemblages should be relatively unaffected. It is from these relatively unsorted assemblages that the most accurate climatic information can be potentially drawn. Before going on to discuss the likelihood that this physiognomic trend may reflect a genuine climatic change, the effect of an increased marine influence is first discussed.

Firstly, it is important to note that an incursion of sea water across the delta-plain may not so much cause floras to develop with adaptations to reduce water loss and prevent excessive salt uptake (so-called halophytic features, which can be similar in nature to xeromorphic characters formed in arid environments: Adam 1990), as submerge vegetation growing in lowland areas, effectively removing from the floral record their continued potential input. This may be particularly true for those delicate elements of the flora which are not robust enough to survive the effects of a transgressive regime. It has been noted that the upland element to the Yorkshire flora is usually concealed by the overwhelming abundance of

species which grew nearer to the site of deposition (Harris 1966) — species which, given the greater water availability on the floodplain, are more likely to be thin cuticled and broad leafed. The possibility of a marine influence great enough to shape the entire floral community preserved in the Scalby Formation is, however, diminished in light of the little sedimentological evidence there is to support this inference (Livera & Leeder 1981; Leeder & Alexander 1985; Kantorowicz 1990). This is in contrast to the Hasty Bank locality at the base of the Saltwick Formation, where a marine influence is clearly indicated by the presence of marine phytoplankton, the thick-cuticled pteridosperm *Pachypteris papillosa*, and the conifer shoot *Brachyphyllum crucis* (Harris 1964).

Lastly, there is the possibility that a climatic change towards drier conditions was the predominant control on leaf physiognomy. The predominance of small-leafed plants with a thick cuticle in the Scalby Formation indicates an adaptation to limit water loss. These features are known as xeromorphic characteristics, which also include sunken stomata and thick-walled mesophyll cells (sclereids, which limit the extent of collapse on wilting). In plants adapted to arid environments where water supply is severely restricted or periodically limited, xeromorphic characteristics develop and enhance water economy. Although it is not suggested here that the Cleveland Basin endured arid conditions during the Bathonian period, it is likely that the environment experienced an annually restricted water supply, more severe in nature than during earlier periods (that is, compared to the interval extending from Late Pliensbachian times). This possibility is supported by the contemporaneous abundance of deciduous genera in the Scalby Formation, which may reflect a seasonal dry spell: including ginkgophytes (*Ginkgo*, *Sphenobaiera* and *Czekanowskia*) and cycadophytes (*Nilsonia*).

Before going on to describe the results gained from CA of the flora at the species level and in specific plant beds, the conclusions based on consideration of the genera are summarized below:

- Axis 1 shows a genuine morphological trend (left to right) from ferns, to mixed macrophyllous taxa, to xerophytic taxa typified by coniferophytes and ginkgophytes.
- Successive non-marine stratigraphic units of the Ravenscar Group are also aligned upon axis 1.
- The Scalby Formation and marine units also show a significant degree of variance along axis 2.

- There is a close correlation of groups of taxa and certain stratigraphic units. There are a significant number of shared genera between the Saltwick and Cloughton Formations, while the Scalby Formation appears to contain a rather different flora:
 - There are proportionally more ferns in the Saltwick Formation, than in the overlying Cloughton and Scalby Formations.
 - There is a higher incidence of mixed macrophyllous ferns, ginkgophytes, cycadophytes and coniferophytes in the Cloughton Formation than in the Saltwick or Scalby Formation.
 - There are proportionally more microphyllous, xeromorphic taxa in the Scalby Formation than in the underlying units.
- The marine units contain only robust, microphyllous taxa which give the appearance of close similarity with the Scalby Formation flora—in fact, this is more likely to be a reflection of sorting in the marine realm rather than environmental or climatic fluctuation.

5.6.2 Yorkshire plant species

Correspondance Analysis of a data matrix compiled at a species level yielded results surprisingly similar to those gained from CA of the plant genera, an alignment which would seemingly allay any concerns over the possibility of significant inconsistency or subjectivity in assigning Yorkshire's plant remains to species. In these examples as well, axis 1 illustrates a general trend of the successive stratigraphic units of the Ravenscar Group (Fig. 5.4), although in this instance axis 2 shows a greater spread in the data. The same physiognomic change seen at the generic level is associated with the temporal advance along axis 1: that is, from fern-dominated to small-leaved taxa. Once again, the Scalby Formation and marine units display a high degree of correspondence. Compared to the results from the genera, however, the trends displayed in these plots are more subtle.

The results of this CA also provide a useful medium in which to test the durability of previously identified associations between disarticulated plant organs. Harris cited several examples of species which he frequently found together in the field: for example, the common co-existence of the conifer shoot *Brachyphyllum mamillare* and the fern leaflet *Coniopteris hymenophylloides* led Harris to infer their close proximity on the delta during life (Harris 1979, p.14). When this example is compared to the CA plots, the two species do not show the expected degree of accordance (Fig. 5.5). However, rather than disputing Harris' observations, this result suggests that other factors might also be influencing their apparently weak distribution. Perhaps the most likely reason relates to the ubiquitous presence of *B. mamillare* in the sequence: because it is so widespread, the conifer shoot does not only occur

Distribution of the Yorkshire flora

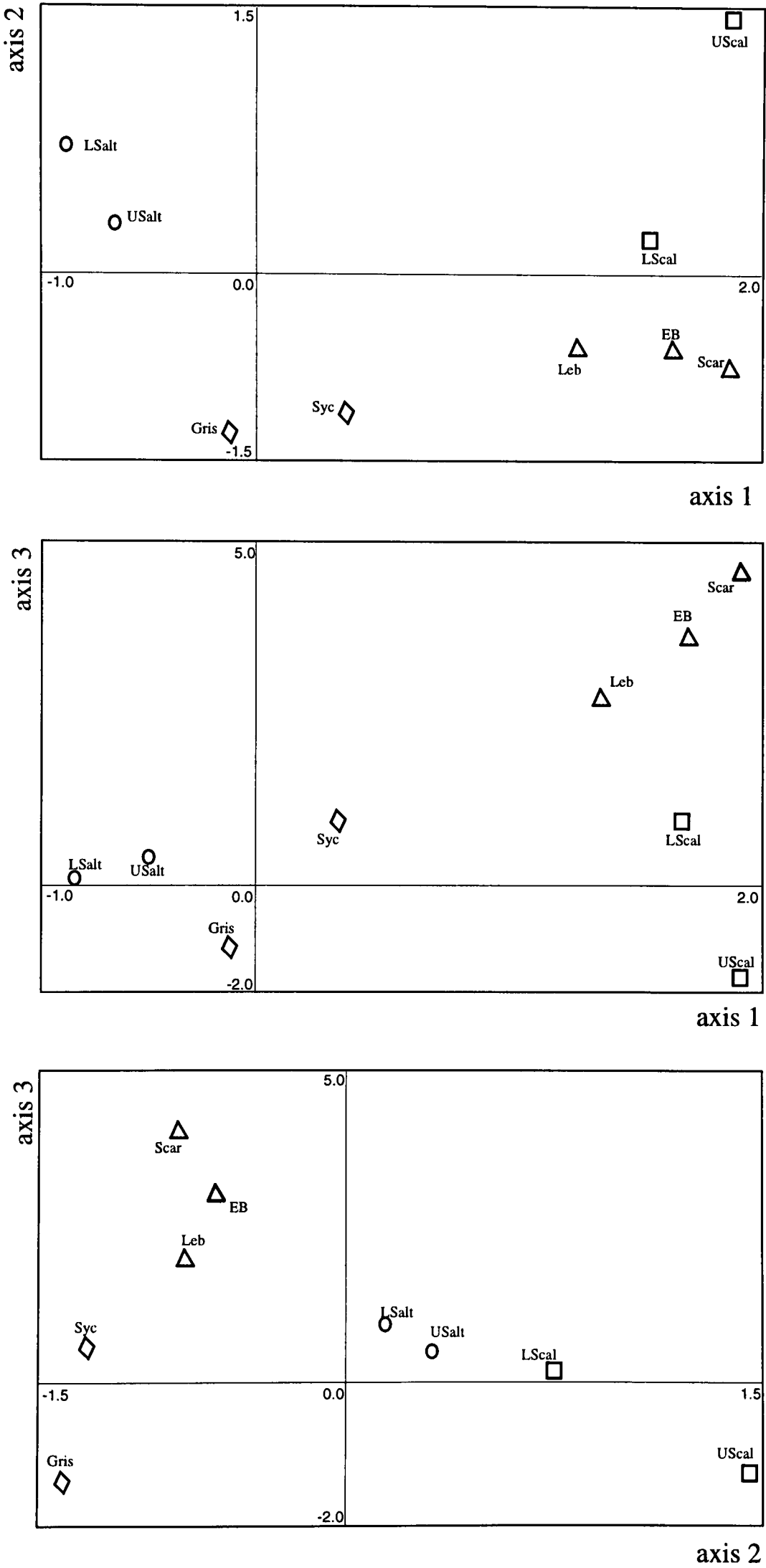


Fig. 5.4 CA site plot for the Yorkshire plant species.
See Fig. 5.1 for key.

Distribution of the Yorkshire flora

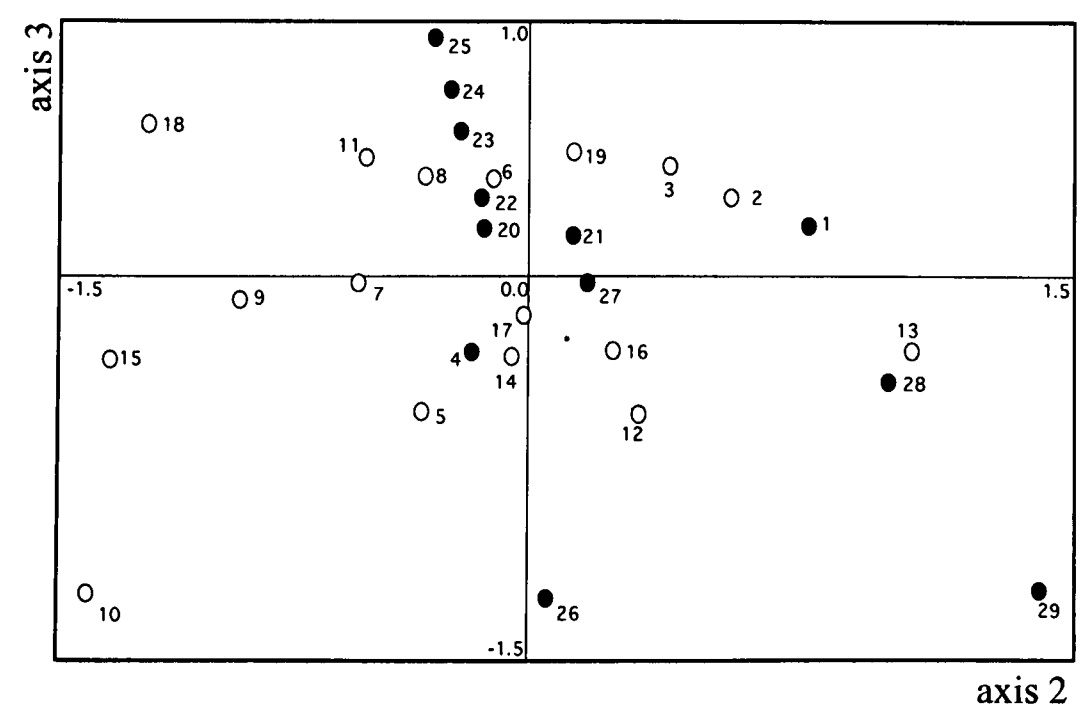
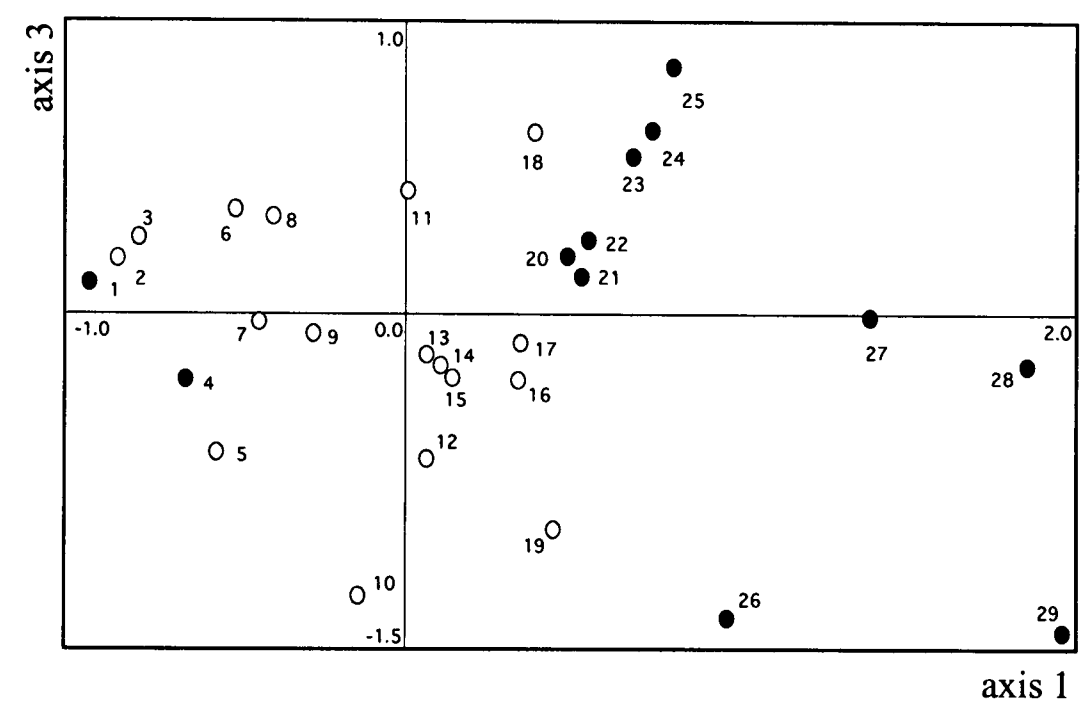
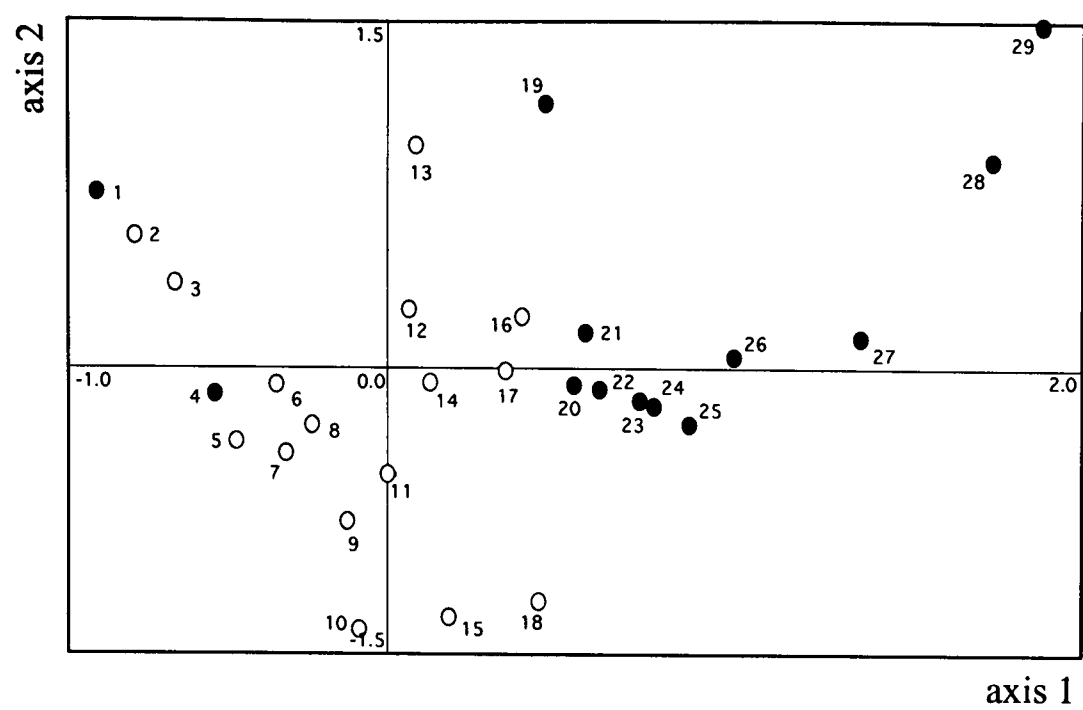


Fig. 5.5 CA species plot for the Yorkshire plant species.
See Fig. 5.2 for key to symbols and Table 4.4, Appendix 4 for key to numbered data points.

in conjunction with *C. hymenophylloides*, but also with a number of other taxa (though not necessarily repeatedly). Therefore the widespread distribution of *B. mamillare* has reduced the apparent closeness of the taxa observed by Harris. *Pachypteris papillosa* and *Brachyphyllum crucis* constitute another such example (Harris 1964, p.129-133): these species show a higher degree of correspondence than in the previous case, simply because they are both found predominantly at the base of the Saltwick Formation. It is suggested that their close association at this level may relate to their interpreted salt-marsh environment of growth (Harris 1964, 1979, p.21).

To summarize briefly:

- A general, though weak, physiognomic trend and temporal advance is represented by axis 1, concurring with results from CA at the generic level.
- CA of the species can be used to test the significance of relationships between taxa which, from field observations, are thought to be closely associated.

5.6.3 Genera from selected Yorkshire plant beds

Axis 1 represents the greatest variation in the data matrix as in the previous analyses. However, unlike the genera and species plots which show a clear separation of taxa and stratigraphic units along axis 1, this example reveals only a weak trend. As Fig. 5.6 shows, there is a high degree of correspondence between the Whitby, Hayburn Wyke, Scalby Wyke and *Solenites* Plant Beds (mid-points of axes 1 and 2). Although this group of beds are derived from widely spaced levels in the Ravenscar Group (Saltwick to Scalby Formations), the assemblages are nevertheless found in similar depositional environments. These beds represent deposition of plant remains into shallow ponds of fresh- or brackish-water on the floodplain (*Solenites*, Whitby Plant Beds), more extensive oxbow lakes (Scalby Wyke Plant Bed) or into a waterlogged floodplain environment where crevasse-splays commonly deposited sand (Hayburn Wyke Plant Bed). The flora of these beds is well preserved and unsorted, including delicate leaves and fructifications. In the Scalby Wyke and Hayburn Wyke examples, however, a more robust, sorted and sometimes charcoaled flora is associated with the crevasse-splay sandstones.

Surrounding this focal group of beds are the Gristhorpe, Hasty Bank, Iron Scar, Ginkgoalean and *Nilsonia* plant assemblages (Fig. 5.6). Both the Gristhorpe and Hasty Bank beds were deposited in a similar ponded, overbank environment to the *Solenites* and Whitby Plant Beds. It is not clear what dictates their surprisingly weak association and position to the left of axis 1, particularly given that the Hasty Bank/Whitby and

Distribution of the Yorkshire flora

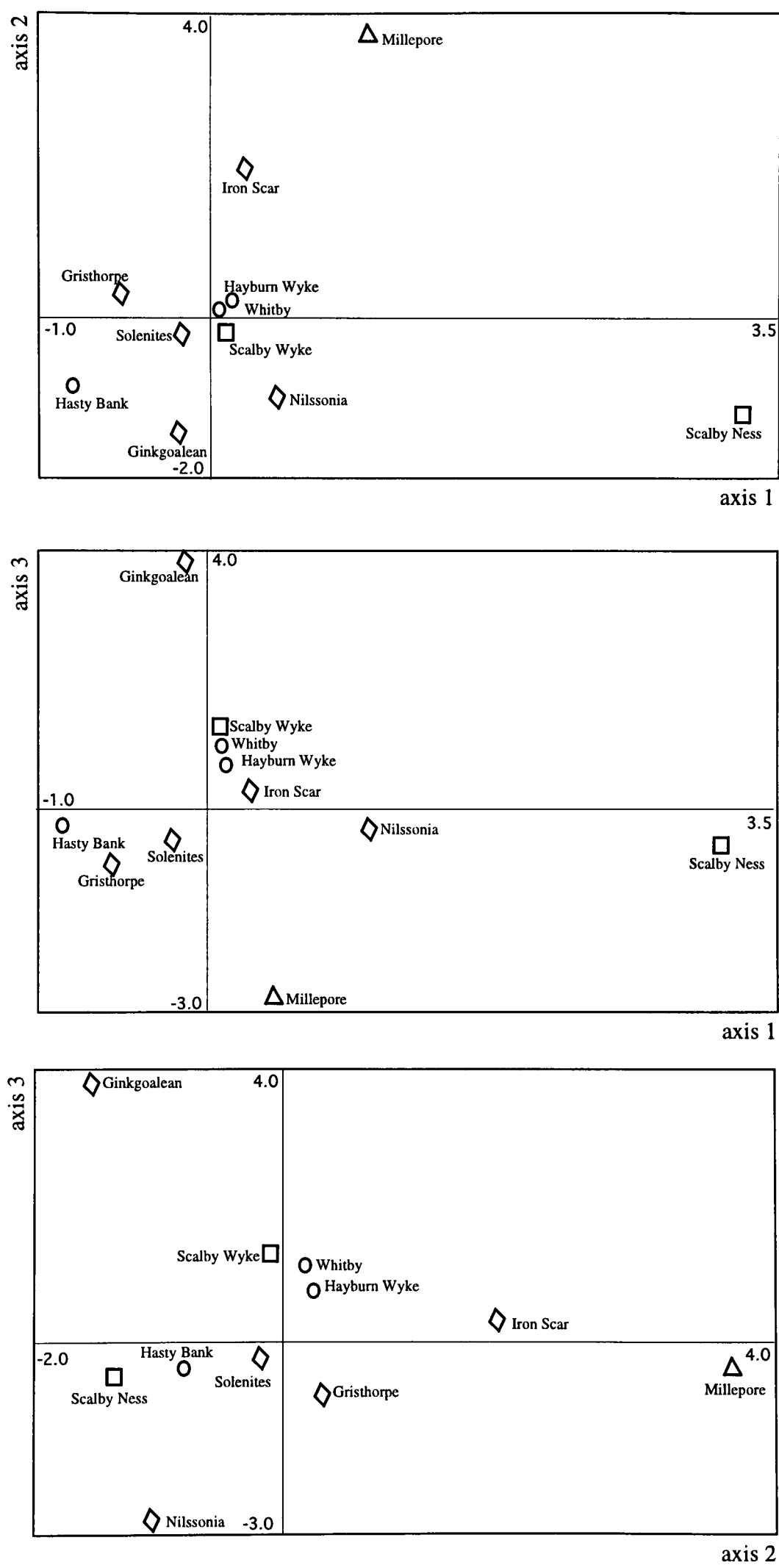


Fig. 5.6 CA site plot for genera of selected plant beds.
The names adjacent to the plotted data indicate those plant beds included in this analysis. See Fig. 5.1 for key to symbols.

Distribution of the Yorkshire flora

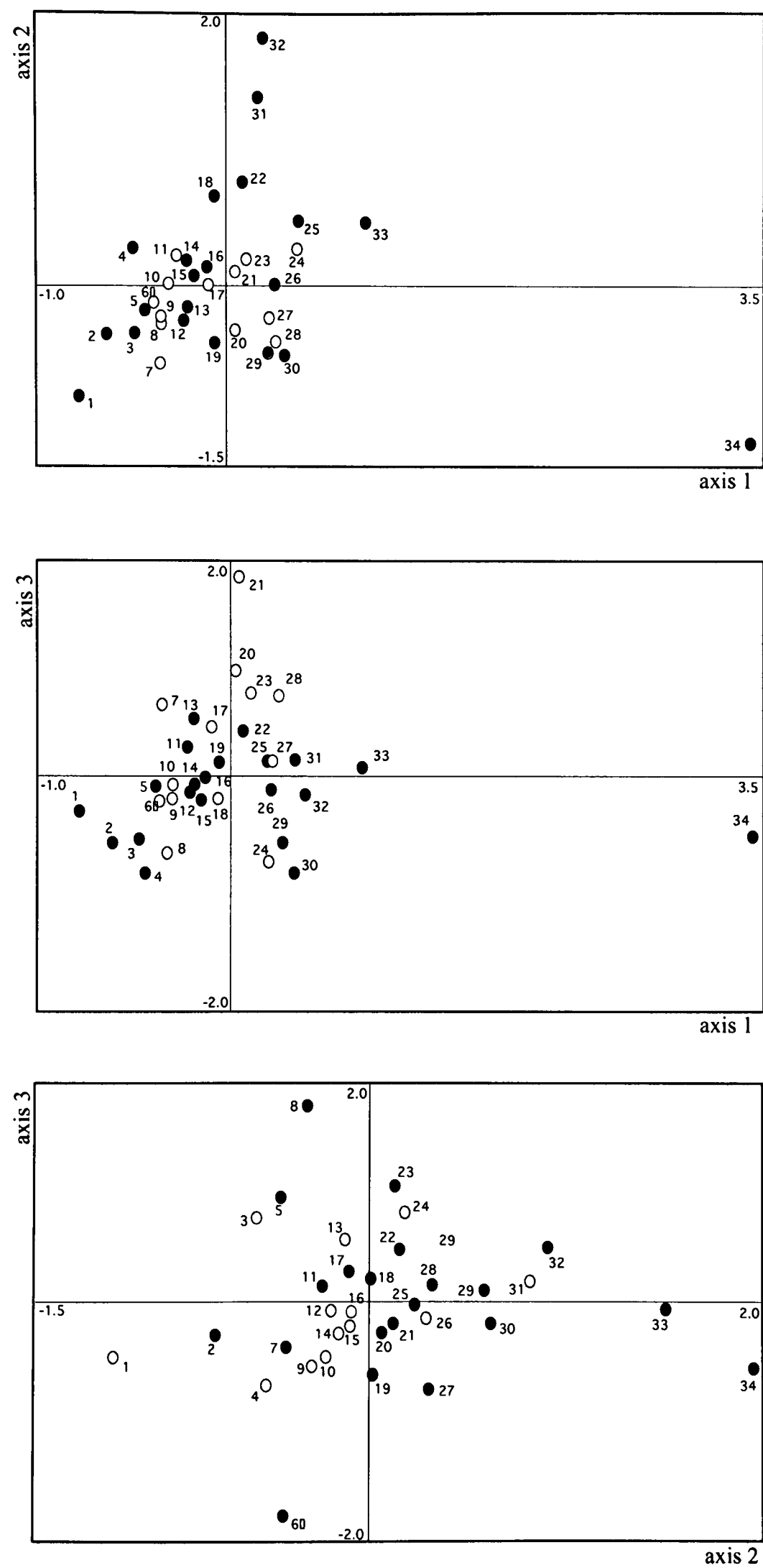


Fig. 5.7 CA genus plot for selected plant beds.
See Fig. 5.2 for key to symbols and Table 4.5, Appendix 4 for key to numbered data points.

Gristhorpe/*Solenites* Plant Beds are practically coeval. The Gristhorpe and Hasty Bank beds are, however, comparatively fine grained and contain a better preserved, more unsorted flora. Given their unsorted nature, it is likely that these beds more accurately reflect the original vegetation growing on the delta-plain. The Iron Scar section is the only plant bed included in this analysis which contains unequivocal evidence for an autochthonous flora. *In situ Equisetum* and an upright tree stump penetrate a palaeosol containing a contrastingly comminuted, poorly preserved, allochthonous flora. Better preserved plant remains occur beneath this palaeosol in thin, muddy beds intercalated with crevasse-splay sandstones, which were deposited under a marine influence (Hancock & Fisher 1982). The mixed nature of this floral assemblage probably controlled its occurrence at a similar point on axis 1 to other beds deposited in the same environment, such as the Hayburn Wyke Plant Bed.

The Ginkgoalean and *Nilsonia* beds reside at roughly the same point of axis 1. Both plant assemblages were laid down during a considerable marine influence, in a lagoonal environment behind a barrier bar. In contrast to the *Nilsonia* bed, which is well preserved and comprises a diverse flora, the Ginkgoalean assemblage is highly abraded and predominantly contains its name-sake (the Ginkgoaleans). This contrast may be explained by the reduced marine influence and diminished degree of sorting during deposition of the *Nilsonia* bed. The only wholly marine assemblage included in this analysis is from the Millepore Bed, which rather than occurring in association with the Ginkgoalean and *Nilsonia* beds, exists as an outlying point high on axis 2 (Fig. 5.6). Reasons for its detached placement may relate to that fact that this bed contains a more robust, highly sorted assemblage than found in any of the other plant beds analysed. The Scalby Ness Plant Bed also has a removed placement in the ordination plots displaying axes 1 and 2: in axes 2 versus 3, however, the bed is more closely associated with the other assemblages (Fig. 5.6). This bed incorporates a well-preserved assemblage dominated by *Ginkgo*, deposited in the upper part of a sandy point-bar system.

In summary, there appears to be a general trend along axis 1 from finer-grained to coarser-grained plant beds. In light of this finding it might be reasonable to assume the presence of a corresponding trend from well-preserved to poorly preserved plant remains. However, such a clear cut accordance is disrupted by the well-preserved but coarse-grained Scalby Ness Bed and, conversely, the poorly preserved but fine-grained Ginkgoalean Bed. Despite these anomalies, it seems likely that axis 1 reflects a taphonomic trend, though the exact nature of this trend is more difficult to decipher. This taphonomic transition overprints and modifies the trend with time along axis 1, which was recognized in the previous analyses. This has, for example, had the effect of positioning beds from the Saltwick and Scalby Formations close by.

In reference to Fig. 5.7, which displays the constituent genera of these select plant beds, there is a surprising, though weak, correspondence with the taxa plots illustrated in Figs. 5.2 and 5.5. In general terms there is a trend from ferns and broad-leafed taxa on the left of axis 1, towards more microphyllous taxa on the right. Despite the absence of a clear separation of taxa, this very broad physiognomic transition compares well to that gained from CA of the genera constrained by stratigraphic units. This affiliation is particularly obvious in beds which are known to contain a more unsorted, better-preserved flora which travelled only a short distance before being deposited: for example, the Hasty Bank, Gristhorpe, *Solenites* and Scalby Ness Plant Beds. These beds are arranged sequentially along axis 1 with time, in contrast to the more sorted beds whose arrangement along axis 1 relates to their grain size, matrix type and the flora's degree of fragmentation.

This investigation has shown that plant remains from beds of the same facies type display cuticle of a similar thickness, and are composed of equivalent suites of leaves, stems and fructifications, which show the same degree of sorting and fragmentation. However, given the particular taphonomic process at work during deposition of a sedimentary facies, this may not be surprising. Additionally, this study has revealed that plant beds laid down in contrasting depositional environments commonly contain similar plant species: those assemblages from the marine units and the Scalby Formation exemplify this case. Therefore, it may be possible that differences between assemblages may not so much reflect variation in drifting (in the sense of Black 1929), as the composition of the adjacent delta vegetation. Perhaps those species which are ubiquitous throughout the Ravenscar Group (*e.g.* *Brachyphyllum mamillare*) were dominant components of the vegetation, while those which characterize individual assemblages or stratigraphic units might reflect particular climatic, environmental, edaphic or taphonomic factors. In general terms, however, it is proposed that the temporal fluctuation revealed by this statistical treatment is predominantly climatically controlled.

To conclude briefly on the basis of the plant bed analysis:

- CA of individual plant assemblages allows sedimentary facies differences and taphonomic processes to be taken into account.
- There is a general (albeit weak) trend along axis 1 from:
 - plant beds to the left of axis 1 containing well-preserved, large-leafed assemblages which after minimal transport, were deposited on the floodplain;
 - to plant beds comprising floodplain mudstones and crevasse-splay sandstones, containing large-leafed and small, robust-leafed assemblages respectively;
 - to plant beds deposited in higher energy environments which contain a small, thick cuticled, robust flora.

- Although the sedimentary facies (and related taphonomic processes) exert a strong control, a subtle physiognomic trend with time can still be discerned along axis 1; but only within those beds containing a well preserved, unsorted flora.

5.7 Conclusions

By subjecting the Yorkshire flora to Correspondence Analysis, the temporal fluctuation found by previous researchers has been reproduced. In agreement with Florin (1958) and Couper (1958), this study has highlighted the large proportion of unique species contained within the Scalby Formation, which are characterized by small leaves. The relative predominance of these xeromorphic taxa in the Scalby Formation does, however, contrast with Harris' (1952*b*) conclusion that there are equal numbers of xeromorphic to delicate leaves through the succession, and challenges his view that the flora should be regarded as a single entity. While it should be stressed that several genera are ubiquitous through the sequence and the trend from broad-leafed to small-leafed taxa with time is by no means obvious in the absence of multivariate analysis, there does appear to be a genuine transition towards more xeromorphic genera. Perhaps, therefore, the flora as a whole is best described as a warm-temperate flora (*sensu* Ziegler *et al.* 1993) containing extreme end-member genera, such as the ferns *Marattia* and *Hausmannia*, and the cycadophytes *Ptilophyllum* and *Otozamites*. Notably, such genera are generally restricted to certain stratigraphic intervals, which produces the physiognomic trend we see in the ordination plots and reflects what might be interpreted as a climatic change towards more seasonally dry conditions.

A trend towards an extended seasonal dry spell and a stressed growing season (in which the plants experienced frequent water shortages) has already been inferred from the growth-ring analysis outlined in the preceding chapter. This inference was based on the general character of the wood from the Bathonian (Scalby Formation), which indicates that growing conditions were comparatively hostile. The results from this CA also indicate adverse growing conditions during this stage, emphasized by the prevalence of leaves with xeromorphic adaptations. While it is important to stress that several genera are scattered both spatially and temporally through the sequence, consequently diminishing the potency of the temporal change, it is possible that these taxa may reflect the superimposition of local fluctuations in the hydrological regime on the climatic conditions. These small-scale fluctuations are difficult to constrain using plant megafossils, due to the somewhat imprecise stratigraphic control in many of the palaeobotanical sources used for this analysis. Moreover, this lack of control has removed the potential to identify any sensitivity of the flora

to medium-scale sea-level fluctuations during the Middle Jurassic: unlike Yorkshire's fossil wood, which was collected within the stratigraphic framework constructed for this thesis. Despite such inherent problems, the sum total of the floral elements indicate a temporal shift towards more xeromorphic taxa in the Bathonian, which can be interpreted as a change to drier conditions in this region. The possibility of a change to warmer conditions in the Bathonian is lessened in light of evidence put forward by Frakes *et al.* (1992) for a cool climate (based on land and ocean floral evidence, and indications of seasonal ice). The palaeoclimatic inferences discussed in this and the preceding chapter concur with those of Hudson (1968), Vakhrameev (1982, 1991), Wright (1985), Boulter & Windle (1993), Hendry & Kalin (1997) and others, all of which are based on alternative sources of evidence.

Chapter 6

Chapter 6

Conclusions

By using an integrative sedimentological and palaeobotanical approach, a picture has been established of the stratigraphic development, the constituent flora, and the palaeoclimatic conditions of the Middle Jurassic of Yorkshire. Examination of the sequence revealed a series of lithological cycles on a variety of scales. The most prominent cycles occur on a medium- and large-scale which, based upon their durations, correspond to the third- and second-order cycles of Haq *et al.* (1988) and Vail *et al.* (1991). Two large-scale cycles (second-order) onto which six medium-scale cycles of relative sea-level are superimposed have been recognized in the Ravenscar Group and underlying Dogger Formation. Comparison and correlation with sections from Scandinavia has shown that the second-order lithological cycles recognized in Yorkshire are regionally pervasive. These cycles are comparable in stratigraphic position and extent. On Bornholm, five large-scale cycles have been identified spanning the Early and Middle Jurassic (Hettangian-Bathonian).

Study of the constituent flora of the Ravenscar Group has exposed temporal trends in the composition of the plant assemblages and nature of wood growth, from which palaeoclimatic information has been obtained. Both datasets imply a trend towards drier climatic conditions during Bathonian times. Growth-ring analysis of fossil wood in a stratigraphic context (Pliensbachian-Bathonian) indicates a distinctly seasonal climate with low to moderate interseasonal variation in growth. Significant intraseasonal influences on wood production are implicit in the abundance of false rings. Wood specimens from the Bathonian Scalby Formation consist of narrow rings which are variable in width, displaying the greatest proportion of latewood and numerous false rings. Compared to the rest of the wood database extending from Late Pliensbachian to Bajocian times, a shorter and more stressed growing season in the Bathonian is evinced by these findings. This can be explained by a climatic change towards a drier climate, superimposed upon strongly regressive conditions which succeeded in accentuating annual seasonality (by lengthening the dry season). Such a change in climatic conditions is also demonstrated by a temporal fluctuation in the Yorkshire floral taxa. Using Correspondence Analysis (CA) a prevalence of xeromorphic taxa in the Bathonian has been revealed, as compared to the Aalenian and Bajocian which contain a ubiquity of ferns and mixed broad-leaved taxa respectively. The suggestion of seasonally dry

conditions in the Bathonian compares well with previous investigations carried out by, for example, Vakhrameev (1991), Boulter & Windle (1993) and Hendry & Kalin (1997). All told, the Yorkshire flora fits well within the bounds of the warm-temperate biome suggested by Ziegler *et al.* (1993), but closer examination has elucidated the presence of a small-scale climatic fluctuation.

The main conclusions drawn from the results of this thesis are summarized below and illustrated in Fig. 6.1.

1. Lithological cycles have been identified on a medium- (third-order) and large-scale (second-order) level in the Middle Jurassic (Aalenian-Bathonian) of the Cleveland Basin. Overall, six medium-scale cycles are superimposed upon one entire large-scale cycle (*opalinum* to *humphriesianum* Zones) and one partial cycle (extending from the *orbis* Zone). Erosional unconformities bound the large-scale cycles, the lateral expression of which can be traced regionally. The medium-scale cycles afford intrabasinal correlation, and show equivalence in the Wessex Basin, but linkage to the Scandinavian basins is more tenuous. Small-scale (fourth-order) cycles are commonplace in the Cleveland Basin, but are restricted in their development.

2. Five large-scale cycles identified in the Early and Middle Jurassic Bornholm Group correspond well in character and stratigraphic extent with those cycles found in Yorkshire. This apparently concurrent development of the Cleveland and Scandinavian basins, on a second-order level, suggests an element of common control. Based on previous work across Western Europe, there is compelling evidence to suggest that these cycles may reflect rifting episodes in the break-up of Pangaea. Third-order, and higher-frequency, cycles most likely relate to local tectonic regimes. The ability to correlate third-order cycles between the Cleveland and Wessex Basins probably relates to the positioning of these basins along a proximal-distal transect (which the Scandinavian basins form no part of).

3. In the context of the stratigraphic framework constructed for the Ravenscar Group, meaningful palaeoclimatic information has been acquired from the constituent plant fossils. The method for deriving palaeoclimatic information entailed growth-ring analysis of fossil wood and CA of fossil leaves. The findings from both approaches indicate the same conclusion: a trend towards drier climatic conditions in Bathonian times.

4. Using characteristics of fossil wood which are understood to be a function of climate, a short-term record of palaeoclimatic fluctuations over the Late Pliensbachian to Bathonian interval has been gained. It was found that features such as wide rings of constant width, a narrow latewood-zone and few false rings, are commonly found together. The opposite is

also true: narrow rings of variable width, a sharp earlywood-latewood transition, a wide latewood zone and abundant false rings frequently co-exist, particularly in samples from the Bathonian Scalby Formation. In the context of sedimentological and other floral evidence, it is inferred that wood from the Scalby Formation grew in a stressed environment. These hostile growing conditions are inferred to be a consequence of water shortages during a time of seasonally dry climatic conditions and low sea level.

5. Congruent findings were obtained from CA of the Yorkshire flora. A physiognomic trend in the flora with time came to light as a result of this study. This temporal trend can be summarized as (1) a fern-dominated flora in the Aalenian (Saltwick Formation); (2) a mixed broad-leafed flora in the Bajocian (Cloughton Formation); and (3) a small-leafed, xerophytic flora in the Bathonian (Scalby Formation). The prevalence of xerophytic taxa in the Bathonian provides strong supporting evidence for the occurrence of water shortages. A trend towards a drier climate in the Bathonian is consequently suggested.

To refine further the results of this thesis, there is scope for several short-term projects. Perhaps most useful would be an investigation of the Lower and Middle Jurassic plant remains from Bornholm and Scania using CA. Bearing in mind the rather low-resolution biostratigraphy, the results gained from such a study could potentially provide new climatic information for the Early Jurassic interval, and also test the data generated for the Middle Jurassic of Yorkshire. Continuing on the palaeobotany theme, yet further palaeoclimatic information could be gained from an analysis of the stomatal density of judiciously selected plant species from the Ravenscar Group. Recent studies have shown that the abundance and character of stomatal pores in plant cuticle can be used as a proxy for atmospheric carbon dioxide (CO₂) concentrations, from which climatic information can be derived (McElwain & Chaloner 1995). An examination of a selection of species from within the “Lower, Middle and Upper Deltaic Series” by McElwain & Chaloner (1996), brought to light elevated CO₂ levels during the Middle Jurassic interval. Perhaps if a similar study were carried out using the stratigraphic framework created for this thesis, then a more refined picture of stomatal variation would emerge, from which further temporal climatic trends could be inferred.

