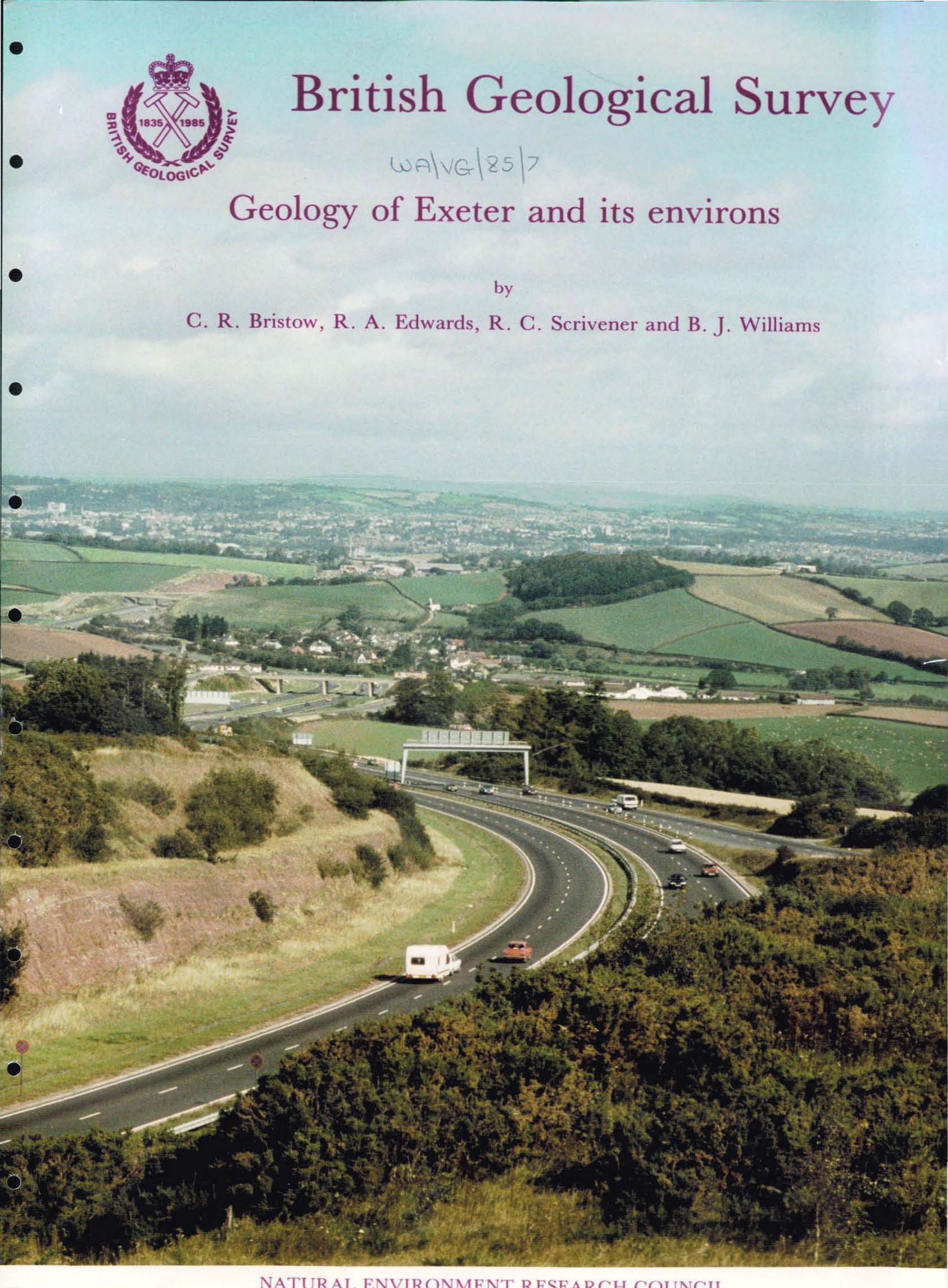
British Geological Survey

Geology of Exeter and its environs

by

C. R. Bristow, R. A. Edwards, R. C. Scrivener and B. J. Williams



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Geological Survey of England and Wales

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Geology of Exeter and its environs
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SUMMARY

A 225 km^2 area around Exeter, described in this report, extends from the villages of Brampford Speke and Whimple in the north to Aylesbeare, Exminster and Woodbury in the south. It is underlain by Carboniferous, Permian, and Triassic solid formations and by a variety of Quaternary superficial deposits. The Namurian Crackington Formation comprises mainly tightly folded shales with subordinate sandstone interbeds. The Permian rocks consist of a lower, predominantly breccia, sequence (Whipton Formation, Teignmouth Breccia, Monkerton Member) that thins and disappears northwards against a possibly fault-controlled ridge of Crackington Formation; the breccias are overlain by sandstones and mudstones (Dawlish Sandstone and Aylesbeare Mudstone). Volcanic rocks occur at the base of the Permian sequence and possibly within the Dawlish Sandstone. The latter splits into five alternating sandstone and mudstone members when traced northwards from Exeter into the Crediton Trough (an area of thick Permian sediments). The Aylesbeare Mudstone is divisible south of Aylesbeare into two members, the lower containing impersistent sandstones. It is overlain by the basal Triassic gravels (Budleigh Salterton Pebble Beds) which are in turn succeeded by the Otter Sandstone.

The Quaternary deposits consist of those laid down by rivers (Peat, Alluvium, River Terrace Deposits, Estuarine Alluvium); and those which are residual or have been affected by solifluction and slope-wash (Blanket Head and Regolith, Older Head, Valley Head).

The major Permian aquifer is the Dawlish Sandstone, especially north of Exeter. The Budleigh Salterton Pebble Beds and Otter Sandstone together constitute an important Triassic aquifer from which public water supply is derived east of the project area.

The major sand and gravel resources are the Dawlish Sandstone and Budleigh Salterton Pebble Beds. Alluvial gravels also form large potential resources. The Crackington Formation is a resource of brick clay, exploited at present at Pinhoe, Exeter.

