Chapter 1 The Permian marine rocks of England

Geological setting

This volume is concerned with rocks laid down in and near epicontinental tropical seas that covered low-lying tracts of northern Europe perhaps for 5–7 million years during the late part of the Permian period; Britain then lay deep within the Laurasian supercontinent, with a climate that was both hot and dry.

During the early Permian and early late Permian, northern Europe was part of one of the world's great deserts, with a topographic and climatic range matching much of that of the present Sahara; widespread barren uplands created during the Variscan earth movements were gradually ground down as early Permian desert erosion led to extensive peneplanation of vast areas of Carboniferous rocks (especially Westphalian Coal Measures), and post-orogenic and extensional subsidence resulted in the formation of extensive, sub-sea-level, inland drainage basins in areas now occupied by the Irish and North seas and some adjoining land areas (Smith, 1970a, b, 1979; Glennie and Buller, 1983; Glennie, 1984; Smith and Taylor, 1992). It was these basins, surrounded by persistent and inhospitable deserts, that were flooded to form the Bakevellia and Zechstein seas (Figure 1.1).

The inferred mode of creation of the two seas gave rise immediately to classic barred basins, with sills that remained sensitively close to world sea levels. Both seas were particularly prone to relative sea-level changes and the thick sedimentary sequences formed in them display an extraordinary variation in their facies and extent. The sea-level changes stemmed from the complex interplay of several main mechanisms, including glacio-eustatic oscillations, isostatic effects, deepening and shallowing caused by periodic reversals in the relative rates of sedimentation and subsidence, and, when the sills became emergent during oceanic low-stands, rapid evaporative downdraw. Cyclicity, caused at least partly by these relative sea-level changes, is on a range of scales and is expressed both by incomplete marginal sequences resulting from repeated transgressions and regressions and in a wide variety of carbonates and evaporites. Some variation of lithology and biota also stemmed from repeated and protracted phases of basinal anoxicity, a natural outcome of restricted circulation in a barred basin; benthic communities at these times were confined to marginal and shoal areas above an oscillating pycnocline.

The marine and associated rocks formed in the late Permian seas of northern Britain have been studied intermittently for more than 150 years, but the recent search for hydrocarbons in the Irish and North seas accelerated the rate of learning and has revealed much new information on the stratigraphy, distribution, depositional environments and diagenesis of the various lithostratigraphical units. The marine and associated Permian strata of the Bakevellia Sea (part of the East Irish Sea) Basin, for example, have been shown to include major deposits of rock-salt, and their thicker counterparts in the English Zechstein Basin have been shown to comprise a complex series of progradational carbonate and sulphate prisms around the margins, and basin-filling halite in the interior (e.g. Taylor and Colter, 1975; Colter and Reed, 1980; Taylor, 1984).

The age of Zechstein and Bakevellia Sea strata in world chronostratigraphic terms is uncertain because these seas lay in the Boreal Realm and their faunas evolved almost independently of those in the Tethyan Realm upon which late Permian stages are now mainly based; a late Permian age is generally agreed, but it is becoming clear from mainly palynological evidence that the initial marine transgressions were probably appreciably later than the early Permian-late Permian boundary previously accepted, and perhaps as late as mid-Tatarian (see Smith *et al.,* 1974 for discussion). Marine fossils found at the various GCR sites featured in this review are strongly facies-linked and throw little light on the precise age of the rocks.

Although few late Permian shorelines in the British Isles can be recognized with certainty, projection of sedimentological and thickness trends suggests that the Bakevellia and Zechstein seas generally extended no more than a few kilometres beyond the present outcrops of late Permian strata and remained separated by a Proto-Pennine barrier (Figure 1.2) that waned with time but was surmounted by the sea only briefly and locally during the third of four main cycles of the English Zechstein sequence. The Zechstein Sea itself was divided into several sub-basins (Figure 1.1), and early Zechstein

Basin marginal depositional environments in north-east England fell into distinct Durham and Yorkshire provinces, separated by the Cleveland High (Figure 1.2). These two provinces form the basis for Chapters 3 and 4.