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Appendix 1

Appendix 1

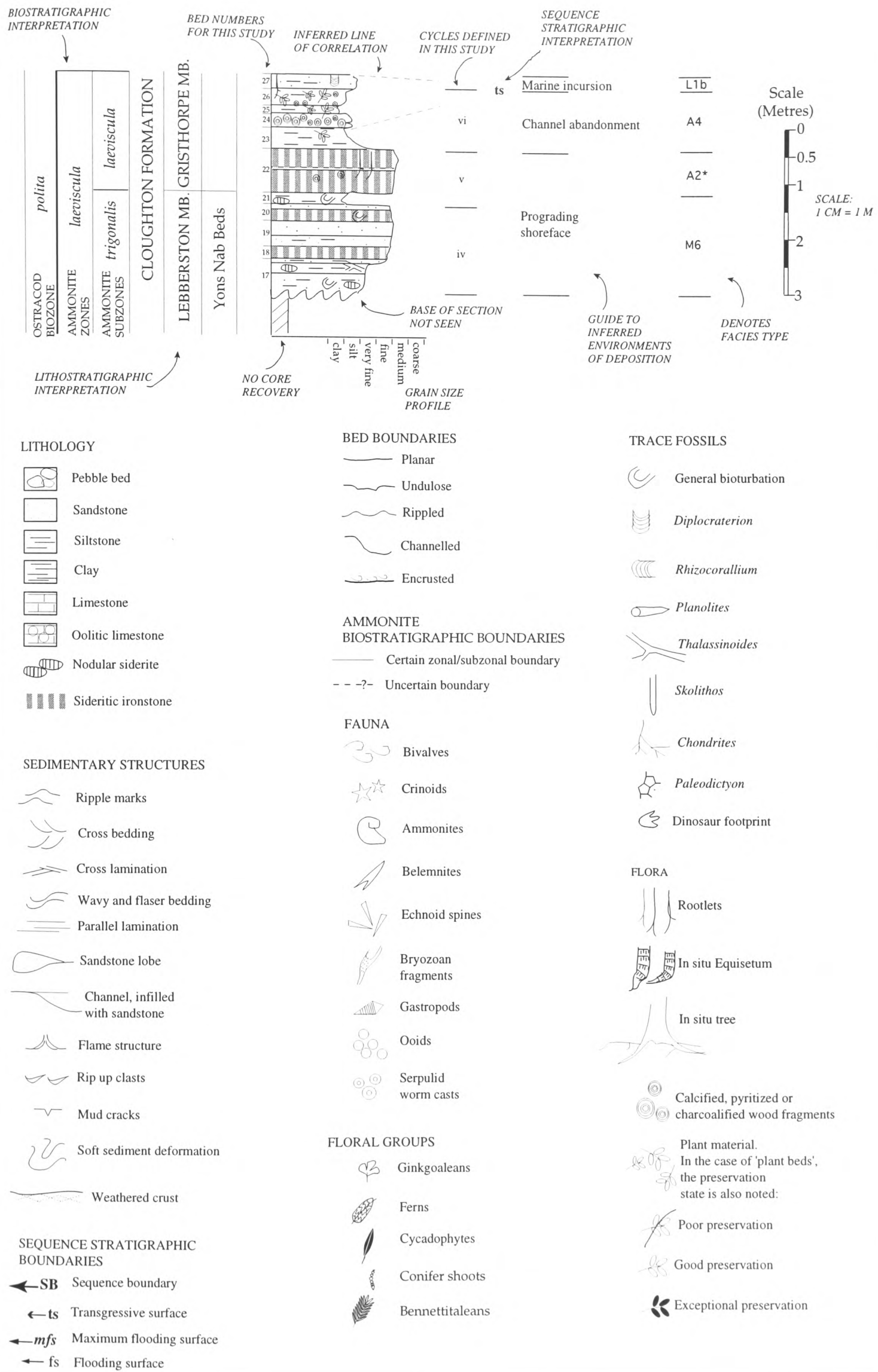
Sedimentary logs recorded in the Cleveland Basin

The sedimentary logs illustrated in this appendix are intended to link in with the descriptions of sedimentary facies in Chapter 2, and provide a secure framework within which fossil wood and plant remains from the sequence are discussed in Chapters 4 and 5. Annotated field photographs and locality maps are also included.

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Fig. 1.1 Key to sedimentary logs



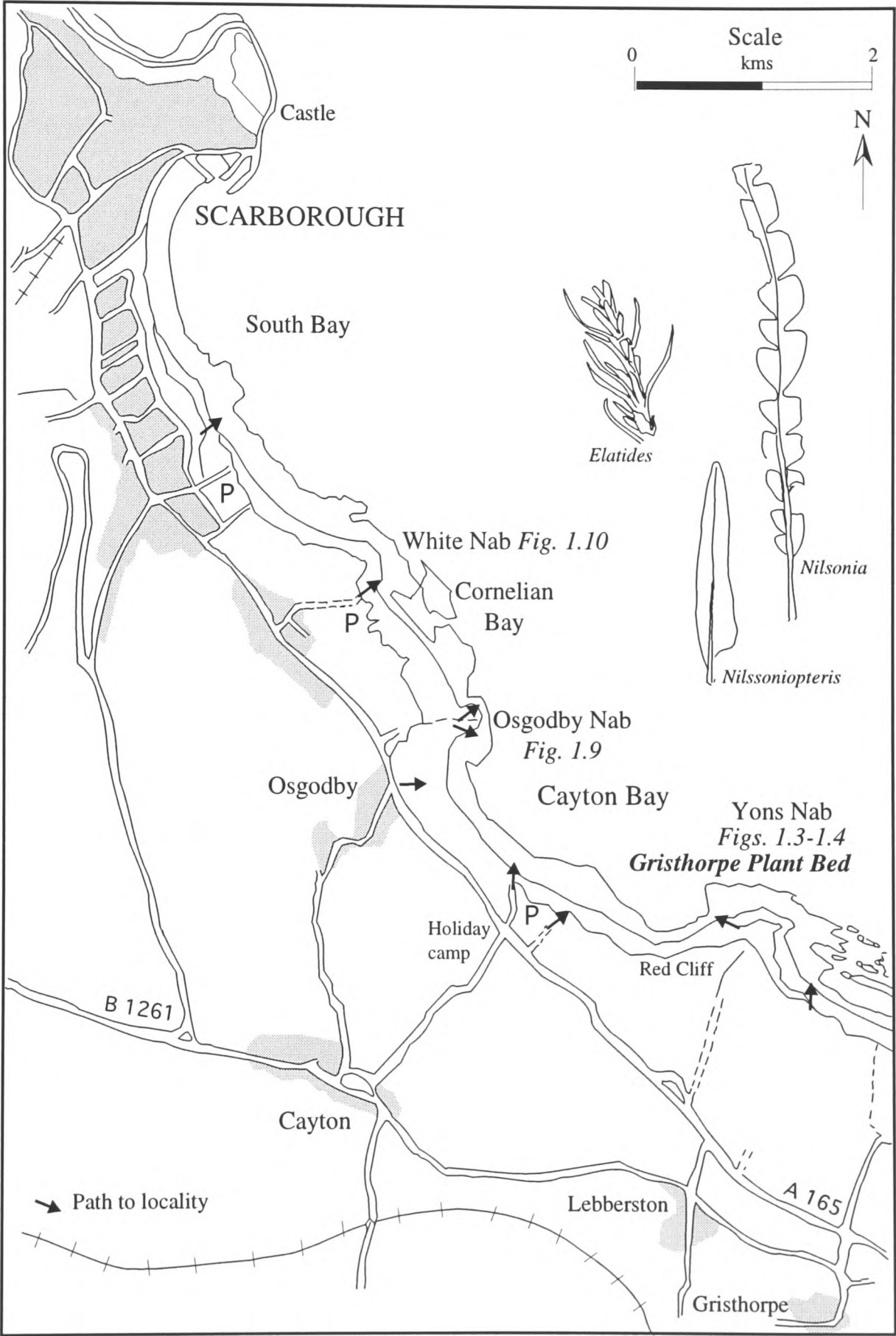


Fig. 1.2 Map of localities between Scarborough and Cayton Bay (redrawn and modified from Rawson & Wright 1992). Figure numbers relate to the sedimentary logs recorded at these localities. Genera commonly found in the Gristhorpe Plant Bed are illustrated.

- Key:
- P Parking
 - Points of access to beach
 - ✂ Rail line

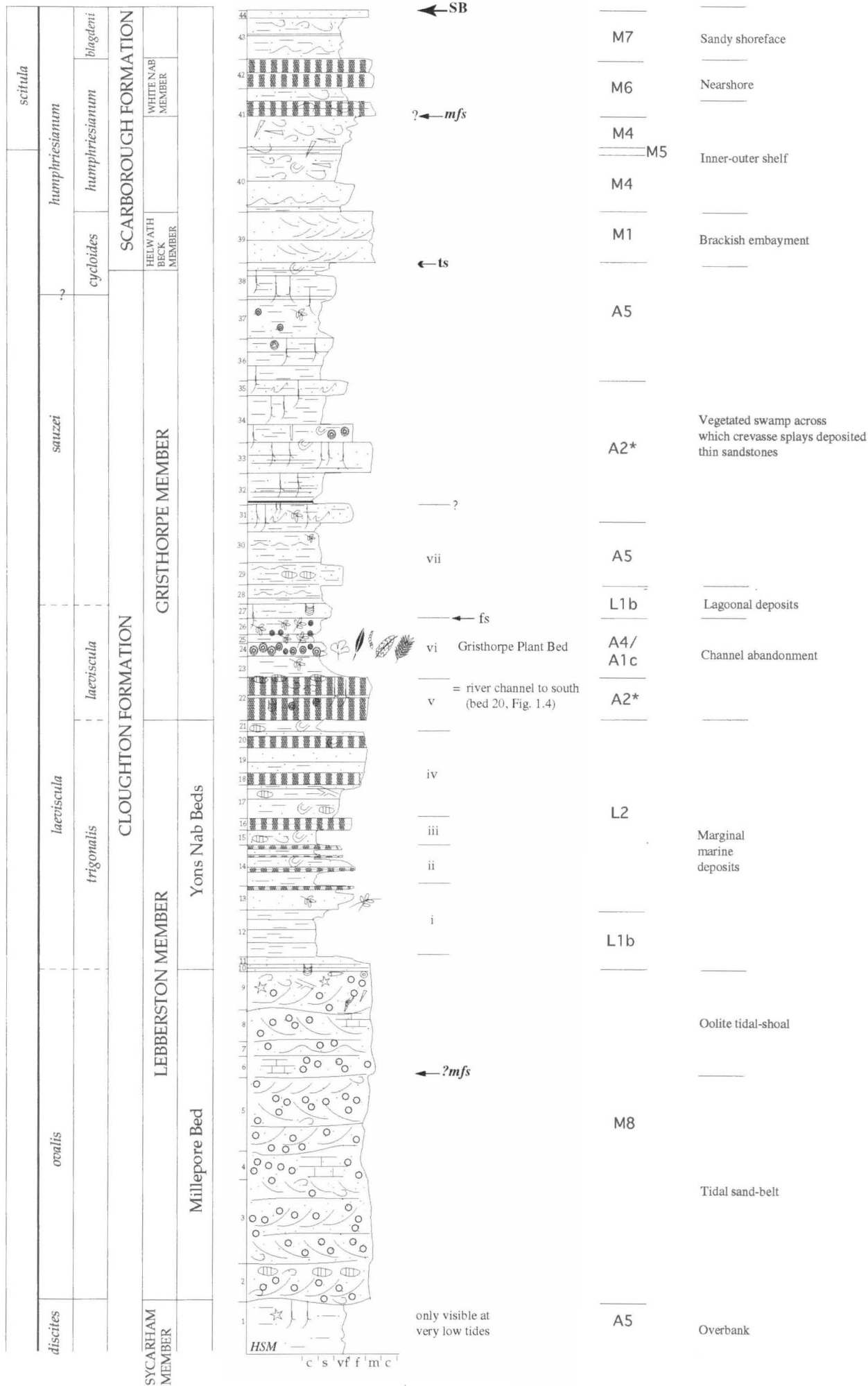
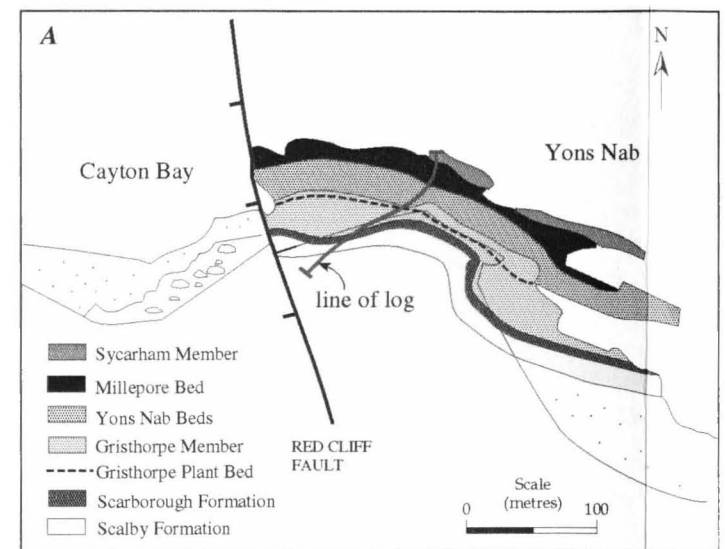


Fig. 1.3 A new sedimentary and stratigraphic log showing the Sycharham, Lebberton and Gristhorpe Members of the Cloughton Formation, overlain by the Scarborough Formation; northern Yons Nab (TA 082 842). Roman numerals alongside the Yons Nab Beds and basal Gristhorpe Member correspond to small-scale, coarsening-upward cycles.

A Geological map of Yons Nab, showing line of measurement for this log.



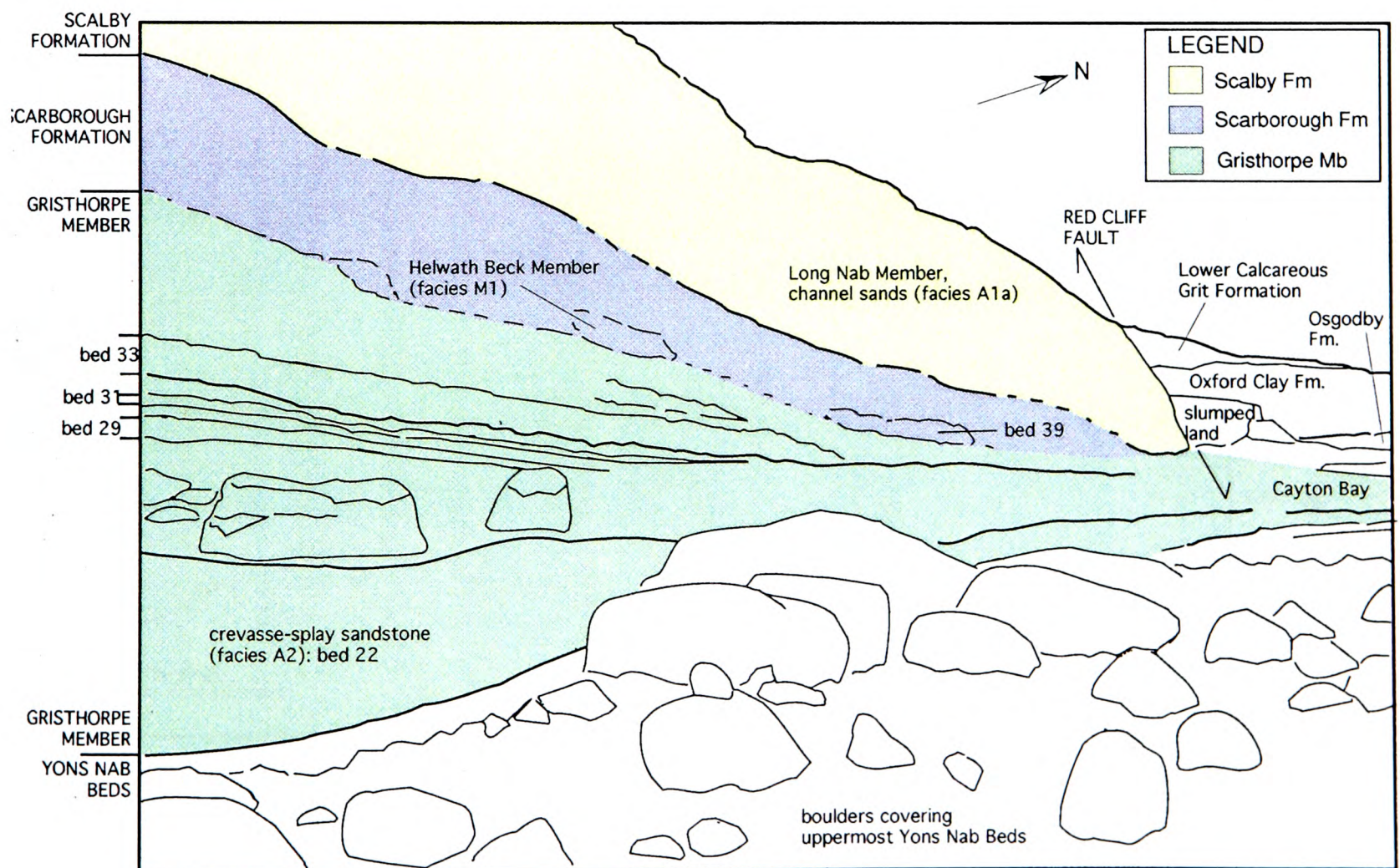


Fig. 1.5 Yons Nab (TA 081 044) looking north towards Cayton Bay. The entire Gristhorpe Member and Scarborough Formation succession is shown, together with the uppermost part of the underlying Yons Nab Beds and the overlying Scalby Formation. An area of slumped land to the right of the photograph indicates the position of the syn-sedimentary Red Cliff Fault, which marks the eastern side of the Peak Trough. The arrows indicate the direction of movement during the Middle Jurassic interval. As a consequence of Yons Nab lying on the upthrown block, the Scarborough Formation is much attenuated at this locality, compared to, for example, the Cloughton Wyke area. Since the Jurassic, the motion of the fault has been reversed, leading to strata of Callovian (Osgodby Formation) and Oxfordian (Oxford Clay and Lower Calcareous Grit Formations) age to be juxtaposed. All bed numbers relate to those shown against the sedimentary log in Fig. 1.3.

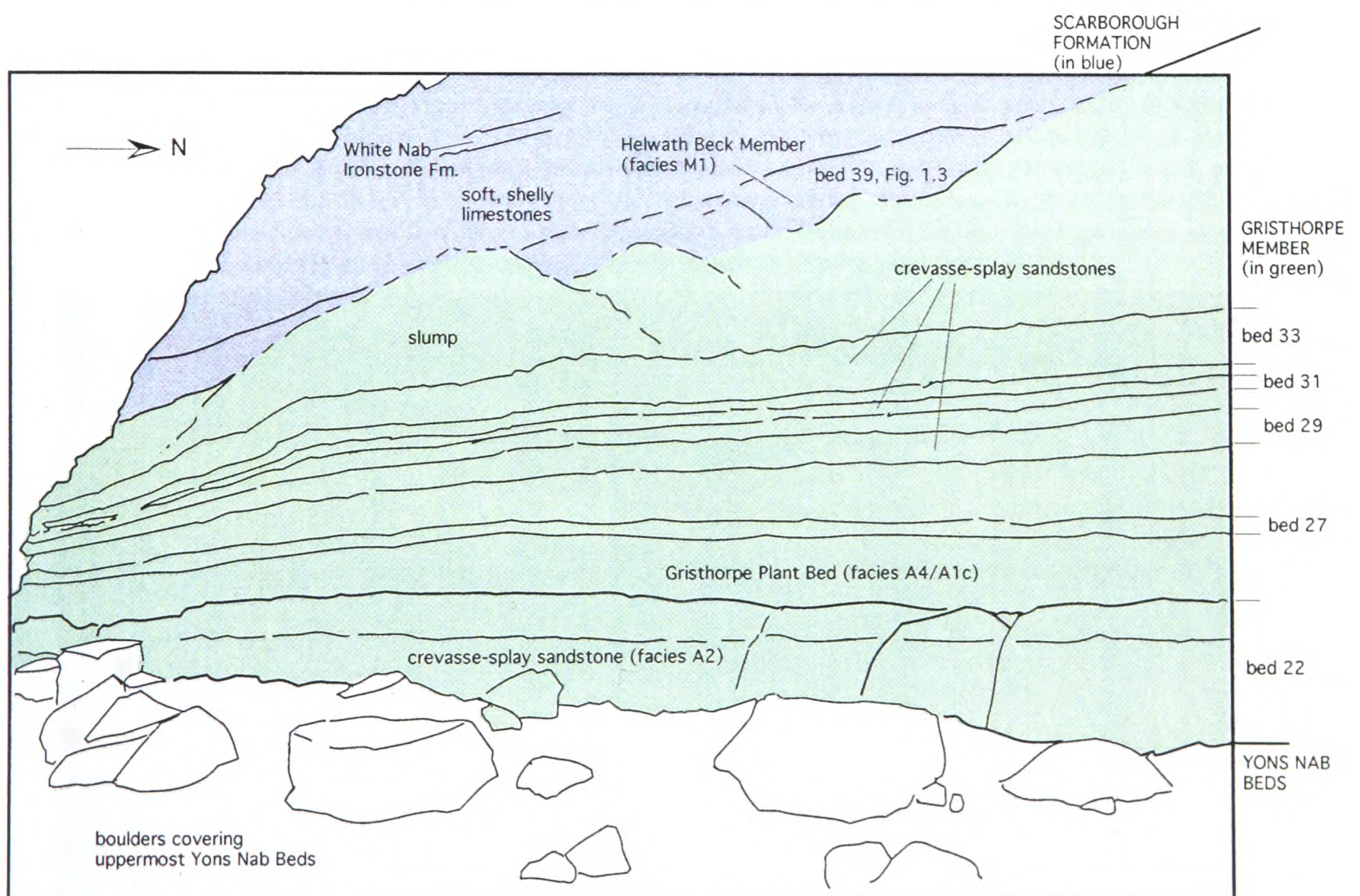


Fig. 1.6 Gristhorpe Member, northern side of Yons Nab (TA 081 044). The figure is standing on a crevasse-splay sandstone which marks the base of the member. To the south, the bed can be traced to the margins of a channel body (bed 20, Fig. 1.4) which downcuts the underlying Yons Nab beds. The bed is heavily bioturbated with a ferruginous upper surface on which numerous internal moulds of bivalves occur, including *Trigonia*, *Pholadomya* and *Pteroperma* (Rawson & Wright 1992). Above rests the Gristhorpe Plant Bed, which is shown in more detail in Fig. 1.7 overleaf. Bed 27 caps the plant bed interval, and is composed of a yellow-coloured, medium-grained sandstone showing both *Diplocraterion* burrows and rootlets. This bed can be traced regionally (e.g. see Cloughton Wyke logs, Fig. 1.15a) and is interpreted as having been deposited during the influence of a brief marine incursion. A sequence of crevasse-splay sandstones (facies A2) and overbank mudstones (facies A5) form the remaining portion of the Gristhorpe Member. In the upper part of the cliff, the poorly exposed Scarborough Formation occurs: most prominent are the Helwath Beck and White Nab Ironstone Members. In the foreground, the Yons Nab Beds occur (facies L1a, b, and L2), covered by boulders. All bed numbers relate to those shown against the sedimentary log in Fig. 1.3.

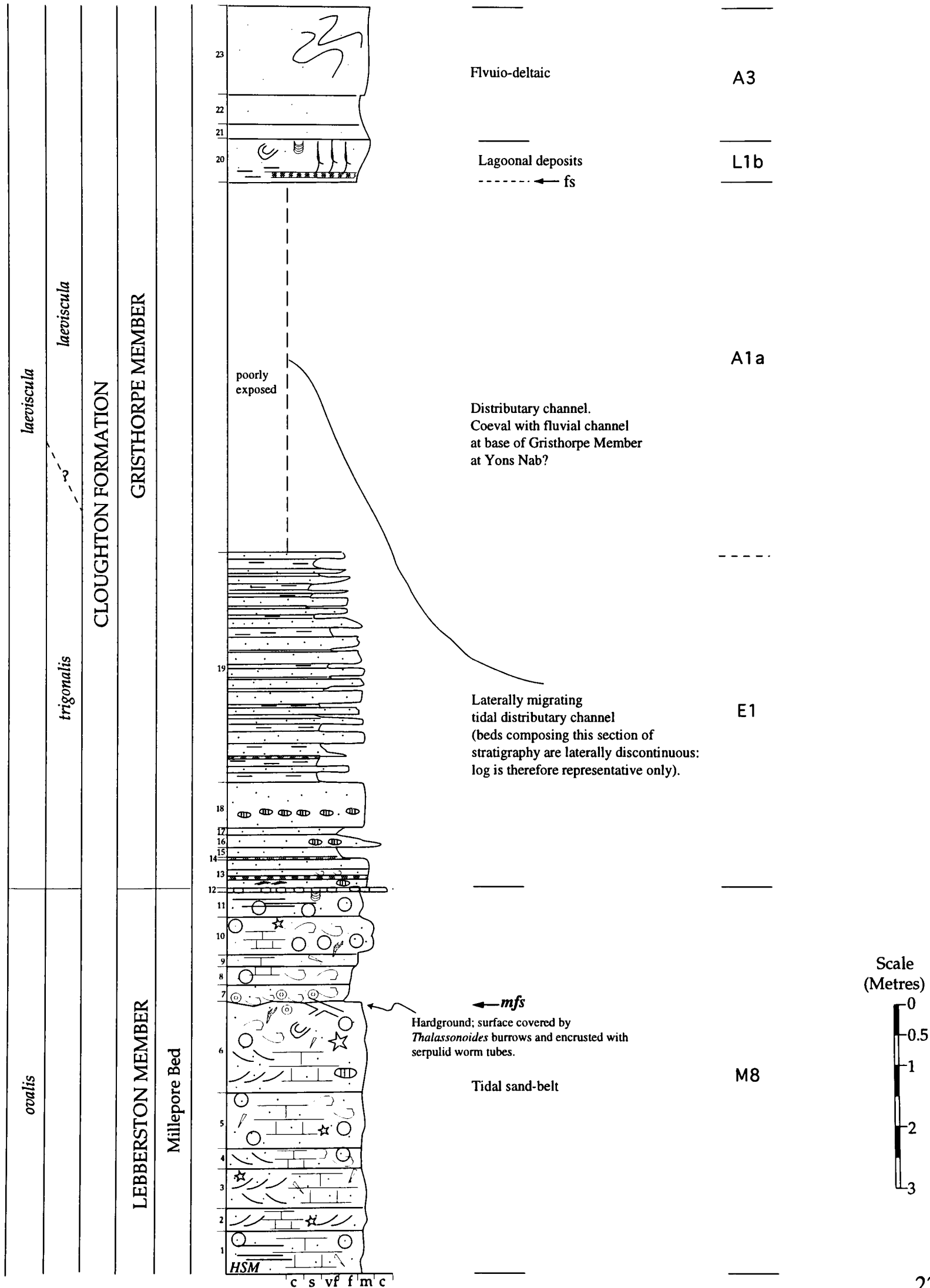


Fig. 1.7 Headland on the northern side of Yons Nab (TA 081 044), showing the Gristhorpe Plant Bed interval in detail. The platform to the left of the photograph corresponds to the upper surface of the crevasse-splay sandstone which forms the base of the Gristhorpe Member (bed 22, Fig. 1.3). Immediately overlying the sandstone lies the plant bed. At the base, a basal claystone occurs which is rich in plant debris (bed 23), succeeded by a wood-rich layer (bed 24), a soft, grey-white claystone which yields the best plant specimens (bed 25), and overlain a hard, micaceous silty claystone (bed 26). Although typical, this succession does vary in a lateral sense: for example, on the headland there are more fragmentary plant remains. The hammer is resting against the marine-influenced sandstone which caps the plant bed (bed 27).



Fig. 1.8 An arrow marks the boundary between the Gristhorpe Member and Helwath Beck Member of the Scarborough Formation. A level of burrowing marks the junction between the black marine mudstones and grey floodplain siltstones; *Skolithos* and 'J'-shaped burrows prevail. Succeeding the black mudstones are delicately laminated siltstones of the Helwath Beck Member, with the bedding picked out by carbonaceous layers. Classified as facies M1, interpreted as having been deposited in a siliciclastic embayment. The boundary is interpreted as a transgressive surface.

Fig. 1.9 A new sedimentary and stratigraphic log for Osgodby Nab (TA 065 864). The log shows the Millepore Bed of the Lebberston Member, succeeded by the lower part of the Gristhorpe Member. Biostratigraphy is based on Parsons (1980) and Bradshaw & Bate (1982). This succession was juxtaposed against the Callovian Cornbrash Formation to the west by the Cayton Bay Fault (Rawson & Wright 1992).



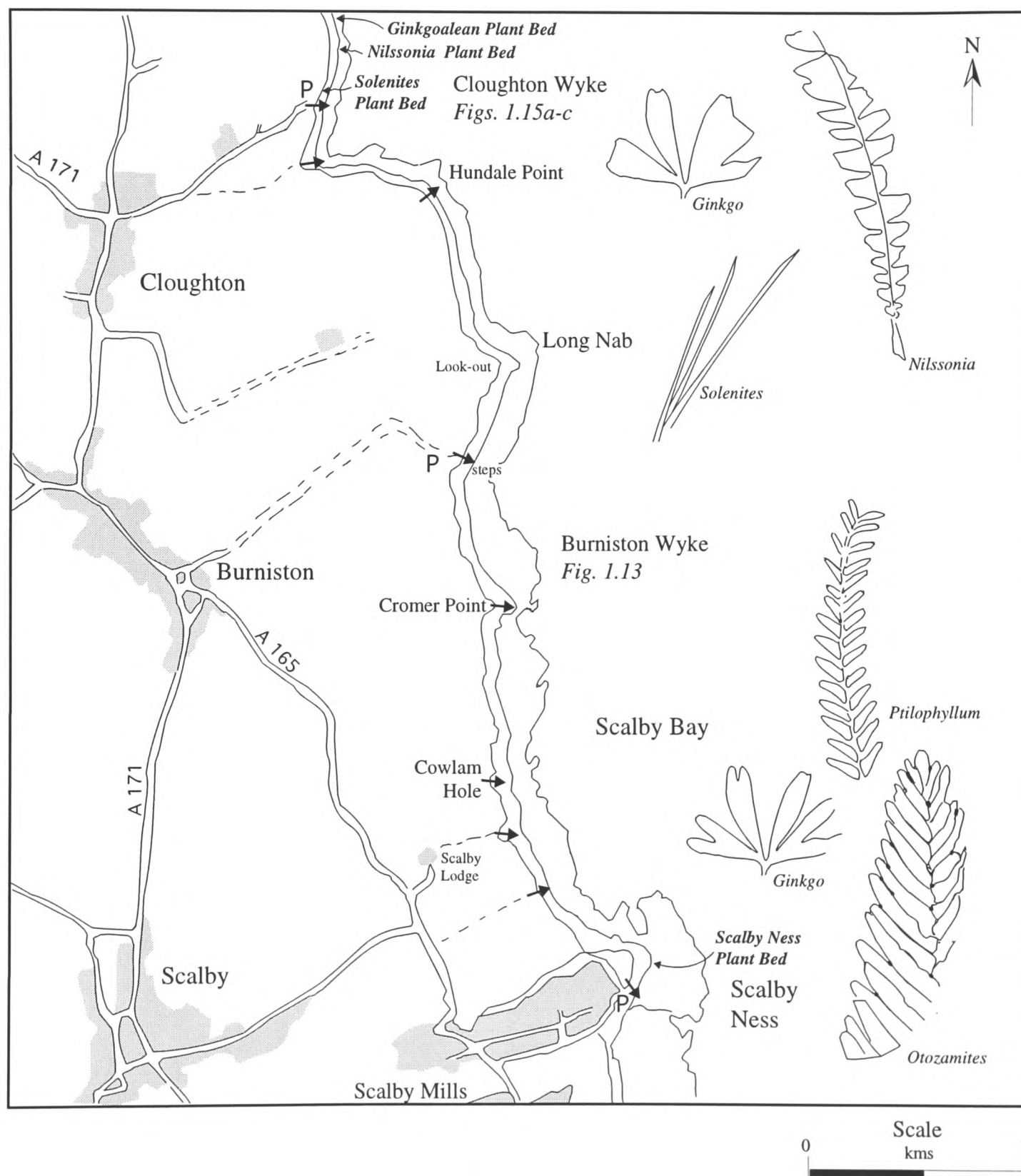


Fig. 1.11 Map of localities between Cloughton Wyke and Scalby Ness (redrawn and modified from Rawson & Wright 1992). Figure numbers relate to the sedimentary logs recorded at these localities. The genera illustrated are typical of the plant beds highlighted.

226



227-

227

227

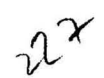




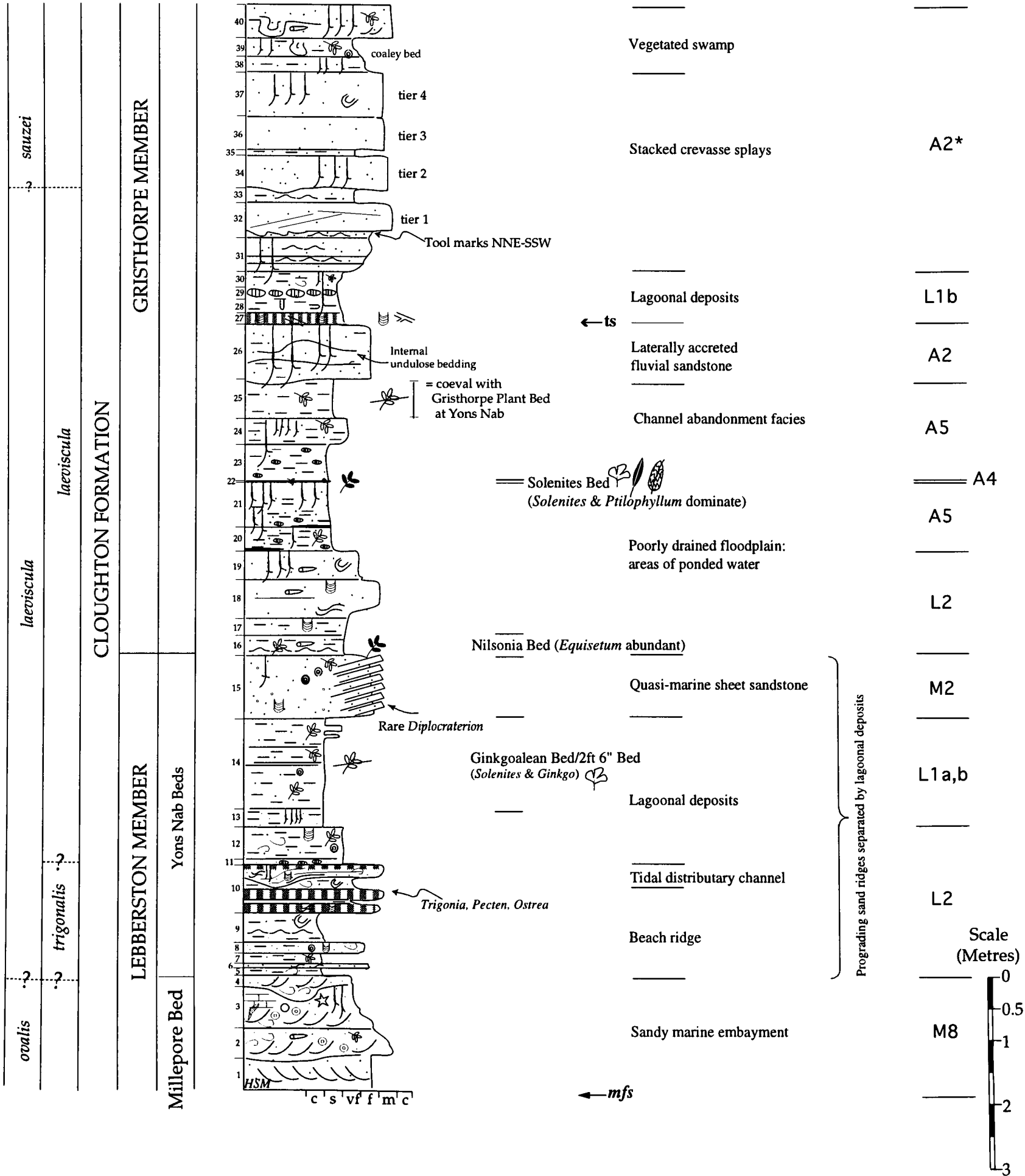
Fig. 1.14 Scalby Formation, Burniston Wyke. Looking north.

The meander-belt sandstone (facies A1a) seen shrouded with seaweed on the foreshore, forms the basal part of the Long Nab Member. Individual, inclined sandstone beds of the point-bar sequence can be seen. One of Black's Channels (labelled BC) occurs at the base of the cliff, in places cutting down into the underlying meander-belt. Laterally the channels grade into the muddy, overbank facies of facies A4 and A5. Thin, crevasse-splay sandstones are intercalated. It is at this stratigraphic level that the Scalby Wyke Plant Bed occurs; the Scalby Ness Plant Bed exists at a slightly higher position in the point-bar sequence. Some 4 m above the base of the cliff, the Burniston Dinosaur Footprint Bed occurs (labelled DF). The prints were made in soft, silty clay subsequently infilled by an incursion of silt and sand, preserving the prints as casts (Black et al. 1934; Rawson & Wright 1992).

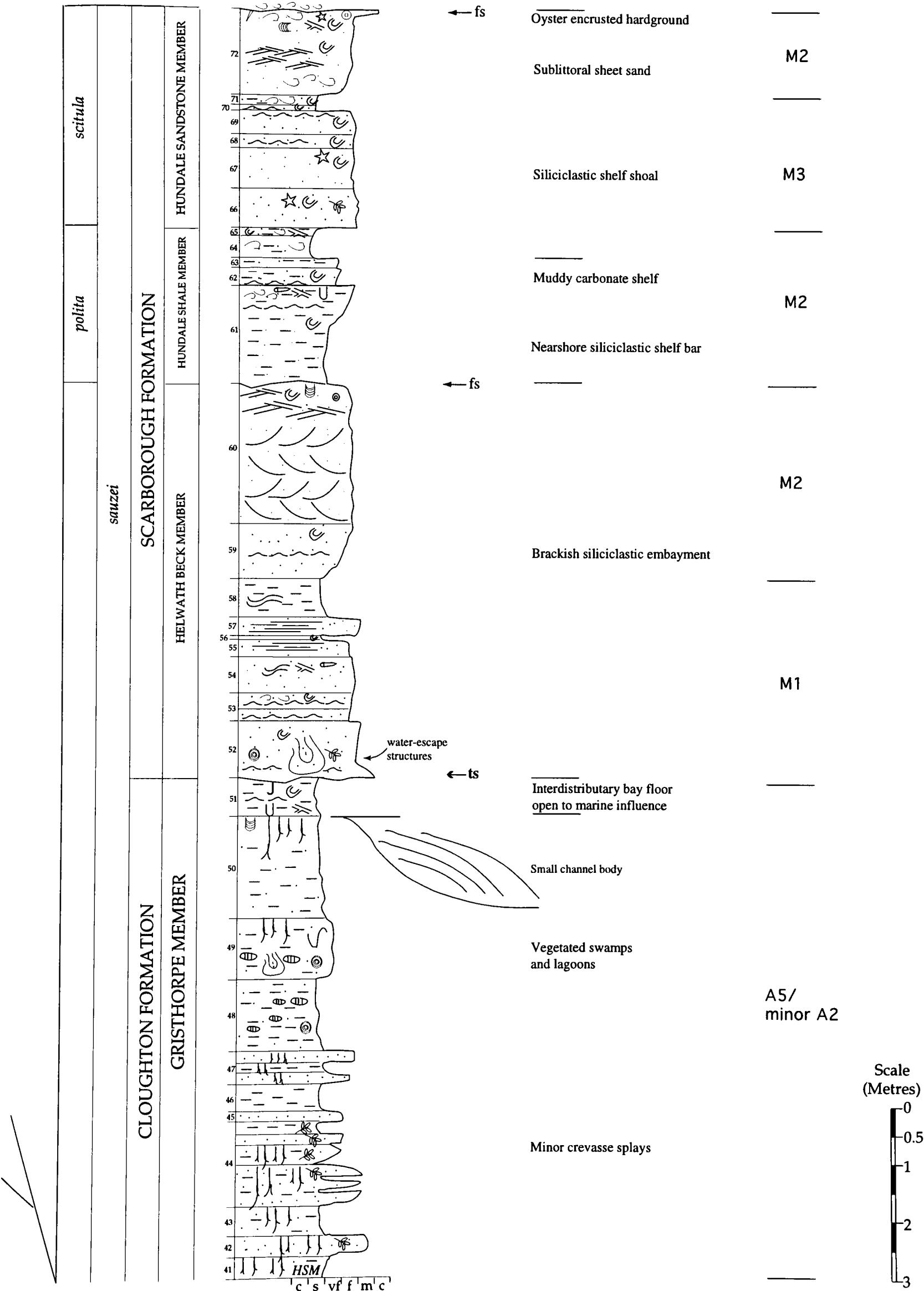
To the right of the photograph, in the distance, Hundale Point can be seen. Here, braided-river channels at the base of the Scalby Formation (Moor Grit Member) form the headland.