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1. INTRODUCTION

1.1 Description of the project

The area described in this report consists of 225 km^2 of country around and including the City of Exeter. The nine 1:10 000-scale sheets that comprise the area (Figure 1) were geologically surveyed during 1982 and 1983 as part of a programme commissioned by the Department of the Environment (Contract PECD 7/1/054), with the objectives of collating existing data and interpreting the lithology and hydrogeology of the Carboniferous, Permo-Triassic and Quaternary rocks, for use in future resource assessment and land-use planning. Individual reports have been prepared for each 1:10 000-scale sheet (Bristow, 1983, 1984a, 1984b; Bristow and Williams, 1984; Edwards, 1984a, 1984b; Scrivener, 1983, 1984; Williams, 1983), incorporating accounts of the geological formations present, with details of exposures and boreholes, together with discussion of the economic geology, with particular reference to hydrogeology and bulk mineral resources. The objective of this report is to summarise the results of the project as a whole.

1.2 Previous work

The original geological survey of the Exeter district was made by Sir Henry de la Beche at the one-inch to one-mile scale (1:63 360) and published in 1834 as part of his geological map of Devon. W.A.E Ussher resurveyed the area at the same scale between 1873 and 1876, and in 1887. The results were incorporated in New Series One-inch geological sheets 325 (Exeter) and 339 (Teignmouth), both published in 1899, and in the

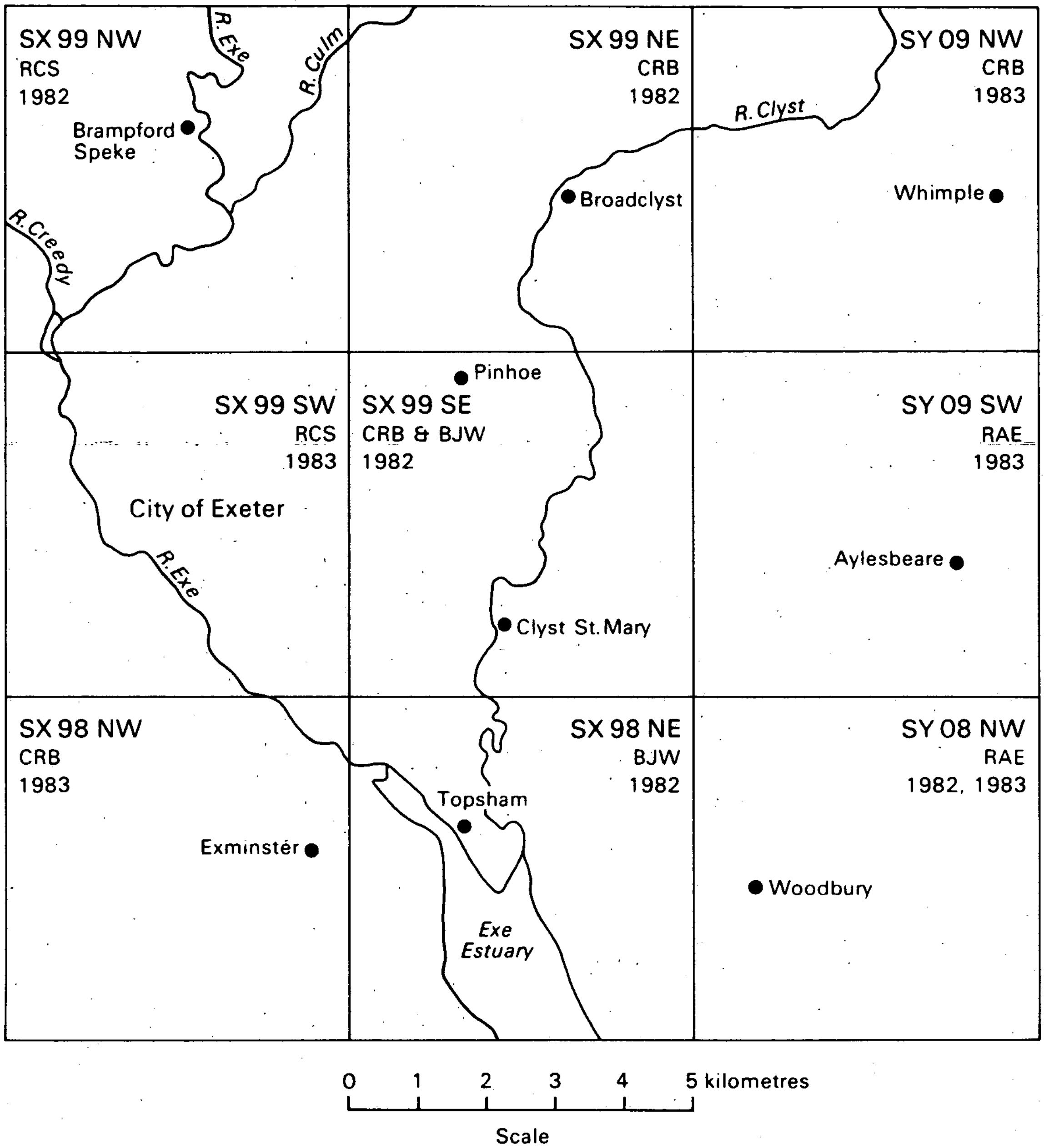


Figure 1 Component 1:10 000 – scale sheets of the Exeter project area showing dates of survey and initials of surveyors, who are identified thus:
CRB: Dr C.R.Bristow
RAE: Dr R.A.Edwards
RCS: Dr R.C.Scrivener
BJW: Mr B.J.Williams

accompanying descriptive memoirs (Ussher, 1902; 1913). A resurvey of those portions of sheets SX 98 NW, SX 98 NE and SY 08 NW south of grid northing 87 was carried out on the six-inch to one-mile (1:10 560) scale by M.R.Henson in 1968-69, and the results incorporated in the 1:50 000 - scale Newton Abbot Sheet (339), published in 1976, and memoir (Selwood and others, 1984).

1.3 Fieldwork

The field survey was carried out by detailed examination on the ground of all exposures, by intensive augering in unexposed areas, combined with examination of topographical features and soil types. Aerial photographs at about the 1:20 000 scale were used, mainly as an aid in tracing features. Data from borehole records in the BGS archives for the project area have been incorporated, where appropriate, into the maps and reports. The grain-size distributions of 67 samples of sands collected from the Permo-Triassic formations of the district were determined, and statistical parameters calculated using a computer program devised by Dr E.C.Freshney.

1.4 Geographical setting

Carboniferous rocks (Crackington Formation) form dissected country rising to 123m AOD in Ashclyst Forest, in the north-eastern part of the project area: north of Exeter they form a series of ridges reaching a maximum height of 158 m AOD at the Roman Signal Station, Stoke Hill.

South of the city, ground underlain by Permian breccias (Alphington and Heavitree Breccias) is deeply dissected by small streams, rising to about 112m AOD west of the village of Kenn, and falling in level north-eastwards towards the River Exe.