The low relief and aridity of the Proto-Pennines and most other hinterlands, together with the prevalence of onshore trade winds, ensured that the Zechstein Sea in England received relatively little terrigenous sediment and most of the late Permian marine rocks there contain less than 2% of siliciclastic grains (mainly wind-blown); in contrast, the hinterland of much of the Bakevellia Sea was generally more elevated and rugged than that of most of the English Zechstein Sea, and terrigeneous input was correspondingly greater. In both basins, occasional storms resulted in flash floods which swept coarse continental debris far across the coastal plains and led to the formation of marginal breccia lenses and wedges.

The distribution of marine Permian strata in mainland Britain is shown in (Figure 1.3), which emphasizes a great disparity between the widely scattered but mainly small occurrences in northwest England and the wide extent and almost continuous outcrop in north-east England. This disparity is reflected in the spread of GCR sites, only one of which is in the north-west and the remainder in the north-east. Altogether, 27 sites have been identified and are described in this volume; almost all meet the exacting requirements laid down by English Nature, the main exception being the site at the former New Edlington Brick-clay Pits in Yorkshire, which have recently been filled but are included here pending denotification and the choice of a suitable alternative site demonstrating comparable geological features.

Rationale of marine Permian site selection

The choice of sites described and discussed in this review was governed by a wide range of criteria, including their representativeness, their content of exceptional or unique geological features, their historical and their national and international importance. Together these sites form a dynamic network that covers most of the geology of the late Permian marine sequence in northern England, but some aspects are under-represented pending the choice of appropriately representative additional sites and the network will undoubtedly evolve as sites deteriorate or are superseded. The wealth of suitable high-quality exposures of these rocks in the Durham Province of north-east England is dramatically indicated by the fact that almost all the chosen sites meet at least two of the main selection criteria, and some sites satisfy all the criteria. Several sites, moreover, gain additional importance by forming links in chains of sites that together form a coherent whole but for which, because of the large scale, no single site could give full coverage. In addition to their geological interest, and arising from the specialized flora that characterizes many thin soils developed on the Magnesian Limestone, several of the GCR sites coincide with (or overlap) sites of special biological interest.

The sites considered here include natural exposures such as river and sea cliffs, but most are quarries (or part of quarries) and cuttings. Several sites include a number of separate exposures and these, and some others, exhibit more than one geological feature worthy of preservation. Outstanding examples of this are the complex of interlinked faces in reef and associated rocks at Ford (Sunderland), that provided the key to the solution of otherwise almost intractable sedimentological and stratigraphical problems, and the spectacular and equally varied coastal cliffs between Trow Point (South Shields) and Sunderland; coastal cliffs at Seaham and Blackhall are other examples. These coastal sites, indeed, are without parallel in Britain and most of Western Europe, and are unrivalled for research and teaching purposes. They are mainly in limestones and dolomites in the upper part of the Permian marine sequence and, in addition to exposing a continuum of rock-types extending basinwards from a marginal barrier system to those deposited near the middle of the basin-margin slope, also furnish magnificent examples of the disruptive effects of evaporite dissolution. Inland, most of the marine Permian GCR sites are in rocks in the lower and middle parts of the sequence, and clearly exhibit the great lateral variation that characterizes carbonate sediments now being formed in tropical nearshore environments; these inland sites include the type sections of three of the main late Permian marine formations.

Late Permian marine and associated strata in north-west England and adjoining areas

Late Permian marine and associated strata are widespread beneath the eastern Irish Sea, but extend far inland only in the Solway Firth and south Lancashire/north Cheshire areas where arms of the Bakevellia Sea extended eastwards. The sequence is up to about 350 m thick in the basin centre, where hydrocarbon exploration has disclosed much new information (Ebburn, 1981; Jackson *et al.,* 1987), but thins sharply towards the basin margins where sequences are condensed and incomplete. Exposures on land are concentrated in these basin-marginal areas, especially in west and

south Cumbria and around Greater Manchester, and most include intercalations of continental strata that indicate periodic proximity to cyclically migrating shorelines.