Fig. 1.15 *a, b & c*. New sedimentary and stratigraphic logs for Cloughton Wyke (TA 021 955) to Hundale Point (TA 026 948) sections. Logs show the Millepore Bed, Lebberton Member and base of the Scalby Formation, in three consecutive parts. The log beneath is part *a*, and the succeeding strata follows overleaf.

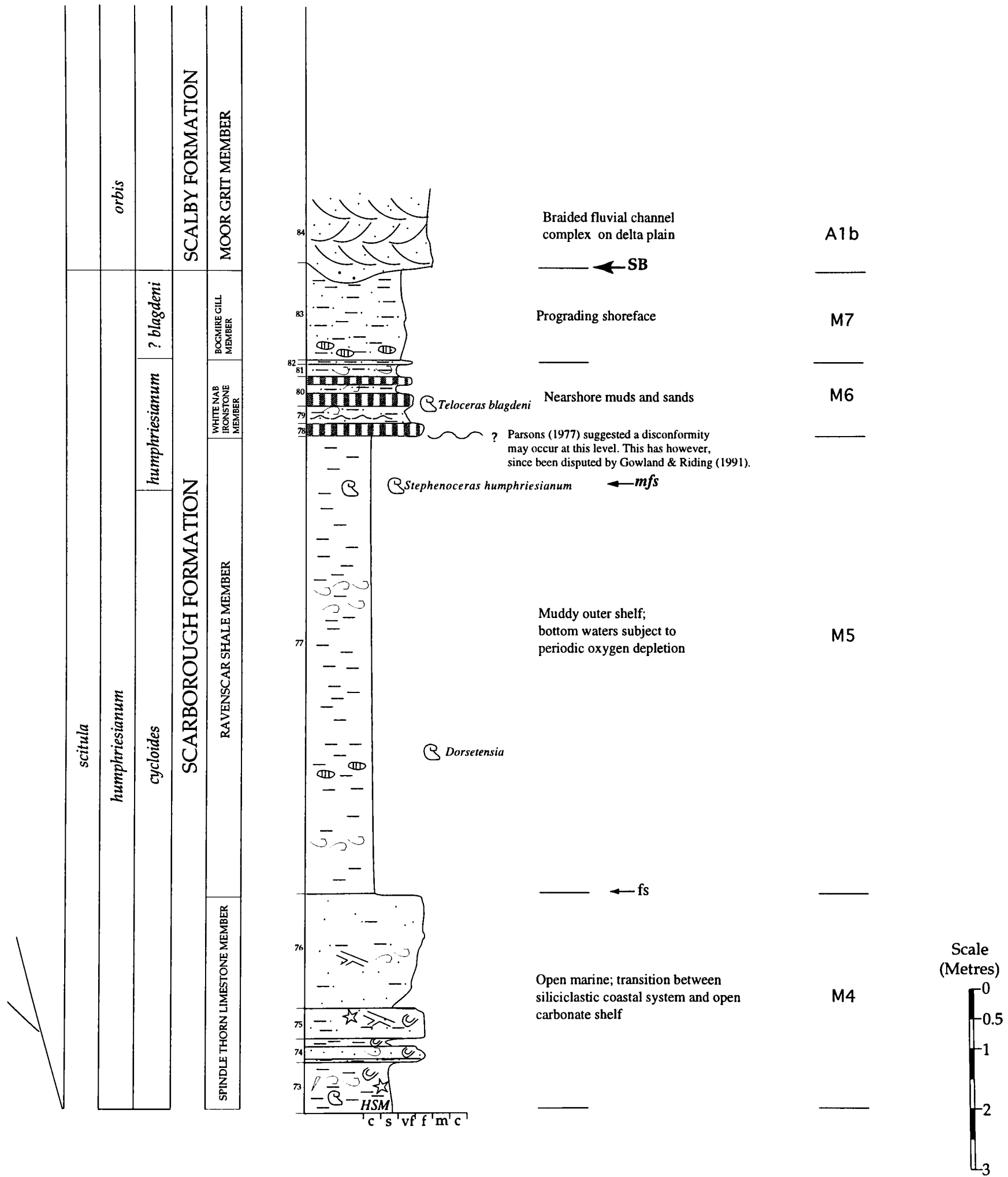
a) This log records the strata from the north of Cloughton Wyke to the cliffs adjacent to the path descending from the car park.



b) This log continues from the previous section, across the centre of Cloughton Wyke, to Hun Dale.



c) Terminal sedimentary log of Cloughton Wyke to Hundale Point section, from the previous section at Hun Dale southwards to Hundale Point.



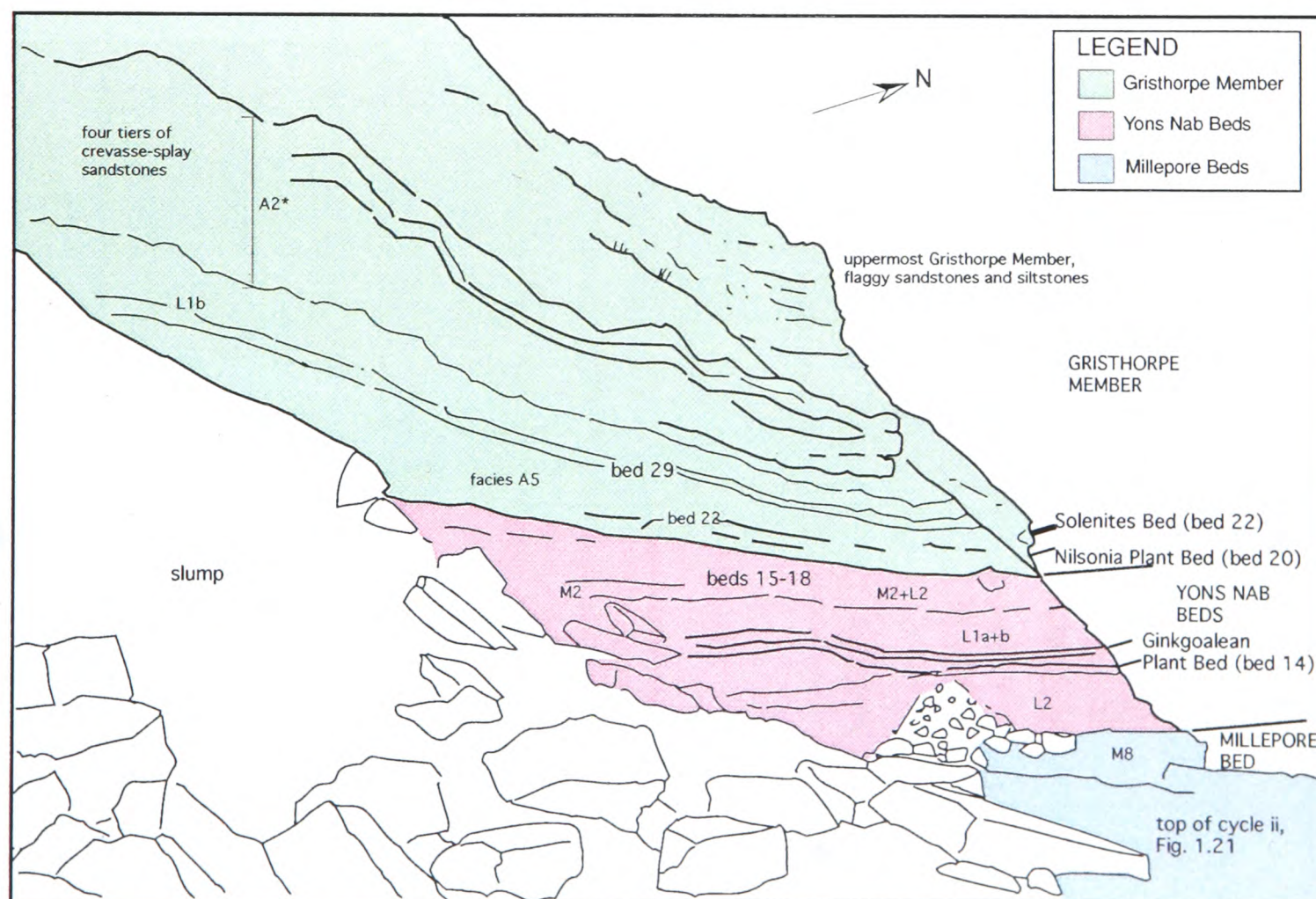


Fig. 1.16 Northern side of Cloughton Wyke, facing north (TA 021 955). Photograph show a sequence spanning the mid-Millepore Bed to upper Gristhorpe Member. Note position of Ginkgoalean, *Nilsonia* and *Solenites* Plant Beds, shown in more detail in Fig. 1.17 overleaf. The upper, reddened surface of cycle ii in the Millepore Bed, corresponds to a maximum marine flooding surface. Bed 29 denotes the position of a brief marine incursion which can be traced across the basin; see Fig. 1.17 for further details.

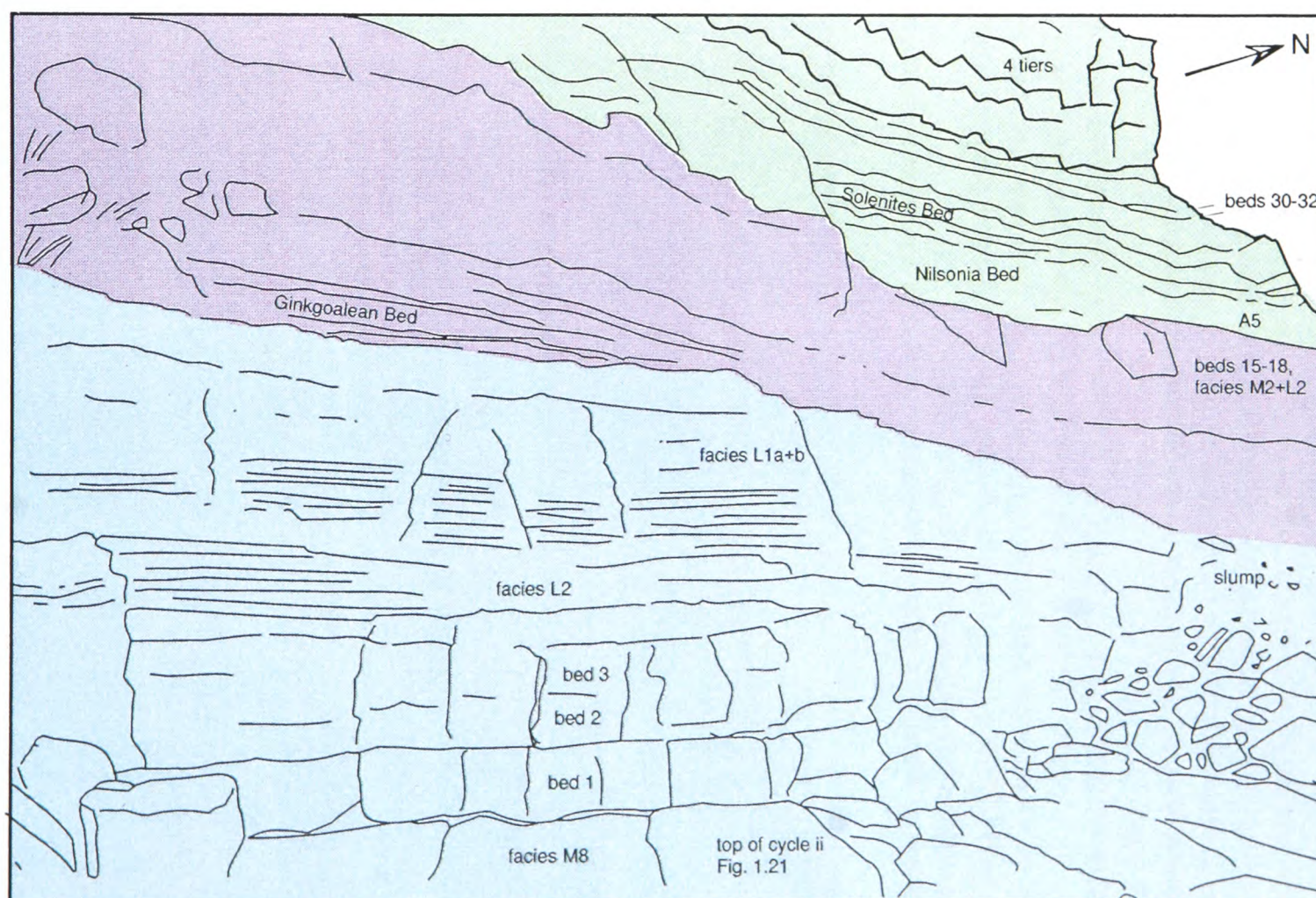


Fig. 1.17 Upper Millepore Bed, Yons Nab Beds and Gristhorpe Member, Cloughton Wyke. See Fig. 1.16 for legend. This diagram shows more clearly the stratigraphic position of the plant beds recorded in the sedimentary log, Fig. 1.15a.



a.



b.

Fig. 1.18 Photographs to show an interval of lagoonal sediments within the otherwise non-marine Gristhorpe Member. All bed numbers relate to the sedimentary logs illustrated in Fig. 1.14.

a. Vertical cliff section showing the mid-portion of the member. The thin (~1cm), laterally continuous *Solenites* Plant Bed is highlighted by an arrow at the base of the cliff (bed 22). The plant-rich seam (facies A4) occurs within a sequence of overbank siltstones (facies A5) and crevasse-splay sandstones (facies A2). The lagoonal facies consist of black mudstones which, at this locality, are grass-covered. The lagoon interval rests upon pale grey, rooted silty sandstones (bed 28).

b. Enlargement of the lagoon interval. The hammer is resting upon the pale grey, rooted silty sandstones described above, which are in turn overlain by a 10-20 cm thick band of orange-coloured, sandy siltstones bearing *Diplocraterion* burrows (bed 29). Above rest a sequence of dark-grey to black, bioturbated, laminated mudstones (beds 30 and 32), divided by a nodular ironstone horizon (bed 31). The interval is interpreted as representing a brief marine flooding event across the Cleveland Basin.

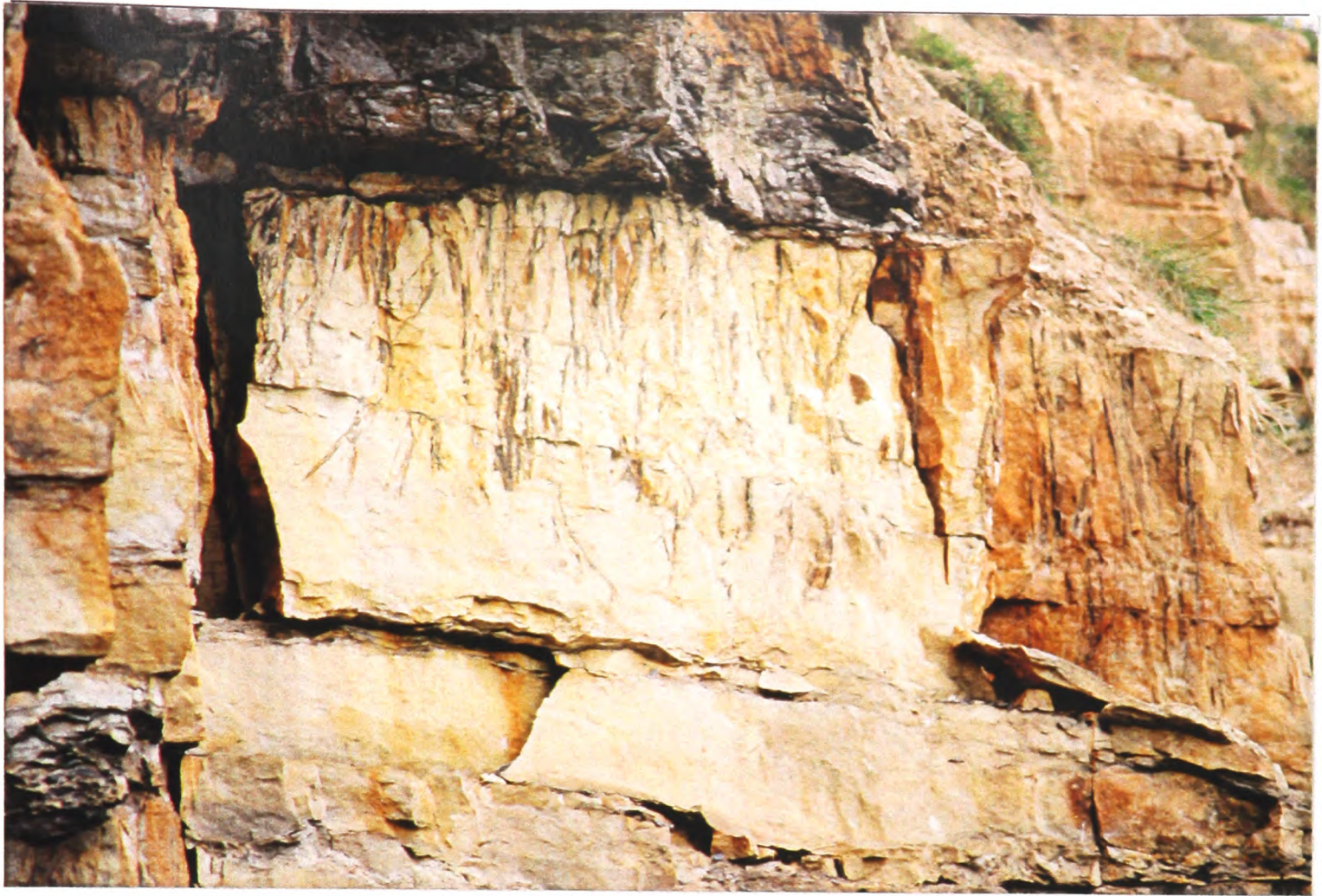


Fig. 1.19 *Equisetum* rootlets penetrating the top of a crevasse-splay sandstone in the mid-Gristhorpe Member, Cloughton Wyke (bed 39, Fig. 1.15a). The bed forms one of four main sandstone tiers found at this level (Fig. 1.16).

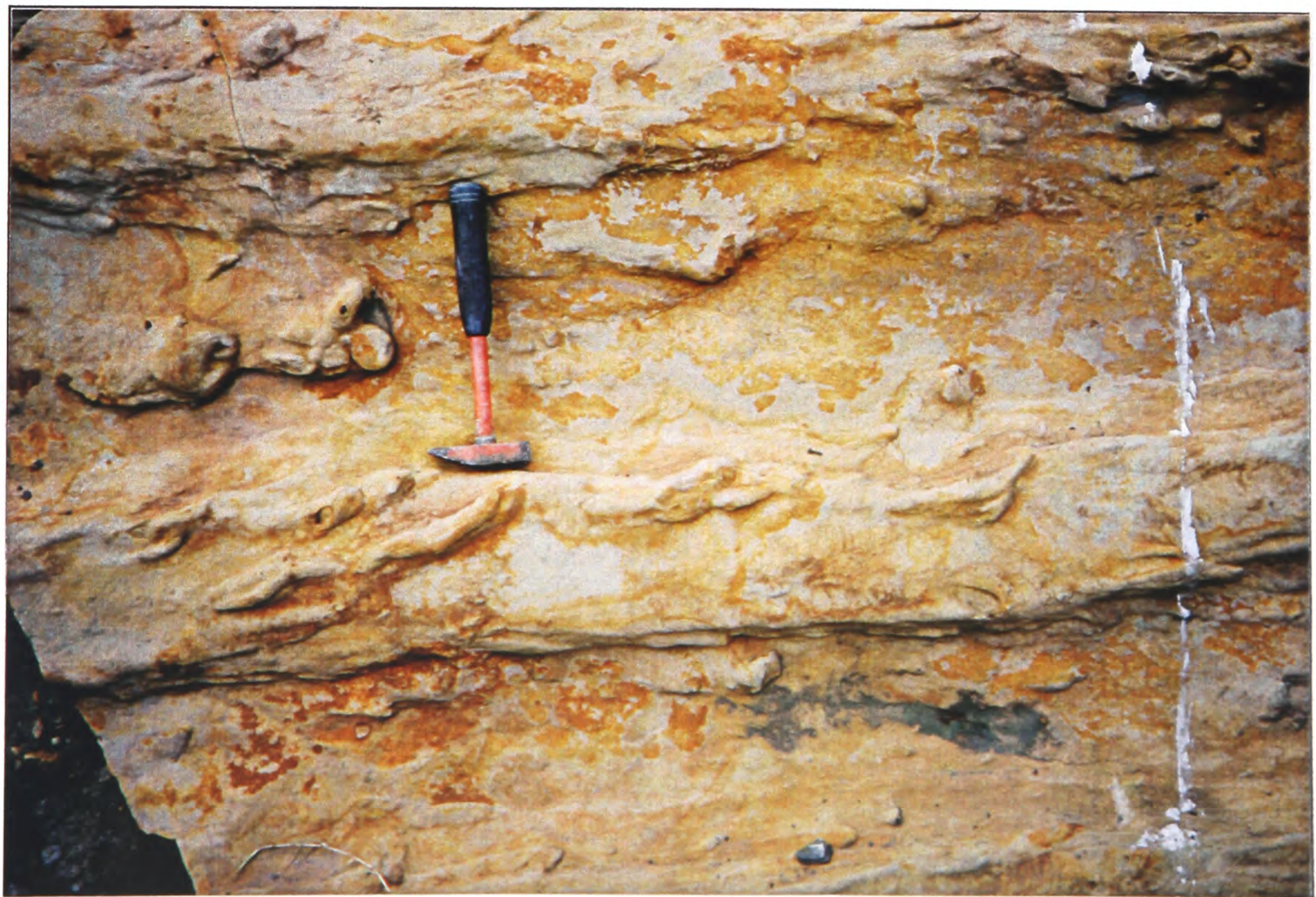
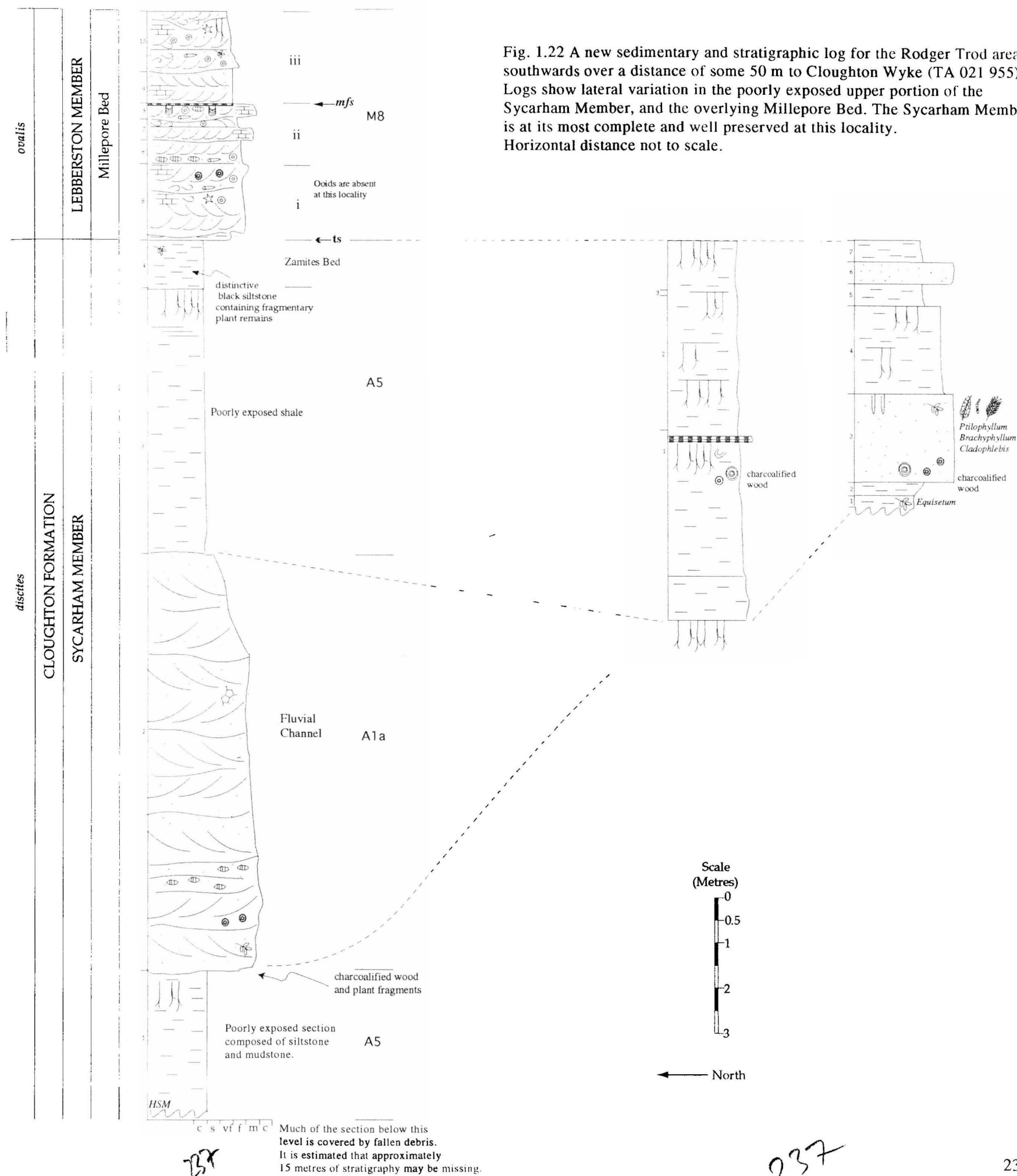


Fig. 1.20 Upturned sandstone block showing grooves and flutes carved into the thinly-bedded sandstone. The structures indicate a current direction flowing NNE-SSW (Rawson & Wright 1992). Such scours are found in the basal sandstone tier in the mid-Gristhorpe Member (bed 34, Fig. 1.15a).



Fig. 1.21 Convoluted sandstone bed at the base of the Scarborough Formation, Cloughton Wyke (bed 55, Fig. 1.15*b*). Deformation of the bed is thought to have been caused by an earthquake shock due to movement along the Peak Fault, 1.6 km to the west (Rawson & Wright 1992).



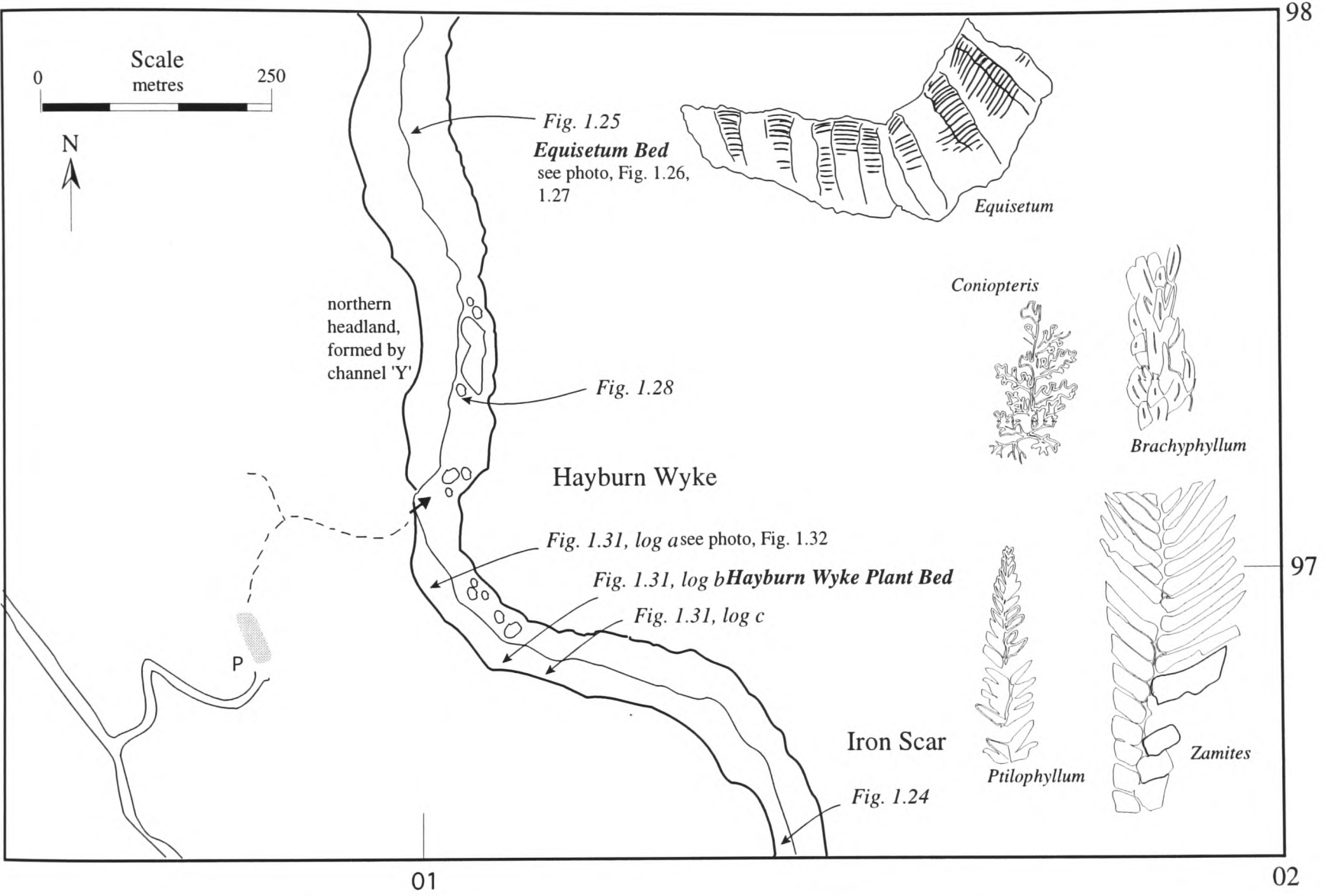


Fig. 1.23 Map of localities between Hayburn Wyke and Iron Scar. Figure numbers relate to the sedimentary logs recorded at these localities. Genera commonly found in the Hayburn Wyke Plant Bed are illustrated, and a typical form of *Equisetum* in the *Equisetum* bed shown .

Fig. 1.24 A new sedimentary and stratigraphic log for Iron Scar (TA 015 968). Logs show uppermost Saltwick Formation, Eller Beck Formation and lowermost Sycarham Member. Numerous *Diplocraterion* burrows near the base of the Eller Beck Formation mark a maximum-flooding surface.

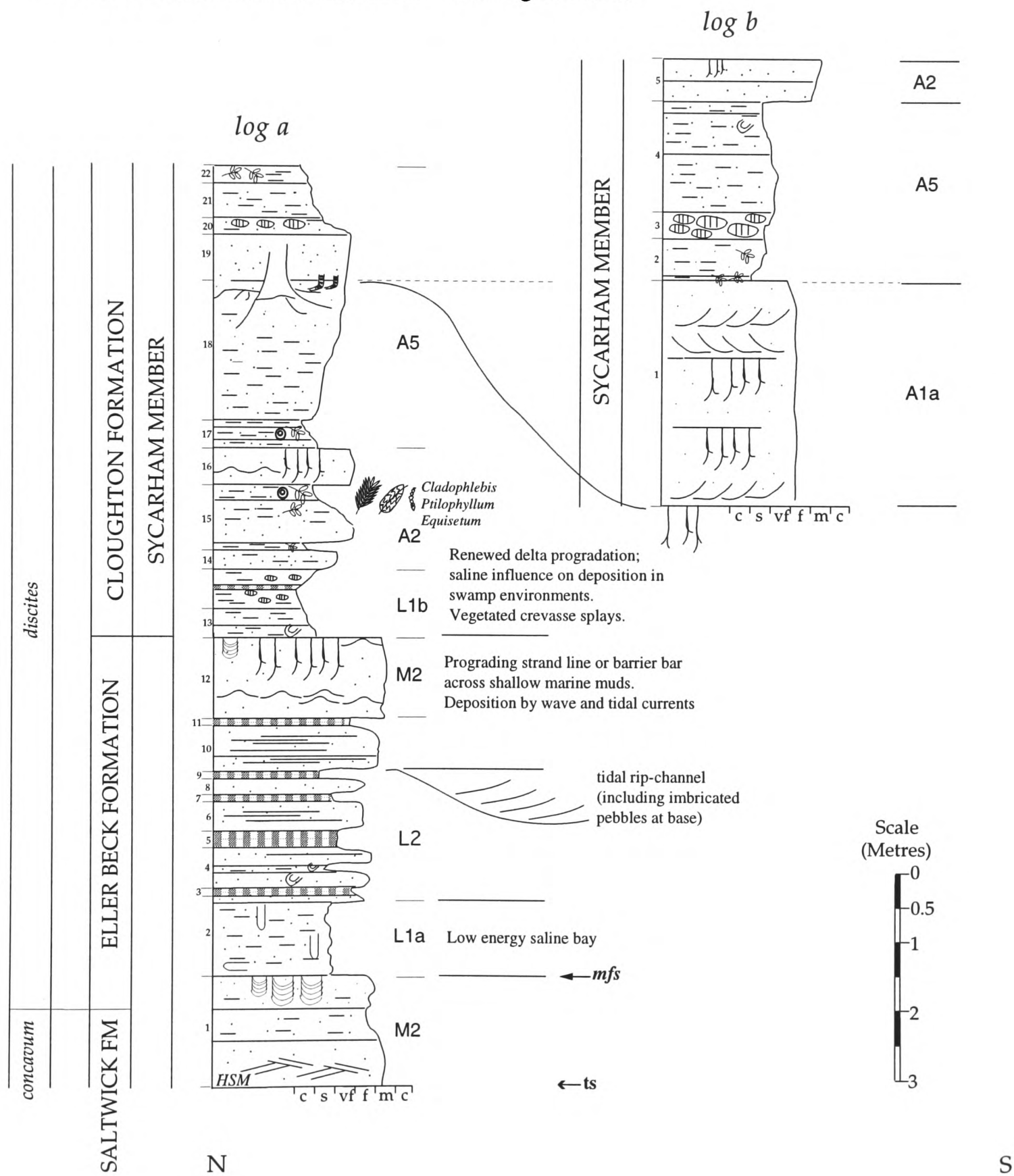


Fig. 1.25 New sedimentary and stratigraphic log for bay to the north of Hayburn Wyke (TA 010 977). The logs represent the lower part of the Saltwick Formation. Log C is repeated from Fig. 1.28 and used as a basis for correlation to Hayburn Wyke.

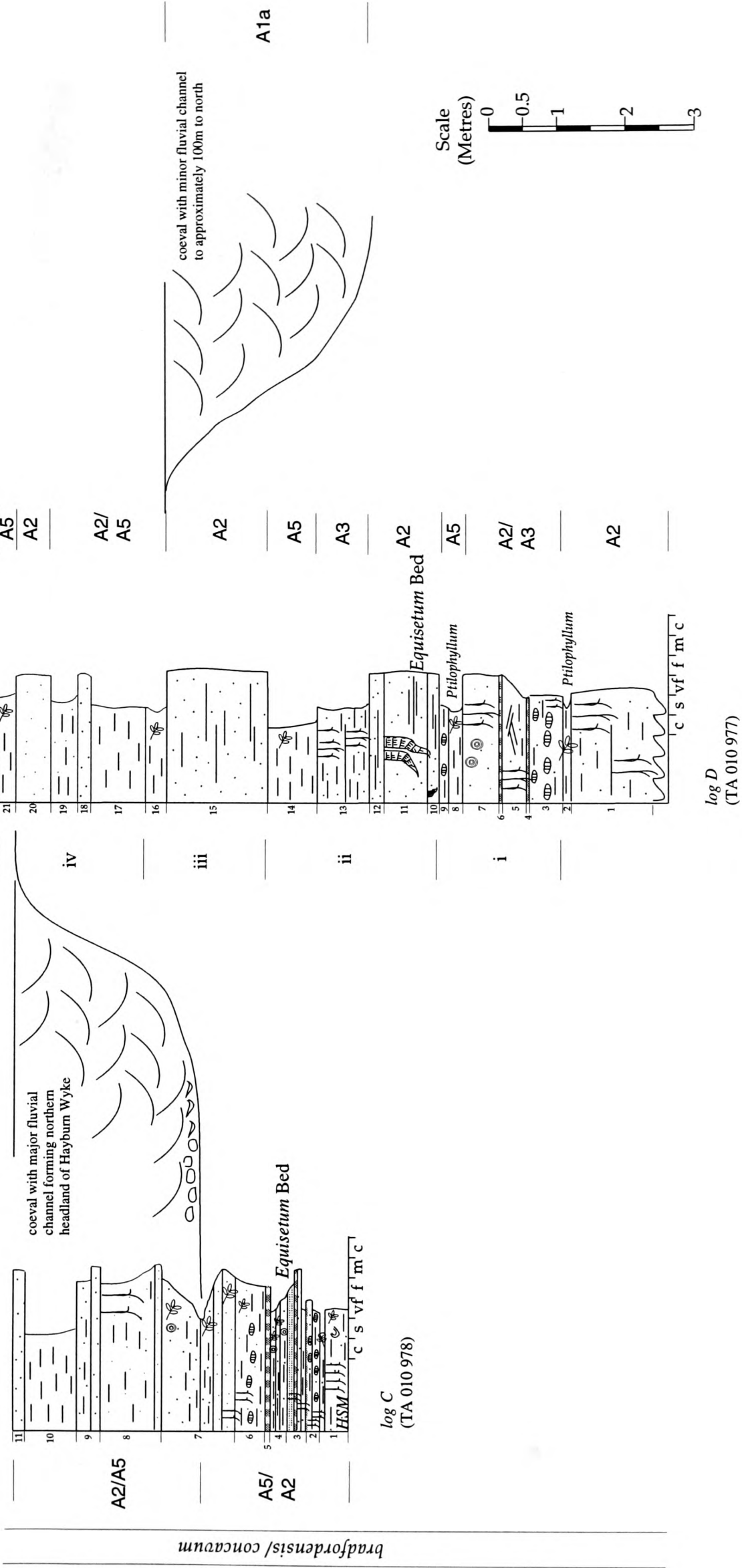


Fig. 1.26 Small-scale (fourth-order) cycles in the Saltwick Formation, north of Hayburn Wyke (TA 010 977). The laterally continuous *Equisetum* Bed is highlighted, an enlargement of which is shown in Fig. 1.27 overleaf. The relatively flat-lying beds can be traced with ease along the coastline. The crevasse-splay sandstone marked as bed 15 can be correlated to the margins of a channel to the north. Bed 20 at the top of the cliff section can be traced to the margins of the major channel body forming the northern headland of Hayburn Wyke (see Figs. 1.28-1.29).

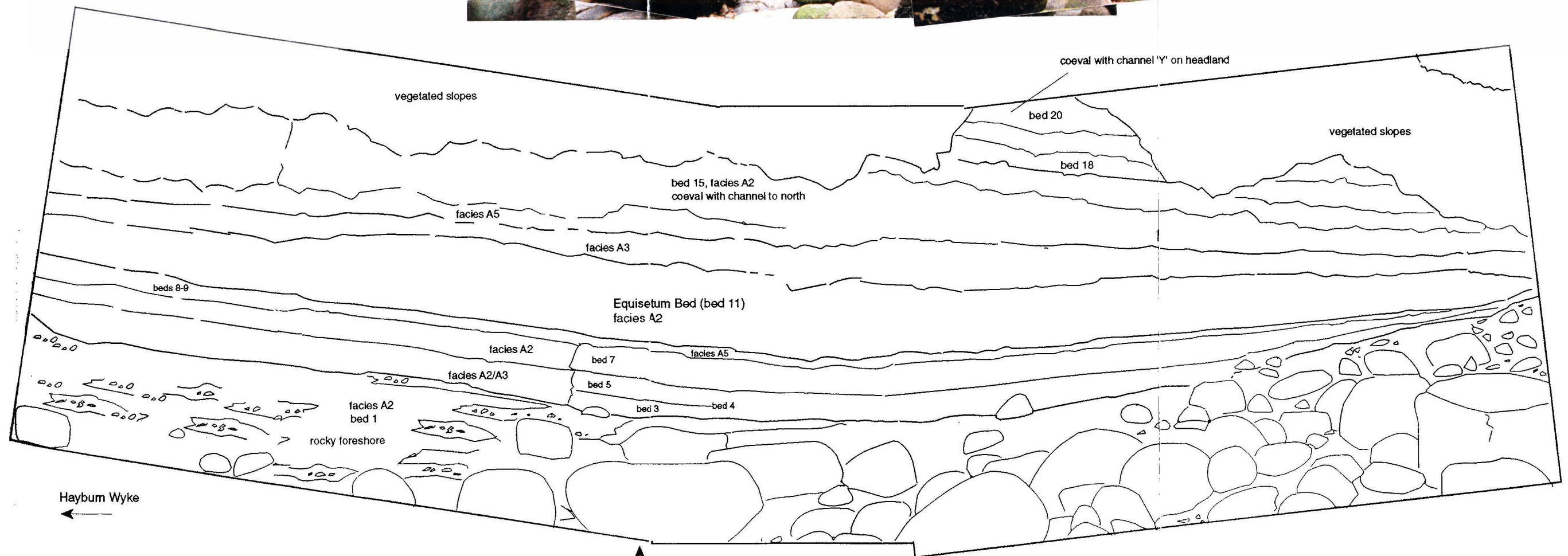




Fig. 1.27 *Equisetum* Bed, northern Hayburn Wyke (bed 15, Fig. 1.25). Two *in situ* stems are indicated by arrows in the crevasse-splay sandstone. Scale: 50 cm.