Ground underlain by the Dawlish Sandstone forms gently undulating lowlands mainly between 15 and 50m AOD in the Exe and Clyst valleys.

The extensive outcrop of the Aylesbeare Mudstone forms a well defined landscape unit of undulating ground that rises scuth-eastwards from around 30m AOD in the Clyst valley to about 150m AOD towards the south-east. This lowland is bordered in the south-east of the project area by a prominent scarp, up to 25m high, capped by the Budleigh Salterton Pebble Beds, which rises tc the highest point in the district (over 175m AOD) near Woodbury Castle. The Commons of Colaton Raleigh, Woodbury and Bicton are sited mainly on the dip-slopes of the pebble beds and ground levels drop to around 60m AOD in the SE before rising again to over 90m AOD on the outcrop of the Otter Sandstone.

The main areas of flat or gently sloping ground are underlain by alluvial deposits, most widespread along the valleys of the Rivers Exe and Clyst, and by River Terrace Deposits bordering streams.

River drainage is mainly southwards to the lower reaches of the Exe valley. The Exe is the most important river and is joined near Stoke Canon by the River Culm, and at Cowley by the River Creedy. The River Clyst flows into the Exe estuary at Topsham. The south-western part of the project area is drained by small streams, including the River Kenn, that flow eastwards into the Exe estuary. The highest part of the pebble beds scarp forms the watershed between streams that drain west to the rivers

Clyst and Exe, and streams that drain east to the River Otter.

The main settlement of the area is the City of Exeter (population c100 000) on the left bank of the River Exe on the high ground between two former tributary streams flowing towards the south-west which are now culverted and obscured by landfill. The medieval city, with its Cathedral in the city centre, and substantial Castle fortifications on the basalt outcrop of Rougemont, succeeded the Roman Town on the same site and it was not until the 18th century that any significant building took place outside the medieval city walls. Towards the end of the 19th century and continuing to the present day large numbers of dwellings, mostly terraced, were constructed in concentric belts around the old city, and included the St Thomas district on the western side of the Exe.

The second largest settlement is Topsham, included within the city limits, situated at the head of the Exe estuary between the rivers Exe and Clyst, and formerly an important port.

The remaining settlements are mainly villages of varying size located in predominantly rural areas. They include Whimple, Aylesbeare, and Woodbury in the east, Brampford Speke and Broadclyst in the north and north-east, Clyst St Mary in the centre, and Exminster in the south-west.

Exeter occupies a strategic position astride the River Exe, and roads and railways radiate from it. The main road and rail communications to the rest of the south-west peninsula pass through the city. The M5 motorway links the city to the Midlands and north of England, and via the M4 to London. Exeter's airport is sited near Clyst Honiton, 8 km east of the city.

1.5 Land use and agricultural land classification

Soil types mentioned in this account are more fully described in Chapter 7. Land underlain by Crackington Formation in the north and north-west of the district is occupied by Halstow and Dunsford soils which are mainly used for growing grass, the steeper slopes being occupied by woodland. Most of the land is classified as grade 3 (Ministry of Agriculture, Fisheries and Food, 1982).

Permian breccias in the south-west of the district give rise to Crediton series soils typical of 'redland' soils that characterise Devon. Mixed farming predominates: there is a long tradition of barley cultivation, and early fat lamb production. There can be problems in cultivation caused by the presence of moderate to strong slopes, and by the shallowness and stoniness of some soils leading to drying out at certain times of the year. Most Crediton soils are included in grade 2, locally with grade 3 in areas where slopes are steep or soils shallower.

Freely-draining very fine sandy loams or loamy sands (mainly Bridgnorth and Crannymoor series) developed on the Dawlish Sandstone are mainly included in grade 1. Bridgnorth and Crannymoor soils drain rapidly and this allows cultivation for most of the year. These soils are prone to drying out,are weakly structured and cap quickly after heavy rain, but are highly productive under good management, and when irrigated. Bromsgrove series soils in the north, developed on mudstones and sandstones of the Dawlish Sandstone Formation, are the most versatile soils in the district, and are capable of growing most arable and horticultural crops, and of withstanding year-round cultivation. They are lcamier and less liable to drought than Bridgnorth soils.

Whimple series soils developed on the Aylesbeare Mudstone outcrop are used mainly for growing grass for dairying. Brinsea soils have similar agricultural potential and are included with areas underlain by Whimple soils in grade 3 of the agricultural land classification. Arable crops are more widely grown on the better-drained sandy loams and loamy sand soils that develop on or near sandstone beds within the Aylesbeare Mudstone; such areas are included in grade 2 near Woodbury and south of Farringdon.

Kiddens series soils at the base of the Budleigh Salterton Pebble Beds scarp are poorly drained and of limited agricultural potential; they are included in grade 4.

The Pebble Beds outcrop is mainly in non-agricultural use, being unenclosed heathland used for recreation, forestry, and military training. Inliers of Aylesbeare Mudstone east of the pebble beds scarp are occupied by Kiddens series soils on which is developed uncultivated wet heath with vegetation of purple moor-grass, ling, and cross-leaved heath.

Land use of soils on Alluvium or on Valley Head (Exe Series, Clyst series, Exminster series, Mixed Bottomlands) is generally restricted to permanent grass owing to heavy soil texture, poor drainage or the risk of flooding, but the pastures are valuable for fattening stock. The land is mainly grade 4.

1.6 Outline of geology

The Exeter district is underlain by solid formations that are Carboniferous, Permian, and Triassic in age, and by a variety of superficial deposits ("drift") of Quaternary age. The distribution of the deposits is shown on Figures 2 and 3 and the geological succession in the district is given in Table 1. The evolution of the stratigraphical nomenclature of the New Red Sandstone is shown in Table 2.