Information on Permian strata in Cumbria has been summarized by Arthurton *et al.* (1978) and for the basin as a whole by Smith (1992). Additionally, many new stratigraphical and structural data have been given by Jackson and Mulholland (1993). The nomenclature and classification of these strata in the several outcrop areas have evolved independently and are presented in ((Table 1.1). Three main cycles and one possible other cycle were recognized in West Cumbria by Arthurton and Hemingway (1972) and four supposedly equivalent cycles (BS1 to 4) were defined by Jackson *et al.* (1987) in the East Irish Sea Basin. Cycles BS1 to BS3 of the Bakevellia Sea sequence probably correlate with Cycles EZ1 (a and b) and EZ2 of the English Zechstein Basin (Smith *et al.,* 1974; Arthurton *et al.,* 1978) and cycles EZ3 and 4 probably equate with red-beds and basin-centre evaporites in the Bakevellia Sea sequences (Jackson *et al.,* 1987; Smith and Taylor, 1992). Attempts to interpret the palaeogeography of the region at various stages during each of the main cycles were given by Smith and Taylor (1992).

The biota of the Bakevellia Sea rocks was summarized by Pattison (1970, 1974) and Pattison *et al.* (1973), and is characterized by its low diversity. Pattison (in Pattison *et al.,* 1973, table 3 columns 14 and 15) listed 32 plant and invertebrate species and several additional, but doubtfully recognized, forms; he noted that bivalves are the most widespread and abundant invertebrates and recognized a sequence of six genera that declined to one (*Bakevellia*) and then none in response to inferred, decreasingly favourable, environmental conditions.

Late Permian marine and associated strata in north-east England

Late Permian marine strata crop out almost continuously (partly beneath drift) from Tynemouth southwards to the outskirts of Nottingham and comprise a sequence of mainly dolomitized limestones that individually and together thicken progressively eastwards (Figure 1.4). These carbonate rocks form the basal part of three main evaporite cycles (EZ1 to EZ3), and at depth farther east are separated by evaporites which, in present coastal districts of Yorkshire and much of the North Sea Basin, form most of the sequence. At outcrop the carbonate units are separated by erosion or emersion surfaces, some in combination with siliciclastic beds or evaporite dissolution residues, and some have been affected by large-scale dissolutional foundering. The main Cycle EZ2 carbonate unit does not crop out in Yorkshire but is thick and widespread in County Durham and Tyne and Wear.

The stratigraphical names used in this account are those of Smith *et al.* (1986), which were proposed to eliminate the misleading use of the same names for different rock units in the two provinces and to bring the nomenclature of the late Permian marine strata in north-east England into line with modern practice. The proposed new names are listed in ((Table 1.2), together with the traditional names used in most of the relevant literature. Type localities for the newly-proposed rock units were nominated by Smith *et al.* (1974) and Smith *et al.* (1986).

Correlation between the late Permian marine sequences in the Durham and Yorkshire provinces ((Table 1.2) is firm at the level of the Marl Slate and Seaham/Brotherton formations and reasonably firm between the early EZ1 carbonate formations, and between the EZ2 carbonate formations. There are, however, unresolved doubts on the precise correlation of the later EZ1 carbonate units of the two provinces (the Ford Formation and the Sprotbrough Member of the Cadeby Formation) and on the stratigraphical affinities (EZ1 or EZ2?) of the biostrome member (Figure 1.4) that lies between the EZ1 shelf-edge reef of the Ford Formation and the EZ2 Roker Dolomite Formation in the Durham Province.

An outline of the lithology and distribution of much of the Permian marine sequence at outcrop in north-east England was given by Sedgwick (1829) and details have been added by the authors of Geological Survey Memoirs and many other workers (see individual site accounts for full references); more recent syntheses are by the writer (Smith, 1970a, 1974a, b, 1980a, b, 1992), Pettigrew (1980), Kaldi (1980, 1986a), Harwood (1981, 1989), Aplin (1985), Goodall (1987) and Hollingworth (1987). Data from outcrop and boreholes are now sufficient for a lateral succession of facies belts to be recognized in three of the main carbonate rock units and for palaeogeographical maps of these to be attempted [see Kaldi (1980, 1986a) and Harwood (1981, 1989) for parts of the sequence in the Yorkshire Province and Smith (1989) for the full sequence in the Durham and Yorkshire provinces]. For reasons not yet fully understood, some of the Cycle EZ1 rocks and facies in the Durham Province differ considerably from their counterparts in the Yorkshire Province, but

remaining parts of the sequences are broadly comparable. In general, the rocks exposed in the Durham Province lie farther from the basin margin than those at outcrop in the Yorkshire Province, and the two sequences together afford a reasonably complete transect from near the shoreline to below the middle of the basin-margin slope.