Fig. 1.28 New sedimentary and stratigraphic logs for the northern headland of Hayburn Wyke, adjacent to the waterfall at the approach to beach. Logs record the middle to upper part of the Saltwick Formation. Roman numerals highlight small-scale cycles.

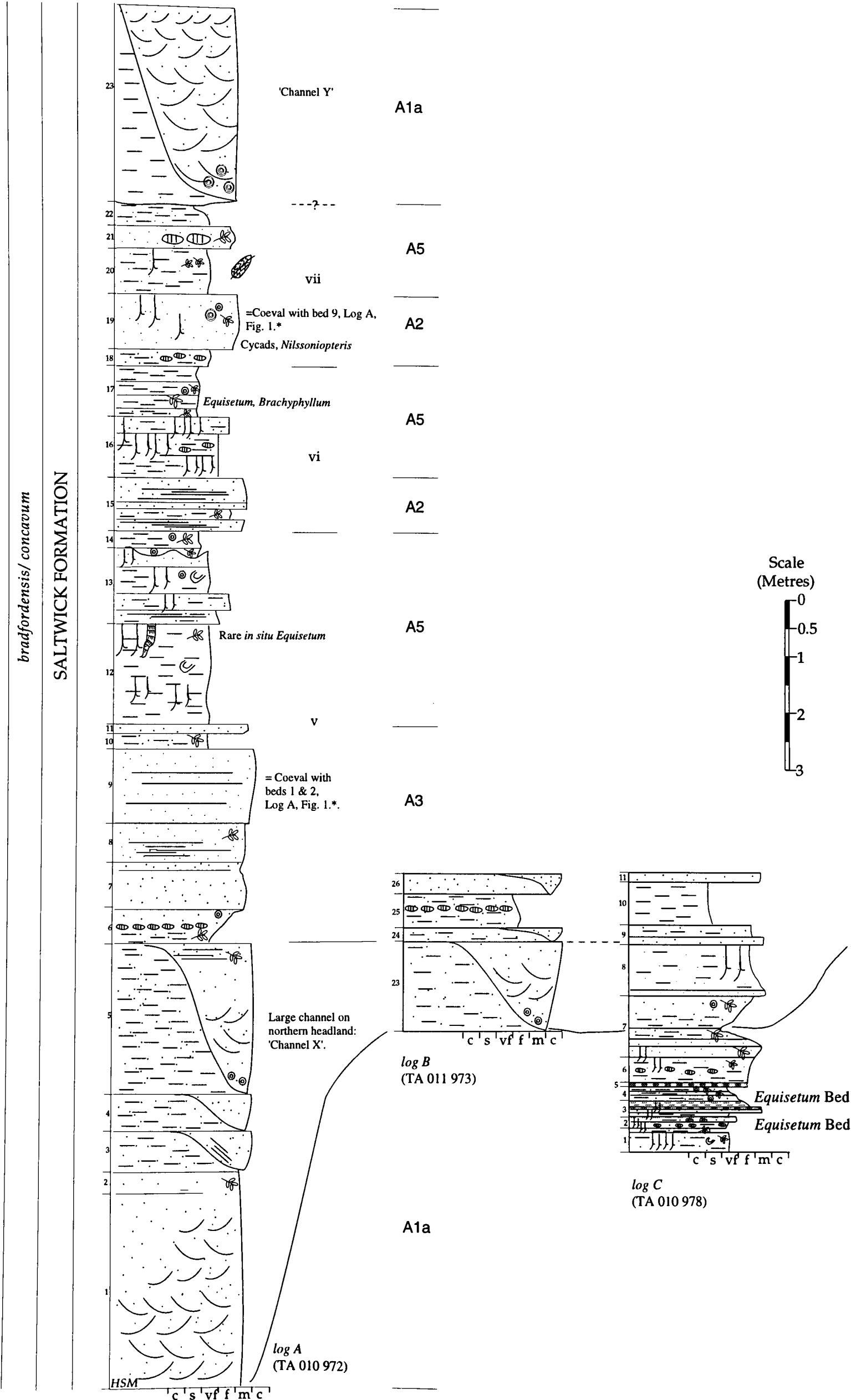




Fig. 1.29 Hayburn Wyke (TA 011 975), facing north. A large channel body (labelled X) forms the northern headland of the bay, which corresponds to beds 1-9, Fig. 1.28. Exposure in this area is rather patchy, but in discrete areas portions of the Saltwick Formation can be studied. The locality at which the upper part of Fig. 1.28 was recorded is indicated by the letter Y, which also denotes a channel body. A path descends to the beach immediately to the left of the outcrop.



Fig. 1.30 This photograph shows in detail channel body Y, highlighted above. The section is recorded by beds 12-23, Fig. 1.28. The channel body is represented by the thick sandstones at the top of the cliff section; the two black layers below the channel yield well preserved plant remains, including *Equisetum* and *Brachyphyllum*.

Fig. 1.31 New sedimentary and stratigraphic logs for Hayburn Wyke (TA 981 971).
The logs show the upper part of the Saltwick Formation, overlain by the Eller Beck Formation.
The sections are arranged south to north across the page.

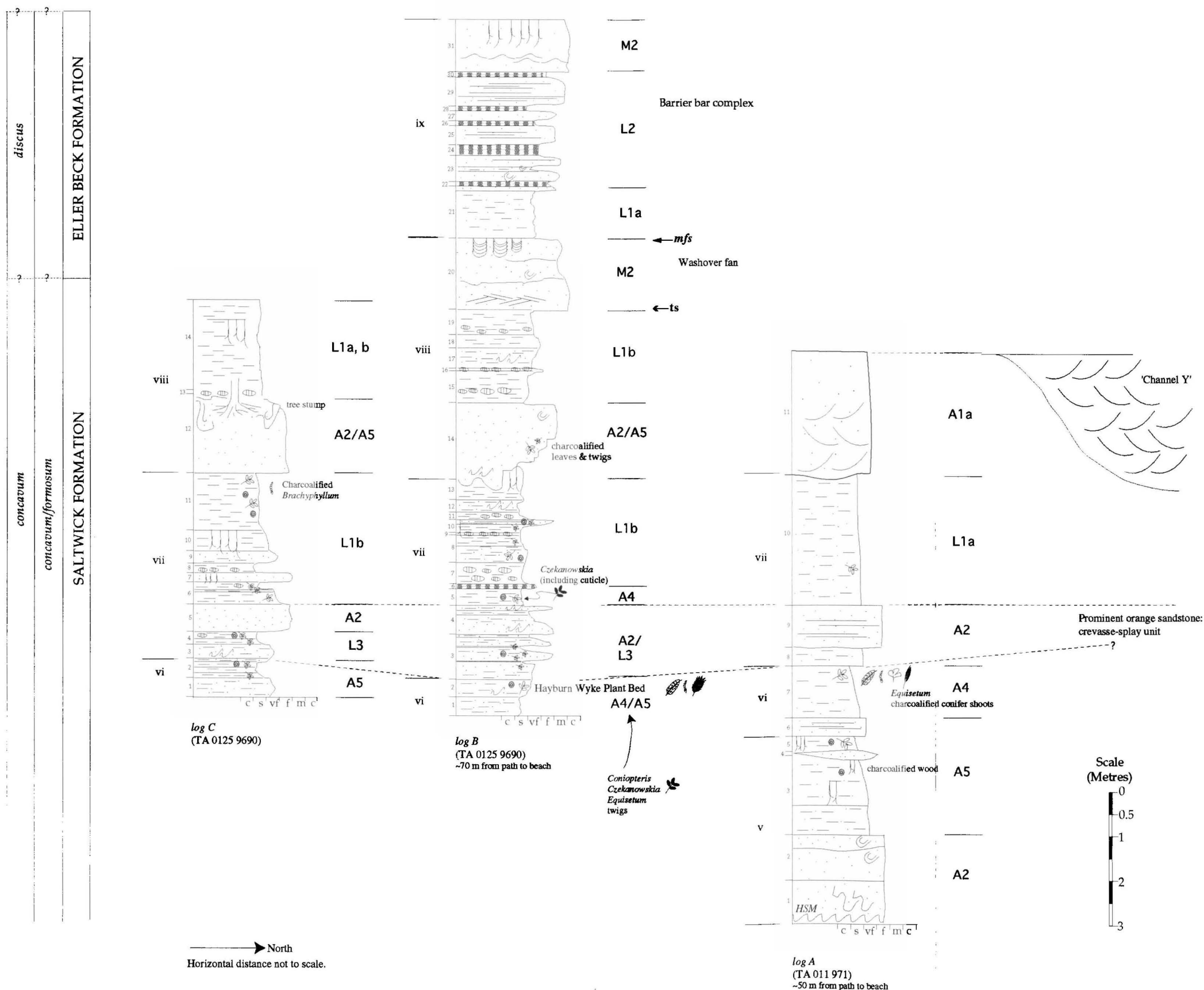




Fig. 1.32 Outcrop of the Saltwick Formation, Hayburn Wyke (TA 011 971), where log a, Fig. 1.31 was recorded. Photograph faces north-west. The label 'EB' mid-way up the cliff section corresponds to the upper sandstone part of the Eller Beck Formation. The letter 'Y' denotes the lateral extent of channel body Y, seen in more detail in Fig. 1.30. The bed marked '9' is a crevasse-splay sandstone which is fairly laterally continuous and thus useful for correlation (see bed 9, Fig. 1.31).



Fig. 1.33 An exposure of the Saltwick Formation immediately to the south of the outcrop shown above. These beds are also shown in log b, Fig. 1.31. Again, 'EB' denotes the Eller Beck Formation, and the lateral extent of channel body Y is marked by the number 14 (bed number in log b, Fig. 1.31). The flaggy sandstone and siltstone intercalations at the base of the cliff form the Hayburn Wyke Plant Bed (beds 1-4, log b, Fig. 1.31).

Fig. 1.34 High Hawsker (NZ 948 082).
 At this locality, the Dogger Formation is composed of a tough, sideritic sandstone containing iron nodules and U-shaped burrows of *Diplocraterion* or *Arencolites*-type. At the base of the ~1.5 m unit, rip-up clasts of the underlying Whitby Mudstone facies occur. A large channel at the base of the overlying Saltwick Formation partly downcuts and erodes the Dogger Formation. Large pieces of wood are entrained in the base of the channel. (See also Figs. 1.35-1.36.)

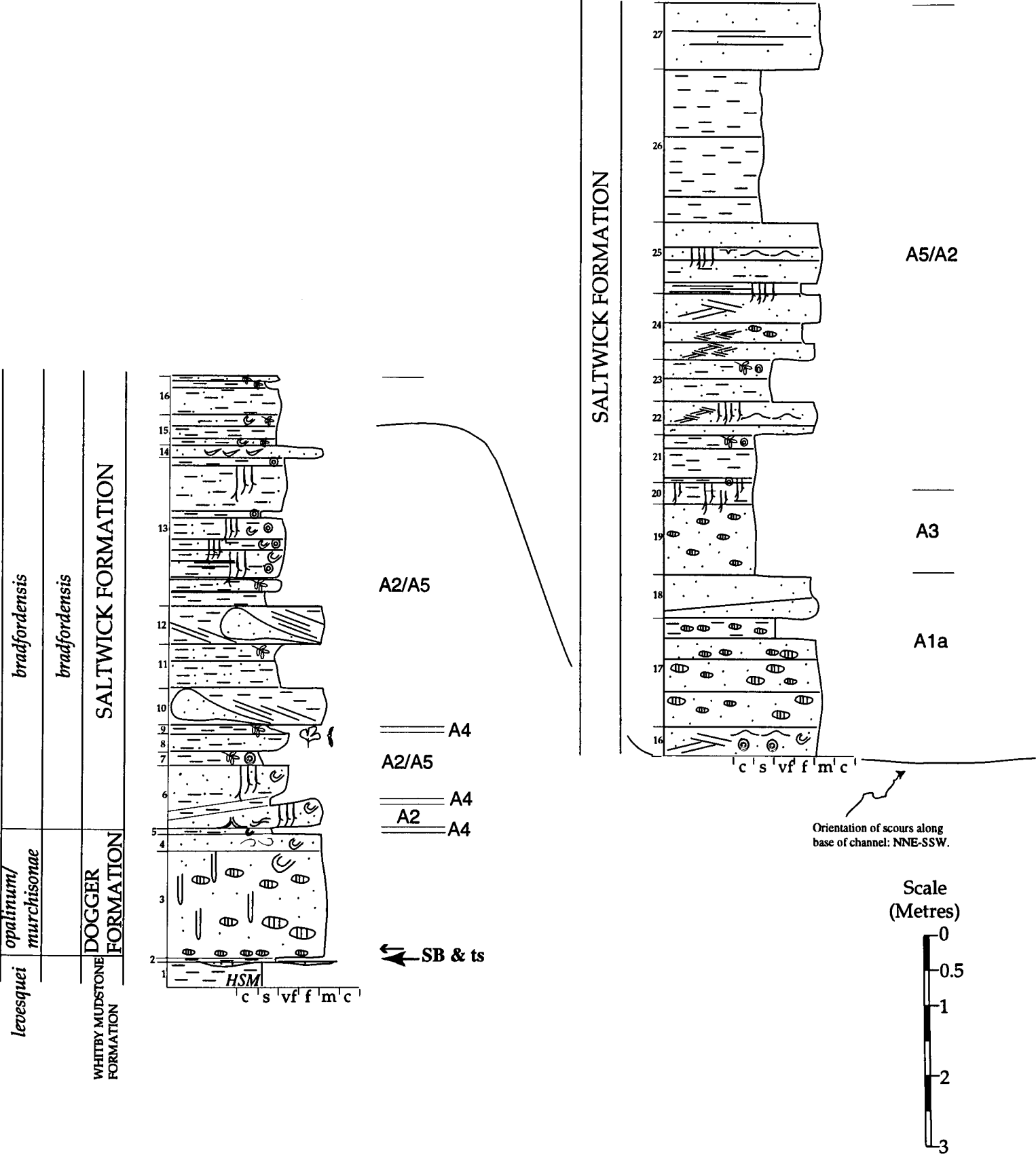




Fig. 1.35 Contact between the Dogger (labelled D) and Saltwick Formation (labelled S), High Hawsker (NZ 948 082).



Fig. 1.36 Detail of *Equisetum* rootlets in the lowermost Saltwick Formation at High Hawsker. The roots extend from laminated overbank siltstones into crevasse-splay sandstones.

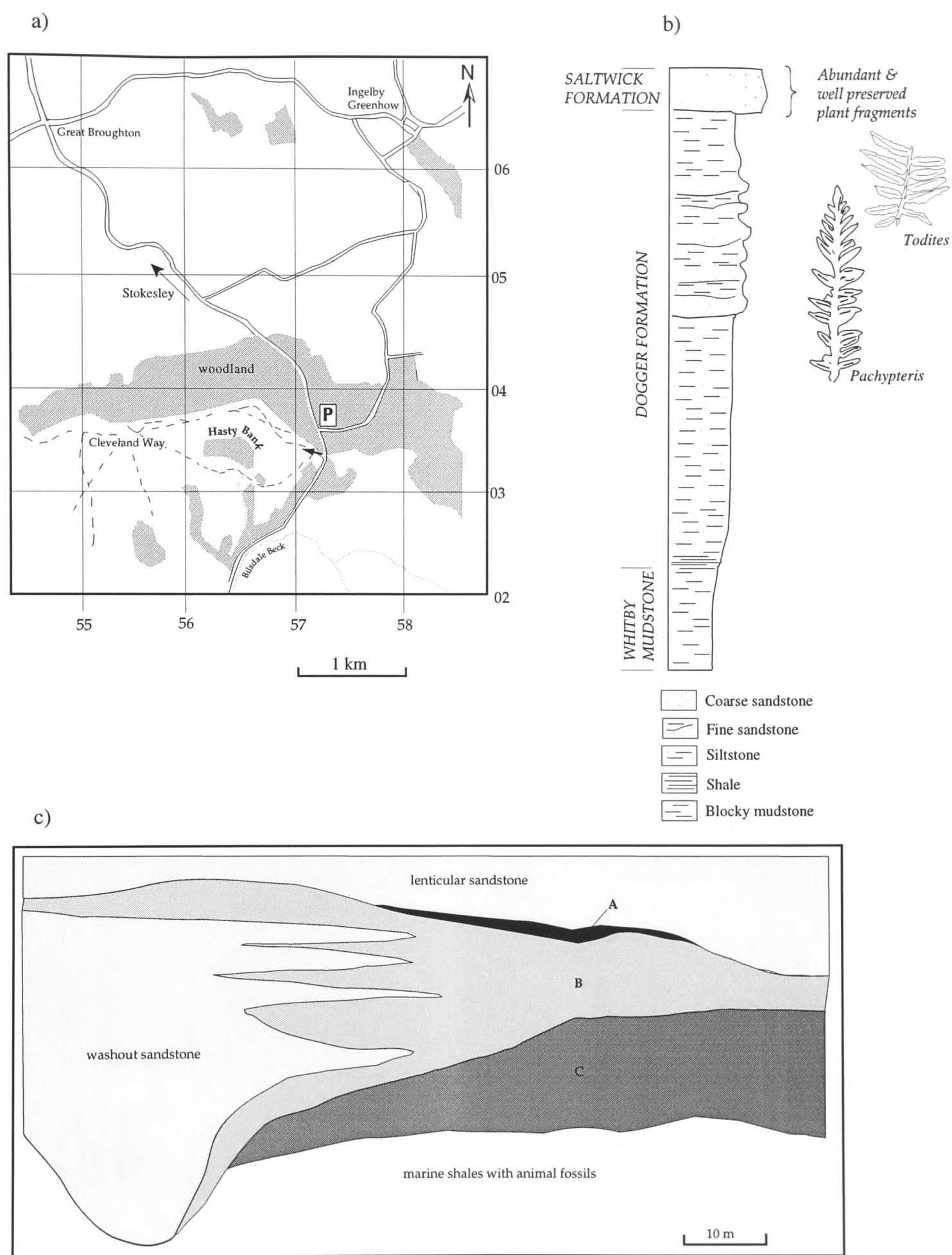


Fig. 1.37 Hasty Bank.

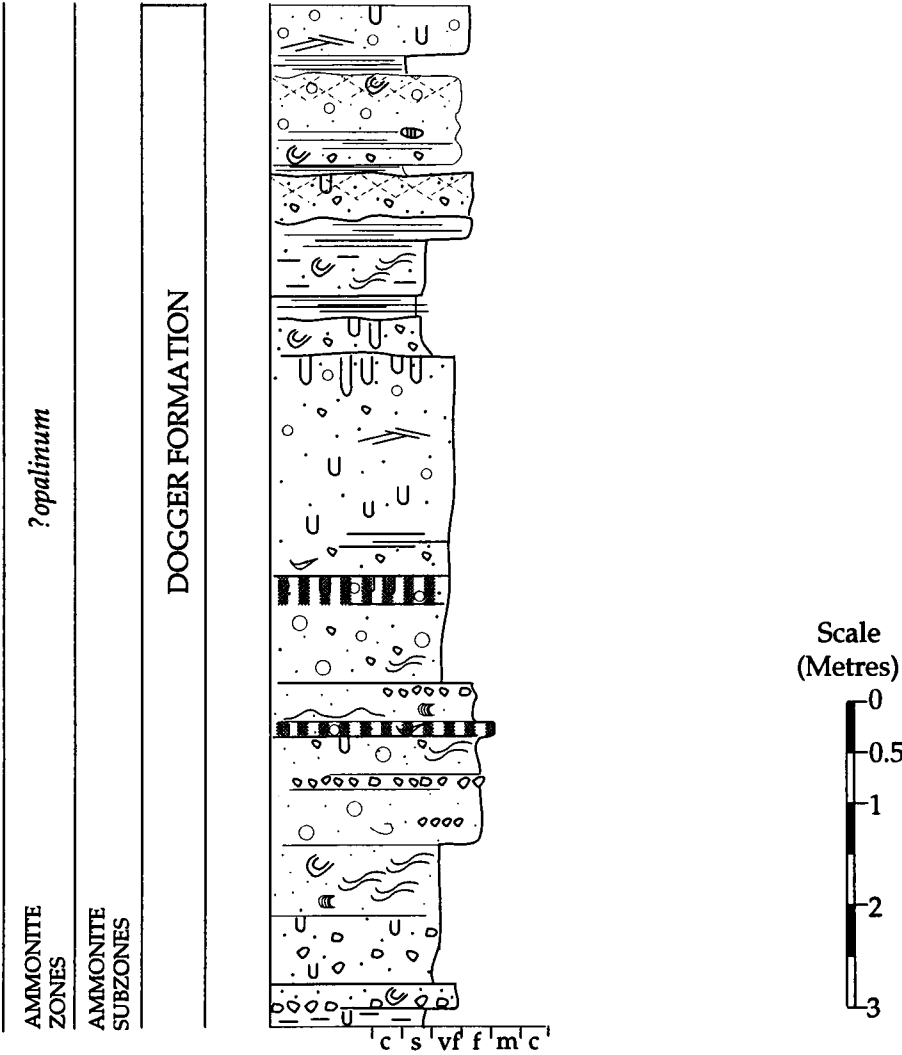
a) Locality map for Hasty Bank (NZ 567 036)

b) Lithological log compiled from Muir (1968). Thickness of the Dogger at this locality is ~7.3 m. Two commonly found genera are shown.

c) Cross-section of the exposure showing the lithological variation. Vertical scale exaggerated 4 x the horizontal. From Hill & Van Konijnenburg-Van Cittert (1973). Fragments of fossilised plants are abundant in the dark clay (A), the siltstone (B) and the claystone (C), forming the main plant bed.

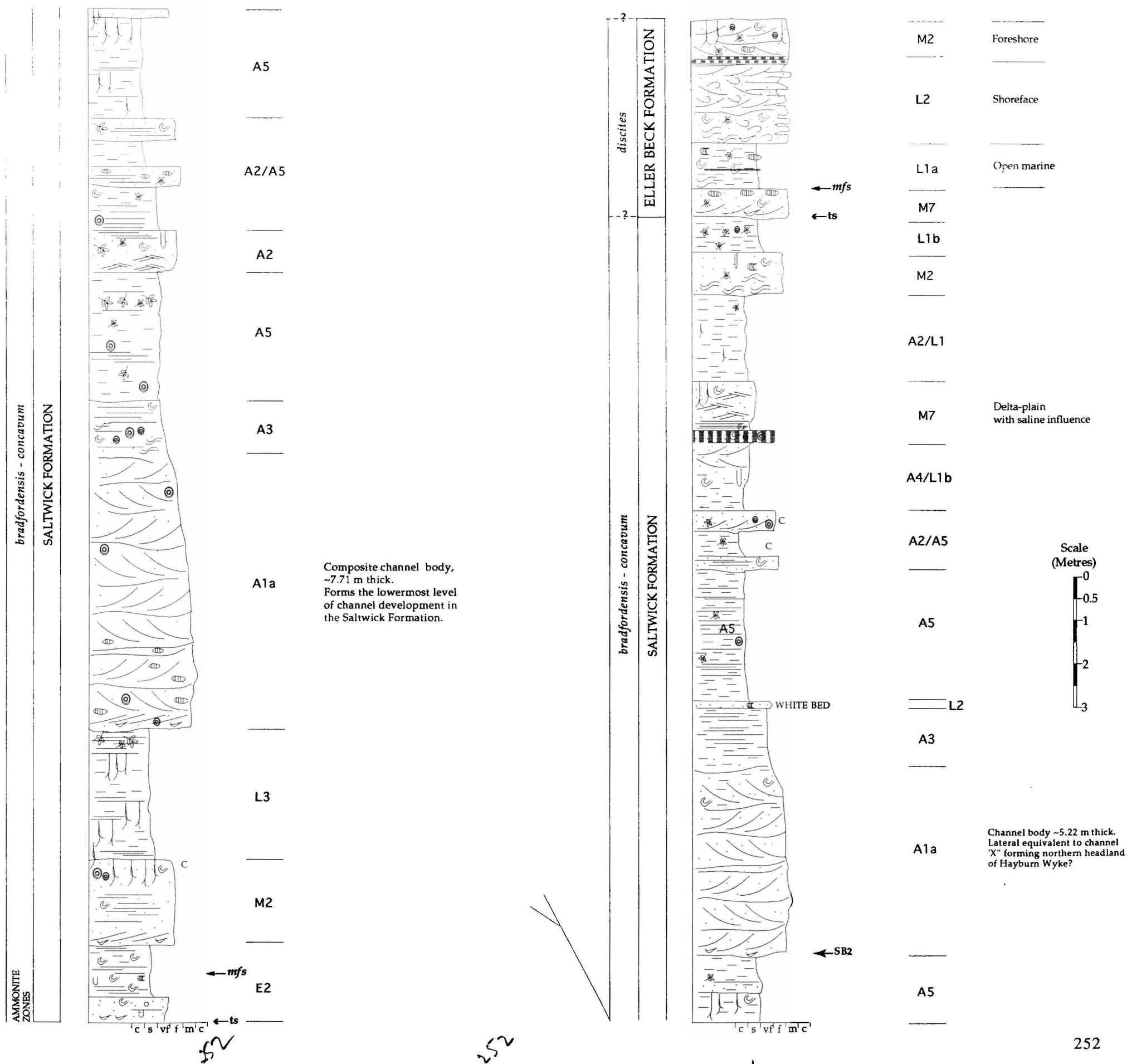
Figs. 1.38*a-e* and 1.39 The following sedimentary logs document two of the many cores drilled by the Institut Francais du Petrole into the Ravenscar (core RV18) and Cloughton (core LN16) areas. For comprehensive details of the full suite of cores see Eschard (1989). The logs shown over the next few pages record the complete Ravenscar Group and underlying Dogger Formation sequence. The section provides a secure framework with which other logs recorded from coastal localities can be compared.

a. Dogger Formation

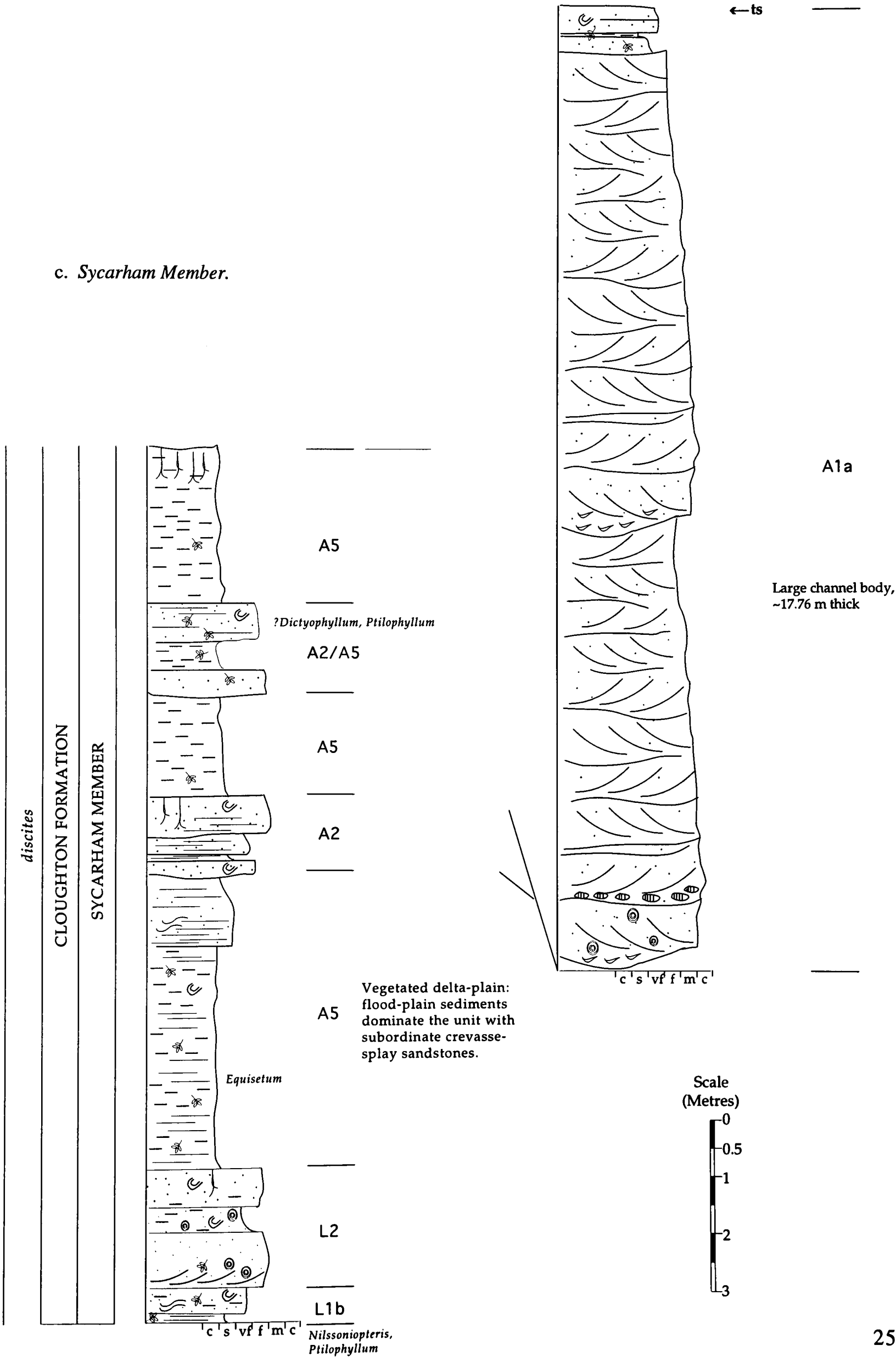


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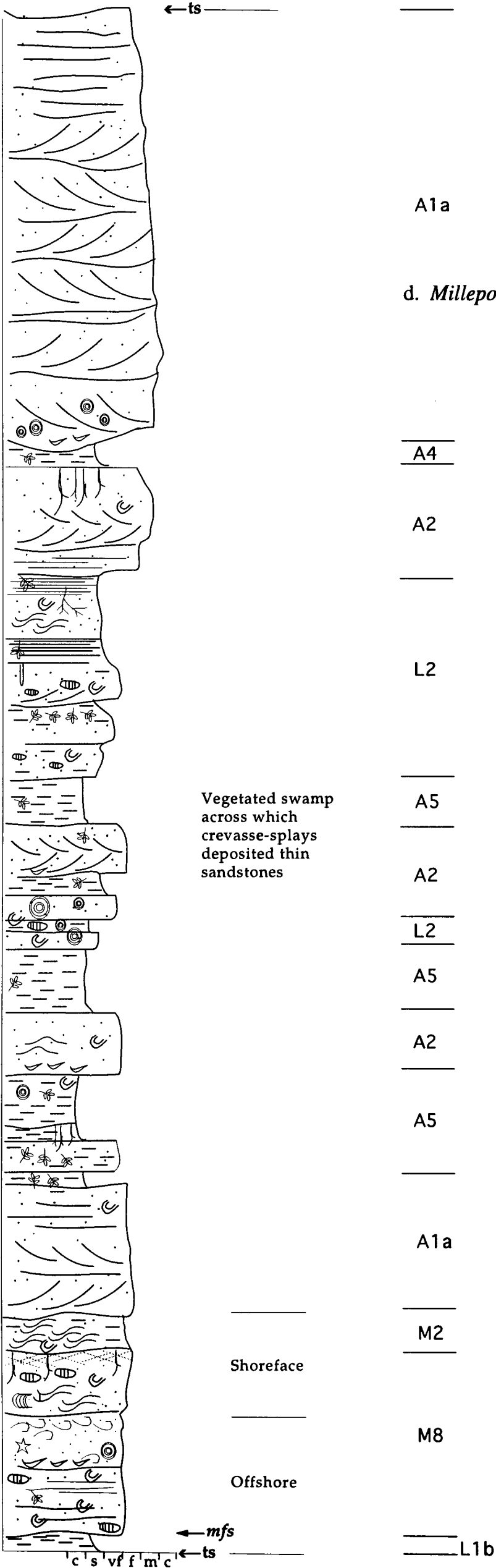
b. Saltwick Formation and overlying Eller Beck Formation.



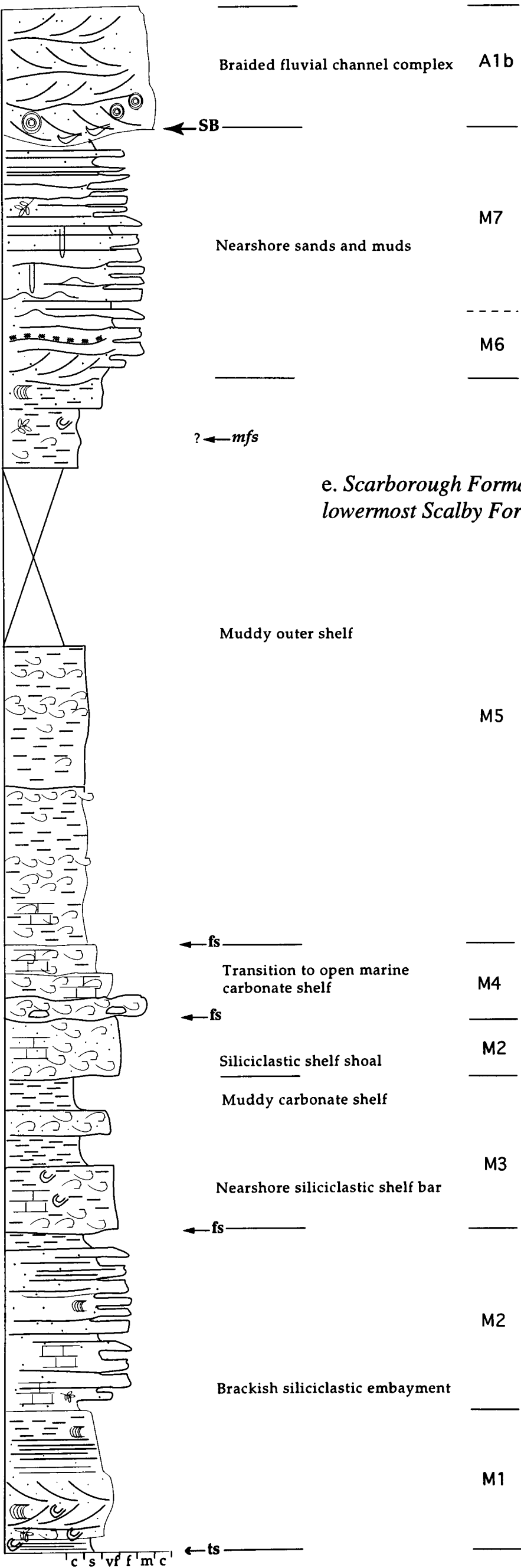
c. Sycarham Member.



ovalis - laeviscula	sauzei
CLOUGHTON FORMATION	
GRISTHORPE MEMBER	
Millepore Bed	



<i>?sauzei</i>	<i>humphriesianum</i>			<i>orbis</i>
	<i>cycloides</i>	<i>hump.</i>	<i>blagdeni</i>	
SCARBOROUGH FORMATION				
HELWATH BECK MEMBER	RAVENSCAR SHALE MEMBER			SCALBY FM.
	HUNDALE SHALE MEMBER	HUNDALE SST. & SP. THORN LMST.	WHITE NAB	BOGMIRE GILL MB. MOOR GRIT MB.



e. Scarborough Formation and lowermost Scalby Formation.

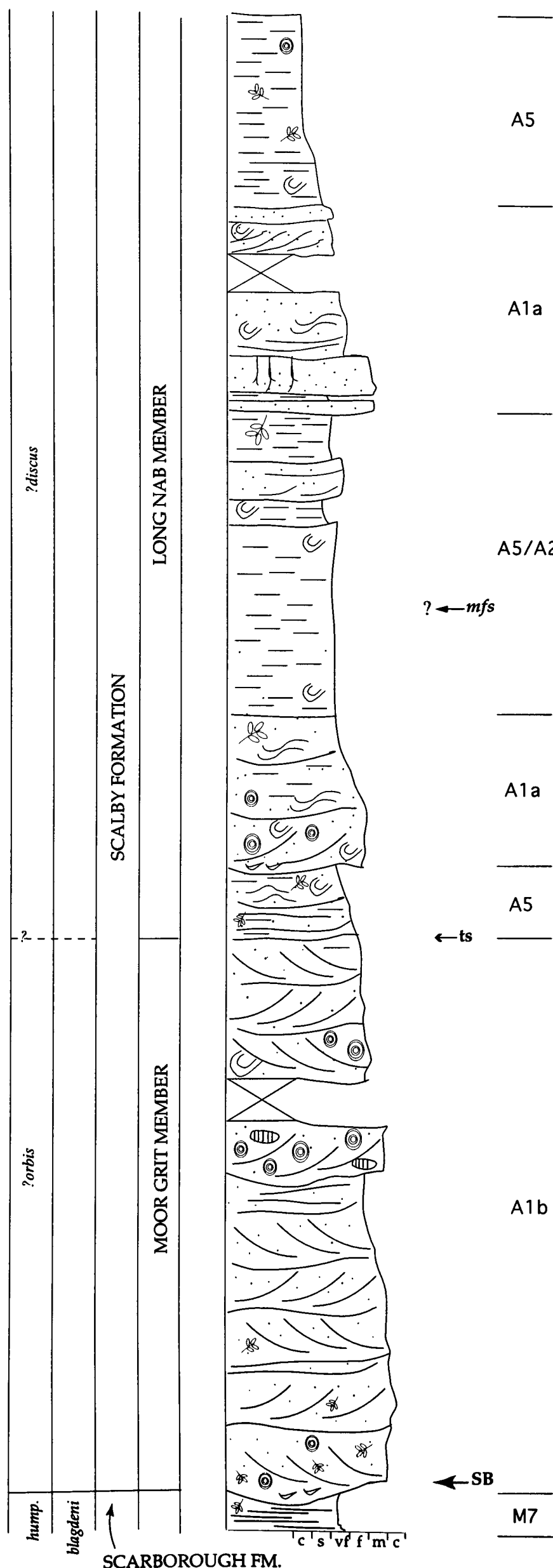


Fig. 1.39 I.F.P. core LN16.
This sedimentary log documents the Scalby Formation from Long Nab. The complete sequence measures approximately 30 m, indicating that the uppermost portion of the unit may be absent: from outcrop studies, the formation in the Long Nab/Burniston Wyke area is estimated to be ~45 m thick (see Fig. 1.13).