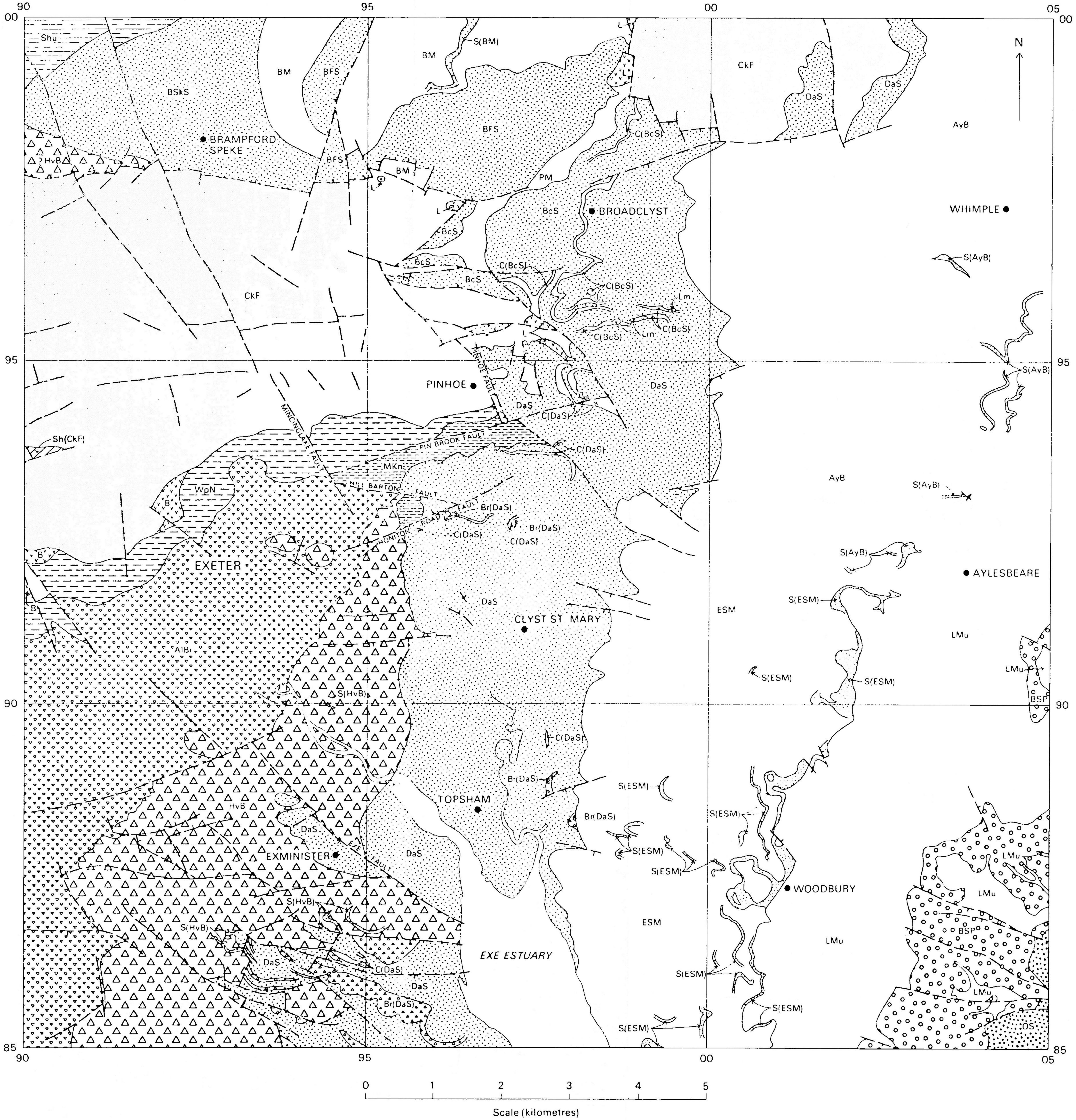
The oldest rocks in the district consist of tightly folded grey shales with subordinate interbeds of fine-grained indurated sandstone and silty sandstone of the Carboniferous Crackington Formation. They are unconformably overlain by, or faulted against, Permian sedimentary rocks that have a regional eastward dip so that successively younger formations crop out from west to east.

West of Pinhoe, the Whipton Formation, comprising poorly sorted, commonly clay-rich sandstones with breccias, mudstones and siltstones forms the basal formation of the New Red sandstone sequence.

Overlying the Whipton Formation south of Exeter is a succession of breccias, collectively termed the Teignmouth Breccia Formation, divided into the Alphington Breccia below and the Heavitree Breccia above. The breccias are distinguished by the occurrence in the Heavitree Breccia of fragments of potassium feldspar (murchisonite). The Heavitree Breccia passes northwards and eastwards laterally and upwards into sandy mudstones and very clayey fine-grained sandstones of the Monkerton Member.