The biota of the English Zechstein sequence is generally more abundant and much more diverse than that of the Bakevellia Sea sequence and includes several vertebrate species. Comprehensive lists by Pattison (in Pattison *et al.,* 1973, table 3) include all the species known to those dates, and are subject to minor subsequent amendments and additions; a bivalve-dominated community similar to that in Bakevellia Sea strata is present in nearshore and littoral carbonate rocks, especially in the Yorkshire Province, but is augmented by a wide range of brachiopods and bryozoans slightly farther offshore where environmental conditions are inferred to have been less stressful. The Zechstein fauna reaches peak diversity and abundance in early parts of a massive shelf-edge reef in the Cycle EZ1 Ford Formation of the Durham Province, where a range of complex faunal communities has been recognized by Honingworth (1987). By contrast, most basinal Zechstein rocks contain no benthic fauna and generally sparse remains of a nektonic fauna.

The Zechstein biota in north-east England, like that of equivalent strata in Germany, has been studied by many workers. Early observations by Winch (1817) and Sedgwick (1829) were followed by more comprehensive works by Howse (1848, 1858), King (1848, 1850) and Geinitz (1861). King's 1850 work was an outstanding monograph that remains a standard work. Lesser, but nevertheless important, studies were contributed by Kirkby between 1857 and 1866, and, considerably later, by Trechmann (1945). More recently, the Durham fauna (especially the bivalves) were studied by Logan (1962, 1967), the Durham reef bryozoans by Southwood (1985), the palaeoecology of the Durham reef by Hollingworth (1987) and the gastropods by Hollingworth and Barker (1991). Work on the microfauna includes important contributions from Robinson (1978) and Pettigrew *et al.* (*in* press) on the ostracods, Swift and Aldridge (1982) and Swift (1986) on the conodonts (mainly in the Yorkshire Province) and Pattison (1981) on the foraminifera. Several of the early workers touched on plant fossils of the English Zechstein, and the macroflora, mainly of algae and of land plants washed into the sea, was studied by . Stoneley (1958) and Schweitzer (1986). The microflora was investigated by Clarke (1965) and summarized by Warrington (in Pattison *et al.,* 1973).