Appendix 2

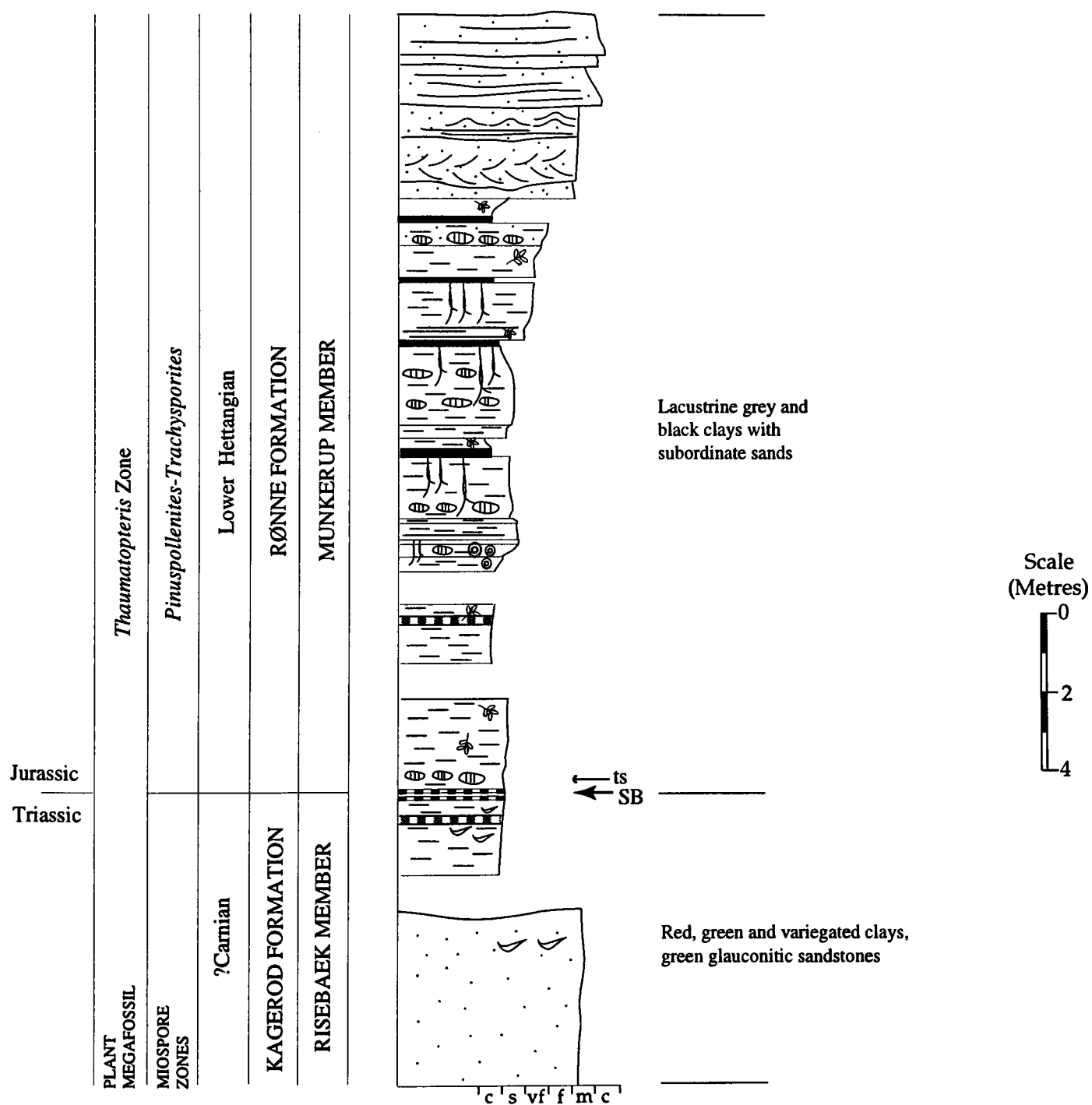
Appendix 2

Sedimentary logs recorded on the island of Bornholm

The sedimentary logs in this appendix are referred to in Chapter 3, which compares the stratigraphic development of Bornholm with that of the Cleveland Basin.

Fig. 2.1 Log of the Munkerup Member, Munkerup	258
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Fig. 2.8 Log of Båga Formation, Korsodde	265
Fig. 2.9 Photos of Båga Formation	268
Fig. 2.10 Log of Båga Formation (Båga Beds), Hasle Klinkerfabrik clay pit	269
Fig. 2.11 Log of Båga Formation (Sorthat Beds), Hasle Klinkerfabrik clay pit	271

Fig. 2.1 Triassic-Jurassic boundary, marked by the Risebæk Member overlain by the Munkerup Member. This section, which occurs on the Arnager-Søse Block in the vicinity of Munkerup, serves as the only example of this portion of stratigraphy currently exposed on Bornholm. Black bands on the log correspond to coal seams, which often contain finely disseminated charcoalfied plant material. Miospore zonation for this and the subsequent logs from Lund (1977); plant megafossil zonation from Troedsson (1951).



a.



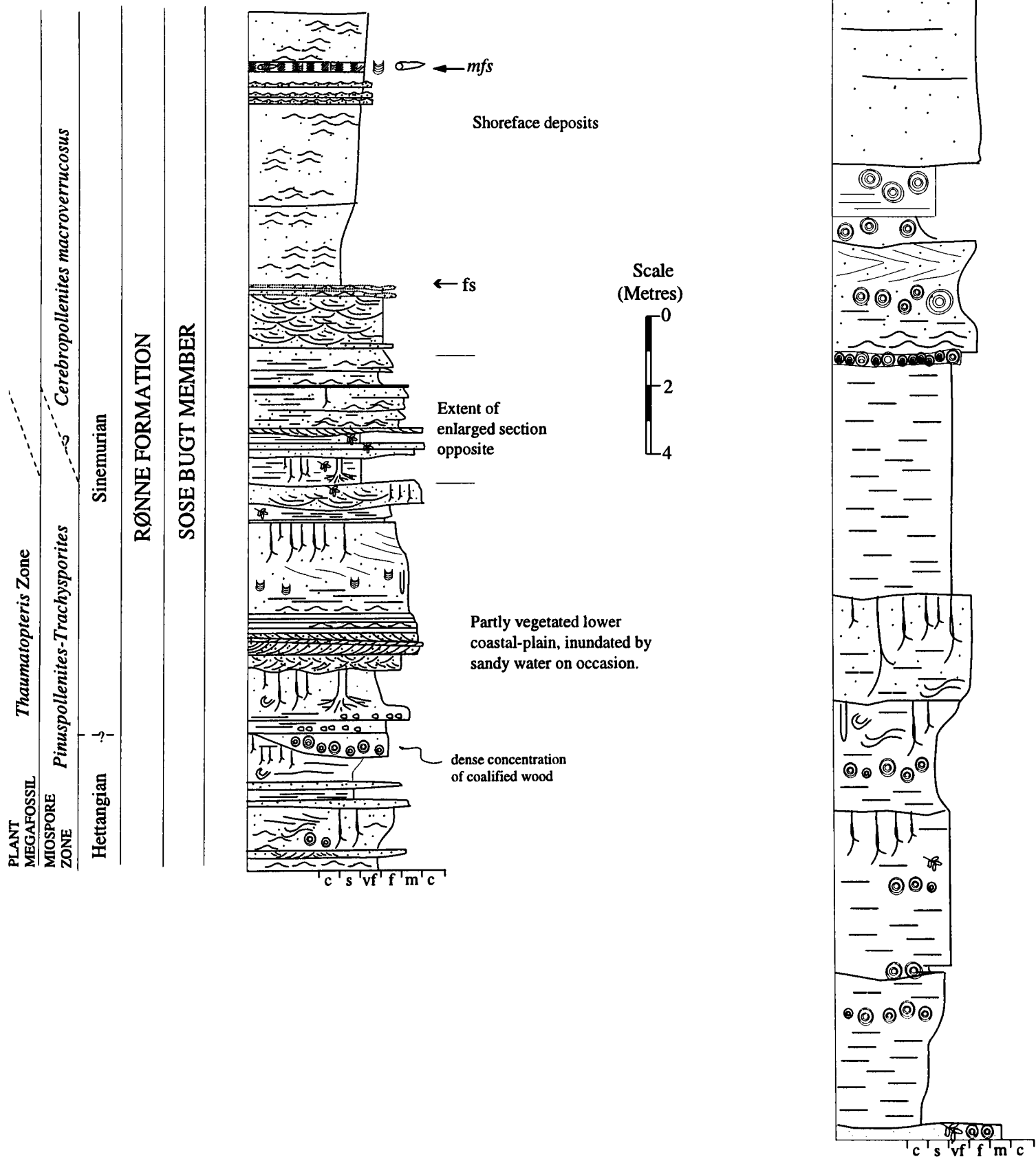
b.



Fig. 2.2 Munkerup Member, Munkerup.

a. A single coarsening-upward cycle capped by a rootlet horizon and coal seam containing highly disseminated, finely-divided plant remains. An enlargement of this coal bed is shown in *b*. The environment of deposition is interpreted as lacustrine, with an inferred fluctuating base-level to explain the development of the cycles.

Fig. 2.3 Sose Bugt Member, Rønne Formation. Section was recorded at Sose Bugt, on the Arnager-Sose Block, and is based upon the work of Surlyk *et al.* (1995). An enlarged plant-bearing section of the exposure is also detailed.



a.



b.

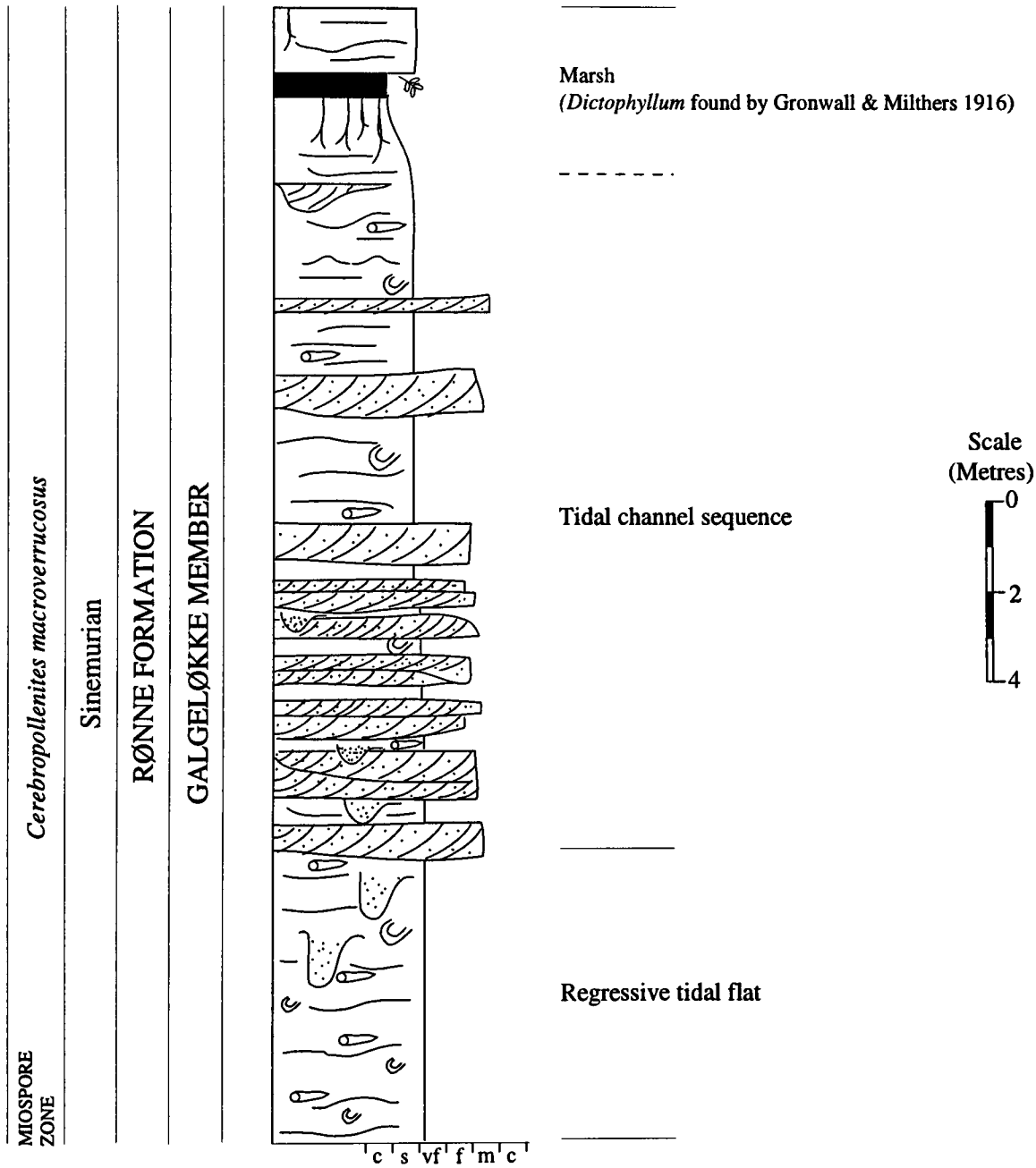


Fig. 2.4 Sose Bugt Member, Sose Bugt.

a. Section shown is dominated by alternating beds of grey, laminated clay and interlaminated clay and silt. The more sandy, yellow-coloured, silty sandstone at the top of the cliff section corresponds to shoreface facies.

b. Wavy- and flaser-bedded siltstones and claystones. The hammer rests on a sandstone bed above which the silty deposits display numerous *Diplocraterion* and *Planolites* burrows. These deposits occur at the top of the sedimentary log in Fig. 2.3, and reflect a gradual increase in marine influence prior to deposition of the Hasle Formation.

Fig. 2.5 Galgeløkke Member, Rønne Formation.
Succession recorded at on Galgeløkke on the Rønne-Hasle Block.
Log is based upon Gravesan *et al.* (1982) and Arndorff (1993).



a.



b.



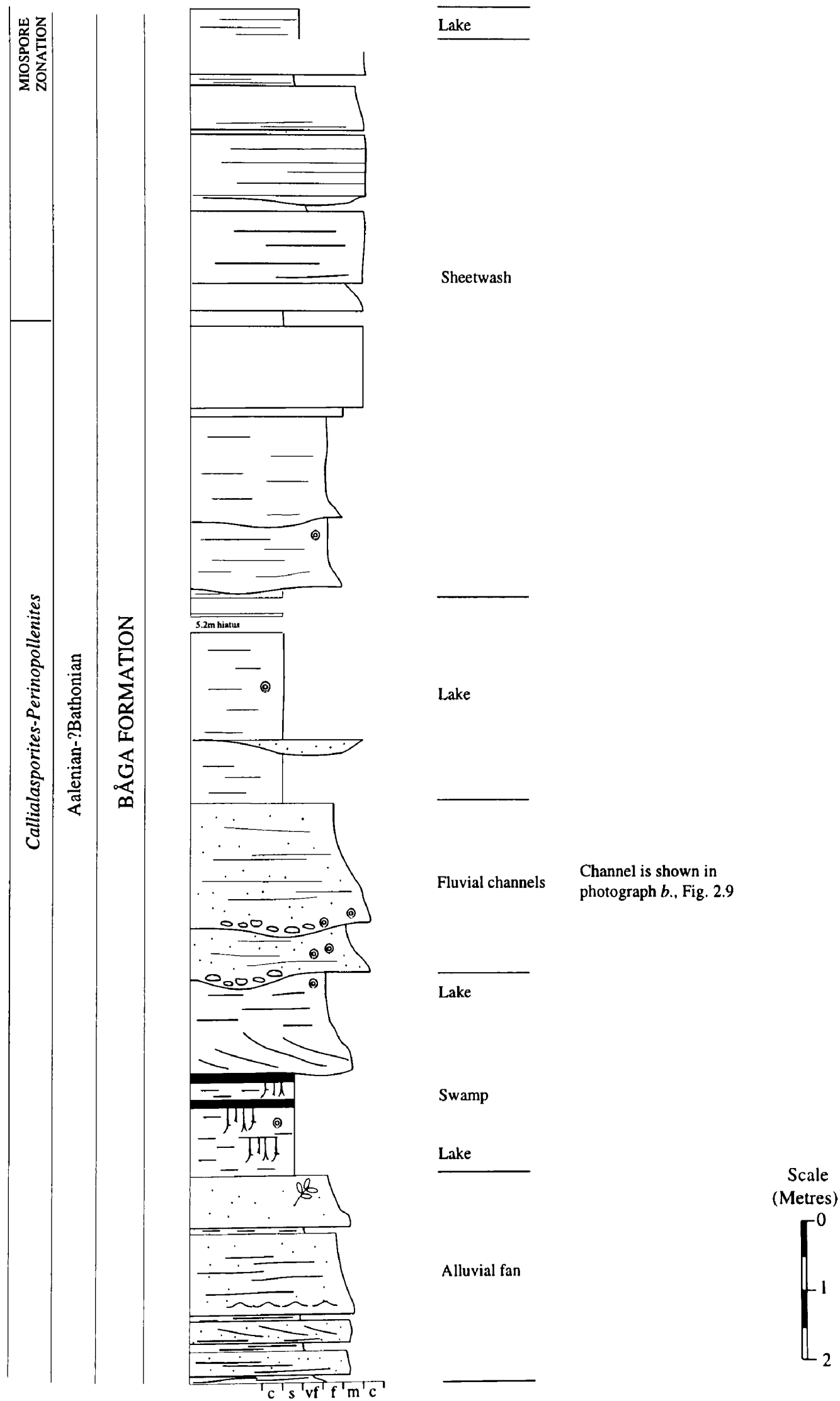
Fig. 2.6 Galgelokke Member, Galgelokke.

a. The basal portion of the member comprising a tidal flat sequence occurs in the lower part of the cliff. The upper part of this unit is highlighted by holes in the cliff leading to Sand Martin nests to the right of the photograph. The boundary between the tidal flat sequence and the overlying cross-bedded and herringbone cross-stratified sandstones is marked by an arrow. This cross-bedded unit forms a unit deposited in a tidal channel, and can be seen in more detail at the bottom of photograph *b*. Arrowed at the top of the cliff in *b*. is a thin layer of black mudstones deposited in a marsh environment.



Fig. 2.7 Hasle Formation, Hasle.
Limonitic, coarse-grained silt and fine-grained sand make up the Hasle Formation, showing horizontal lamination, low-angled trough cross-bedding and hummocky cross-stratification.

Fig. 2.8c Upper Båga Formation (Aalenian-Bathonian), Korsodde.



a.



b.



Fig. 2.9 Båga Formation, Korsodde.

a. Poorly exposed lacustrine sediments of mid- to late-Pliensbachian age. A poorly developed cyclicity occurs within this section, where lake/lacustrine deposits shoal upwards into more swampy, rooted mudstones.

b. Large, erosive-based fluvial channel, showing thin coal-rich beds at the base which include abundant, poorly-preserved fragments of wood. Above the channel, more silty sands occur which are inferred to be of lacustrine origin.

Fig. 2.10a Båga Formation (Toarcian-Aalenian), Hasle Klinkerfabrik clay pit (redrawn from Gravesen *et al.* (1982) and Koppelhus & Nielsen (1994). Continued overleaf. This section is equivalent to the Båga Beds of Gry (1969). Miospore zonation from Koppelhus (1991) and Koppelhus & Nielsen (1994).

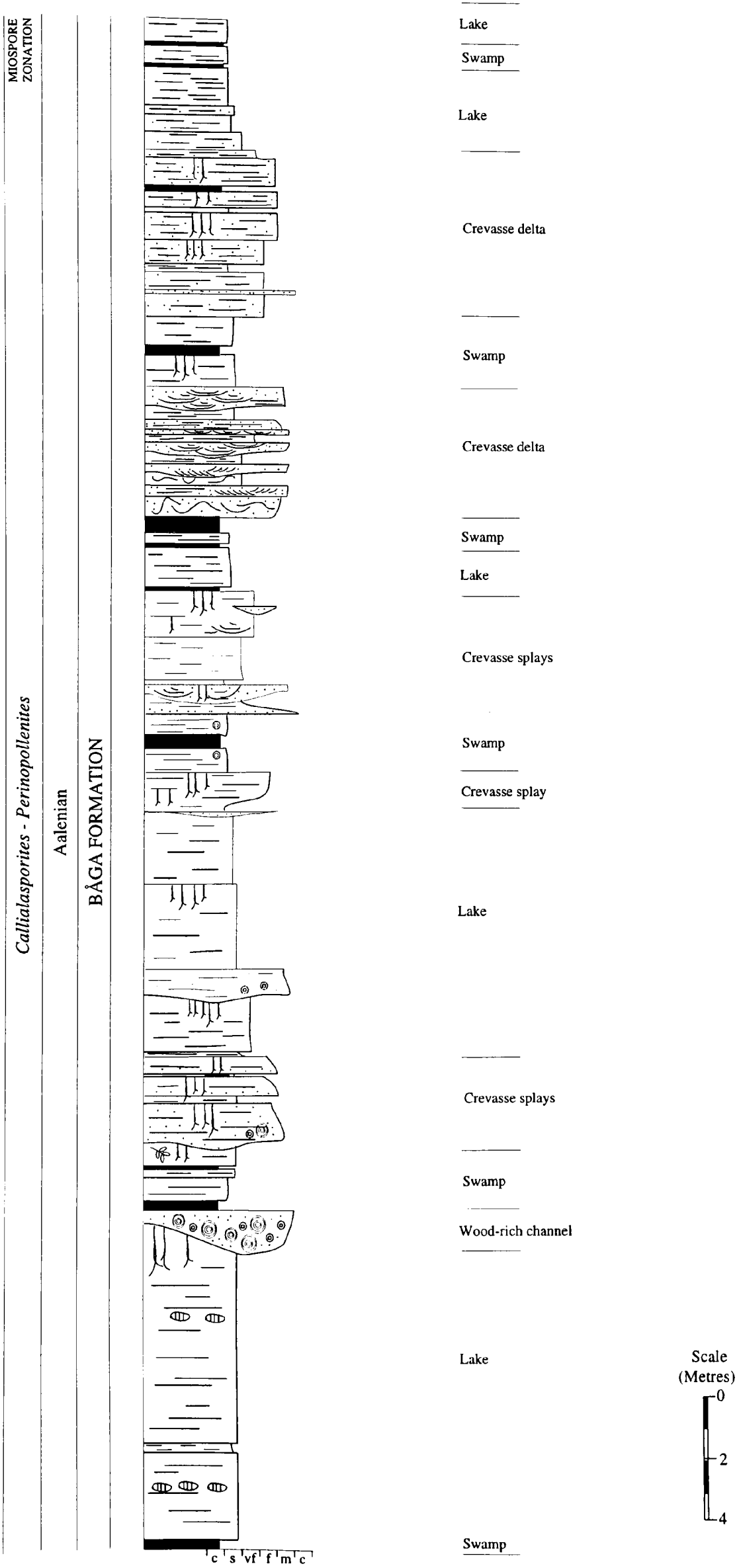


Fig. 2.10*b* Båga Formation (Aalenian-?Bathonian), Hasle Klinkerfabrik clay pit.

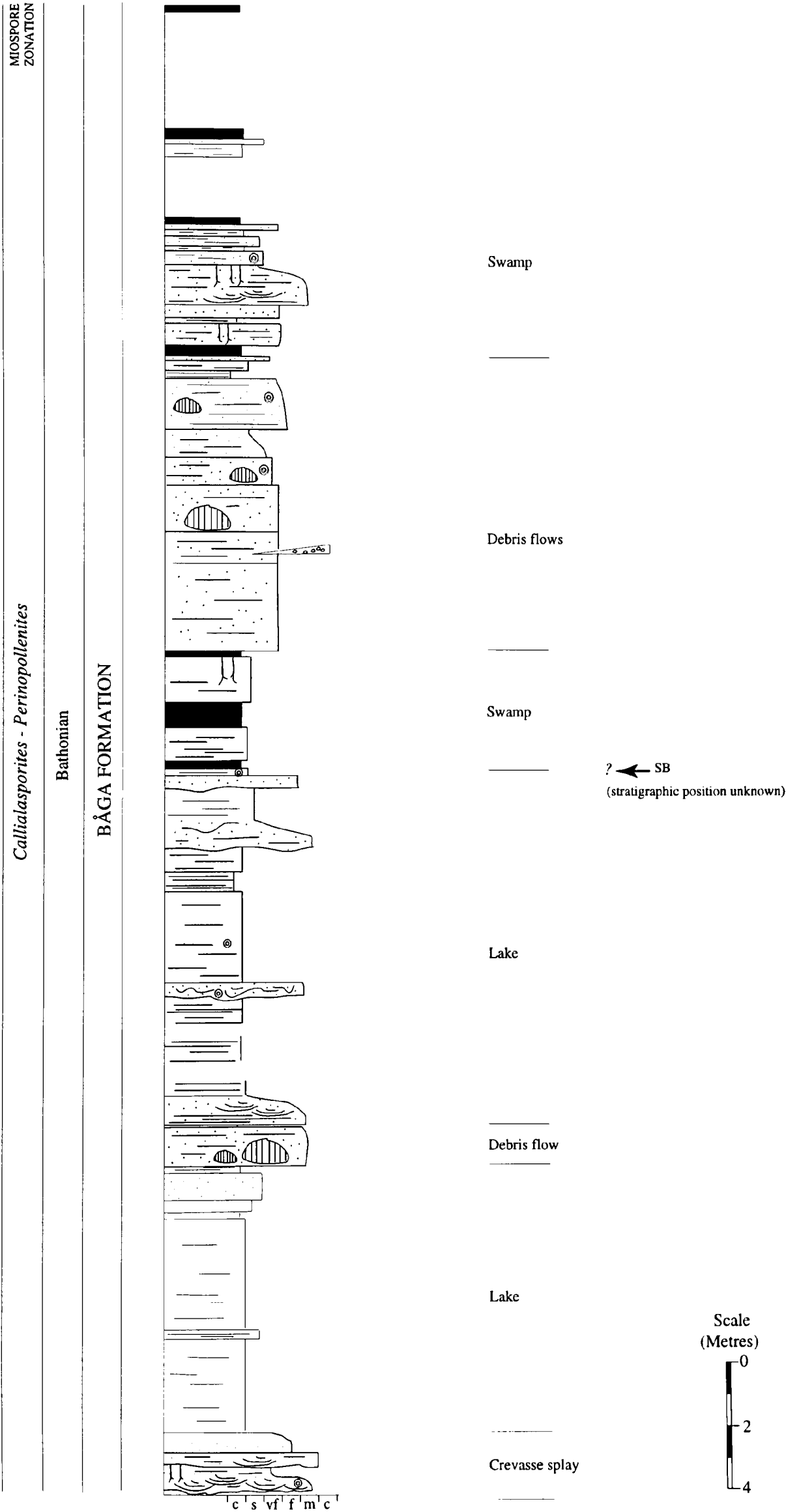
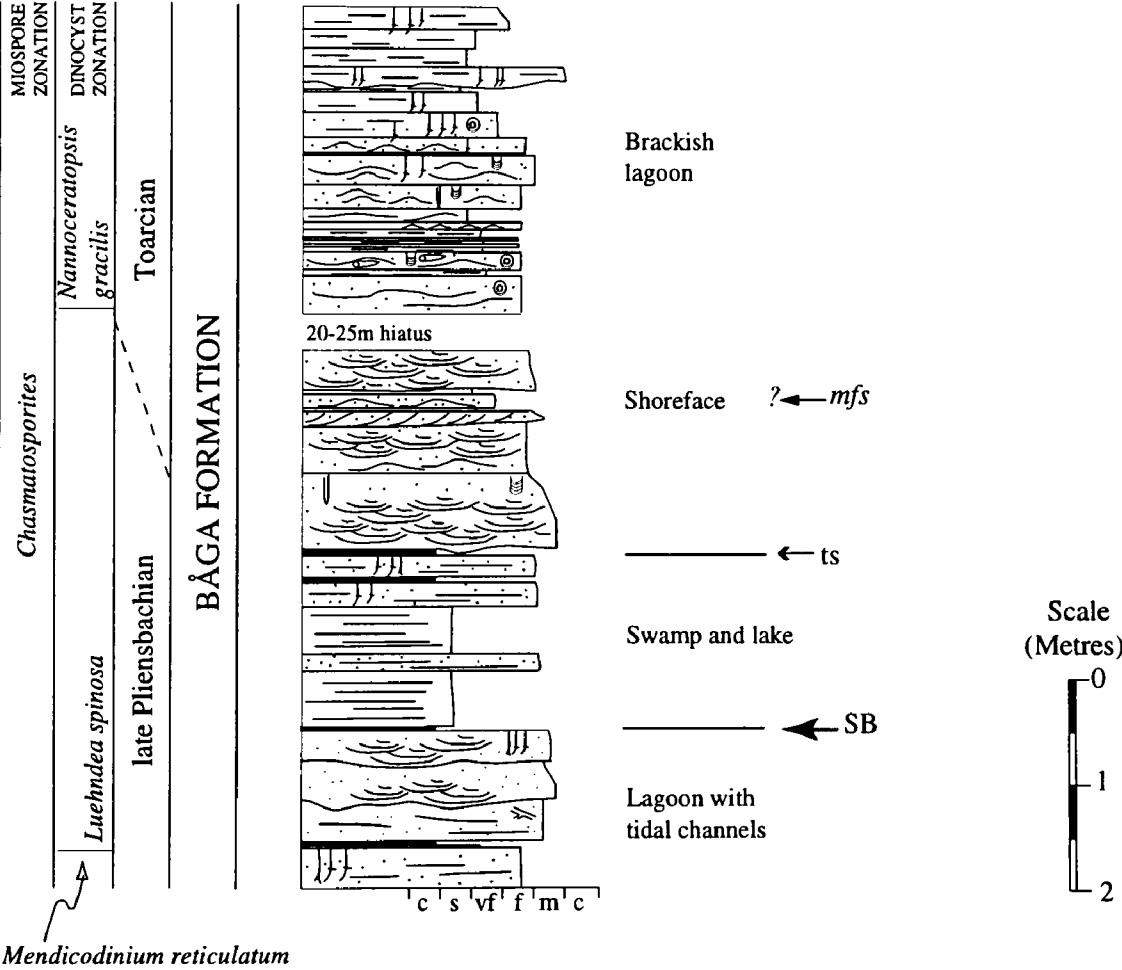


Fig. 2.11 Båga Formation (late Pliensbaian-Toarcian), Hasle Klinkerfabrik clay pit (redrawn from Koppelhus & Nielsen 1994). This section is equivalent to the Sorthat Beds of Gry (1969). Miospore zonation from Koppelhus (1991) and Koppelhus & Nielsen (1994); dinocyst zonation based on Woollam & Riding (1983), and emended using Riding & Thomas (1992).



Appendix 3

Appendix 3

Results from growth-ring analysis of fossil wood from Yorkshire

The following tables show information gathered from the transverse and longitudinal planes of fossil wood specimens collected from the Yorkshire Jurassic succession (Late Pliensbachian-Bathonian). Tables 3.1-3.40 (p. 273-297) contain data obtained from the transverse plane, and Tables 3.41-3.46 (p. 298-304) contain data recovered from the longitudinal planes. With perhaps the exception of the false ring data, the tables should be self-explanatory. Where false rings are present, their position and number within each growth ring is noted. Position is defined as 'e' for early, 'm' for middle and 'l' for late; the number shown in front reflects the number of false rings found.

Table 3.1 CLEVELAND IRONSTONE FORMATION

Results of growth-ring analysis

In the following tables, an absence of data or the letter 'x' denote poor preservation of the specimen, hindering collection of relevant information.

J.67949		J.67950		J.67951		J.67952		J.67953		J.67954		J.67955		J.67956	
Pyrite		Pyrite		Pyrite & carbonate		Pyrite		Pyrite		Pyrite		Pyrite		Pyrite	
Medium	Polished block	Polished block	Polished block	Polished block	Polished block	Polished block	Polished block	Polished block	Polished block	Polished block	Polished block	Polished block	Polished block	Polished block	Polished block
Number of rings	9		6	17		17		2		8		7		9	
Mean RW (mm)	x		x	1.65		0.72		2.61		x		1.01		x	
Standard deviation	x		x	0.6		0.33		0.53		x		0.05		x	
Mean sensitivity (RW)	x		x	0.33		0.28		0.15		x		0.04		x	
Max. width	x		x	2		1.39		2.98		x		1.05		x	
Min. width	x		x	0.5		0.38		2.23		x		0.95		x	
Mean no. cells	30		57	x		30		71		35		49		37	
Standard deviation	14.76		16.49	x		9.98		12.02		16.74		7.82		15.76	
Mean sensitivity (cells)	0.34		0.35	x		0.36		0.12		0.38		0.19		0.37	
Max. number	69		78	x		50		79		61		61		60	
Min. number	22		35	x		15		62		19		37		16	
Mean L:W (mm)	x		x	x		0.5		0.05		x		0.06		x	
Mean L:W cells	3		3	x		6		2		3		3		3	
L:W (width)	x		x	x		0.69		0.02		x		0.06		x	
L:W (cells)				x		0.2		0.02				0.06			
False rings	x		x	x		29%		0%		38%		14%		x	
Cells mm-2	x		x	x		363		297		x		x		x	
Cell L:W (EW)	x		x	x		1.37		1.16		x		x		x	
Cell L:W (LW)	x		x	x		0.7		0.52		x		x		x	
Mean RTD (µm)	x		x	x		46		43		x		x		x	

Table 3.2 CLEVELAND IRONSTONE FORMATION, HAWSKER BOTTOM TO CASTLE CHAMBERS: J.67953

Ring no.	Mean RW (mm)	Mean no. cells	Mean LWW (mm)	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	2.23	62	0.05	2	0.29	0.24		272	1.22	0.5	42
2	2.98	79	0.05	1				322	1.09	0.54	44
Mean values	2.61	71	0.05	2	0.15	0.12	0%	297	1.16	0.52	43
Mean sensitivity & False Rings											

Table 3.3 CLEVELAND IRONSTONE FORMATION, HAWSKER BOTTOM TO CASTLE CHAMBERS: J.67949

Ring no.	Mean RW (mm)	Mean no. cells	Mean LWW (mm)	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cells L:W (LW)	Mean RTD (µm)
1		16		3							
2		30		3		0.61					
3		19		2		0.45					
4		19		2		0					
5		17		2		0.11					
6		28		3		0.49					
7		60		4		0.73					
8		36		3		0.5					
9		44		4		0.2					
Mean value		30		3		0.34					
Mean sensitivity & % False Rings											

Table 3.4 CLEVELAND IRONSTONE FORMATION, STAITHES TO PORT MULGRAVE: J.67956

Ring no.	Mean RW (mm)	Mean no. cells	Mean LWW (mm)	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cells L:W (LW)	Mean RTD (µm)
1		59		2							
2		78		2		0.28					
3		69		2		0.12					
4		35		4		0.65					
5		56		3		0.46					
6		44		4		0.24					
Means values											
Mean sensitivity		57		3		0.35					
% False Rings											

Table 3.5 CLEVELAND IRONSTONE FORMATION, STAITHES TO PORT MULGRAVE: J.67950

Ring no.	Mean RW (mm)	Mean no. cells	Mean LWW (mm)	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cells L:W (LW)	Mean RTD (µm)
1		69		3							
2		29		4		0.82					
3		59		4		0.68					
4		38		3		0.43					
5		32		2		0.17					
6		30		2		0.06					
7		22		3		0.31					
8		28		2		0.24					
9		22		2		0.24					
Mean values											
Mean sensitivity		37		3		0.37					
% False Rings											

Table 3.6 CLEVELAND IRONSTONE FORMATION, HAWSKER BOTTOM TO CASTLE CHAMBERS: J.67951

Ring no.	Mean RW (mm)	Mean no. cells	Mean LW/W (mm)	Mean LW cells	AS: RW	AS: cells	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	2										
2	2				0						
3	1				0.67						
4	1				0						
5	2				0.67						
6	2				0						
7	2				0						
8	2				0						
9	1.5				0.29						
10	1.5				0						
11	1.5				0						
12	1				0.4						
13	0.5				0.67						
14	3				1.43						
15	2				0.4						
16	2				0						
17	1				0.67						
Mean values	1.65				0.33						
Mean sensitivity											
% False Rings											

Table 3.7 CLEVELAND IRONSTONE FORMATION, HAWSKER BOTTOM TO CASTLE CHAMBERS: J.67952

Ring no.	Mean RW (mm)	Mean no. cells	Mean LWW (mm)	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cells L:W (LW)	Mean RTD (µm)
1	0.65	28	0.22	9				340	1.62	0.65	41
2	1	44	0.24	10	0.42		0.44	352	1.67	0.66	48
3	1.44	32	0.25	7	0.36		0.33	339	1.52	0.69	45
4	1.16	33	0.21	7	0.21	0.03 2l (3+2)		350	1.5	0.65	42
5	0.86	50	0.24	7	0.3	0.33		345	1.49	0.68	47
6	1.39	33	0.12	4	0.47	0.33		330	1.39	0.7	42
7	1.29	30	0.08	5	0.07	0.09 1e		356	1.5	0.72	47
8	1.36	24	0.18	7	0.05	0.22 1e		364	1.46	0.7	48
9	1.33	33	0.14	4	0.02	0.31 1m		362	1.25	0.69	42
10	0.86	28	0.11	4	0.43	0.16		384	1.37	0.78	57
11	1.22	16	0.19	8	0.35	0.55		440	1.32	0.77	45
12	1.08	15	0.07	5	0.05	0.06		405	1.36	0.68	51
13	0.75	44	0.09	3	0.36	0.98 1m		360	1.3	0.75	49
14	0.41	23	0.13	4	0.59	0.82		364	1.26	0.65	50
15	0.38	16	0.07	4	0.08	0.35		370	1.2	0.7	44
16	0.9	38	0.14	5	0.81	0.81		352	1	0.75	38
17	0.72	30	0.08	3	0.23	0.24		361	1.12	0.69	44
Mean values	0.99	30	0.15	6	0.28	0.36		363	1.37	0.7	46
Mean sensitivity % False Rings							29%				

Table 3.8 CLEVELAND IRONSTONE FORMATION, HAWSKER BOTTOM TO CASTLE CHAMBERS: J.67955

Ring no.	Mean RW (mm)	Mean no. cells	Mean LWW (mm)	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cells L:W (LW)	Mean RTD (µm)
1	0.97	43	0.07	3							
2	1.02	53	0.07	4	0.05	0.21					
3	1.05	54	0.06	3	0.03	0.02					
4	1	48	0.06	3	0.05	0.12					
5	1.1	61	0.05	3	0.09	0.24	1e (2)				
6	0.95	37	0.06	4	0.05	0.49					
7	0.99	48	0.05	3	0.04	0.26					
Mean values	1.01	49	0.06	3	0.04	0.19					
Mean sensitivity											
% False Rings							14%				

Table 3.9 CLEVELAND IRONSTONE FORMATION, HAWSKER BOTTOM TO CASTLE CHAMBERS: J.67954

Ring no.	Mean RW (mm)	Mean no. cells	Mean LWW (mm)	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cells L:W (LW)	Mean RTD (µm)
1		24		3							
2		23		2		0.04					
3		30		3		0.26					
4		52		3		0.54					
5		49		3		0.06					
6		19		2		0.77					
7		19		2		0					
8		61		3		1.02	4(1e,2m,1l)				
Mean values		35		3		0.38					
Mean sensitivity											
% False Rings							38%				

Composition	J.67943		J.67944		J.67945		J.67946		J.67947	
Medium	Pyrite & carbonate		Pyrite & carbonate		Pyrite & carbonate		Carbonate		Carbonate	
	Polished block	Thin section	Thin section	Thin section	Thin section	Thin section	Thin section	Polished block	Polished block	Polished block
Number of rings	11	30		22			18		15	
Mean RW (mm)	1.3	1.41		1.3			1.79		1.1	
Standard deviation	0.35	0.87		0.4			0.66		0.33	
Mean sensitivity (RW)	0.24	0.36		0.3			0.26		0.43	
Max. width	2	4.08		1.9			3.13		1.68	
Min. width	0.9	0.5		0.9			0.72		0.43	
Mean no. cells	42	47		57			39		53	
Standard deviation	11.28	23.39		16.7			12.14		15.69	
Mean sensitivity (cells)	0.17	0.41		0.44			0.29		0.43	
Max. number	65	121		85			69		84	
Min. number	31	27		27			22		25	
Mean LWW (mm)	0.18	0.07		0.2			0.16		0.13	
Mean LW cells	10	6		5			9		11	
L/W (width)	0.14	0.05		0.15			0.09		0.12	
L/W (cells)	0.24	0.13		0.09			0.23		0.21	
False rings	0%	70%		50%			0%		7%	
Cells mm-2	502	661		678			493		459	
Cell L:W (EW)	1.2	1.06		1.12			1.17		1.07	
Cell L:W (LW)	0.4	0.75		0.71			0.61		0.68	
Mean RTD (µm)	50	45		44			50		41	

Table 3.11 DOGGER FORMATION, BLEA WYKE: J.67943

Ring no.	Mean RW (mm)	Mean no. cells	Mean LWW (mm)	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	2	65	0.2	10				600	1.3	0.42	47
2	1.37	51	0.2	12	0.37	0.24		552	1.2	0.41	50
3	0.97	36	0.2	13	0.34	0.34		456	1.19	0.45	51
4	1.42	44	0.2	13	0.38	0.2		395	1.28	0.39	45
5	1.18	42	0.2	7	0.18	0.05		425	1.19	0.4	50
6	1.38	40	0.2	13	0.16	0.05		428	1.22	0.47	49
7	1.69	57	0.2	10	0.2	0.35		522	1.16	0.38	48
8	1.09	31	0.15	7	0.43	0.29		550	1.12	0.4	52
9	1.09	34	0.2	10	0	0.09		521	1.18	0.41	48
10	0.9	34	0.13	9	0.19	0		563	1.15	0.38	53
11	0.9	30	0.13	8	0.12	0.13		510	1.2	0.39	55
Mean values	1.3	42	0.18	10	0.24	0.17	0%	502	1.2	0.4	50
Mean sensitivity % False Rings											

Table 3.12 DOGGER FORMATION, BLEA WYKE: J.67947

Ring no.	Mean RW (mm)	Mean no. cells	Mean LWW (mm)	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	1.24	59	0.1	9				598	1	0.69	38
2	0.43	30	0.02	5	0.87	0.65		600	1.11	0.7	36
3	1.38	84	0.03	4	1.05	0.88		611	1.1	0.71	41
4	1.01	62	0.05	6	0.47	0.3		689	1.05	0.68	45
5	1.68	45	0.2	12	0.49	0.4		602	1.02	0.74	39
6	0.89	57	0.2	15	0.61	0.5	1e	659	1.1	0.69	49
7	1.36	70	0.07	10	0.42	0.39		633	1.13	0.7	44
8	0.98	38	0.07	10	0.32	0.59		600	1.06	0.71	36
9	0.52	25	0.1	9	0.61	0.41		568	1.04	0.63	42
10	1.24	50	0.1	9	0.82	0.67		248	1.1	0.62	40
11	1.29	54	0.2	9	0.04	0.08		236	1.12	0.69	41
12	1.39	57	0.2	15	0.07	0.54		211	1.05	0.68	37
13	1.1	42	0.2	10	0.23	0.3		205	1.06	0.67	45
14	1.09	44	0.2	10	0.01	0.05		200	1.03	0.7	46
15	1.04	34	0.2	8	0.05	0.26		229	1.1	0.63	43
Mean values	1.1	53	0.13	11	0.43	0.43	7%	459	1.07	0.68	41
Mean sensitivity % False Rings							7%				