The Dawlish Sandstone Formation overlies and (south of

Figure 2 Solid geology of Exeter and its environs



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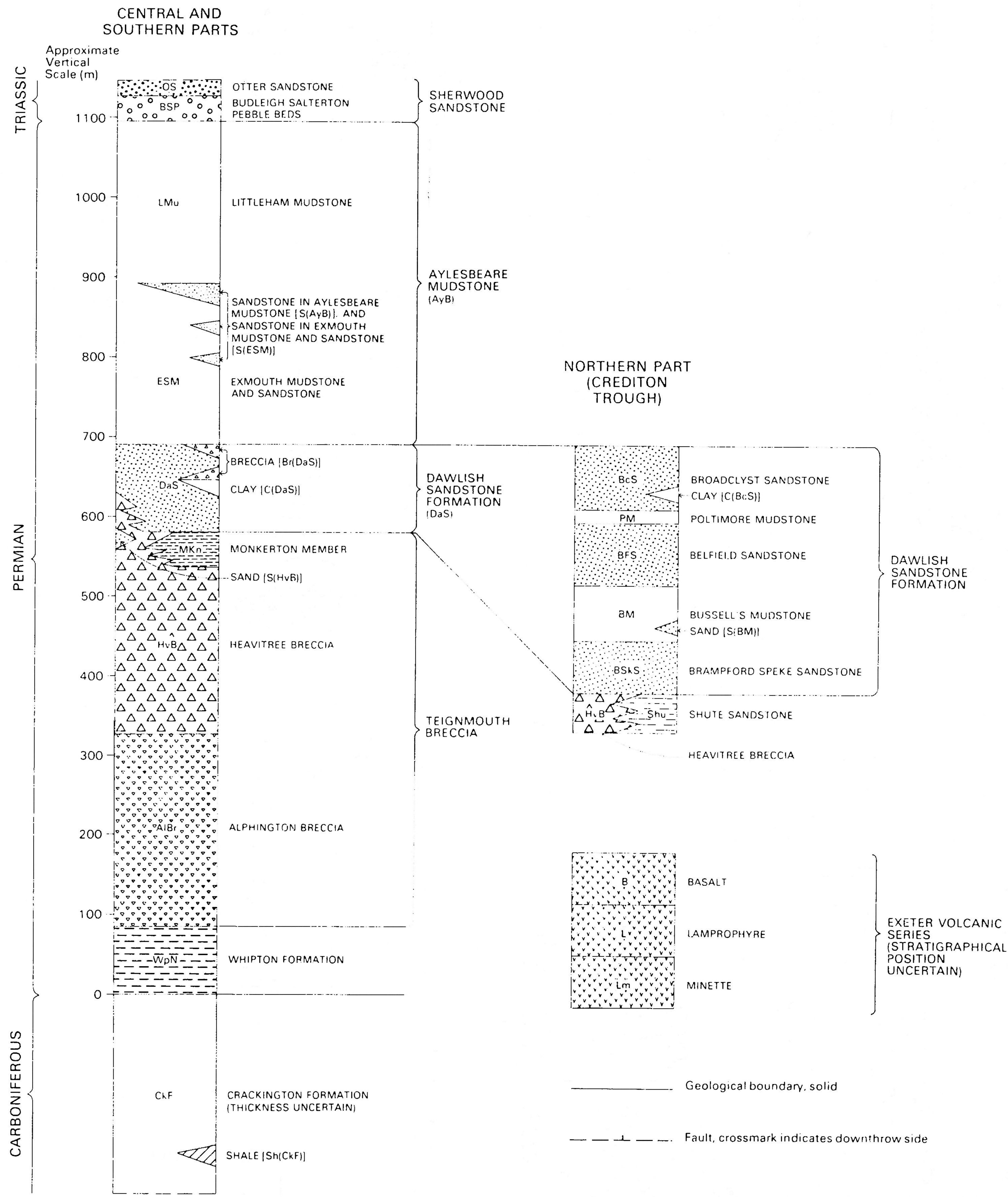
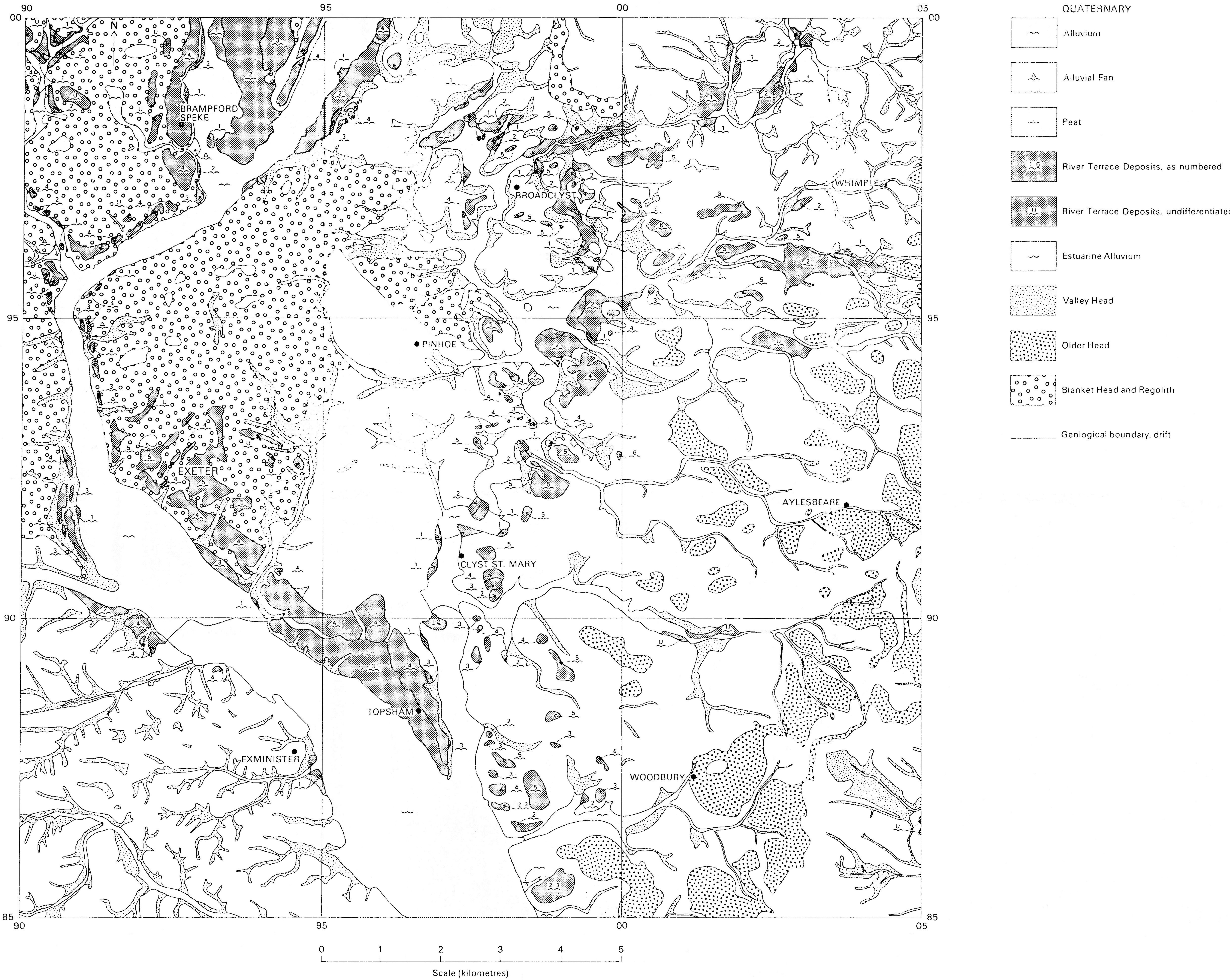


Figure 3 Quaternary ('Drift') geology of Exeter and its environs



Exminster) interdigitates with the Heavitree Breccia. North-east of Pinhoe, the Dawlish Sandstone Formation oversteps the Monkerton Member to rest directly on the Crackington Formation, there being no representatives of the thick breccia sequences that crop out south-west of Exeter. As it is traced into the Crediton Trough (an area of thick Permo-Triassic sediments which extend into the north-western part of the project area), the Dawlish Sandstone Formation splits into five argillaceous and arenaceous members.

In and west of Exeter, volcanic rocks occur at the base of the New Red Sandstone sequence. The stratigraphical position of volcanic rocks occurring within the Permian rocks of the district north of Exeter is less certain, and some of these may be contemporaneous with the Dawlish Sandstone Formation.