Despite many variations caused by local factors, chiefly around the margins of the basin, the main structural controls and environmental influences on late Permian marine sedimentation in northwest Europe were shared throughout the Zechstein Sea. For this reason, the patterns of sedimentation and the biotas of the several sub-basins have much in common with each other, so that the results of research in one area are commonly applicable to other areas. This research, initially in England and Germany but later spread ing to Denmark, Holland and Poland, has shown that the similarities of geometry, lithology, sedimentology and biota of the various sequences permit reasonably firm correlation between the carbonate units of the first three cycles in England with those of northern Germany and Holland ((Table 1.3) and thence basinwide. Problems remaining include uncertainty over the number (two or three?) and precise equivalence in England of the subcycles of the Cycle 1 carbonate unit in Germany and Poland and the widespread doubts on the position of the Cycle 1/Cycle 2 contact in places where Cycle 1 evaporites are absent.
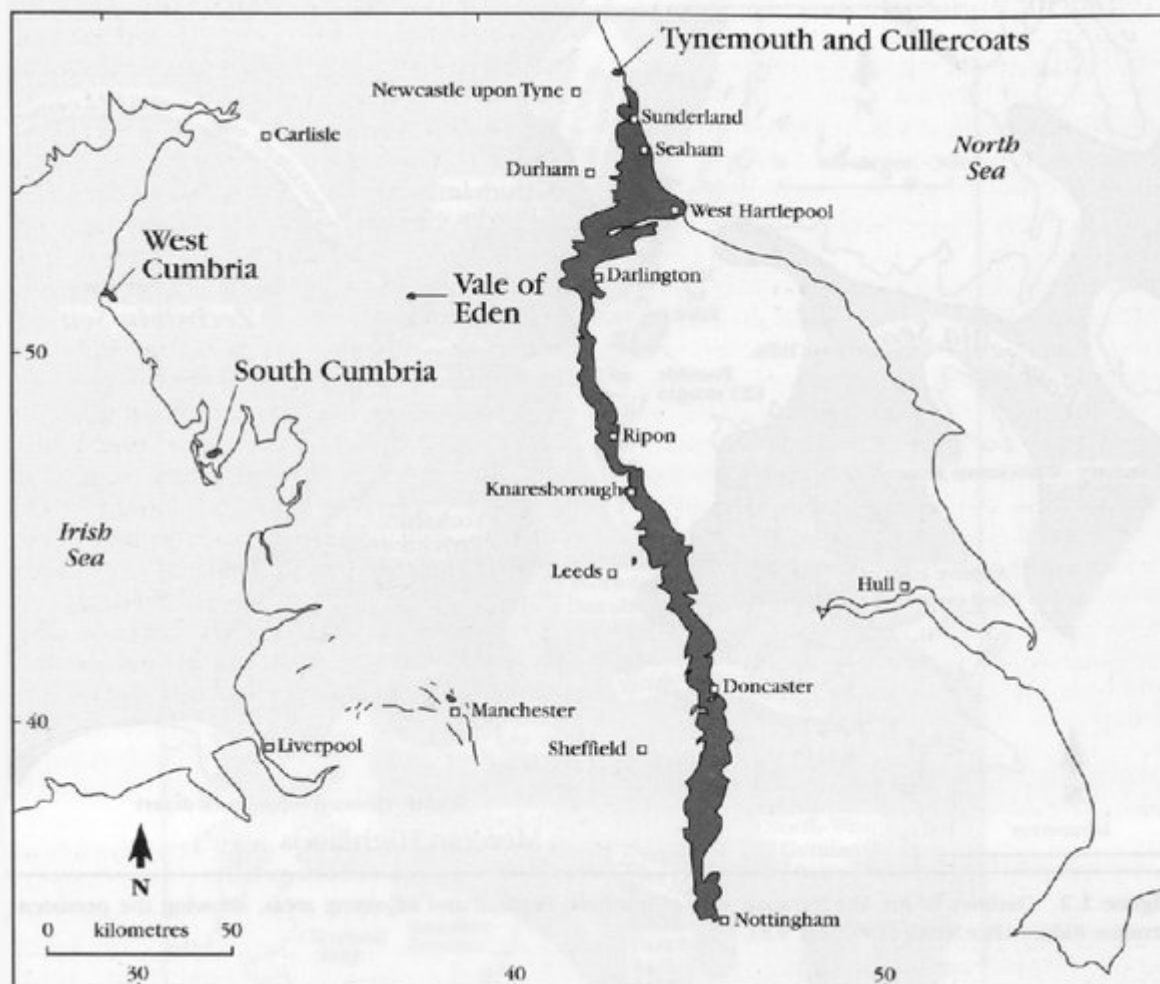
References