Table 3.13 DOGGER FORMATION, BLEA WYKE: J.67944

Ring no.	Mean RW (mm)	Mean no. cells	Mean LWW (mm)	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	1.5	55	0.06	4				550	1	0.6	50
2	1.28	51	0.03	4	0.16	0.07	1m (2)	570	1.1	0.79	47
3	1.09	38	0.03	3	0.16	0.29	1m (6)	560	1.02	0.81	45
4	1.72	87	0.03	4	0.45	0.78	2m (3+4)	600	1.05	0.62	42
5	1.81	46	0.03	3	0.05	0.62	2m (3+3)	610	1.1	0.99	45
6	2.34	66	0.16	8	0.26	0.36	1m (5)	580	1.06	0.85	51
7	1.09	33	0.09	5	0.73	0.51	1l (3)	580	1.02	0.78	50
8	1.97	70	0.06	5	0.58	0.72	1m (4)	600	1.1	0.65	56
9	1	41	0.09	7	0.58	0.52	1e (4)	600	1.05	0.63	51
10	0.94	21	0.06	5	0.65	0.65		590	1.05	0.84	45
11	0.94	33	0.09	5	0.06	0.44	1m (5)	580	1.08	0.86	46
12	0.66	27	0.16	8	0	0.2	2 (1m:7 + 1l:3)	585	1.09	0.99	45
13	0.5	28	0.19	9	0.35	0.04		600	1.08	0.68	42
14	0.63	27	0.13	5	0.28	0.04	1l (4)	605	1.1	0.72	45
15	0.72	27	0.09	3	0.23	1	1e (5)	590	1.1	0.71	52
16	0.53	36	0.06	4	0.13	0.28	2 (1e:5 + 1m:3)	575	0.99	0.73	50
17	0.78	29	0.03	4	0.3	0.18	2m (5+5)	600	1.05	0.79	51
18	0.72	29	0.06	5	0.38	1		600	1.05	0.81	49
19	0.94	36	0.06	7	0.27	0.18	1m (7)	610	1.12	0.72	45
20	1.22	43	0.09	5	0.26	0.18		720	1.1	0.69	35
21	0.81	36	0.08	5	0.4	0.18		750	1.01	0.68	36
22	1.45	52	0.09	7	0.57	0.36		790	0.97	0.71	41
23	1.25	44	0.09	4	0.15	0.17	1e (2)	890	1.05	0.72	25
24	1.59	49	0.02	9	0.24	0.12	1e (4)	820	1.05	0.68	36
25	4.08	121	0.01	7	0.88	0.85	1m (3)	790	1.1	0.6	45
26	4.01	105	0.09	5	0.02	0.14	3 (1e:4; 1m:4; 1l:3)	790	0.97	0.74	43
27	1.18	40	0.03	16	1.09	0.89		800	1	0.8	49
28	1.96	54	0.02	8	0.49	0.3	1e (8)	770	1.11	0.66	48
29	1.19	30	0.01	7	0.49	0.57	1m (5)	750	1.09	0.79	43
30	2.27	63	0.03	10	0.62	0.67		780	1.05	0.81	41
Mean values	1.41	47	0.07	6				661	1.06	0.75	45
Mean sensitivity					0.36	0.41					
% False Rings							70%				

Table 3.14 DOGGER FORMATION, BLEA WYKE: J.67945

Ring no.	Mean RW (mm)	Mean no. cells	Mean LWW (mm)	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	0.65	27	0.05	6				752	1.22	0.69	41
2	1	38	0.1	8	0.42	0.34		824	1.19	0.73	47
3	0.9	50	0.14	9	0.11	0.27		787	1.09	0.69	41
4	0.9	43	0.1	5	0	0.15	11	801	1.1	0.78	48
5	1.2	52	0.2	5	0.29	0.23	1m	760	1.1	0.7	45
6	1.2	57	0.2	6	0	0.09	2m,11	715	1.15	0.65	39
7	1.6	64	0.3	7	0.29	0.26	1m	723	1.2	0.8	45
8	0.9	40	0.2	4	0.07	0.46	3m	737	1.23	0.78	41
9	1.8	73	0.2	4	0.07	0.58		712	1.15	0.72	49
10	0.9	39	0.2	4	0.07	0.61	2m	690	1.1	0.69	50
11	1.5	76	0.3	4	0.5	0.64	1e,2m	655	1.09	0.7	43
12	1.9	85	0.3	6	0.23	0.11	1e,2m	680	1.05	0.65	42
13	1.4	64	0.3	5	0.3	0.28	2e,2m	640	1.08	0.76	43
14	1	43	0.2	5	0.33	0.39		600	1.11	0.75	48
15	1	53	0.15	6	0	0.21		605	1.12	0.68	47
16	1.8	80	0.3	6	0.57	0.41		598	1.09	0.69	41
17	0.9	37	0.2	5	0.67	0.74		615	1.13	0.76	40
18	1.5	67	0.25	3	0.5	0.58	1m	611	1.07	0.72	38
19	2	85	0.3	4	0.28	0.24		602	1.1	0.74	40
20	1.8	63	0.3	5	0.11	0.3	1e	592	1.15	0.69	41
21	1.1	51	0.2	5	0.48	0.21		609	1.07	0.67	47
22	1.6	68	0.25	6	0.37	0.29		600	1.12	0.7	48
Mean values	1.3	57	0.22	5	0.3	0.44		678	1.12	0.71	
Mean sensitivity % False Rings							50%				

Table 3.15 DOGGER FORMATION, BLEA WYKE: J.67946

Ring no.	Mean RW (mm)	Mean no. cells	Mean LWW (mm)	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	1.8	31	0.13	6				451	1.1	0.61	44
2	2.64	56	0.14	7	0.38	0.53		413	1.23	0.56	45
3	2.89	46	0.14	6	0.09	0.19		464	1.18	0.64	51
4	3.13	69	0.16	7	0.08	0.4		469	1.12	0.58	57
5	1.82	44	0.23	11	0.53	0.44		483	1.3	0.61	43
6	2.01	39	0.19	9	0.1	0.12		572	1.23	0.63	52
7	2.11	43	0.15	10	0.05	0.1		502	1.15	0.6	48
8	2.02	36	0.14	7	0.04	0.18		464	1.11	0.56	43
9	1.83	53	0.24	11	0.1	0.38		400	1.09	0.68	50
10	1.15	28	0.16	10	0.46	0.62		411	1.34	0.63	56
11	1.94	41	0.11	10	0.51	0.38		422	1.12	0.59	53
12	1.09	25	0.14	9	0.56	0.48		408	1.09	0.6	54
13	1.77	43	0.22	8	0.48	0.53		544	1.12	0.67	61
14	1.83	42	0.27	8	0.03	0.02		568	1.2	0.56	55
15	1.35	37	0.15	9	0.3	0.13		600	1.26	0.58	43
16	0.87	23	0.11	8	0.43	0.47		596	1.18	0.54	44
17	0.72	22	0.18	8	0.19	0.04		549	1.08	0.68	48
18	1.17	31	0.16	10	0.43	0.34		550	1.1	0.67	44
Mean values	1.79	39	0.16	9	0.26	0.29		493	1.17	0.61	50
Mean sensitivity % False Rings							0%				

Table 3.16 SALTWICK FORMATION
Results from growth-ring analysis

	J.67936	J.67937
Composition	Charcoal	Charcoal
Medium	SEM	SEM
Number of rings	7	6
Mean RW (mm)	2.73	2.41
Standard deviation	0.76	0.5
Mean sensitivity (RW)	0.24	0.22
Max. width	4.06	3.2
Min. width	2.06	1.88
Mean no. cells	11	11
Standard deviation	2.93	1.64
Mean sensitivity (cells)	0.22	0.12
Max. number	17	12
Min. number	8	8
Mean LWW (mm)	0.22	0.29
Mean LW (cells)	2	3
L/W (width)	0.08	0.12
L/W (cells)	0.18	0.27
False rings	0%	0%
Cells mm-2	397	398
Cell L:W (EW)	1.06	1.06
Cell L:W (LW)	0.89	0.83
Mean RTD (µm)	29	29

Table 3.17 SALTWICK FORMATION, HAYBURN WYKE: J.67936

Ring no.	Mean RW (mm)	Mean no. cells	Mean LWW (mm)	Mean LW (cells)	AS (RW)	AS (cells)	False rings	Cells mm2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	4.06	17	0.25	3				420	1.04	0.97	25
2	2.18	10	0.25	3	0.6	0.52		390	1.08	0.82	28
3	2.81	12	0.13	2	0.25	0.18		367	1.1	0.87	30
4	2.37	11	0.13	2	0.17	0.09		400	1.05	0.86	31
5	2.06	8	0.25	2	0.14	0.32		412	1.01	0.91	29
6	2.18	9	0.25	2	0.06	0.12		389	1.08	0.86	33
7	3.43	12	0.25	2	0.45	0.29		405	1.06	0.92	26
Mean values	2.73	11	0.22	2				397	1.06	0.89	29
Mean sensitivity					0.24	0.22					
% False Rings							0%				

Table 3.18 SALTWICK FORMATION, HAYBURN WYKE: J.67937

Ring no.	Mean RW (mm)	Mean no. cells	Mean LWW (mm)	Mean LW (cells)	AS (RW)	AS (cells)	False rings	Cells mm2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	2.36	9	0.36	3				390	1.01	0.9	25
2	2	8	0.32	2	0.16	0.12		411	1.1	0.85	32
3	2.8	12	0.28	3	0.33	0.4		405	1.05	0.79	29
4	3.2	11	0.28	3	0.13	0.09		390	1.09	0.68	27
5	1.88	11	0.28	2	0.52	0		400	1.1	0.86	31
6	2.2	12	0.24	2	0.16	0.09		396	1.05	0.9	30
Mean values	2.41	11	0.29	3				398	1.06	0.83	29
Mean sensitivity					0.22	0.12					
% False Rings							0%				

Table 3.19 GRISTHORPE MEMBER
Results of growth-ring analysis

Composition	J.67913	J.67915	J.67916	J.67917	J.67918	J.67919	J.67920
Medium	Pyrite		Pyrite		Pyrite		Pyrite
	Thin section	Thin section	Thin section	Thin section	Thin section	Thin section	Thin section
Number of rings	8	4	3	8	3	3	8
Mean RW (mm)	2.6	3.62	1.86	2.58	3	3.85	1.86
Standard deviation	0.27	1.04	0.23	0.27	0.51	0.26	0.61
Mean sensitivity (RW)	0.12	0.19	0.11	0.1	0.22	0.04	0.32
Max. width	3	4.64	2.12	3	3.12	4.11	2.8
Min. width	2.2	2.19	1.67	2.2	2.19	3.6	1.2
Mean no. cells	68	107	85	68	82	97	85
Standard deviation	8.62	19.19	0	8.62	5.57	11.37	21.19
Mean sensitivity (cells)	0.18	0.12 x		0.07	0.07	0.09	0.23
Max. number	81	125	85	81	87	110	119
Min. number	60	80	85	60	76	88	65
Mean LWW (mm)	0.04	0.02	0.03	0.04	0.05	0.09	0.03
Mean LW (cells)	5	8	3	5	4	6	3
L/W (width)	0.02	0.005	0.02	0.02	0.02	0.02	0.02
L/W (cells)	0.07	0.07	0.04	0.07	0.05	0.06	0.04
False rings	38%	0%	0%	38%	33%	66%	25%
Cells mm-2	260	729	862	401	615	593	499
Cell L:W (EW)	1.49	1.11	1.12	1.08	1.11	1.13	0.94
Cell L:W (LW)	0.87	0.7	0.78	0.77	0.75	0.88	0.39
Mean RTD (µm)	57	45	17	47	32	35	29

Table 3.19 GRISTHORPE MEMBER, continued

Composition	J.67921	J.67924	J.67925	J.67926	J.67928	J.67933	J.67934
Medium	Pyrite Thin section	Pyrite Thin section	Pyrite Thin section	Pyrite Polished block	Pyrite Polished block	Pyrite Thin section	Pyrite Thin section
Number of rings	4	3	3	4	9	4	5
Mean RW (mm)	2.83	3.8	1.89	4.64	2.07	2.4	1.05
Standard deviation	0.29	0.75	0.31	0.54	0.61	0.73	0.76
Mean sensitivity (RW)	0.08	0.22	0.15	0.13	0.48	0.29	0.3
Max. width	3.2	4.5	2.24	5.07	2.58	3.4	2.5
Min. width	2.5	3	1.65	3.92	1.02	1.7	0.6
Mean no. cells	83	97	51	190	98	111	63
Standard deviation	7.07	22.61	15.95	24.92	26.62	30.58	42.02
Mean sensitivity (cells)	0.1	0.19	0.37	0.14	0.41	0.25	0.32
Max. number	92	122	62	212	124	143	140
Min. number	81	78	33	160	61	72	36
Mean LWW (mm)	0.02	0.02	0.05	0.17	0.08	0.03	0.01
Mean LW (cells)	4	4	5	13	5	4	3
L/W (width)	0.007	0.005	0.03	0.04	0.04	0.01	0.009
L/W (cells)	0.05	0.04	0.09	0.07	0.05	0.04	0.05
False rings	50%	0%	33%	0%	0%	25%	60%
Cells mm-2	417	228	435	398	401	300	1117
Cell L:W (EW)	1.08	1.48	1.45	0.95	1.06	1.25	1.01
Cell L:W (LW)	0.5	0.87	0.46	0.47	0.71	0.78	0.66
Mean RTD (µm)	34	84	69	45	41	78	19

Table 3.20 GRISTHORPE MEMBER, YONS NAB: J.67915

Ring no.	Mean RW	Mean no. cells	Mean LWW	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	2.19	80	0.22	7				878	1.29	0.75	35
2	3.66	111	0.2	10	0.5	0.31		650	1.05	0.69	49
3	4	113	0.23	9	0.09	0.02		700	1.1	0.66	50
4	4.64	125	0.24	8	0.15	0.1		690	1.03	0.71	48
Mean values	3.62	107	0.22	8				729	1.11	0.7	45
Mean sensitivity					0.19	0.12					
% False Rings							0%				

Table 3.21 GRISTHORPE MEMBER, YONS NAB: J.67913

Ring no.	Mean RW	Mean no. cells	Mean LWW	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	2.9	74	0.3	5				290	1.68	0.97	52
2	2.5	81	0.3	4	0.15	0.09		260	1.47	0.82	53
3	3	79	0.6	6	0.18	0.25	1e	240	1.52	0.79	58
4	2.4	61	0.3	5	0.22	0.26	1e	250	1.43	0.85	61
5	2.6	64	0.4	4	0.08	0.05		255	1.33	0.91	66
6	2.2	60	0.6	6	0.17	0.6		230	1.47	0.85	59
7	2.4	61	0.3	5	0.09	0.16		270	1.57	0.79	53
8	2.6	64	0.4	4	0.08	0.05	1e	285	1.51	0.94	50
Mean values	2.6	68	0.4	5				260	1.49	0.87	57
Mean sensitivity					0.12	0.18					
% False Rings							38%				

Table 3.22 GRISTHORPE MEMBER, YONS NAB: J.67917

Ring no.	Mean RW	Mean no. cells	Mean LW	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	2.9	74	0.3	5				420	1.12	0.62	37
2	2.5	81	0.3	4	0.15	0.09	1e	390	1.05	0.92	40
3	3	79	0.6	6	0.18	0.03	1e	400	1.1	0.7	47
4	2.4	61	0.3	5	0.22	0.26		380	1.02	0.77	45
5	2.6	64	0.4	4	0.08	0.05		425	1.09	0.91	52
6	2.2	60	0.6	6	0.17	0.06	1e	400	1.1	0.8	53
7	2.4	61	0.3	5	0.08	0.02		395	1.05	0.75	49
8	2.6	64	0.4	4	0.08	0.05		400	1.13	0.69	50
Mean values	2.58	68	0.4	5				401	1.08	0.77	47
Mean sensitivity % False Rings					0.1	0.07	38%				

Table 3.23 GRISTHORPE MEMBER, YONS NAB: J.67916

Ring no.	Mean RW	Mean no. cells	Mean LW	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	1.8 x		0.03	5				880	1.1	0.79	19
2	1.67	85	0.03	3	0.07			850	1.15	0.75	15
3	2.12 x		0.03	3	0.26			855	1.1	0.8	16
Mean values	1.86	85	0.03	3				862	1.12	0.78	17
Mean sensitivity % False Rings					0.11	x	0%				

Table 3.24 GRISTHORPE MEMBER, YONS NAB: J.67919

Ring no.	Mean RW	Mean no. cells	Mean LW	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	4.11	110	0.07	7				590	1.09	0.95	30
2	3.84	88	0.09	5	0.06	0.22	1E (3)	605	1.1	0.99	35
3	3.6	94	0.11	5	0.06	0.06 2 (1e:3+1m:3)		585	1.19	0.7	39
Mean values	3.85	97	0.09	6	0.04	0.09	66%	593	1.13	0.88	35
Mean sensitivity % False Rings											

Table 3.25 GRISTHORPE MEMBER, YONS NAB: J.67918

Ring no.	Mean RW	Mean no. cells	Mean LWW	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	3	83	0.05	4				568	1.03	0.63	34
2	2.19	76	0.05	4	0.31	0.09	1e (3)	619	1.07	0.89	27
3	3.12	87	0.05	5	0.35	0.13		658	1.23	0.72	36
Mean values	3	82	0.05	4	0.22	0.07		615	1.11	0.75	32
Mean sensitivity % False Rings							33%				

Table 3.26 GRISTHORPE MEMBER, YONS NAB: J.67921

Ring no.	Mean RW	Mean no. cells	Mean LWW	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	2.5	81	0.02	5	0.11	0.24		314	1.21	0.45	42
2	3.2	92	0.03	4	0.09	0.09		420	1.03	0.61	34
3	2.9	84	0.02	4	0.1	0.07	1m	426	1.04	0.47	31
4	2.7	75	0.03	4			2m	508	1.03	0.45	27
Mean values	2.83	83	0.02	4.25	0.08	0.1		417	1.08	0.5	34
Mean sensitivity % False Rings							50%				

Table 3.27 GRISTHORPE MEMBER, YONS NAB: J.67920

Ring no.	Mean RW	Mean no. cells	Mean LWW	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	1.5	65	0.04	3			2 (1e:5+1m:4)	510	0.91	0.29	27
2	2	95	0.03	3	0.29	0.38		520	0.94	0.27	31
3	1.4	70	0.04	3	0.35	0.3	1m (4)	458	0.92	0.41	31
4	2.8	119	0.04	3	0.67	0.52		500	0.89	0.52	25
5	2.6	108	0.03	4	0.07	0.11		510	0.99	0.4	30
6	2.1	94	0.03	3	0.52	0.14		498	0.95	0.39	29
7	1.2	65	0.04	3	0.55	0.36		487	0.98	0.45	30
8	1.3	69	0.04	3	0.08	0.06		505	0.94	0.38	28
Mean values	1.86	85	0.03	3	0.32	0.23		499	0.94	0.39	29
Mean sensitivity % False Rings							2.5%				

Table 3.28 GRISTHORPE MEMBER, YONS NAB: J.67925

Ring no.	Mean RW	Mean no. cells	Mean LWW	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	1.65	33	1.18	6	0.23	0.61	11 (3)	385	1.45	0.42	65
2	1.79	62	0.16	5	0.22	0.5	1m (3)	470	1.52	0.59	72
3	2.24	59	0.19	5	0.22	0.5	1m (3)	450	1.39	0.38	71
Mean values	1.89	51	0.51	5	0.15	0.37	33%	435	1.45	0.46	69
Mean sensitivity % False Rings											

Table 3.29 GRISTHORPE MEMBER, YONS NAB: J.67924

Ring no.	Mean RW	Mean no. cells	Mean LWW	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	4.5	122	0.2	5	0.4	0.44		224	1.47	0.87	68
2	3	78	0.2	4	0.26	0.14		228	1.55	0.9	90
3	3.9	91	0.2	4	0.26	0.14		232	1.42	0.84	95
Mean values	3.8	97	0.2	4	0.22	0.19	0%	228	1.48	0.87	84
Mean sensitivity % False Rings											

Table 3.30 GRISTHORPE MEMBER, YONS NAB: J.67928

Ring no.	Mean RW	Mean no. cells	Mean LWW	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	2.19	107	0.05	4	0.07	0		480	1	0.68	37
2	2.05	107	0.1	7	0.23	0.15		497	0.95	0.63	34
3	2.58	124	0.1	5	0.48	0.54		415	1.08	0.6	39
4	1.58	71	0.1	4	0.47	0.39		435	1.02	0.72	40
5	2.54	105	0.1	4	0.21	0.09		339	1.16	0.79	47
6	2.05	96	0.08	4	0.67	0.61		411	1.1	0.8	45
7	1.02	51	0.08	4	0.86	0.83		349	1.1	0.78	40
8	2.57	123	0.1	4	0.84	0.67		333	1.07	0.71	42
9	1.05	61	0.05	4	0.84	0.67		350	1.05	0.7	46
Mean values	2.07	98	0.08	5	0.48	0.41	0%	401	1.06	0.71	41
Mean sensitivity % False Rings											

Table 3.31 GRISTHORPE MEMBER, YONS NAB: J.67926

Ring no.	Mean RW	Mean no. cells	Mean LWW	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	5.07	212	0.2	17				346	0.91	0.41	40
2	4.53	181	0.17	12	0.11	0.16		411	0.96	0.5	47
3	3.92	160	0.13	11	0.14	0.12		397	0.95	0.49	43
4	5.04	210	0.2	12	0.25	0.27		436	0.99	0.48	48
Mean values	4.64	190	0.17	13	0.13	0.14	0%	398	0.95	0.47	45
Mean sensitivity % False Rings											

Table 3.32 GRISTHORPE MEMBER, YONS NAB: J.67934

Ring no.	Mean RW	Mean no. cells	Mean LWW	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	0.6	42	0.01	2				1480	1.05	0.57	23
2	0.7	36	0.02	2	0.15	0.15	2e+m	976	0.97	0.65	13
3	1.5	90	0.01	4	0.72	0.85	1e	1120	0.95	0.72	17
4	1.4	82	0.03	4	0.07	0.09	2m	1020	1.02	0.69	21
5	2.5	140	0.02	3	0.56	0.52		990	1.05	0.65	19
Mean values	1.05	63	0.01	3	0.3	0.32	60%	1117	1.01	0.66	19
Mean sensitivity % False Rings											

Table 2.33 GRISTHORPE MEMBER, YONS NAB: J.67933

Ring no.	Mean RW	Mean no. cells	Mean LWW	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	2.1	105	0.2	3				320	1.29	0.64	64
2	2.4	126	0.3	4	0.13	0.18	1m	280	1.19	0.7	59
3	3.4	143	0.3	4	0.34	0.13		300	1.36	0.92	69
4	1.7	72	0.3	4	0.67	0.67		310	1.15	0.87	62
Mean values	2.4	111	0.27	4	0.29	0.25	25%	300	1.25	0.78	78
Mean sensitivity % False Rings											

Table 3.34 SCALBY FORMATION
Results of growth-ring analysis

Composition	J.67896	J.67901	J.67903	J.67904	J.67907	HSM94 YNMA
Medium	Charcoal	Charcoal	Charcoal	Charcoal	Charcoal	Charcoal
Number of rings	SEM 5	SEM 12	SEM 11	SEM 5	SEM 21	SEM 5
Mean RW (mm)	1.27	0.37	0.41	0.55	1.85	0.63
Standard deviation	0.7	0.09	0.21	0.2	0.79	0.39
Mean sensitivity (RW)	0.69	0.16	0.41	0.33	0.27	0.55
Max. width	20	0.6	0.81	0.9	4.5	1.2
Min. width	4.4	0.25	0.17	0.42	0.89	0.26
Mean no. cells	112	13	17	15	10	24
Standard deviation	51.95	1.61	8.67	1.71	3.51	14.96
Mean sensitivity (cells)	0.53	0.12	0.36	0.11	0.26	0.52
Max. number	172	15	35	17	18	45
Min. number	44	10	8	13	6	11
Mean LWW (mm)	0.86	0.03	0.03	0.03	0.23	0.03
Mean LW (cells)	9	3	3	3	3	4
L/W (width)	0.67	0.08	0.07	0.05	0.12	0.05
L/W (cells)	0.08	0.23	0.18	0.2	0.3	0.17
False rings	20%	8%	9%	0%	9%	40%
Cells mm-2	508	277	192	175	191	274
Cell L:W (EW)	1.1	1.22	1.09	1.11	1.12	1.25
Cell L:W (LW)	0.88	0.76	0.77	0.75	0.64	0.82
Mean RTD (µm)	80	29	32	40	31	28

Table 3.35 SCALBY FORMATION, WHITE NAB: J.67896

Ring no.	Mean RW (mm)	Mean no. cells	Mean LWW (mm)	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	0.64	78	0.89	10				490	1.02	0.92	71
2	1.45	119	0.89	9	0.77	0.42		520	1	0.91	89
3	0.44	44	0.92	10	1.07	0.92		680	1.09	0.85	89
4	2	172	0.95	9	1.28	1.18		390	1.25	0.81	81
5	1.81	149	0.64	7	0.09	0.14	1m (5)	460	1.16	0.89	69
Mean values	1.27	112	0.86	9				508	1.1	0.88	80
Mean sensitivity					0.69	0.53					
% False Rings							20%				

Table 3.36 SCALBY FORMATION, YONS NAB: HSM94 YNMA

Ring no.	Mean RW (mm)	Mean no. cells	Mean LWW (mm)	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	0.26	11	0.02	2				285	1.33	0.85	20
2	1.2	45	0.04	5	1.31	1.21 +2m:5,5+11:4	1m (4)	295	1.26	0.79	25
3	0.86	34	0.03	3	0.33	0.28		270	1.32	0.88	31
4	0.36	13	0.03	4	0.82	0.89		262	1.19	0.78	29
5	0.48	16	0.02	4	0.29	0.21		260	1.15	0.8	36
Mean values	0.63	24	0.03	4				274	1.25	0.82	28
Mean sensitivity					0.55	0.52					
% False Rings							40%				

Table 3.37 SCALBY FORMATION, YONS NAB: J.67904

Ring no.	Mean RW (mm)	Mean no. cells	Mean LWW (mm)	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	0.42	13	0.02	2				x	1.1	0.71	41
2	0.9	x	0.04	3	0.73			x	1.1	0.81	38
3	0.46	14	0.04	3	0.65			165	1.12	0.75	45
4	0.52	17	0.04	4	0.12	0.19		170	1.15	0.7	39
5	0.44	15	0.03	4	0.17	0.13		190	1.1	0.8	37
Mean values	0.55	15	0.03	3	0.33	0.11		175	1.11	0.75	40
Mean sensitivity % False Rings							0%				

Table 3.38 SCALBY FORMATION, YONS NAB: J.67903

Ring no.	Mean RW (mm)	Mean no. cells	Mean LWW (mm)	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	0.21	10	0.02	2				300	1.33	0.67	22
2	0.28	12	0.02	2	0.28	0.18		160	1.2	0.5	33
3	0.81	35	0.03	3	0.97	0.98	11 (3)	185	1.02	0.89	28
4	0.63	27	0.03	3	0.25	0.26		190	1.1	0.69	30
5	0.25	11	0.02	2	0.86	0.84		190	1.09	0.71	32
6	0.32	13	0.02	3	0.25	0.17		180	1.02	0.73	35
7	0.58	19	0.03	3	0.58	0.38		220	1.03	0.89	34
8	0.58	23	0.06	3	0	0.19		190	1.02	0.92	37
9	0.49	18	0.03	5	0.17	0.24		160	1.01	0.81	32
10	0.17	8	0.03	3	0.97	0.77		175	1.05	0.88	34
11	0.21	8	0.03	2	0.21	0		160	1.07	0.79	33
Mean values	0.41	17	0.03	3	0.41	0.36		192	1.09	0.77	32
Mean sensitivity % False Rings							9%				

Table 3.39 SCALBY FORMATION, YONS NAB: J.67901

Ring no.	Mean RW (mm)	Mean no. cells	Mean LWW (mm)	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	0.4	13	0.03	3				281	1.25	0.77	31
2	0.38	15	0.03	3	0.05	0.14		274	1.19	0.75	26
3	0.25	10	0.02	2	0.41	0.4		280	1.18	0.74	25
4	0.28	11	0.02	2	0.11	0.09	11	265	1.2	0.79	27
5	0.32	13	0.05	4	0.13	0.17		274	1.2	0.75	30
6	0.4	15	0.05	3	0.22	0.17		271	1.25	0.74	31
7	0.37	14	0.04	3	0.08	0.14		281	1.26	0.78	28
8	0.39	15	0.03	4	0.05	0.07		275	1.21	0.77	28
9	0.32	13	0.03	4	0.2	0.14		277	1.28	0.74	27
10	0.31	13	0.04	4	0.03	0		286	1.21	0.76	30
11	0.43	13	0.03	3	0.32	0		281	1.22	0.77	31
12	0.6	15	0.03	4	0.33	0.14		280	1.23	0.75	28
Means values	0.37	13	0.03	3				277	1.22	0.76	29
Mean sensitivity % False Rings					0.16	0.12	8%				

Table 3.40 SCALBY FORMATION, SCARBOROUGH SOUTH CLIFF: J.67907

Ring no.	Mean RW (mm)	Mean no. cells	Mean LWW (mm)	Mean LW cells	AS (RW)	AS (cells)	False rings	Cells mm-2	Cell L:W (EW)	Cell L:W (LW)	Mean RTD (µm)
1	4.5	18	0.25	3			2 (e:2+m:2)	x	1.13	0.75	36
2	2.5	12	0.43	3	0.57	0.43		x	x	0.89	x
3	2.3	11	0.54	4	0.08	0.09		x	x	0.69	x
4	1.5	10	0.29	3	0.42	0.09		x	1.17	0.33	32
5	2.36	12	0.18	3	0.45	0.18		x	1.19	0.41	30
6	2.07	18	0.25	5	0.13	0.4		x	1.16	0.51	29
7	1.68	9	0.18	2	0.21	0.67		140	1.08	x	33
8	1.79	10	0.29	3	0.06	0.1		x	1.09	0.58	35
9	0.89	9	0.18	3	0.67	0.1		170	1.15	0.68	35
10	1.25	6	0.18	3	0.34	0.4		220	1.16	x	33
11	1.21	7	0.25	2	0.03	0.15		280	1.13	x	35
12	1.61	8	0.18	2	0.28	0.13		x	1.11	x	31
13	1.61	7	0.18	2	0	0.13		220	1.08	0.79	30
14	1.96	9	0.18	3	0.19	0.25		280	1.01	0.66	29
15	1.14	9	0.14	4	0.53	0		150	1.09	0.71	24
16	1.36	18	0.14	3	0.18	0.67	2 (e:1+m:1)	130	1.11	0.67	26
17	1	8	0.11	3	0.31	0.77		130	1.2	0.74	31
18	1.79	13	0.11	3	0.59	0.48		x	1.19	0.7	29
19	1.71	10	0.14	4	0.05	0.26		x	1.12	0.68	27
20	1.69	10	0.21	3	0.01	0		x	1.1	0.56	30
21	2.86	11	0.32	2	0.51	0.1		x	1.02	0.59	29
Mean values	1.85	10	0.23	3	0.27	0.26		191	1.12	0.64	31
Mean sensitivity % False Rings							9%				

Table 3.41 CLEVELAND IRONSTONE FORMATION
SUMMARY OF INFORMATION GATHERED IN THE LONGITUDINAL PLANES
 Key: r= round; o= oval; h= hexagonal; alt.= alternate; opp= opposite

	J.67953	J.67952	J.67951	J.67956	J.67950	J.67948	J.67954
RADIAL L.S.							
Cross-field pits:							
pit diameter			14µm	14µm	13µm	10µm	13µm
max. number pits/field			1	1	4	3	1
mean number pits/field			1	1	3	2	1
Circular-bordered pits:							
pit diameter			28µm	22µm	21µm	20µm	24µm
aperture diameter			9µm	9µm	6µm	8µm	7µm
uniseriate pits	50%		100%	90%	90%	80%	100%
biseriate pits	50%		0%	10%	10%	20%	0%
triseriate pits	0%		0%	0%	0%	0%	0%
Pit characteristics:							
spaced	0%		0%	0%	0%	0%	0%
touching/distorted	100%		100%	100%	100%	100%	100%
round, hexagonal, oval?	r		r	r	r	r	r
If biseriate, opposite or alternate?	alt.		x	alt.	alt. & opp.	alt. & opp.	x
Pits grouped?							
each pit isolated	0%		0%	33%	0%	0%	0%
in pairs	0%		0%	34%	0%	0%	0%
in triplets	0%		0%	33%	0%	0%	0%
longer strings with gaps	0%		0%	0%	0%	0%	0%
equally spaced	100%		100%	0%	100%	100%	100%
TANGENTIAL L.S.							
Uniseriate rays:							
min. cell number	100%	100%	100%	100%	100%	100%	100%
max. cell number	2	3	2	3	2	3	3
mean cell number	6	7	8	6	8	8	8
Biseriate rays:	4	5	4	4	5	6	5
Triseriate rays:	0%	0%	0%	0%	0%	0%	0%
	0%	0%	0%	0%	0%	0%	0%

Table 3.42 DOGGER FORMATION
SUMMARY OF INFORMATION GATHERED IN THE LONGITUDINAL PLANES

	HSM93 BW2	HSM93BW3	J.67947	J.67943	J.67942	J.67948	J.67954
RADIAL L.S.							
Cross-field pits:							
pit diameter	7µm	8µm	7µm	7µm	9µm	10µm	13µm
max. number pits/field	1	2	2	2	2	3	1
mean number pits/field	1	1	1	1	1	2	1
Circular-bordered pits:							
pit diameter	12µm	14µm	18µm	13µm	14µm	20µm	24µm
aperture diameter	absent	absent	4µm	absent	absent	8µm	7µm
uniseriate pits	100%	100%	50%	70%	50%	80%	100%
biseriate pits	0%	0%	40% rare		50%	20%	0%
triseriate pits	0%	0%	10%	30%	0%	0%	0%
Pit characteristics:							
spaced	100%	100%	20%	30%	100%	0%	0%
touching/distorted	0%	0%	80%	70%	0%	100%	100%
round, hexagonal, oval?	o	o	r	r	o	r	r
If biseriate, opposite or alternate?	x	x	alt. & opp.	alt. & opp.	x	alt. & opp.	x
Pits grouped?							
each pit isolated	0%	0%	25%	25%	25%	0%	0%
in pairs	0%	0%	25%	25%	25%	0%	0%
in triplets	0%	0%	25%	25%	25%	0%	0%
longer strings with gaps	100%	100%	25%	25%	25%	0%	0%
equally spaced	0%	0%	0%	0%	0%	100%	100%
TANGENTIAL L.S.							
Uniseriate rays:							
min. cell number	100%	100%	100%	100%	100%	100%	100%
max. cell number	2	2	3	4	3	3	3
mean cell number	12	9	10	18	13	8	8
	7	5	8	9	7	6	5
Biseriate rays:							
	0%	0%	0%	0%	0%	0%	0%
Triseriate rays:							
	0%	0%	0%	0%	0%	0%	0%

Table 3.43 SALTWICK FORMATION
SUMMARY OF INFORMATION GATHERED IN THE LONGITUDINAL PLANES

	J.67941	J.67940	HSM94 HY2	J.67939	HSM94 HYB	J.67938	J.67936	J.67935
RADIAL L.S.								
Cross-field pits:								
pit diameter	10µm	14µm	13µm	15µm	15µm	12µm	13µm 12µm	
max. number pits/field	1	1	1	1	1	4	1	1
mean number pits/field	1	1	1	1	1	4	1	1
Circular-bordered pits:								
pit diameter	19µm	18µm	19µm	18µm	17µm	14µm	17µm 15µm	
aperture diameter	5µm	6µm	6µm	8µm	6µm absent	absent	absent	
uniseriate pits	100%	90%	100%	100%	100%	100%	100%	100%
biseriate pits	0%	10%	0%	0%	0%	0%	0%	0%
triseriate pits	0%	0%	0%	0%	0%	0%	0%	0%
Pit characteristics:								
spaced	100%	100%	20%	30%	100%	0%	0%	100%
touching/distorted	0%	0%	80%	70%	0%	100%	100%	0%
round, hexagonal, oval?	o	r-o	r	r		r-o	r r-o	
If biseriate, opposite or alternate?	x	alt.	x	x	x	x	x x	
Pits grouped?								
each pit isolated	0%	0%	0%	0%	0%	0%	0%	0%
in pairs	0%	0%	0%	0%	0%	33%	33%	33%
in triplets	0%	0%	0%	0%	0%	33%	33%	33%
longer strings with gaps	100%	100%	100%	100%	100%	33%	33%	33%
equally spaced	0%	0%	0%	0%	0%	0%	0%	0%
TANGENTIAL L.S.								
Uniseriate rays:								
min. cell number	100%	100%	100%	100%	100%	100%	100%	100%
max. cell number	3	3	6	4	3	3	2	1
mean cell number	9	12	18	13	8	5	7	7
	6	6	8	7	5	4	5	5
Biseriate rays:								
Triseriate rays:	0%	0%	0%	0%	0%	0%	0%	0%
	0%	0%	0%	0%	0%	0%	0%	0%

	J.67929	J.67928	J.67927	J.67926
RADIAL L.S.				
Cross-field pits:				
pit diameter	9µm	10µm	9µm	10µm
max. number pits/field	4	1	2	2
mean number pits/field	3	1	1	1
Circular-bordered pits:				
pit diameter	15µm	13µm	12µm	12µm
aperture diameter	4µm	absent	absent	2µm
uniseriate pits	50%	60%	50%	50%
biseriate pits	50%	40%	50%	50%
triseriate pits	(rare)	0%	0%	0%
Pit characteristics:				
Spaced	0%	50%	0%	0%
Touching/distorted	100%	50%	100%	100%
round, hexagonal, oval?	r	r	r	r
If biseriate, opposite or alternate?	alt. & opp.	alt.	alt.	alt.
Pits grouped?				
each pit isolated	0%	0%	0%	25%
in pairs	0%	0%	0%	25%
in triplets	0%	0%	0%	25%
longer strings	100%	100%	100%	25%
equally spaced	0%	0%	0%	0%
TANGENTIAL L.S.				
Uniseriate rays:	50%	90%	80%	50%
min. cell number	7	2	7	2
max. cell number	20	9	11	22
mean cell number	10	5	11	8
Biseriate rays:	50%	10%	20%	50%
min. cell number	10	2	18	4
max. cell number	21	7	23	7
mean cell number	17	5	19	7
Triseriate rays:	0%	0%	0%	0%

Those specimens displaying a tangential longitudinal section alone:

	HSM95 GPB	J.67931	J.67930	J.67923
TANGENTIAL L.S.				
Uniseriate rays:	90%	50%	80%	80%
min. cell number	4	6	2	3
max. cell number	14	14	7	12
mean cell number	6	9	5	6
Biseriate rays:	10%	50%	20%	20%
min. cell number	4	5	5	5
max. cell number	10	7	14	7
mean cell number	7	6	10	6
Triseriate rays:	0%	0%	0%	0%

	J.67922	J.67921	J.67914
TANGENTIAL L.S.			
Uniseriate rays:	90%	100%	90%
min. cell number	2	2	2
max. cell number	10	12	16
mean cell number	6	5	7
Biseriate rays:	10%	0%	10%
min. cell number	8	0	7
max. cell number	25	0	13
mean cell number	17	0	10
Triseriate rays:	0%	0%	0%

Table 3.45 SCARBOROUGH FORMATION
SUMMARY OF INFORMATION GATHERED FROM THE LONGITUDINAL PLANES

	HSM93 CW10	J.67912	J.67913	J.67914
RADIAL L.S.				
Cross-field pits:				
pit diameter	9µm	10µm	9µm	10µm
max. number pits/field	2	1	1	1
mean number pits/field	1	1	1	1
Circular-bordered pits:				
pit diameter	15µm	11µm	12µm	15µm
aperture diameter	5µm	absent	3µm	absent
uniseriate pits	100%	100%	100%	100%
biseriate pits	0%	0%	0%	0%
triseriate pits	0%	0%	0%	0%
Pit characteristics:				
Spaced	100%	0%	100%	100%
Touching/distorted	0%	100%	0%	0%
round, hexagonal, oval?	r	r-o	o	r
If biseriate, opposite or alternate?	x	x	x	x
Pits grouped?				
each pit isolated	33%	0%	0%	0%
in pairs	34%	0%	0%	0%
in triplets	33%	0%	0%	0%
longer strings	0% ?100%	?100%	?100%	
equally spaced	0%	0%	0%	0%
TANGENTIAL L.S.				
Uniseriate rays:	100%	100%	100%	100%
min. cell number	3	2	5	4
max. cell number	9	10	15	8
mean cell number	7	7	11	6
Biseriate rays:	0%	0%	0%	0%
Triseriate rays:	0%	0%	0%	0%

Table 3.46a SCALBY FORMATION
SUMMARY OF INFORMATION GATHERED IN THE LONGITUDINAL PLANES

	J.67909	J.67908	HSM93 SSC1	J.67906	J.67905	J.67904	J.67903	J.67902
RADIAL L.S.								
Cross-field pits:								
pit diameter	14µm	12µm	11µm	10µm	9µm	10µm	9µm	11µm
max. number pits/field	1	1	1	2	1	1	1	1
mean number pits/field	1	1	1	2	1	1	1	1
Circular-bordered pits:								
pit diameter	13µm	14µm	15µm	12µm	?11µm	16µm	17µm	18µm
aperture diameter	3µm	5µm	4µm	absent	6µm	absent	absent	absent
uniseriate pits	100%	100%	100%	100%	100%	100%	100%	100%
biseriate pits	0%	0%	0%	0%	0%	0%	0%	0%
triseriate pits	0%	0%	0%	0%	0%	0%	0%	0%
Pit characteristics:								
Spaced	100%	100%	0%	0%	100%	100%	0%	0%
Touching/distorted	0%	0%	100%	100%	0%	0%	100%	100%
round, hexagonal, oval?	r	r	r	r	r	r	r	r
If biseriate, opposite or alternate?	x	x	x	x	x	x	x	x
Pits grouped?								
each pit isolated	0%	0%	50%	50%	10%	0%	0%	0%
in pairs	34%	34%	50%	50%	0%	34%	34%	34%
in triplets	33%	33%	0%	0%	40%	33%	33%	33%
longer strings	33%	33%	0%	0%	40%	33%	33%	33%
equally spaced	0%	0%	0%	0%	0%	0%	0%	0%
TANGENTIAL L.S.								
Uniseriate rays:								
min. cell number	2	1	1	2	1	2	3	3
max. cell number	9	7	7	8	5	11	12	16
mean cell number	4	3	2	4	3	8	7	7
Biseriate rays:	0%	0%	0%	0%	0%	0%	0%	0%
Triseriate rays:	0%	0%	0%	0%	0%	0%	0%	0%

Table 3.46b SCALBY FORMATION
SUMMARY OF INFORMATION GATHERED IN THE LONGITUDINAL PLANES, CONTINUED

	J.67901	HSM93 YN47	J.67900	J.67899	J.67898	HSM94 WN18a	J.67897	J.67895
RADIAL L.S.								
Cross-field pits:								
pit diameter								
max. number pits/field	10µm	10µm	9µm	9µm	8µm	7µm	9µm	6µm
mean number pits/field	1	1	2	1	4	4	1	10
	1	1	1	1	2	3	1	6
Circular-bordered pits:								
pit diameter								
aperture diameter	16µm	17µm	18µm	22µm	15µm	15µm	14µm	10µm
uniseriate pits	absent	24µm	100%	100%	6µm	5µm	6µm	absent
biseriate pits	100%	100%	100%	100%	100%	100%	100%	100%
triseriate pits	0%	0%	0%	0%	0%	0%	0%	0%
	0%	0%	0%	0%	0%	0%	0%	0%
Pit characteristics:								
Spaced	0%	0%	0%	100%	100%	0%	100%	100%
Touching/distorted	100%	100%	100%	0%	0%	100%	0%	0%
round, hexagonal, oval?	r		r	r	r	r	r	r
If biseriate, opposite or alternate?	x	x	x	x	x	x	x	x
Pits grouped?								
each pit isolated	0%	0%	0%	0%	30%	0%	0%	0%
in pairs	33%	34%	34%	0%	0%	0%	0%	34%
in triplets	34%	33%	33%	0%	0%	0%	0%	33%
longer strings	33%	33%	33%	100%	70%	0%	0%	33%
equally spaced	0%	0%	0%	0%	0%	100%	100%	0%
TANGENTIAL L.S.								
Uniseriate rays:								
min. cell number	100%	100%	100%	100%	100%	80%	100%	100%
max. cell number	2	4	6	5	1	3	7	3
mean cell number	10	9	20	22	11	11	13	8
	7	6	9	14	5	6	11	5
Biseriate rays:	0%	0%	0%	0%	(rare)	20%	0%	0%
Triseriate rays:	0%	0%	0%	0%	0%	0%	0%	0%

Appendix 4

Appendix 4

Data obtained from Correspondence Analysis of the Yorkshire flora

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Table 4.1 The occurrence of floral elements through the succession.
 For each of the 55 genera, the number of species present within a particular stratigraphic interval is shown.