Much of the eastern third of the district is underlain by reddish brown mudstones of the Aylesbeare Mudstone. North of Aylesbeare the formation is undivided, but to the south of Aylesbeare, the formation is divided into two members, the Exmouth Mudstone and Sandstone below, and the Littleham Mudstone above. The two members are distinguished by the presence in the Exmouth Mudstone and Sandstone of lenticular channel sandstones, the most persistent and thickest of which occurs at the top of the member and is correlated with the sandstone forming Straight Point in the sea-cliffs near Exmouth, south of the present district.

The overlying Budleigh Salterton Pebble Beds cap a scarp on the Littleham Mudstone in the south-east of the district and are considered to be Triassic in age. They consist of well rounded mainly metaquartzite pebbles, cobbles and boulders in a coarse- to fine-grained gravel and silty sand matrix; lenticular beds of sand occur within the gravels.

The youngest solid formation in the project area, the Otter Sandstone, has an outcrop area of less than $1 km^2$ in the south-east, and consists of fine- to medium-grained micaceous sands and weakly cemented sandstones.

The Quaternary deposits of the district are divisible broadly into those laid down by river action, and those transported by solifluction under periglacial conditions.

The first group ranges from clay to gravel and includes Peat, Alluvium, River Terrace Deposits, and Estuarine Alluvium. The second group, collectively termed Head, is divisible into younger Valley Head which occurs along the lower slopes and bottoms of valleys and Older Head which occurs mainly in the east of the district along interfluves. Blanket Head and Regolith has been recognised in the north-west of the district and includes both transported material and weathered bed-rock (regolith) that has moved little or not at all.

Table 1. Geological succession in the Exeter project area

SUPERFICIAL DEPOSITS (Drift)

Quaternary	Peat	
	Alluvium	
	Alluvial Fan	
	River Terrace Deposits	
	Estuarine Alluvium	
	Valley Head	
	Older Head	
	Blanket Head and Regolith	
SOLID (estimated maximum thicknesses in metres)		
Triassic	Otter Sandstone	15
	Budleigh Salterton Pebble Beds	30
Permian	Aylesbeare Mudstone	400
	Littleham Mudstone	200
	Exmouth Mudstone and Sandstone	200
	Dawlish Sandstone Formation	120
	Broadclyst Sandstone	80
	Poltimore Mudstone	15
	Belfield Sandstone	80
	Bussell's Mudstone	70
	Brampford Speke Sandstone	65
	Teignmouth Breccia Formation	580
	Shute Sandstone	60
	Monkerton Member	40
	Heavitree Breccia	300
	Alphington Breccia	240
	Whipton Formation	25
	Exeter Volcanic Series	
Carboniferous	Crackington Formation	uncertain because of tight folding

2. CRACKINGTON FORMATION

The oldest rocks in the Exeter project area consist of tightly folded grey shales and mudstones with subordinate interbeds of sandstone and silty sandstone that are rarely

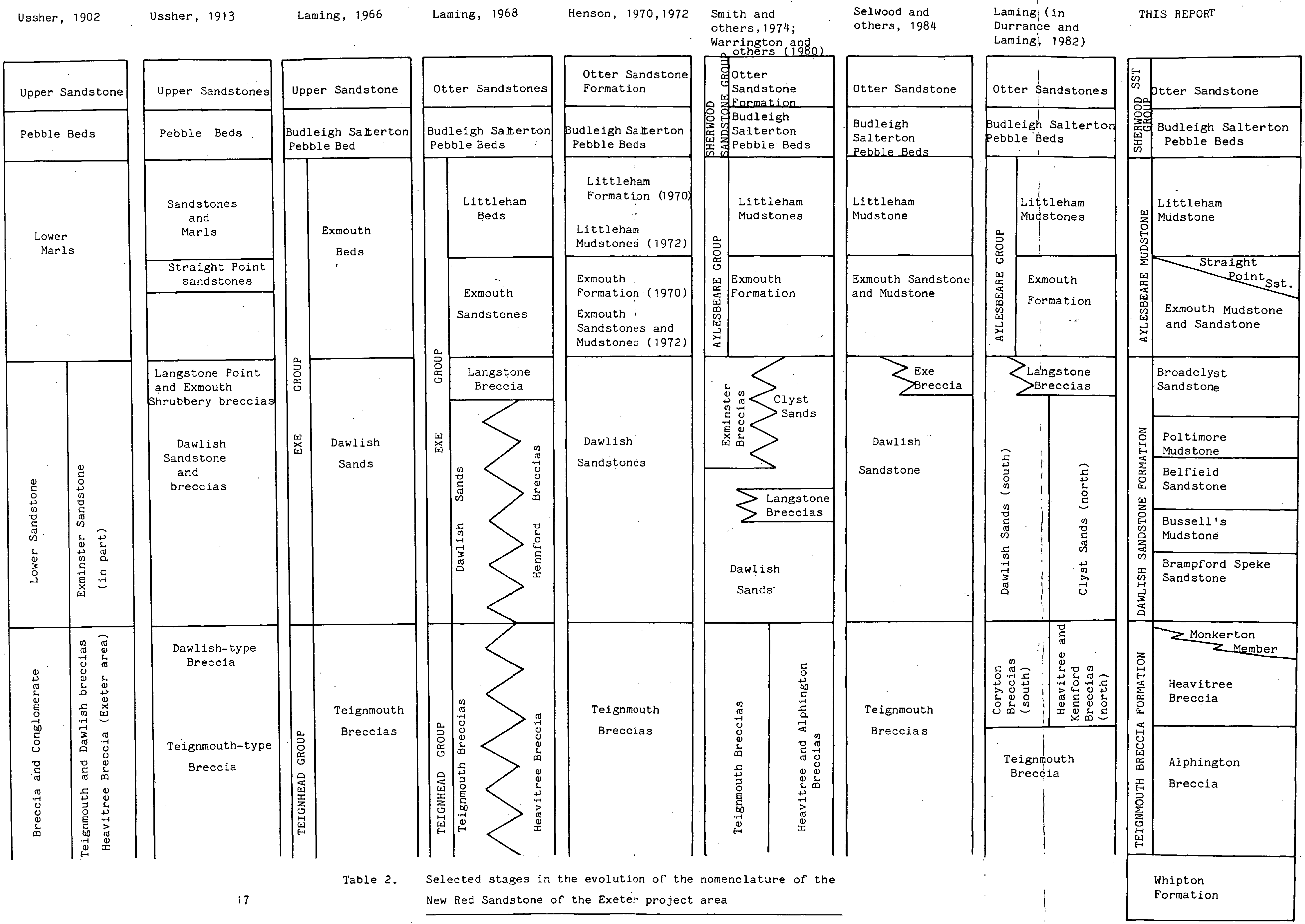


Table 2. Selected stages in the evolution of the nomenclature of the New Red Sandstone of the Exeter project area

thicker than 0.4m and are generally much thinner. The sandstones are dominantly fine-grained, well-cemented, and occur at 0.5 to 2.0m intervals; shale: sandstone ratios are generally between 3:1 and 4:1. Sole markings, including load casts, groove marks, and prod casts occur commonly on the basal surfaces of sandstones, and thus the way-up of the strata can be determined at many localities. Some of the sandstones grade up within individual beds from medium-grained sandstone to silty sandstone or siltstone, and at a few localities cross-lamination is visible on weathered surfaces.