(Figure 1.1) The Zechstein Sea and its environs. After Smith (1980a, fig. 1).
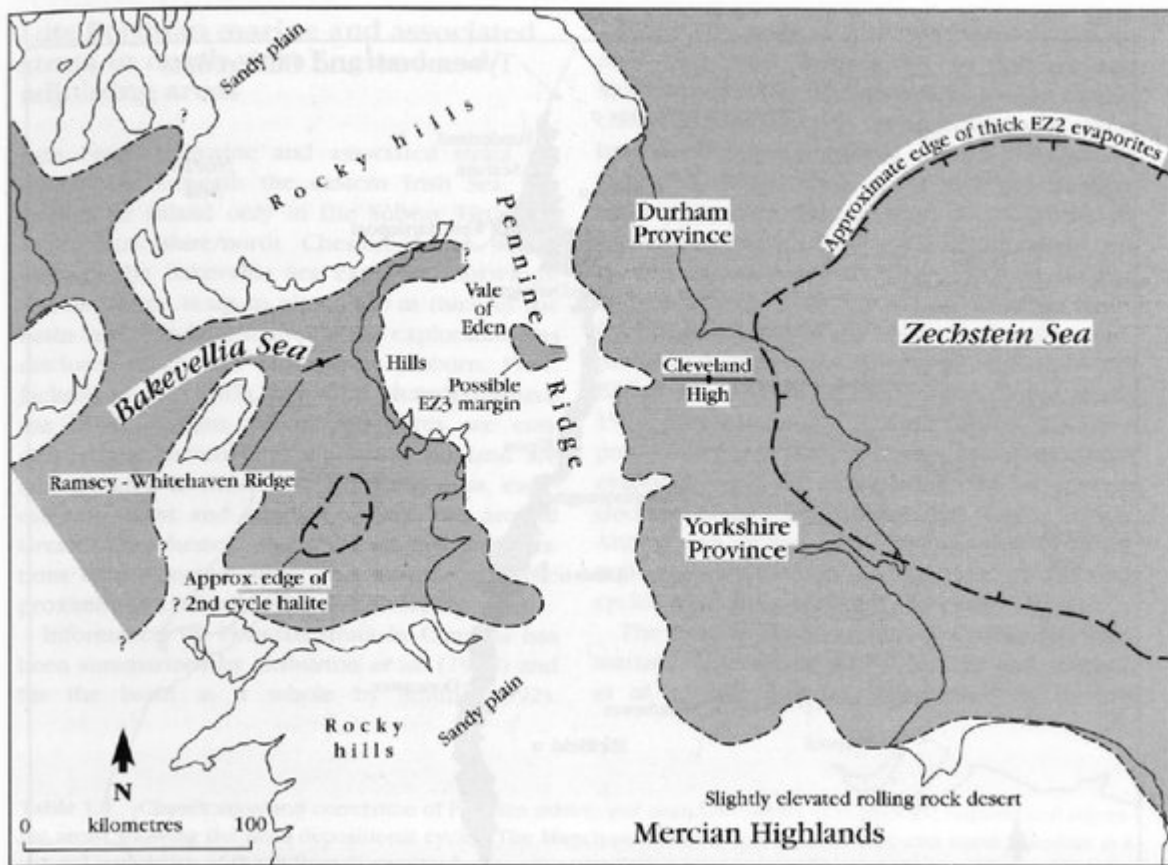
(Figure 1.2) Outlines of the late Permian seas of northern England and adjoining areas, showing the persistent Pennine Ridge. After Smith (1992, fig. 9.8).

(Figure 1.3) Outcrops of marine Permian strata in mainland Britain.

Cycles	Manx-Furness Basin (Central area)	South Cumbria	West Cumbria	Vale of Eden
BS4	*St Bees Evaporites and Shales* — Anhydrite / Anhydrite / Dolomite	*St Bees Shales (with Brockram)*	*St Bees Shales (with Brockram)* — Blocky Facies	*Eden Shales (with Brockram)* — Blocky Facies / D-Bed / Belah Dolomite
BS3	Halite			C-Bed
BS2	Anhydrite	Roosecote Anhydrite / Roosecote Dolomite / Haverigg Haws Anhydrite	Fleswick Anhydrite / Fleswick Dolomite	B-Bed
BS1	Dolomite / Dolomite, anhydrite, mudstone, etc.	Gleaston Dolomite ('Magnesian Limestone') / 'Grey Beds'	*St Bees Evaporites* — Sandwith Anhydrite / Sandwith Dolomite / Saltom Dolomite / Saltom Siltstone	A-Bed and Hilton Plant Beds