	LSalt	USalt	EB	Syc	Leb	Gris	Scar	LScal	UScal	n species
<i>Angiopteris</i>	1	1	0	0	0	1	0	0	0	1
<i>Anozamites</i>	2	1	0	1	1	1	0	0	0	6
<i>Aspidistes</i>	1	0	0	0	0	1	0	0	0	2
<i>Baiera</i>	1	1	0	1	0	1	0	1	1	6
<i>Blidalea</i>	1	1	0	1	1	1	0	1	1	7
<i>Brachyphyllum</i>	3	3	2	3	2	2	2	2	2	21
<i>Cladophlebis</i>	2	2	0	0	0	0	0	0	0	4
<i>Clathropteris</i>	1	1	0	0	0	0	0	0	0	2
<i>Coniopteris</i>	5	4	0	1	0	5	0	2	2	19
<i>Ctenis</i>	3	3	0	2	0	3	0	2	2	15
<i>Ctenozamites</i>	3	2	1	2	0	2	0	2	4	16
<i>Cycadolepis</i>	3	4	0	2	0	3	0	0	0	12
<i>Cyparissidium</i>	0	0	0	0	0	1	0	0	1	2
<i>Czekanowskia</i>	6	5	0	1	0	3	0	1	3	19
<i>Deltolopsis</i>	1	0	0	0	0	1	0	0	0	2
<i>Desmiophyllum</i>	1	1	0	0	0	0	0	0	0	2
<i>Dicksonia</i>	2	0	0	0	0	1	0	0	0	3
<i>Dictyophyllum</i>	1	1	0	1	0	1	0	0	0	4
<i>Dictyozamites</i>	1	0	0	0	0	0	0	0	0	1
<i>Elatides</i>	1	0	0	0	0	1	0	0	1	3
<i>Elatocladus</i>	3	2	0	3	0	3	0	0	0	11
<i>Equisetum</i>	1	1	0	1	0	1	0	1	1	6
<i>Eretmophyllum</i>	2	2	0	1	0	2	0	0	1	8
<i>Geinitzia</i>	2	2	1	2	1	2	0	1	1	12
<i>Ginkgo</i>	5	3	0	1	1	3	0	1	1	15
<i>Hausmannia</i>	1	0	0	0	0	0	0	0	0	1
<i>Klukia</i>	1	1	0	0	0	1	0	0	0	3
<i>Kylikopteris</i>	1	1	0	0	0	1	0	0	0	3
<i>Lindleycladus</i>	1	1	0	0	0	0	0	0	0	2
<i>Marattia</i>	1	0	0	0	0	0	0	0	0	1
<i>Marskea</i>	1	1	0	0	0	0	0	0	0	2
<i>Matonidium</i>	1	1	0	1	0	1	0	0	0	4
<i>Nilsonia</i>	7	6	0	2	0	4	0	0	2	21
<i>Nilssonopteris</i>	2	1	0	1	0	3	0	0	0	7
<i>Osmundopsis</i>	0	0	0	0	0	1	0	0	0	1
<i>Otozamites</i>	11	10	0	3	2	4	0	3	6	39
<i>Pachypteris</i>	2	2	0	1	1	1	0	1	1	9
<i>Pagiophyllum</i>	5	5	3	4	3	4	3	4	4	35
<i>Paracycas</i>	1	0	0	0	0	0	0	0	0	1
<i>Phlebopteris</i>	1	0	0	1	0	1	0	0	0	3
<i>Pityocladus</i>	0	0	0	0	0	0	0	0	1	1
<i>Poteridium</i>	1	0	0	0	0	0	0	0	0	1
<i>Pseudoctenis</i>	5	3	0	0	0	2	0	0	1	11
<i>Pseudotorellia</i>	1	1	0	0	0	0	0	0	1	3
<i>Pterophyllum</i>	2	2	0	1	0	3	0	0	2	10
<i>Ptilophyllum</i>	3	3	0	2	1	2	0	0	0	11
<i>Sagenopteris</i>	2	2	0	0	0	2	0	0	0	6
<i>Solenites</i>	1	1	0	1	0	1	0	0	0	4
<i>Sphenarion</i>	0	0	0	0	0	0	0	0	1	1
<i>Sphenobaiera</i>	4	3	0	0	0	1	0	0	0	8
<i>Stachypteris</i>	1	1	0	0	0	0	0	0	0	2
<i>Stenopteris</i>	2	2	0	1	0	2	0	1	1	9
<i>Todites</i>	0	0	0	0	0	1	0	0	0	1
<i>Torreya</i>	1	1	0	1	0	1	0	0	1	5
<i>Zamites</i>	2	2	1	1	1	1	0	1	1	10
Total species	112	89	8	43	14	75	5	24	43	

Note: The Saltwick and Scalby Formations are divided into two, which may cause duplication of some data in this table, increasing the number of occurrences per interval.
 [n = number of occurrences of species]

Table 4.2 Key to abbreviated genera and species in Tables 4.3-4.5
Sorted alphabetically.

Abbreviation	Genus	Abbreviation	Species
Angi op	<i>Angiopteris</i>	Zami te	<i>Zamites</i>
Anom oz	<i>Anonozamites</i>	A.ni ls	<i>Anomozamites nilssoni</i>
Asph id	<i>Aspidistes</i>	A.th om	<i>Aspidistes thomasi</i>
Baie ra	<i>Baiera</i>	A.th om	<i>Anomozamites thomasi</i>
Bils da	<i>Blisdalea</i>	B.ar de	<i>Brachyphyllum ardenicum</i>
Brac hy	<i>Brachyphyllum</i>	B.cr uc	<i>Brachyphyllum crucis</i>
Clad op	<i>Cladophlebis</i>	B.du ra	<i>Bilsdalea dura</i>
Clat ho	<i>Clathopteris</i>	B.fu rc	<i>Baiera furcata</i>
Coni op	<i>Coniopteris</i>	B.ma mi	<i>Brachyphyllum mamillare</i>
Cten is	<i>Ctenis</i>	C.ak ta	<i>Cladophlebis aktashensis</i>
Cten oz	<i>Ctenozamites</i>	C.be ll	<i>Coniopteris bella</i>
Cyca do	<i>Cycadolepis</i>	C.bl ac	<i>Czekanowskia blacki</i>
Cypa ri	<i>Cyparissidium</i>	C.bl ac	<i>Cyparissidium blackii</i>
Czek an	<i>Czekanowskia</i>	C.bu re	<i>Coniopteris burejensis</i>
Delt ol	<i>Deltolepis</i>	C.cy ca	<i>Ctenozamites cycadea</i>
Desm io	<i>Desmiophyllum</i>	C.erip	<i>Cycadolepis eriphous</i>
Dick so	<i>Dicksonia</i>	C.ex il	<i>Ctenis exilis sp. nov.</i>
Dict yo	<i>Dictyophyllum</i>	C.fu rc	<i>Czekanowskia furcula</i>
Dict yz	<i>Dicytozamites</i>	C.ha ib	<i>Cladophlebis haiburnensis</i>
Elat id	<i>Elatides</i>	C.ha ll	<i>Cycadolepis hallei</i>
Elat oc	<i>Elatocladus</i>	C.hy me	<i>Coniopteris hymenophylloides</i>
Equi se	<i>Equisetum</i>	C.hy pe	<i>Cycadolepis hypene</i>
Eret mo	<i>Eretmophyllum</i>	C.ka ne	<i>Ctenis kaneharai</i>
Gein it	<i>Geinitzia</i>	C.le ck	<i>Ctenozamites leckenbyi</i>
Gink go	<i>Ginkgo</i>	C.ma rg	<i>Otozamites marginatus</i>
Haus ma	<i>Hausmannia</i>	C.me ga	<i>Ctenozamites megalostoma</i>
Kluk ia	<i>Klukia</i>	C.mi cr	<i>Czekanowkia microphylla</i>
Kyli ki	<i>Kylikipteris</i>	C.mu rr	<i>Coniopteris murrayana</i>
Lind le	<i>Lindleycladus</i>	C.ni te	<i>Cycadolepis nitens</i>
Mara tt	<i>Marattia</i>	C.ob ov	<i>Clathropteris obovata</i>
Mars ke	<i>Marskea</i>	C.pe le	<i>Cycadolepis pelecus</i>
Mato ni	<i>Matonidium</i>	C.re ed	<i>Ctenis reedi</i>
Nils so	<i>Nilssonia</i>	C.ru dl	<i>Cyparissidium rudlandicum</i>
Nils sp	<i>Nilssonopteris</i>	C.si mp	<i>Coniopteris simplex</i>
Osmu no	<i>Osmunopsis</i>	C.sp .A	<i>Czekanowskia sp. A</i>
Otoz am	<i>Otozamites</i>	C.sp .A	<i>Ctenozamites sp. A</i>
Pach yp	<i>Pachypteris</i>	C.sp .B	<i>Czekanowskia sp. B</i>
Pagi op	<i>Pagiophyllum</i>	C.sp .C	<i>Czekanowskia sp. C</i>
Para cy	<i>Paracycas</i>	C.sp .D	<i>Czekanowskia sp. D</i>
Phle bo	<i>Phlebopteris</i>	C.sp .E	<i>Czekanowskia sp. E</i>
Pity oc	<i>Pityocladus</i>	C.sp he	<i>Cycadolepis spheniscus</i>
Pote ri	<i>Poteridium</i>	C.st en	<i>Cycadolepis stenopus</i>
Pseu do	<i>Pseudoctenis</i>	C.st ew	<i>Ctenis cf. stewartiana</i>
Pseu dt	<i>Pseuotorellia</i>	C.su lc	<i>Ctenis sulcicaulis</i>
Pter op	<i>Pterophyllum</i>	C.th om	<i>Czekanowskia thomasi</i>
Ptil op	<i>Ptilophyllum</i>	C.th ys	<i>Cycadolepis thysanota</i>
Sage no	<i>Sagenopteris</i>	D.cr ep	<i>Deltolepis crepidota</i>
Sele no	<i>Selenocarpus</i>	D.gr am	<i>Desmiophyllum gramineum</i>
Sole ni	<i>Solenites</i>	D.ha we	<i>Dictyozamites hawelli</i>
Sphe na	<i>Sphenarion</i>	D.ke nd	<i>Dicksonia kendalli</i>
Sphe no	<i>Sphenobaiera</i>	D.ma ri	<i>Dicksonia mariopteris</i>
Stac hy	<i>Stachypteris</i>	D.mi tr	<i>Deltolepis mitra</i>
Sten op	<i>Stenopteris</i>	D.ru go	<i>Dictyophyllum rugosum</i>
Todi te	<i>Todites</i>	E.be an	<i>Equisetum beani</i>
Torr ey	<i>Torreya</i>	E.col um	<i>Equisetum columnare</i>

Key, continued.

Abbreviation	Species
E.la te	<i>Equisetum laterale</i>
E.la xu	<i>Elatocladus laxis</i>
E.lo bi	<i>Eboracia lobifolia</i>
E.pu be	<i>Eretmophyllum pubescens</i>
E.ra mo	<i>Elatocladus ramosus</i>
E.se to	<i>Elatocladus setosus</i>
E.si de	<i>Elatocladus sideriticus</i>
E.sp .A	<i>Equisetum sp. A</i>
E.th om	<i>Elatides thomasi</i>
E.wh it	<i>Eretmophyllum whitbiensis</i>
E.wi ll	<i>Elatides williamsonii</i>
E.za mi	<i>Elatocladus zamioides</i>
G.di gi	<i>Ginkgo digitata</i>
G.di va	<i>Geinitzia divaricata</i>
G.hu tt	<i>Ginkgo huttoni</i>
G.lo ng	<i>Ginkgo longifolia</i>
G.ri gi	<i>Ginkgo rigida</i>
G.si bi	<i>Ginkgo sp. cf. sibirica</i>
G.wh it	<i>Ginkgo whitbiensis</i>
H.di ch	<i>Hausmannia dichotoma</i>
K.ar gu	<i>Kylikipteris arguta</i>
K.ex il	<i>Klukia exilis</i>
L.la nc	<i>Lindleycladus lanceolatus</i>
M.an gl	<i>Marattia anglica</i>
M.ge op	<i>Matonidium goepperti</i>
M.ju ra	<i>Marskea jurassica</i>
N.co mp	<i>Nilssonia compta</i>
N.ke nd	<i>Nilssonia kendalli</i>
N.ma jo	<i>Nilssoniopteris major</i>
N.pr is	<i>Nilssoniopteris pristis</i>
N.re vo	<i>Nilssonia revoluta</i>
N.sp .A	<i>Nilssonia sp. A</i>
N.sp .B	<i>Nilssonia sp. B</i>
N.sy ll	<i>Nilssonia syllis</i>
N.te nu	<i>Nilssonia tenuicaulis</i>
N.te nu	<i>Nilssonia tenuinervis</i>
N.th om	<i>Nilssonia thomasi</i>
N.vi tt	<i>Nilssoniopteris vittata</i>
O.an gl	<i>Otozamites anglica</i>
O.be an	<i>Otozamites beani</i>
O.fa ls	<i>Otozamites falsus</i>
O.gr am	<i>Otozamites gramineus</i>
O.gr ap	<i>Otozamites graphicus</i>
O.le ck	<i>Otozamites leckenbyi</i>
O.ma rg	<i>Otozamites marginatus</i>
O.mi me	<i>Otozamites mimetes</i>
O.pa ra	<i>Otozamites parallelus</i>
O.pe nn	<i>Otozamites penna</i>
O.si mp	<i>Otozamites simpsoni</i>
O.st ur	<i>Osmundopsis sturii</i>
O.te nu	<i>Otozamites tenuatus</i>
O.th om	<i>Otozamites thomasi</i>
O.ve no	<i>Otozamites venosus</i>
P.ct ei	<i>Paracycas cteis</i>
P.cy ca	<i>Pterophyllum cycadites</i>

Abbreviation	Species
P.du nk	<i>Phlebopteris dunkeri</i>
P.fo ss	<i>Pterophyllum fossum</i>
P.fr ag	<i>Pagiophyllum fragilis</i>
P.ha ll	<i>Poteridion hallei</i>
P.he rr	<i>Pseudoctenis herriesi</i>
P.hi rs	<i>Ptilophyllum hirsutum</i>
P.in si	<i>Pagiophyllum insigne</i>
P.ku rr	<i>Pagiophyllum kurrii</i>
P.la nc	<i>Pseudoctenis lanei</i>
P.la ne	<i>Pseudoctenis lanei</i>
P.locu	<i>Pseudoctenis locusta</i>
P.ma cu	<i>Pagiophyllum maculosum</i>
P.ol eo	<i>Pseudoctenis oleosa</i>
P.or di	<i>Pagiophyllum ordinatum</i>
P.pa pi	<i>Pachypteris papillosa</i>
P.pe ct	<i>Ptilophyllum pectinoides</i>
P.pe ct	<i>Ptilophyllum pecten</i>
P.po ly	<i>Phlebopteris polypodioides</i>
P.sc ar	<i>Pityocladus scarburgensis</i>
P.sp .A	<i>Pseudoctenis sp. A</i>
P.sp .B	<i>Pseudoctenis sp. B</i>
P.th om	<i>Pterophyllum thomasi</i>
P.ti bi	<i>Pseudotorellia tibia</i>
S.co lo	<i>Sagenopteris colopodes</i>
S.gy ro	<i>Sphenobaiera gyron</i>
S.lo ng	<i>Sphenobaiera longifolia</i>
S.mu ir	<i>Sphenarion muiriae</i>
S.na na	<i>Stenopteris nana</i>
S.ni ti	<i>Stenopteris nitida</i>
S.op hi	<i>Sphenobaiera ophioglossum</i>
S.pe ct	<i>Sphenobaiera pecten</i>
S.ph il	<i>Sagenopteris philipsi</i>
S.sp ic	<i>Stachypteris spicans</i>
S.vi mi	<i>Solenites vimineus</i>
S.wi ll	<i>Stenopteris williamsonis</i>
T.de nt	<i>Todites denticulata</i>
T.gr ac	<i>Torreya gracilis</i>
T.th om	<i>Todites thomasi</i>
T.va li	<i>Torreya valida</i>
Z.gi ga	<i>Zamites gigas</i>
Z.qu in	<i>Zamites quinae</i>

A total of:
57 genera
158 species

Table 4.3 Yorkshire plant genera: presence/absence

Species Scores (ordered by axis 1)
Includes key to Fig. 5.2, Chapter 5

AXIS	1	2	3	4	No. of occurrences	Key
EIGEN VALUE % VARIANCE	0.276 33.1	0.165 52.9	0.114 66.5	0.077 75.8		
Angi op	-1.250	0.637	0.795	-0.619	1	1
Dicy oz	-1.250	0.637	0.795	-0.619	1	1
Haib ur	-1.250	0.637	0.795	-0.619	1	1
Haus ma	-1.250	0.637	0.795	-0.619	1	1
Mara tt	-1.250	0.637	0.795	-0.619	1	1
Mars ke	-1.250	0.637	0.795	-0.619	1	1
Para cy	-1.250	0.637	0.795	-0.619	1	1
Pote ri	-1.250	0.637	0.795	-0.619	1	1
Sewa rd	-1.250	0.637	0.795	-0.619	1	1
Clat ho	-0.814	0.307	0.021	-0.110	2	2
Desm io	-0.814	0.307	0.021	-0.110	2	2
Lind le	-0.814	0.307	0.021	-0.110	2	2
Stac hy	-0.814	0.307	0.021	-0.110	2	2
Torr ey	-0.814	0.307	0.021	-0.110	2	2
Aspi di	-0.750	0.146	0.137	0.387	2	3
Delt ol	-0.750	0.146	0.137	0.387	2	3
Dick so	-0.750	0.146	0.137	0.387	2	3
Osmu nd	-0.750	0.146	0.137	0.387	2	3
Clad op	-0.626	0.090	-0.160	0.391	3	4
Kluk ia	-0.626	0.090	-0.160	0.391	3	4
Kyli ki	-0.626	0.090	-0.160	0.391	3	4
Sphe no	-0.626	0.090	-0.160	0.391	3	4
Sphe no	-0.626	0.090	-0.160	0.391	3	4
Cyca do	-0.343	0.013	-0.432	0.223	4	5
Dict yo	-0.343	0.013	-0.432	0.223	4	5
Elat oc	-0.343	0.013	-0.432	0.223	4	5
Equi se	-0.343	0.013	-0.432	0.223	4	5
Sole ni	-0.343	0.013	-0.432	0.223	4	5
Pseu dt	-0.253	-0.394	0.543	-0.114	3	6
Ebor ac	-0.252	-0.382	0.277	0.263	4	7
Pseu do	-0.252	-0.382	0.277	0.263	4	7
Elat id	-0.210	-0.502	0.620	0.218	3	8
Eret mo	-0.100	-0.349	-0.028	0.154	5	9
Nils on	-0.100	-0.349	-0.028	0.154	5	9
Pter op	-0.100	-0.349	-0.028	0.154	5	9
Anom oz	0.043	0.317	-0.567	-0.211	5	10
Ptil op	0.043	0.317	-0.567	-0.211	5	10
Baie ra	0.119	-0.328	-0.063	-0.093	6	11
Coni op	0.119	-0.328	-0.063	-0.093	6	11
Cten is	0.119	-0.328	-0.063	-0.093	6	11
Czek an	0.119	-0.328	-0.063	-0.093	6	11
Nils so	0.119	-0.328	-0.063	-0.093	6	11
Phle bo	0.119	-0.328	-0.063	-0.093	6	11
Sten op	0.119	-0.328	-0.063	-0.093	6	11
Todi te	0.119	-0.328	-0.063	-0.093	6	11
Cypa ri	0.311	-1.071	0.533	0.636	2	12
Bils da	0.329	-0.062	-0.212	-0.357	7	13
Gink go	0.329	-0.062	-0.212	-0.357	7	13
Otoz am	0.329	-0.062	-0.212	-0.357	7	13
Pach yp	0.329	-0.062	-0.212	-0.357	7	13
Cten oz	0.458	0.109	0.169	0.081	7	14
Gein it	0.599	0.287	0.010	-0.173	8	15
Zami te	0.599	0.287	0.010	-0.173	8	15
Pity oc	0.871	-1.796	1.588	-0.120	1	16
Sphe na	0.871	-1.796	1.588	-0.120	1	16
Brac hy	0.891	0.784	0.350	0.348	9	17
Pagi op	0.891	0.784	0.350	0.348	9	17

Yorkshire plant genera

Sample Scores

AXIS	1.000	2.000	3.000	4.000	No. of occurrences
EIGEN VALUE	0.276	0.165	0.114	0.077	
lower Saltwick	-1.250	0.637	0.795	-0.619	54
upper Saltwick	-0.378	-0.022	-0.753	0.399	40
Gristhorpe	-0.249	-0.346	-0.522	1.393	40
Sycarham	0.507	-0.219	-1.246	-0.281	27
upper Scalby	0.871	-1.796	1.588	-0.120	27
lower Scalby	1.215	-0.222	-0.237	-1.327	17
Lebberston	1.586	1.533	-1.107	-1.945	10
Eller Beck	2.489	2.732	1.560	1.119	5
Scarborough	3.225	4.755	3.072	4.516	2

Table 4.4 Yorkshire plant species: presence/absence

Species Scores (ordered by axis 1)
Includes key to Fig. 5.5, Chapter 5

AXIS	1	2	3	4	No. of occurrences	Key
EIGEN VALUE	0.395	0.287	0.221	0.155		
% VARIANCE	28.7	49.5	65.6	76.9		
A.bl ac	-0.937	0.741	0.140	0.249	1	1
M.an gl	-0.937	0.741	0.140	0.249	1	1
M.br au	-0.937	0.741	0.140	0.249	1	1
O.hi ll	-0.937	0.741	0.140	0.249	1	1
P.du nk	-0.937	0.741	0.140	0.249	1	1
H.di ch	-0.937	0.741	0.140	0.249	1	1
C.bu re	-0.937	0.741	0.140	0.249	1	1
D.ke nd	-0.937	0.741	0.140	0.249	1	1
C.ha rr	-0.937	0.741	0.140	0.249	1	1
N.sp .A	-0.937	0.741	0.140	0.249	1	1
N.ke nd	-0.937	0.741	0.140	0.249	1	1
D.mi tr	-0.937	0.741	0.140	0.249	1	1
P.ct ei	-0.937	0.741	0.140	0.249	1	1
P.sp .A	-0.937	0.741	0.140	0.249	1	1
O.le ck	-0.937	0.741	0.140	0.249	1	1
O.gr am	-0.937	0.741	0.140	0.249	1	1
A.th om	-0.937	0.741	0.140	0.249	1	1
D.ha we	-0.937	0.741	0.140	0.249	1	1
S.gy ro	-0.937	0.741	0.140	0.249	1	1
H.se to	-0.937	0.741	0.140	0.249	1	1
P.ha ll	-0.937	0.741	0.140	0.249	1	1
S.la xu	-0.937	0.741	0.140	0.249	1	1
C.ob ov	-0.797	0.529	0.250	-0.050	2	2
S.sp ic	-0.797	0.529	0.250	-0.050	2	2
C.ha ib	-0.797	0.529	0.250	-0.050	2	2
C.ak ta	-0.797	0.529	0.250	-0.050	2	2
N.th om	-0.797	0.529	0.250	-0.050	2	2
N.sy ll	-0.797	0.529	0.250	-0.050	2	2
P.he rr	-0.797	0.529	0.250	-0.050	2	2
P.sp .B	-0.797	0.529	0.250	-0.050	2	2
P.pa pi	-0.797	0.529	0.250	-0.050	2	2
Z.qu in	-0.797	0.529	0.250	-0.050	2	2
O.pa ra	-0.797	0.529	0.250	-0.050	2	2
O.si mp	-0.797	0.529	0.250	-0.050	2	2
O.an gl	-0.797	0.529	0.250	-0.050	2	2
O.fa ls	-0.797	0.529	0.250	-0.050	2	2
O.te nu	-0.797	0.529	0.250	-0.050	2	2
P.hi rs	-0.797	0.529	0.250	-0.050	2	2
C.sp he	-0.797	0.529	0.250	-0.050	2	2
C.th ys	-0.797	0.529	0.250	-0.050	2	2
G.si bi	-0.797	0.529	0.250	-0.050	2	2
S.lo ng	-0.797	0.529	0.250	-0.050	2	2
S.op hi	-0.797	0.529	0.250	-0.050	2	2
C.sp .B	-0.797	0.529	0.250	-0.050	2	2
C.sp .C	-0.797	0.529	0.250	-0.050	2	2
C.sp .D	-0.797	0.529	0.250	-0.050	2	2
D.gr am	-0.797	0.529	0.250	-0.050	2	2
M.ju ra	-0.797	0.529	0.250	-0.050	2	2
T.gr ac	-0.797	0.529	0.250	-0.050	2	2
L.la nc	-0.797	0.529	0.250	-0.050	2	2
C.pe le	-0.656	0.317	0.359	-0.350	1	3
K.ex il	-0.565	-0.127	-0.241	0.254	3	4
C.mu rr	-0.565	-0.127	-0.241	0.254	3	4
K.ar gu	-0.565	-0.127	-0.241	0.254	3	4
S.co lp	-0.565	-0.127	-0.241	0.254	3	4

S.ph il	-0.565	-0.127	-0.241	0.254	3	4
N.co mp	-0.565	-0.127	-0.241	0.254	3	4
P.la ne	-0.565	-0.127	-0.241	0.254	3	4
C.su lc	-0.565	-0.127	-0.241	0.254	3	4
C.re ed	-0.565	-0.127	-0.241	0.254	3	4
P.fo ss	-0.565	-0.127	-0.241	0.254	3	4
G.di gi	-0.565	-0.127	-0.241	0.254	3	4
S.pe ct	-0.565	-0.127	-0.241	0.254	3	4
C.th om	-0.565	-0.127	-0.241	0.254	3	4
E.la xu	-0.565	-0.127	-0.241	0.254	3	4
D.ma ri	-0.520	-0.349	-0.541	0.555	2	5
A.th om	-0.520	-0.349	-0.541	0.555	2	5
C.de nt	-0.520	-0.349	-0.541	0.555	2	5
N.te nu	-0.520	-0.349	-0.541	0.555	2	5
N.ma jo	-0.520	-0.349	-0.541	0.555	2	5
G.lo ng	-0.520	-0.349	-0.541	0.555	2	5
G.wh it	-0.520	-0.349	-0.541	0.555	2	5
E.wi ll	-0.520	-0.349	-0.541	0.555	2	5
C.hy pe	-0.404	-0.078	0.375	-0.806	3	6
B.ar de	-0.404	-0.078	0.375	-0.806	3	6
E.co lu	-0.328	-0.418	-0.025	-0.389	4	7
E.la te	-0.328	-0.418	-0.025	-0.389	4	7
E.sp .A	-0.328	-0.418	-0.025	-0.389	4	7
D.ru go	-0.328	-0.418	-0.025	-0.389	4	7
C.si mp	-0.328	-0.418	-0.025	-0.389	4	7
N.sp .B	-0.328	-0.418	-0.025	-0.389	4	7
C.ka ne	-0.328	-0.418	-0.025	-0.389	4	7
P.pe ct	-0.328	-0.418	-0.025	-0.389	4	7
E.pu be	-0.328	-0.418	-0.025	-0.389	4	7
S.vi mi	-0.328	-0.418	-0.025	-0.389	4	7
C.fu rc	-0.328	-0.418	-0.025	-0.389	4	7
G.di va	-0.328	-0.418	-0.025	-0.389	4	7
E.se to	-0.328	-0.418	-0.025	-0.389	4	7
E.ra mo	-0.277	-0.276	0.383	-1.034	2	8
O.mi me	-0.126	-0.804	-0.079	-0.602	3	9
T.th om	-0.103	-1.438	-1.223	0.861	1	10
O.st ur	-0.103	-1.438	-1.223	0.861	1	10
C.ma rg	-0.103	-1.438	-1.223	0.861	1	10
D.cr ep	-0.103	-1.438	-1.223	0.861	1	10
P.lo cu	-0.103	-1.438	-1.223	0.861	1	10
S.ni ti	-0.103	-1.438	-1.223	0.861	1	10
C.ha ll	-0.103	-1.438	-1.223	0.861	1	10
C.st en	-0.103	-1.438	-1.223	0.861	1	10
C.ni te	-0.103	-1.438	-1.223	0.861	1	10
C.mi cr	-0.103	-1.438	-1.223	0.861	1	10
C.ru dl	-0.103	-1.438	-1.223	0.861	1	10
E.za mi	-0.103	-1.438	-1.223	0.861	1	10
P.pe ct	-0.001	-0.463	0.444	-0.042	5	11
A.ni ls	-0.001	-0.463	0.444	-0.042	5	11
E.lo bi	0.046	0.277	-0.502	0.124	4	12
E.wh it	0.046	0.277	-0.502	0.124	4	12
S.na na	0.096	0.849	-0.262	-0.122	3	13
O.ma rg	0.096	0.849	-0.262	-0.122	3	13
P.ti bi	0.096	0.849	-0.262	-0.122	3	13
N.te nu	0.113	-0.036	-0.277	-0.364	5	14
P.th om	0.113	-0.036	-0.277	-0.364	5	14
E.fi lu	0.140	-1.365	-0.299	-0.728	2	15
P.po ly	0.140	-1.365	-0.299	-0.728	2	15
N.pr is	0.140	-1.365	-0.299	-0.728	2	15
P.in si	0.140	-1.365	-0.299	-0.728	2	15
P.wo od	0.343	0.249	-0.275	0.120	5	16
C.be ll	0.343	0.249	-0.275	0.120	5	16
C.hy me	0.343	0.249	-0.275	0.120	5	16
N.vi tt	0.343	0.249	-0.275	0.120	5	16
E.be an	0.350	-0.008	-0.125	-0.286	6	17

T.de nt	0.350	-0.008	-0.125	-0.286	6	17
C.le ck	0.350	-0.008	-0.125	-0.286	6	17
S.wi ll	0.350	-0.008	-0.125	-0.286	6	17
O.gr ap	0.350	-0.008	-0.125	-0.286	6	17
B.fu rc	0.350	-0.008	-0.125	-0.286	6	17
B.cr uc	0.350	-0.008	-0.125	-0.286	6	17
C.er ip	0.382	-1.292	0.625	-2.316	1	18
E.si de	0.382	-1.292	0.625	-2.316	1	18
P.ol eo	0.472	1.116	-0.573	-0.008	2	19
C.cy ca	0.472	1.116	-0.573	-0.008	2	19
C.bl ac	0.472	1.116	-0.573	-0.008	2	19
E.th om	0.472	1.116	-0.573	-0.008	2	19
P.la nc	0.487	-0.098	0.224	-0.053	7	20
O.be an	0.487	-0.098	0.224	-0.053	7	20
G.hu tt	0.487	-0.098	0.224	-0.053	7	20
B.du ra	0.487	-0.098	0.224	-0.053	7	20
O.pe nna	0.504	0.101	0.157	0.324	6	21
C.me ga	0.543	-0.090	0.323	0.075	7	22
P.fr ag	0.543	-0.090	0.323	0.075	7	22
Z.gi ga	0.639	-0.159	0.573	0.234	8	23
G.ri gi	0.639	-0.159	0.573	0.234	8	23
P.or di	0.664	-0.179	0.701	0.400	8	24
B.ma mi	0.779	-0.223	0.958	0.605	9	25
P.ku rr	0.779	-0.223	0.958	0.605	9	25
P.ma cu	0.779	-0.223	0.958	0.605	9	25
P.cy ca	0.889	0.026	-1.254	0.298	2	26
T.va li	0.889	0.026	-1.254	0.298	2	26
C.ex il	1.264	0.111	-0.009	-0.826	3	27
C.st ew	1.705	0.812	-0.326	-0.081	2	28
C.sp .A	1.705	0.812	-0.326	-0.081	2	28
N.re vo	1.880	1.491	-1.285	-0.265	1	29
C.sp .A	1.880	1.491	-1.285	-0.265	1	29
O.th om	1.880	1.491	-1.285	-0.265	1	29
O.ve no	1.880	1.491	-1.285	-0.265	1	29
C.sp .E	1.880	1.491	-1.285	-0.265	1	29
S.mu ir	1.880	1.491	-1.285	-0.265	1	29
C.bl ac	1.880	1.491	-1.285	-0.265	1	29
P.sc ar	1.880	1.491	-1.285	-0.265	1	29

Yorkshire plant species
Sample Scores

AXIS	1	2	3	4	No. of occurrences
EIGEN VALUE	0.395	0.287	0.221	0.155	
lower Saltwick	-0.9365	0.7406	0.1399	0.2493	125
upper Saltwick	-0.6564	0.3167	0.3591	-0.3496	92
Gristhorpe	-0.1028	-1.4382	-1.2227	0.8611	84
Sycarham	0.3824	-1.2918	0.6253	-2.3164	47
Lebberston	1.3112	-0.6398	2.3160	1.3455	13
lower Scalby	1.5303	0.1338	0.6334	0.1030	27
Eller Beck	1.7006	-0.5819	3.0139	2.2429	7
upper Scalby	1.8803	1.4908	-1.2850	-0.2650	48
Scarborough	1.9000	-0.7402	4.0410	3.5743	4

Table 4.5 Selected plant beds: presence/absence

Species Scores (ordered by axis 1)
Includes key to Fig. 5.7, Chapter 5

AXIS	1	2	3	4	No. of occurrences	Key
EIGEN VALUE	0.734	0.649	0.569	0.542		
% VARIANCE	15.5	29.2	41.3	52.7		
Mara tt	-0.898	-0.805	-0.319	-1.393	1	1
Angi op	-0.898	-0.805	-0.319	-1.393	1	1
Sele no	-0.898	-0.805	-0.319	-1.393	1	1
Para cy	-0.898	-0.805	-0.319	-1.393	1	1
Mars ke	-0.898	-0.805	-0.319	-1.393	1	1
Osmu no	-0.706	-0.276	-0.555	-0.551	2	2
Dick so	-0.706	-0.276	-0.555	-0.551	2	2
Cten oz	-0.706	-0.276	-0.555	-0.551	2	2
Elat id	-0.706	-0.276	-0.555	-0.551	2	2
Bils da	-0.706	-0.276	-0.555	-0.551	2	2
Dict yo	-0.527	-0.260	-0.507	-0.074	3	4
Asph id	-0.514	0.253	-0.791	0.292	1	5
Pseu do	-0.459	-0.141	-0.032	-0.505	3	6
Eret mo	-0.459	-0.141	-0.032	-0.505	3	6
Elat oc	-0.439	-0.126	-0.100	-0.053	3	7
Sole ni	-0.423	-0.585	0.609	0.269	4	8
Sage no	-0.387	-0.223	-0.042	0.096	4	9
Cten is	-0.387	-0.223	-0.042	0.096	4	9
Nils so	-0.386	-0.163	-0.127	-0.159	4	9
Sten op	-0.341	0.012	-0.601	0.585	2	10
Cyca do	-0.271	0.240	-0.078	-0.183	5	11
Clat ho	-0.256	-0.167	0.502	-0.287	3	12
Pach yp	-0.256	-0.167	0.502	-0.287	3	12
Sphe no	-0.256	-0.167	0.502	-0.287	3	12
Phle bo	-0.237	-0.098	0.276	0.153	6	13
Mato ni	-0.210	0.214	0.010	0.618	2	14
Todi te	-0.196	0.067	-0.130	0.705	3	15
Kluk ia	-0.196	0.067	-0.130	0.705	3	15
Pter op	-0.196	0.067	-0.130	0.705	3	15
Ebor ac	-0.129	0.106	0.457	0.614	3	16
Equi se	-0.108	0.022	-0.152	0.496	8	17
Mato nd	-0.096	0.745	0.114	-0.133	3	18
Delt ol	-0.075	-0.420	-1.889	1.809	2	19
Baie ra	0.012	-0.342	1.783	0.609	4	20
Stac hy	0.035	0.129	1.014	-0.412	1	21
Clad op	0.071	0.812	0.430	-0.246	6	22
Lind le	0.094	0.175	0.811	0.944	1	23
Gein it	0.187	1.478	-0.064	0.004	4	24
Anom oz	0.230	1.942	-0.593	-0.325	2	25
Pagi op	0.230	1.942	-0.593	-0.325	2	25
Coni op	0.271	0.005	0.157	-0.026	8	26
Czek an	0.282	-0.260	0.163	0.010	7	27
Gink go	0.290	-0.450	0.786	0.070	7	28
Otoz am	0.330	-0.400	-0.457	0.399	7	29
Nils so	0.379	-0.488	-0.702	0.534	6	30
Ptil op	0.431	0.515	-0.186	-0.386	7	31
Brac hy	0.445	0.292	0.165	-0.250	7	32
Zami te	0.866	0.495	0.101	-0.075	5	33
Sphe na	3.395	-1.228	-0.516	-0.847	1	34
Cypa ri	3.395	-1.228	-0.516	-0.847	1	34
Pity oc	3.395	-1.228	-0.516	-0.847	1	34