These rocks are lithologically similar to the succession of distal turbidites described by Edmonds and others (1968) from the Okehampton district and the north Cornish coast, and termed by them Crackington Formation. This term has thus been adopted for the Carboniferous rocks of the Exeter area, and supplants the "Exeter Type Culm Measures" of Ussher (1902).

At a few localities near Exeter, for example at Pynes Water Works and near Exwick, dark grey shales with sparse thin silty sandstone and calcareous sandstone interbeds have been identified (Scrivener, 1983; 1984). These rocks are lithologically similar to Lower Carboniferous rocks of the Okehampton district, but at Pynes, the ammonoid Isohomoceras subglobosum indicative of the Chokerian Stage of the Namurian was collected during the present survey (Riley, 1984).

The remainder of the Crackington Formation of the Exeter area yielded ammonoids and other fossils indicating the Chokerian, Alportian, Kinderscoutian and Marsdenian Stages of the

Namurian (Riley, 1984), confirming the work of Butcher and Hodson (1960). The record in Butcher and Hodson (1960) of the Lower Carboniferous (Brigantian) Goniatities sphaericostriatus from the river-cliff section [9142 9272 to 9146 9255] at Bonhay Road, Exeter, has not been repeated during the present survey. The Crackington Formation has two main areas of outcrop within the project area. The smaller outcrop is in the north-east, around Ashclyst Forest; the larger outcrop is in the north-west, roughly within the area delimited by a line joining Exeter city centre, Pinhoe, Huxham, and Upton Pyne. Exposures are generally sparse and are chiefly restricted to road cuttings, small quarries, and stream sections. Excellent exposures, however, are visible in Pinhoe Brickpit [955 946] and there are several good road-cutting sections near Exeter. Details of exposures in the project area are given in the individual 1:10 000 sheet reports (Bristow, 1983, 1984; Scrivener, 1983, 1984; Bristow and Williams, 1984). The beds are commonly weathered and may show extensive red or yellowish-brown staining, particularly on joint surfaces. Much of the outcrop is mantled by Blanket Head and Regolith (see Chapter 6) between 0.5 and 3m thick.

No accurate calculation of the thickness of the Crackington Formation in the Exeter area can be made because of fold repetition; parts of the sequence may also be duplicated, or cut out, by strike faulting. The thickness probably exceeds several hundred metres.

The sandstones of the Crackington Formation contain internal structures and sole structures that are characteristic of deposition from turbidity currents, which flowed into a sea in which mud was accumulating. Measurements of flute and groove casts at Pinhoe Brickpit indicate that the sand-bearing turbidity currents flowed into the basin mainly from the south-west, with a lesser proportion from the north-east (Bristow and Williams, 1984, figure 2).

3. VOLCANIC ROCKS

The volcanic rocks of the Exeter area have been collectively known as the Exeter Traps (Ussher, 1902) or Exeter Volcanic Series (Dewey, 1935). Their mineralogy and petrology have been investigated by Hobson (1892) and Teall (in Ussher, 1902), while more recent contributions including geochemical data are by Tidmarsh (1932), Knill (1969) and Cosgrove (1972).

In the Exeter project area, the volcanic rocks fall into two geographical and petrological groups. The first consists of basalts that crop out in Exeter city centre and at two places west of the city. The second group forms nine small outcrops between Pinhoe and the northern boundary of the area, and consists predominantly of lamprophyres, except for three small outcrops of minette near Wishford Farm [990 955].

Field evidence indicates that the basalts are lava flows resting directly on the Crackington Formation and overlain by the Whipton Formation. The small size of the outcrops and their scattered distribution suggests that they were formerly part of a more extensive lava flow that was partly removed by erosion prior to deposition of the Permian sediments.

Of the three basalt outcrops only the south-westernmost [904 916] which forms part of the Pocombe Quarry mass has been named. It has been called olivine-basalt or olivine-trachyte by Teall(1902), "ciminite" by Tidmarsh (1932) and trachybasalt by Knill (1969). Specimens from Pocombe Quarry [SX 898 916] just west of the boundary of the project area, consist of phenocrysts of olivine (almost all altered to iddingsite or hematite) in a groundmass of plagioclase and orthoclase with some olivine and augite. All specimens are much altered, with iron oxides and carbonates replacing ferruginous silicates. In hand specimens, the rock is dense, fine-grained, purplish brown, and may be massive, vesicular, or cut by dolomite veins. In places the latter form a network that gives the rock a brecciated appearance. Scrivener (1984, table 2) has reproduced chemical analyses of the Pocombe Quarry trachybasalt originally published by Tidmarsh (1932) and Cosgrove (1972).

The Barley House [9025 9214] outcrop is poorly exposed, but its boundary was defined in the present survey using a gamma-ray scintillometer which responded to high potassium levels in the lava. The geometry of the outcrop suggests that it has a pipe-like form.

The largest outcrop of basalt is under Rougemont Castle [921 930] in Exeter city centre. It is similar to the Pocombe Quarry lava, and is probably a sheet-like flow resting on Crackington Formation.