(Table 1.1) Classification and correlation of Permian marine and associated strata in north-west England and adjoining areas, showing the main depositional cycles. The Manchester Marl of south Lancashire and north Cheshire is a general correlative of the St Bees Evaporites but precise correlation is uncertain. Based on Smith (1992, table 9.2). Cycles after Jackson et al. (1987).
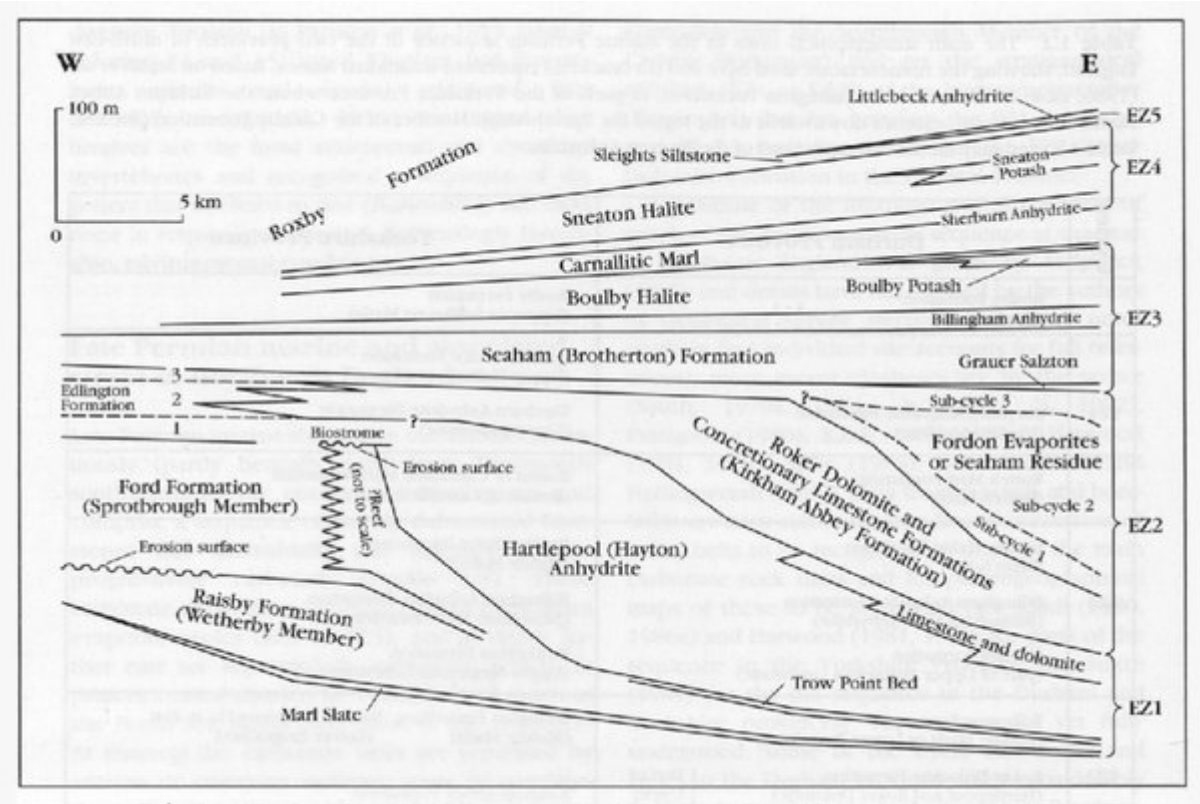
(Figure 1.4) Late Permian (Zechstein) lithostratigraphical units in north-east England; names as in the Durham Province with Yorkshire Province names (where different) in brackets. In Yorkshire, the Wetherby Member and Sprotbrough Member together comprise the Cadeby Formation. The erosion surface shown between the Wetherby and Sprotbrough members is the Hampole Discontinuity which lies up to 3 m below the top of the Wetherby Member; it has not been recorded in the Durham Province. Slightly modified from Smith (1989, fig. 1).