Species Scores (ordered by axis 2)
Includes key to plot of axis 2:3

AXIS	1	2	3	4	Key
Sphe na	3.395	-1.228	-0.516	-0.847	1
Cypa ri	3.395	-1.228	-0.516	-0.847	1
Pity oc	3.395	-1.228	-0.516	-0.847	1
Mara tt	-0.898	-0.805	-0.319	-1.393	2
Angi op	-0.898	-0.805	-0.319	-1.393	2
Sele no	-0.898	-0.805	-0.319	-1.393	2
Para cy	-0.898	-0.805	-0.319	-1.393	2
Mars ke	-0.898	-0.805	-0.319	-1.393	2
Sole ni	-0.423	-0.585	0.609	0.269	3
Nils so	0.379	-0.488	-0.702	0.534	4
Gink go	0.290	-0.450	0.786	0.070	5
Delt ol	-0.075	-0.420	-1.889	1.809	6
Otoz am	0.330	-0.400	-0.457	0.399	7
Baie ra	0.012	-0.342	1.783	0.609	8
Osmu no	-0.706	-0.276	-0.555	-0.551	9
Dick so	-0.706	-0.276	-0.555	-0.551	9
Cten oz	-0.706	-0.276	-0.555	-0.551	9
Elat id	-0.706	-0.276	-0.555	-0.551	9
Bils da	-0.706	-0.276	-0.555	-0.551	9
Dict yo	-0.527	-0.260	-0.507	-0.074	10
Czek an	0.282	-0.260	0.163	0.010	11
Sage no	-0.387	-0.223	-0.042	0.096	12
Cten is	-0.387	-0.223	-0.042	0.096	12
Clat ho	-0.256	-0.167	0.502	-0.287	13
Pach yp	-0.256	-0.167	0.502	-0.287	13
Sphe no	-0.256	-0.167	0.502	-0.287	13
Nils so	-0.386	-0.163	-0.127	-0.159	14
Pseu do	-0.459	-0.141	-0.032	-0.505	15
Eret mo	-0.459	-0.141	-0.032	-0.505	15
Elat oc	-0.439	-0.126	-0.100	-0.053	16
Phle bo	-0.237	-0.098	0.276	0.153	17
Coni op	0.271	0.005	0.157	-0.026	18
Sten op	-0.341	0.012	-0.601	0.585	19
Equi se	-0.108	0.022	-0.152	0.496	20
Todi te	-0.196	0.067	-0.130	0.705	21
Kluk ia	-0.196	0.067	-0.130	0.705	21
Pter op	-0.196	0.067	-0.130	0.705	21
Ebor ac	-0.129	0.106	0.457	0.614	22
Stac hy	0.035	0.129	1.014	-0.412	23
Lind le	0.094	0.175	0.811	0.944	24
Mato ni	-0.210	0.214	0.010	0.618	25
Cyca do	-0.271	0.240	-0.078	-0.183	26
Asph id	-0.514	0.253	-0.791	0.292	27
Brac hy	0.445	0.292	0.165	-0.250	28
Zami te	0.866	0.495	0.101	-0.075	29
Ptil op	0.431	0.515	-0.186	-0.386	30
Mato nd	-0.096	0.745	0.114	-0.133	31
Clad op	0.071	0.812	0.430	-0.246	32
Gein it	0.187	1.478	-0.064	0.004	33
Anom oz	0.230	1.942	-0.593	-0.325	34
Pagi op	0.230	1.942	-0.593	-0.325	34

Yorkshire plant beds
Sample Scores

NAME	1	2	3	4	No. of occurrences
EIGEN VALUE	0.361	0.294	0.268	0.243	
Hasty Bank	-0.898	-0.805	-0.319	-1.393	18
Gristhorpe	-0.514	0.253	-0.791	0.292	11
Solenites Bed	-0.169	-0.229	-0.410	0.879	32
Ginkgoalean	-0.111	-1.560	3.954	1.299	4
Scalby Wyke	0.031	-0.111	1.351	0.605	20
Whitby	0.035	0.129	1.014	-0.412	11
Hayburn Wyke	0.094	0.175	0.811	0.944	35
at Iron Scar	0.192	1.853	0.118	-0.278	3
Nilssonina Bed	0.365	-1.093	-2.986	3.327	7
Millepore Bed	0.974	3.630	-0.395	-0.941	20
Scalby Ness	3.395	-1.228	-0.516	-0.847	7

Plant bed locations

Plant bed	Stratigraphic unit	Ammonite zone	Grid reference
Scalby Ness	Scalby Fm.	<i>discus</i>	TA 037 911
Scalby Wyke	Scalby Fm.	<i>discus</i>	TA 030 328
Gristhorpe	Gristhorpe Mb.	<i>laeviscula</i>	TA 081 844
Solenites Bed	Gristhorpe Mb.	<i>laeviscula</i>	TA 021 951
Nilssonina Bed	Gristhorpe Mb.	<i>laeviscula</i>	TA 021 954
Ginkgoalean	Gristhorpe Mb.	<i>laeviscula</i>	TA 081 844
Millepore Bed	Millepore Bed	<i>ovalis</i>	TA 021 956
at Iron Scar	Sycarham Mb.	<i>discites</i>	TA 015 968
Hayburn Wyke	Saltwick Fm.	<i>bradfordensis</i>	TA 013 969
Whitby	Saltwick Fm.	<i>bradfordensis</i>	NZ 905 114
Hasty Bank	Saltwick Fm.	<i>bradfordensis</i>	NZ 567 036

Appendix 5

Appendix 5

Plates showing a selection of the Yorkshire flora

A selection of the most common Yorkshire plant species are shown below. For a comprehensive catalogue of the Yorkshire flora see Harris (1961-1979).

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Fig. 5.1 *Equisetum columare* Brongniart (J.67963). From Hasty Bank.
Large rhizome showing slightly expanded node; the leaf sheath comprises 50-80 segments (linear leaflets) which appear to be pressed against the stem



Fig. 5.2 *Todites williamsoni* (Brongniart) (J.67964). From the Gristhorpe Plant Bed, Yons Nab.
Specimen shows portions of a large fertile leaf. Leaves of *T. williamsoni* can be wholly fertile or wholly sterile, but are of similar size and shape. This example displays fertile pinnules which are almost uniform in width up to the apex.



Fig. 5.3 *Coniopteris hymenophylloides* (Brongniart) Seward (J.67966). From the Gristhorpe Plant Bed, Yons Nab. Disarticulated pinnae which are linear lanceolate in shape, tapering steadily in the distal half.



Fig. 5.4 *C. hymenophylloides* and *Ptilophyllum pectinoides* (Phillips) (J.67967). From the Gristhorpe Plant Bed, Yons Nab. Pinnules of *C. hymenophylloides* are partly covered by those of *P. pectinoides*. No organic matter remains where *P. pectinoides* once occurred, but the counterpart can be seen clearly. Leaves of *P. pectinoides* are simply pinnate and attached to the upper side of the rachis.



Fig. 5.5 *P. pectinoides* (J. 67968). From Hasty Bank.
Lower part of a large leaf. Pinnae arise at an angle of approximately 60° from rachis, are straight, and taper towards the apex. The lower angle of the pinna is slightly expanded (decurrent).



Fig. 5.6 *Otozamites graphicus* (Leckenby) (J.67969). From Scalby Ness.
Shape of leaf is lanceolate as a whole and tapers at the apex. Pinna become shorter and narrower in the upper part

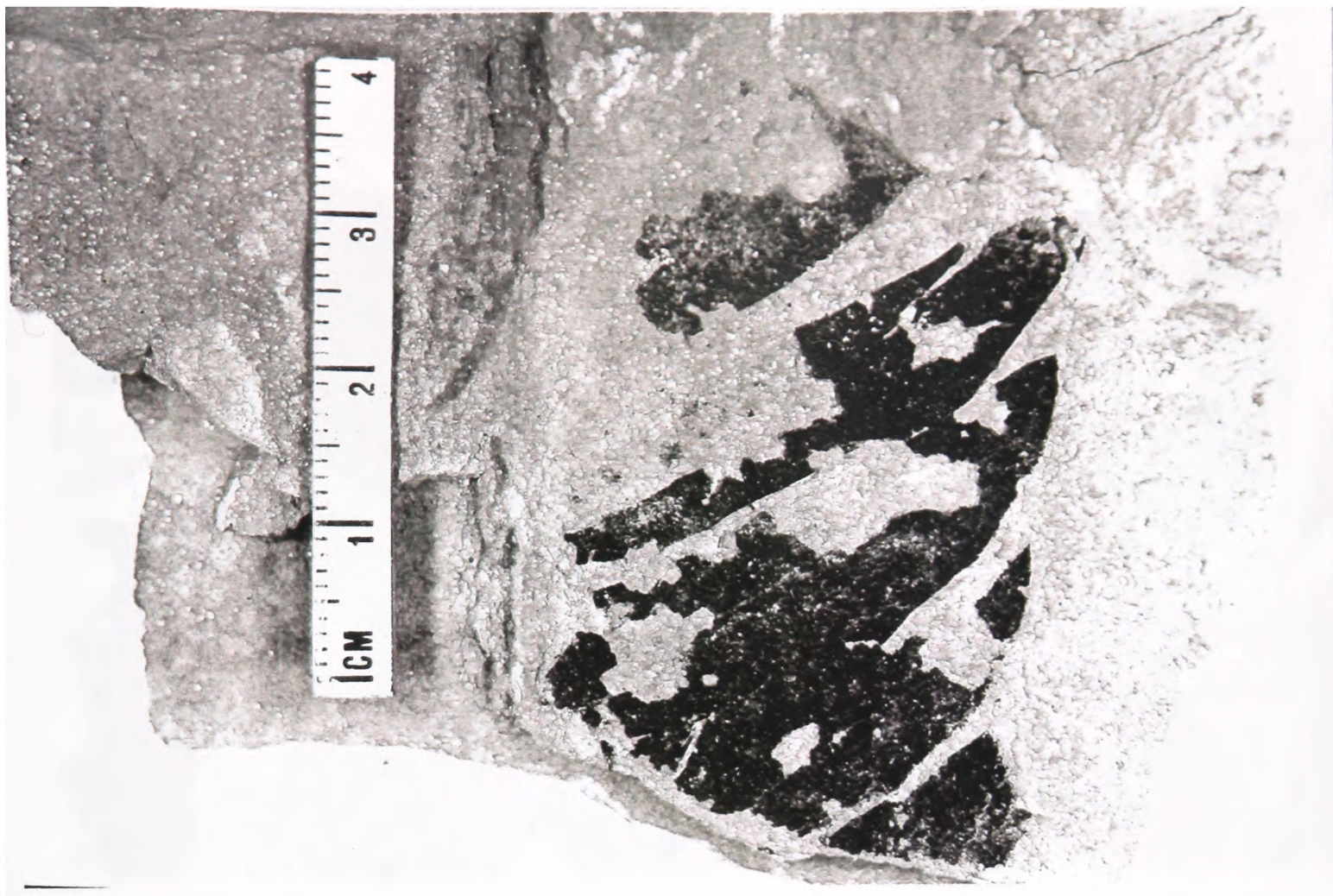


Fig. 5.7 *Zamites gigas* (Lindley & Hutton) (J.67970). From Scalby Ness.
One half of the leaf and the central rachis is not preserved. However, several pinnae can be seen of uniform length and breadth; they are typically straight, although they curve slightly towards the apex. The base of each pinnae appears symmetrical.

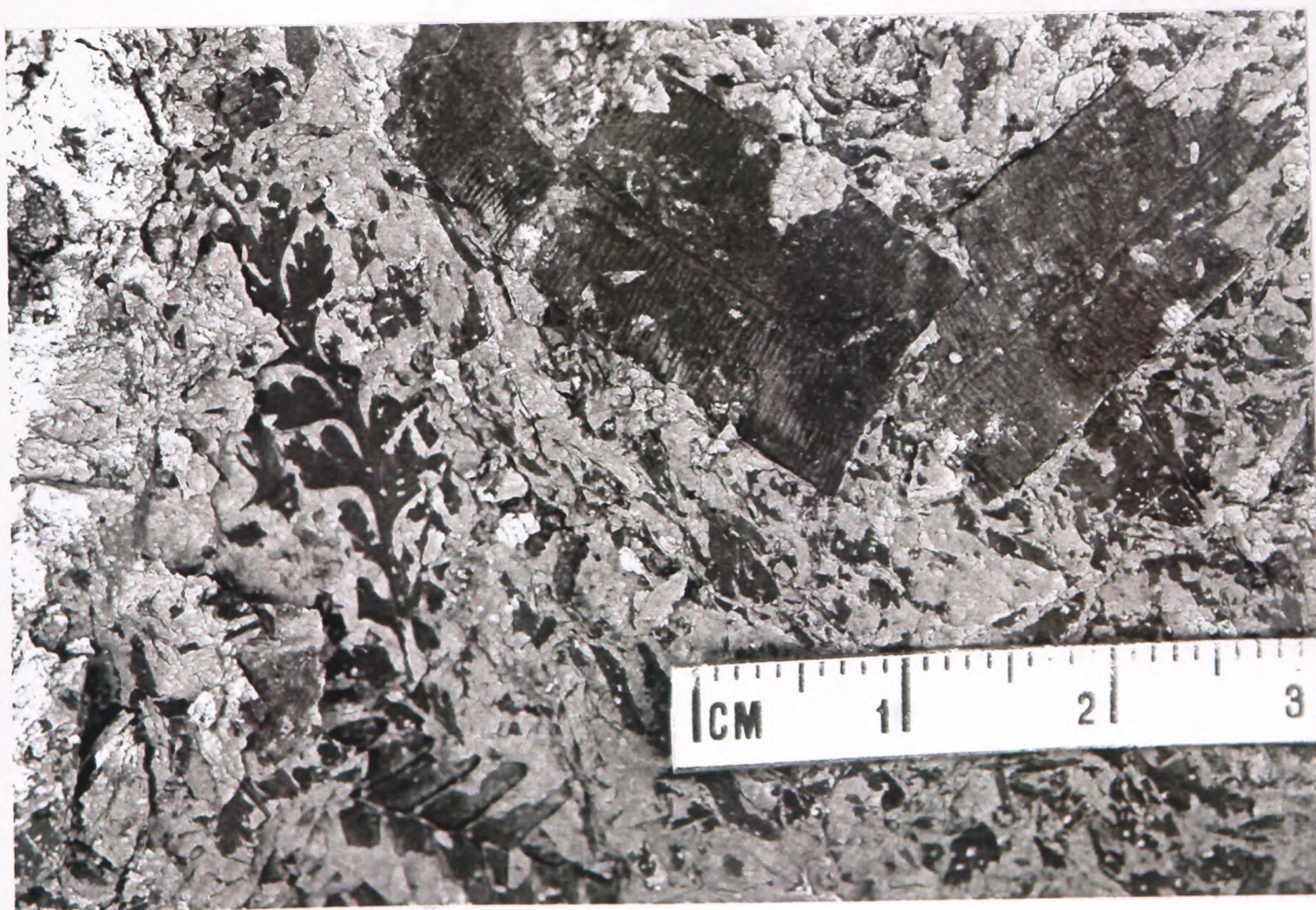


Fig. 5.8 *Nilssoniopteris vittata*, *P. pectinoides*, *C. hymenophylloides* (J.67972). From the Gristhorpe Plant Bed, Yons Nab.
Leaflets of *C. hymenophylloides* and *P. pectinoides* can be seen to the left of the photo; two broken pinnae of *N. vittata* to the right. The straight veins in *N. vittata* can be seen clearly in this example.

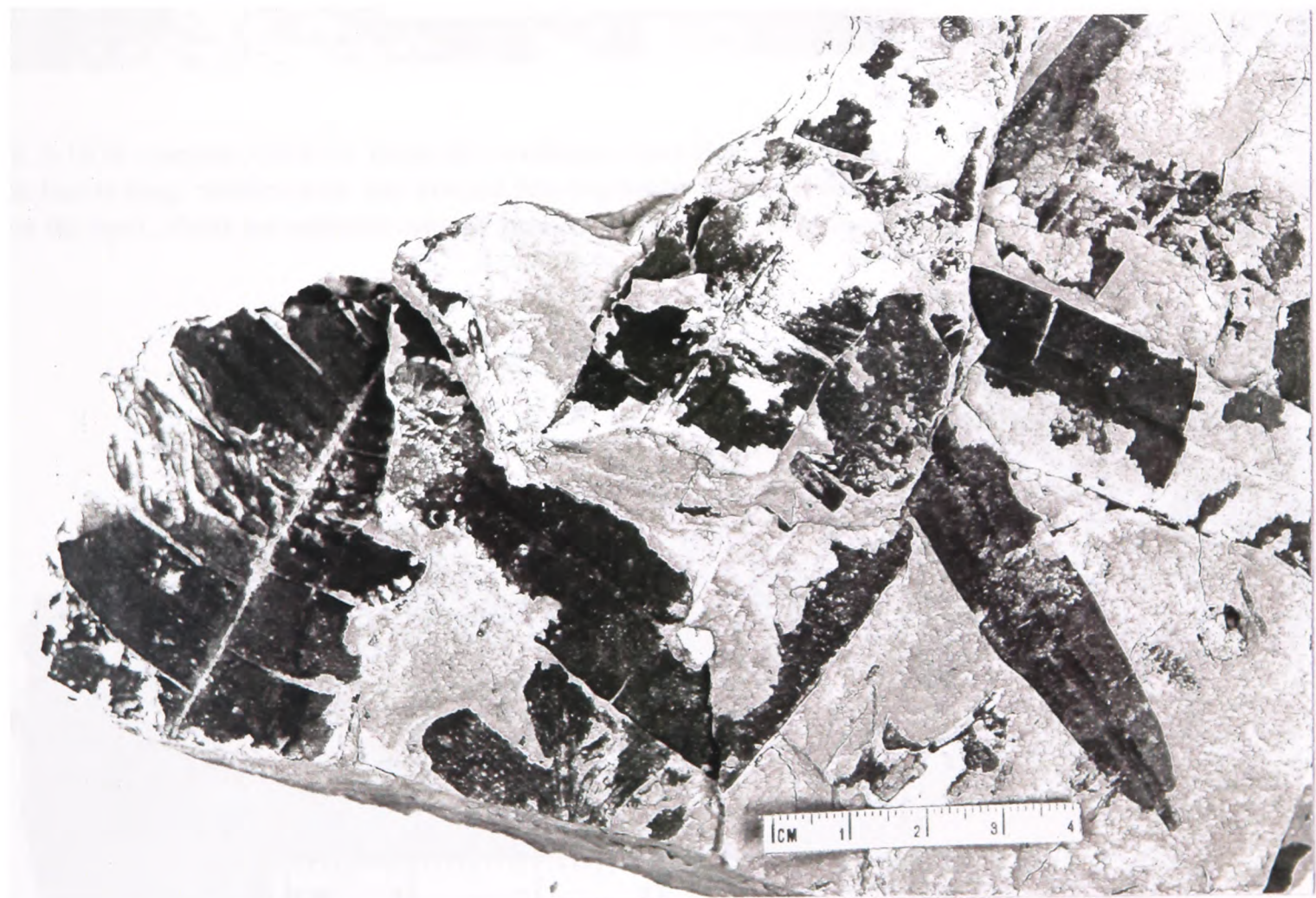
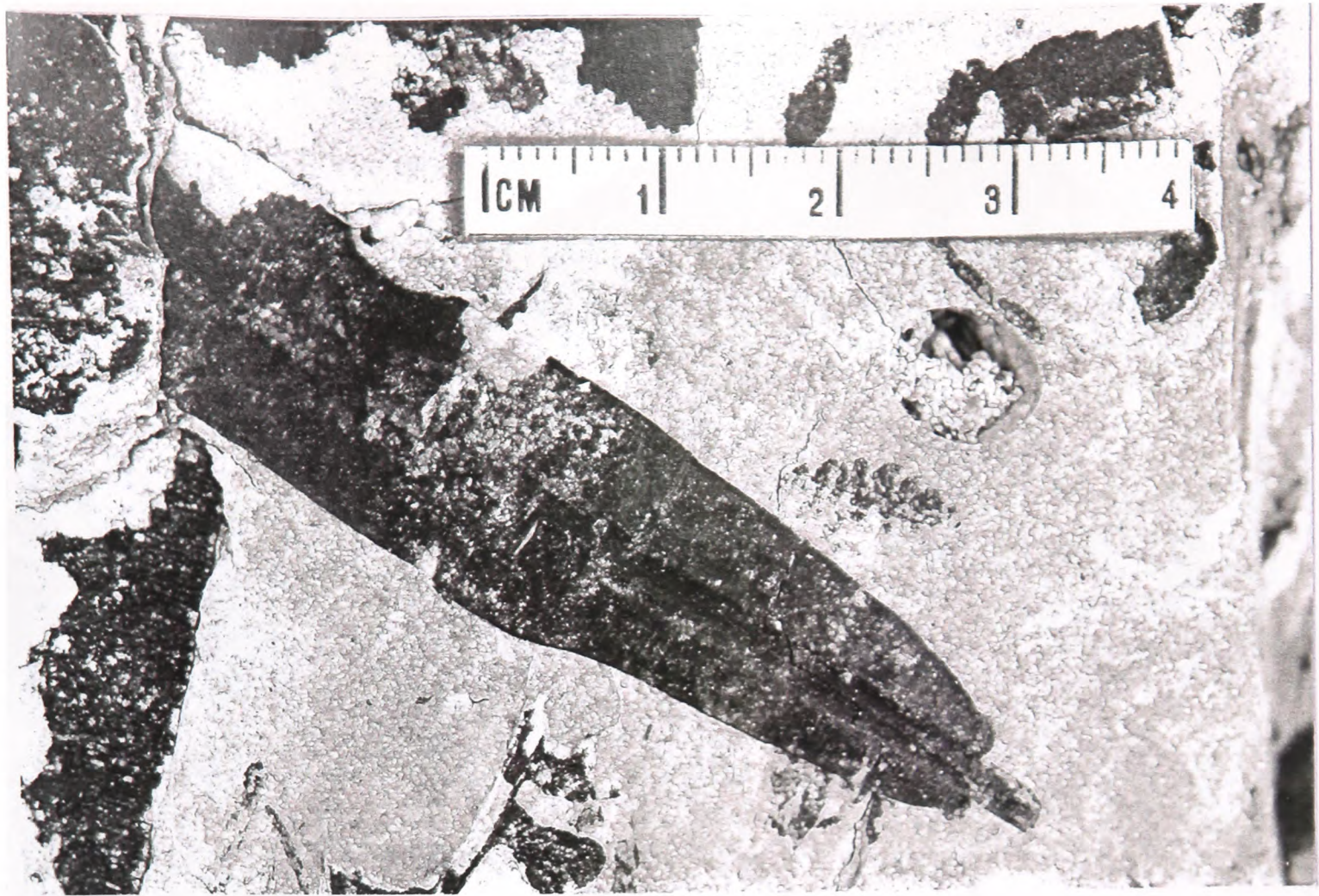


Fig. 5.9 *N. vittata*, *Nilsonia compta* (Philips) Brongniart, *Ctenis sulcicaulis* (Philips) Ward (J.67971a+b).
 From the Gristhorpe Plant Bed, Yons Nab.
a. This photograph shows *N. vittata* in close-up. The leaf is linear-lanceolate in shape, tapering in the basal portion. Veins are conspicuous and straight.
b. The entire specimen in which *N. vittata* shown above is contained. As well as *N. vittata*, the segmented leaf of *N. compta* is present and the basal portion of *C. sulcicaulis*.



Fig. 5.10 *N. compta* (J.67974). From the Gristhorpe Plant Bed, Yons Nab.
The leaf is long, oblanceolate, and divided into segments which are usually broader than long in the lower part, tapering near the apex. Veins are apparent running parallel to the lateral margins of the segments.



Fig. 5.11 *Nilsonia kendalli* Harris (J.67975). From Hasty Bank.
This species of *Nilsonia* displays triangular and rectangular shaped segments, which point towards the apex. Veins are fine and faintly marked, extend parallel to the side of the segments.

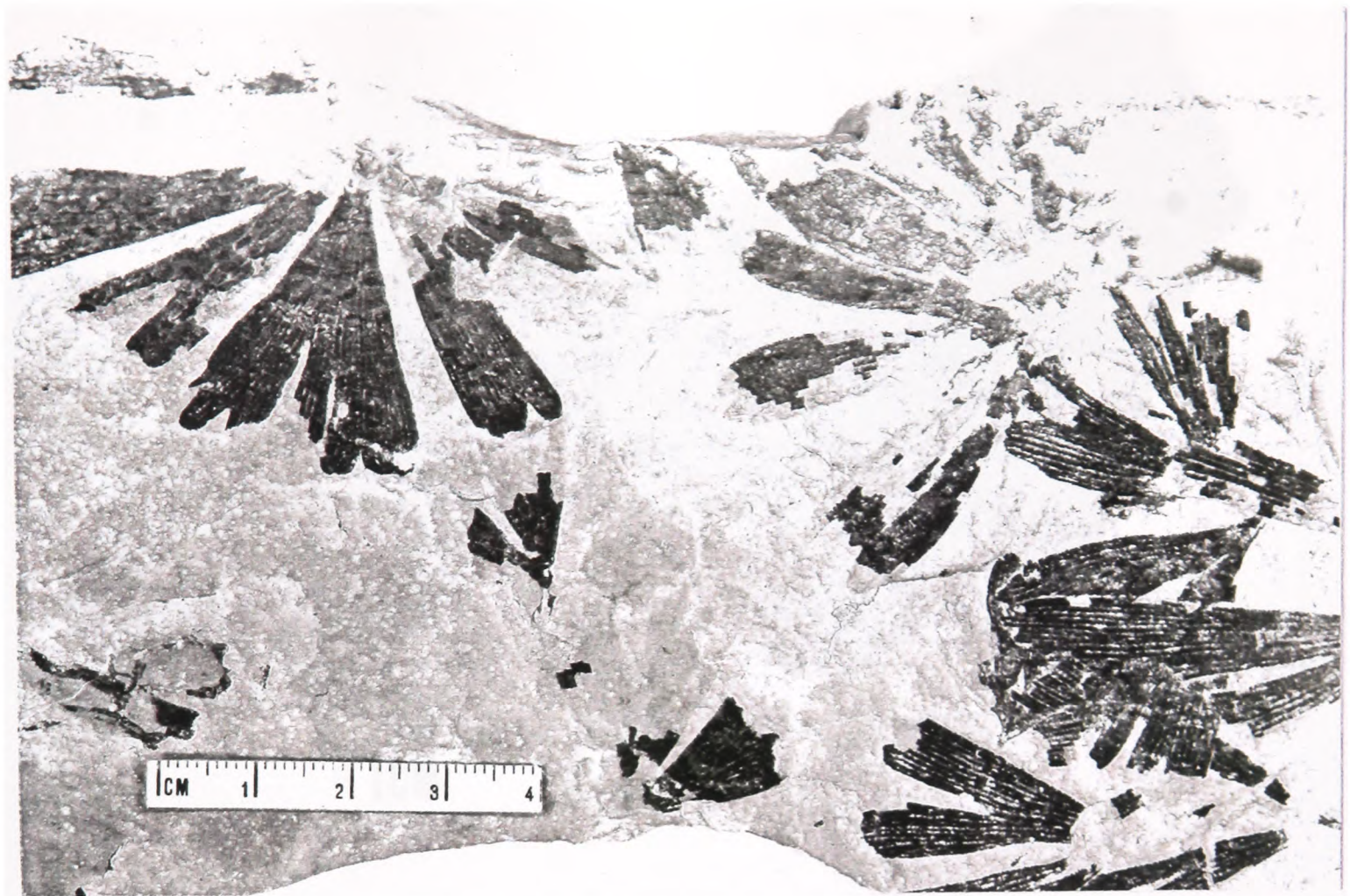


Fig. 5.12 *Ginkgo huttoni* (Sternberg) Heer (J.67977). From Scalby Ness.
Leaves typically divided into six lobes, the apices of which are rounded, truncate or notched.

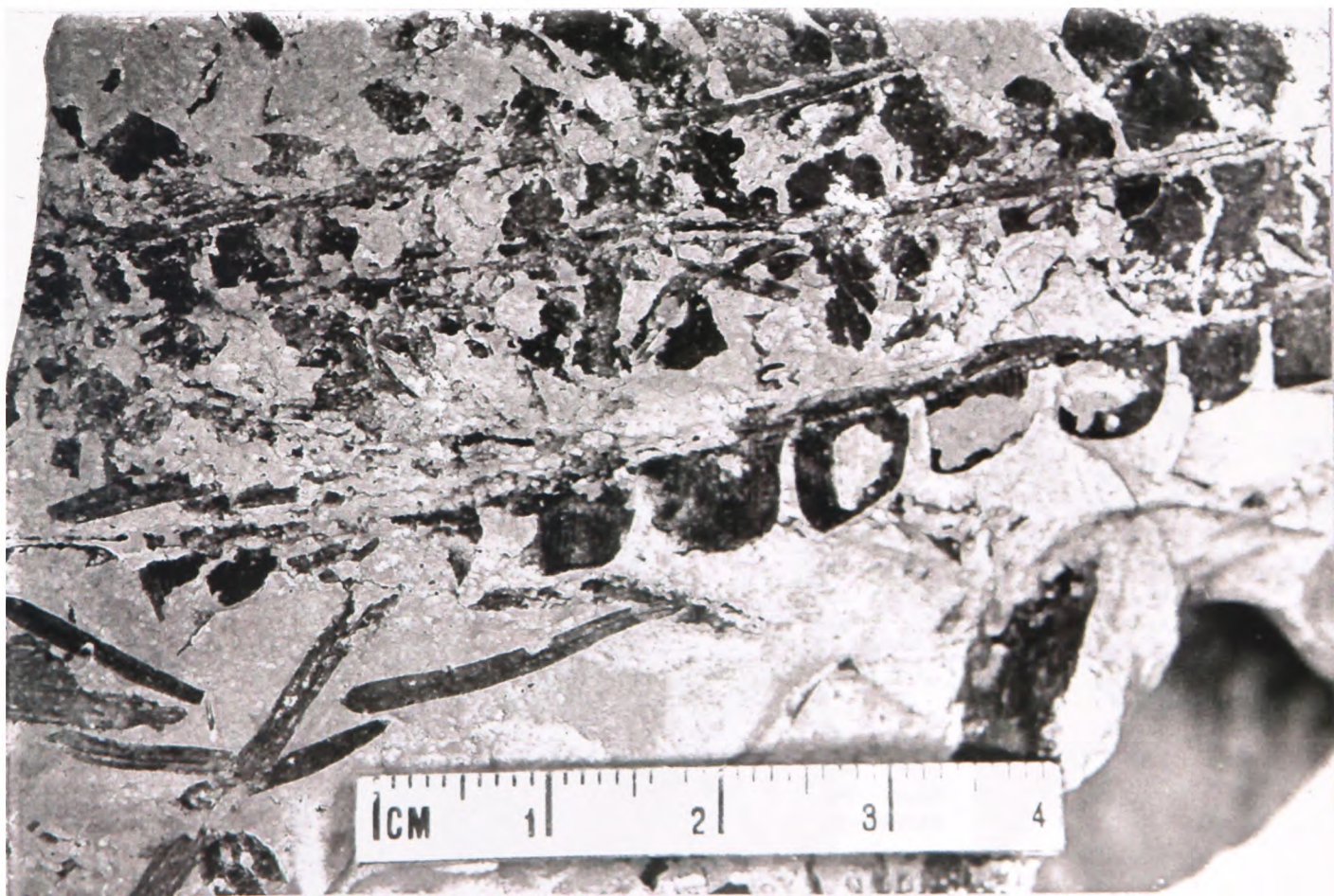


Fig. 5.13 *Solenites vimineus* (Phillips) Harris, *N. kendalli* (J.67978). From Hasty Bank.
Simple linear shoots of *S. vimineus* occur to be bottom left of the photograph. These are associated with leaves of *N. kendalli*, displaying rectangular pinnae pointing towards the apex.



Fig. 5.14 *Pachypteris papillosa* (Thomas & Bose) (J. 67976). From Hasty Bank.
Pinnae are ovate to lanceolate, blunt ended and have a rounded, decurrent lower margin. The mid-rib is clearly seen in this species. The venation is simple or forked.

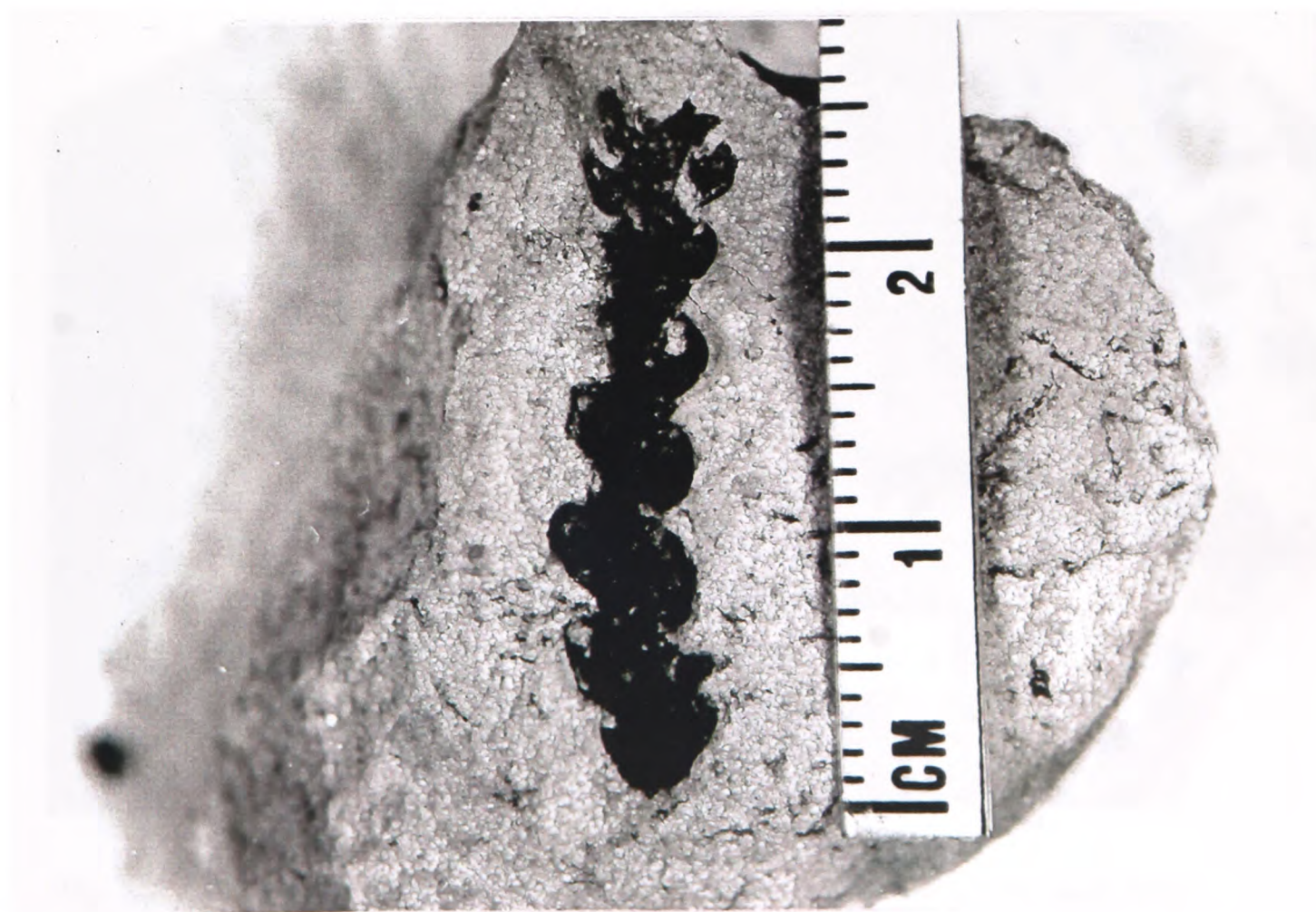


Fig. 5.15 *Brachyphyllum mamillare* Lindley & Hutton (J.67979). From the Gristhorpe Plant Bed, Yons Nab.
Single leaf showing individual leaf bases.

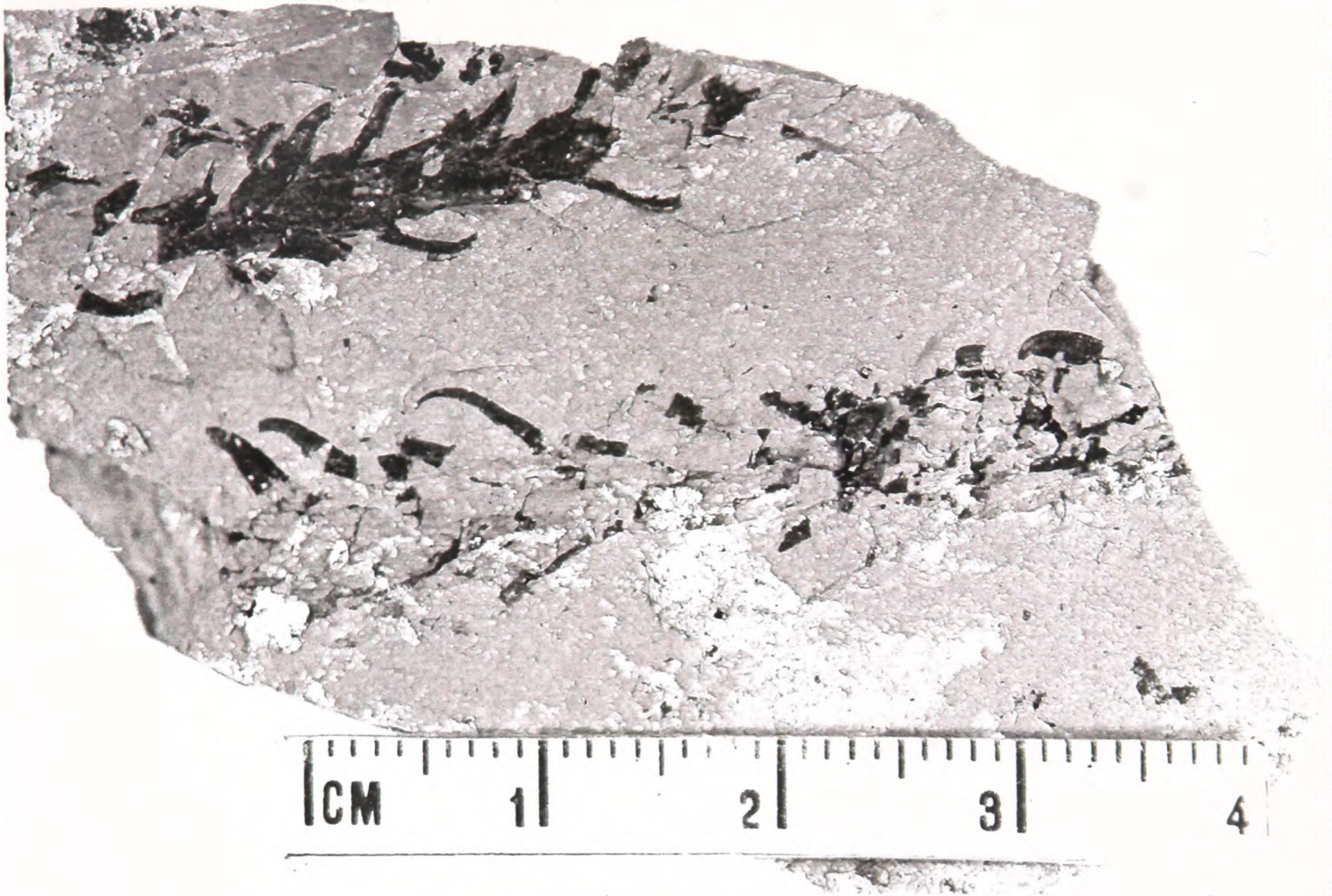


Fig. 5.16 *Elatides thomasi* Harris (J.67980). From Hasty Bank.
Extended slender leaves extending from main axis of shoot.



Fig. 5.17 *Elatides williamsonii* (Lindley & Hutton), *N. compta* (J.67981). From Hasty Bank.
Lying next to the linear lanceolate leaf of *N. compta* is the caduous shoot of *E. williamsonii*.