Cycles	Durham Province	Yorkshire Province
	Roxby Formation (Upper Marls)	Roxby Formation (Upper or Saliferous Marls)
EZ4	Sherburn Anhydrite Formation (Upper Anhydrite)	Sneaton Halite Formation (Upper Halite) — Sherburn Anhydrite Formation (Upper Anhydrite)
	Rotten Marl Formation (Rotten Marl)	Rotten or Carnallitic Marl Formation (Rotten or Carnallitic Marl)
EZ3	Boulby Halite Formation (Main Salt) — Billingham Anhydrite Formation (Billingham Main Anhydrite) — Seaham Formation (part of Upper Magnesian Limestone)	Boulby Halite Formation (Middle Halite) — Billingham Anhydrite Formation (Billingham Main Anhydrite) — Brotherton Formation (Upper Magnesian Limestone)
EZ2	Edlington Formation (Middle Marls or Lower Evaporites) — Roker Dolomite Formation (Hartlepool and Roker Dolomite) / Concretionary Limestone Formation (Concretionary Limestone) [Part of Upper Mag. Lst.]	Edlington Fm in West : Fordon Evaporite Fm in East (Middle Marls) (Lower Evaporites) — Kirkham Abbey Formation (Unnamed, ?absent at crop)
EZ1	Hartlepool Anhydrite Formation (Hartlepool Anhydrite) — b Ford Formation (Middle Magnesian Limestone) — a Raisby Formation (Lower Magnesian Limestone) — Marl Slate Formation (Marl Slate)	Hayton Anhydrite Formation (Unnamed) — Sprotbrough Member ('upper subdivision') / Wetherby Member ('lower subdivision') [Cadeby Formation (Lower Magnesian Limestone)] — Marl Slate Formation (Marl Slate)

(Table 1.2) The main stratigraphical units in the marine Permian sequence of the two provinces of north-east England, showing the nomenclature used here and (in brackets) equivalent traditional names. Based on Smith et al. (1986, table 1). Note that the Edlington Formation, in parts of the Yorkshire Province where the Kirkham Abbey Formation is absent, extends downwards to the top of the Sprotbrough Member of the Cadeby Formation (see also Table 1.3) and may include an equivalent of the Hayton Anhydrite.

Groups	Cycles	Yorkshire Province (Outcrop area)	Durham Province (County Durham, east Tyne and Wear, County Cleveland)	Yorkshire Province (East and North Yorks and Humberside)	North Germany and Holland	Cycles
Eskdale Group	EZ5	Roxby Formation	Roxby Formation	Littlebeck Anhydrite Formation / Sleights Siltstone Formation	Ohre Anhydrit / Unterer Ohre Ton	Z5
Staintondale Group	EZ4	Sherburn Anhydrite Fm / Rotten Marl Formation	Sherburn Anhydrite Formation / Rotten Marl Formation	Sneaton Halite Formation / Sherburn Anhydrite Formation / Upgang Formation / Carnallitic Marl Formation	Aller Salze / Pegmatitanhydrit / Thin unnamed carbonate / Roter Salzton	Z4
Teesside Group	EZ3	Billingham Anhydrite Fm / Brotherton Formation	Boulby Halite Formation / Billingham Anhydrite Formation / Seaham Formation	Boulby Halite Formation / Billingham Anhydrite Fm / Brotherton Formation / Grauer Salzton	Leine Salze / Hauptanhydrit / Plattendolomit / Grauer Salzton	Z3
Aislaby Group	EZ2	Edlington Formation	Seaham Residue — Roker Dolomite and Concretionary Limestone Formation	Fordon Evaporite Formation — Kirkham Abbey Formation	Stassfurt Salze and Basalanhydrit — Hauptdolomit and equivalents	Z2
Don Group	EZ1	b Sprotbrough Member / a Wetherby Member [Cadeby Fm]	Hartlepool Anhydrite Formation / Ford Formation / Raisby Formation / Marl Slate Formation	Hayton Anhydrite Formation / Cadeby Formation / Marl Slate Formation	Werraanhydrit / Zechsteinkalk / Kupferschiefer	Z1
		Basal Permian (Yellow) Sands and Breccias	Yellow (Basal Permian) Sands and Breccias	Basal Permian Sands and Breccias	Rotliegendes	

(Table 1.3) Classification and correlation of Permian marine and associated strata in north-east England, showing the main depositional cycles and a representative sequence from Holland and northern Germany. After Smith (1989, table 1).