The lamprophyres and minettes of the project area occur at the following localities: north of Sprydoncote [9880 9995]; Hazel Wood [987 997]; Bampfylde House [962 972], near Huxham [9515 9955]; at two places [975 955 and 976 953] near West Clyst: and at three places [9860 9555, 990 956, and 9945 9570] near Wishford Farm. In hand specimens most of these rocks are pale reddish brown, hard, vesicular and fine-grained, with dispersed mafic phenocrysts. They are extremely altered and many of the original minerals have been replaced by hematite or carbonates. Knill (1969) examined specimens from Hazel Wood (Sprydoncote in her paper), Bampfylde House (Barton in her paper), West Clyst and Wishford Farm; she noted that they all had high potassium and low sodium contents. She grouped them into two types on the basis of their mineralogy and texture; "syenitic lamprophyres" were recorded at the first three localities, and "minette" was recorded at Wishford Farm. In thin section, unweathered specimens of the first type consist of reddish brown anhedral pseudomorphs of hematite after olivine, and microphenocrysts of hematised augite and biotite in a groundmass of orthoclase laths, iron oxides and sporadic apatite. The olivine pseudomorphs may either be opaque, or the grains may be outlined by dense hematite and the core replaced by either feebly polarizing clay minerals or calcite; small pegmatite patches of orthoclase are present (Knill, 1969, p.126). Fresh specimens of minette consist of phenocrysts of biotite (two generations), euhedral augite (commonly pseudomorphed by calcite) and occasional prisms of apatite in a granular groundmass of orthoclase, rare albite, abundant carbonate granules and granular iron oxides. Small pegmatitic patches of simply-twinned orthoclase are also present (Knill, 1969, p.124).

The age and stratigraphical relationships of the lamprophyres and minettes are uncertain. With the exception of the Wishford Farm occurrences, all are in contact with the Crackington Formation, although at some localities this contact is faulted. The Bampfylde House, Huxham and Hazel Wood outcrops are oval and have the general aspect of volcanic necks, although Ussher (1902, p.65) recorded Permian sandstone at Hazel Wood "apparently passing under the Trap".

At West Clyst, Ussher (1902, p.63) noted pipes of "New Red Sandstone in the Trap" and concluded that the sandstone was deposited on top of the lamprophyre. Another secticn was exposed in an excavation [9731 9514] for a bridge over the M5 Motorway 200m W of West Clyst Farm (A.J.J. Goode, in Bristow, 1983). There, Permian sandstone rested on deeply weathered igneous rocks, probably lamprophyre. This outcrop is too small to show on the map.

At Wishford Farm, three apparently separate outcrops of lamprophyre occur. Their stratigraphical relationships to the mudstones and sandstones of the surrounding Broadclyst Sandstone are uncertain, but they have the appearance of necks or intrusions. Ussher (1902, p.93) thought that the Crackington Formation might crop out nearby, but this has not been confirmed in the present survey. Ussher (1902, pp.28, 31, 34, 36, 41, 43) noted many localities where lavas rest on Permian sands and breccias. Knill (1969, p.116) recorded weathered lava overlying a coarse breccia at Budlake just beyond the present district.

From the above evidence it can be seen that, although the volcanic rocks occur in close proximity to the Crackington Formation, only at West Clyst within the Broadclyst district is there evidence that they occur at the local base of the Dawlish Sandstone. The field evidence suggests that some of the lamprophyres are contemporaneous with the Dawlish Sandstone .

Basaltic lava from Dunchideock, about 2 km W of the boundary of the project area has been radiometrically dated by Miller and Mohr (1964) at 281 ± 11 million years, very close to the generally accepted date of 280 million years for the boundary between the Carboniferous and Permian periods. The Dunchideock lavas did not flow directly onto a surface of Crackington Formation as did the basalt lavas in the project area, but are separated from the Crackington Formation by thin beds of New Red Sandstone facies. Thus the volcanic eruptions took place at or soon after the beginning of red-bed deposition. Further potassium-argon age determinations on biotite samples from minettes at Killerton Park, just north of the project area, gave ages of 279±6 million years (Miller and others, 1961) and 283± 5 million years (Rundle, 1981), also close to the age of the Permo-Carboniferous boundary. The stratigraphical relationships of the Killerton lava are, however, uncertain and it cannot be determined whether the igneous rock might be part of a lava flow or a neck or pipe (Ussher, 1902, p.,65).

Tidmarsh (1932), Knill (1969) and Edmonds and others (1968) all favoured the possibility of interaction at depth between basalt and peridotite and either solidified granite or magmatic phases of the Dartmoor Pluton to explain the highly potassic nature of many of the Stephanian and Permian volcanic rocks. Recent work (Written communication, Dr C.C.Rundle, 1984) indicates that the Dartmoor granite may have been emplaced 280 to 285 million years ago, ie. close in age to the Exeter Volcanic Series volcanism.

Cosgrove (1972) proposed a plate-tectonic model for the origin of the lavas, but Hawkes (in Durrance and Laming, 1982) pointed out that in late Carboniferous/early Permian times the area was one of crustal tension where continental deposition took place in linear fault-bounded basins (grabens). The eruption of the lavas took place during this period of crustal tension. Whittaker (1975) noted the association of major grabens such as those in Africa and the Rhine Graben with alkali-rich lavas; he suggests that potassium-rich lavas such as those associated with the New Red Sandstone of SW England may be present near the "roots" of the larger grabens.

4. NEW RED SANDSTONE ROCKS

4.1 Introduction

The major terrestrial red-bed sequence of Devon, of which about 2000m is exposed in the Exeter area, is conveniently referred to as the New Red Sandstone, a term which also embraces the Mercia Mudstone Group cropping out east of the project area. The red-bed strata are of Permian and Triassic age. The sequence contains two major fining-upwards sequences. The first cycle commences at the base with coarse-grained breccia (Teignmouth Breccia) succeeded upwards by sandstone (Dawlish Sandstone) which is in turn overlain by mudstone with a few sandstones (Exmouth Mudstone and Sandstone) and finally by mudstone (Littleham Mudstone). The second cycle commences with coarse conglomerates of the Budleigh Salterton Pebble Beds at the base, succeeded upwards by sandstone (Otter Sandstone) overlain (east of the project area) by mudstone (Mercia Mudstone). Because of the lack of indigenous fossils, dating of the sequence and in particular the definition of the Permo-Triassic boundary is unsatisfactory. The Otter Sandstone near Sidmouth has yielded Rhynchosaurus indicating a mid Triassic (Anisian) age (Walker, 1969). There are no reliable age indicators below the Otter Sandstone except for the radiometric dates quoted above for the lavas. Henson (1971) has argued that the Aylesbeare Mudstone is Triassic because it shows affinities (common metaquartzite grains, similar palaeocurrent directions) with the overlying Budleigh Salterton Pebble Beds and Otter Sandstone rather than with the underlying strata. However, the most convenient horizon to place the Permo-Triassic boundary is at the base of the Budleigh Salterton Pebble

Beds (Smith and others, 1974) .

A list of New Red Sandstone formations present in the Exeter project area and their maximum thicknesses are given in Table 1; their distribution is shown in Figure 2. Considerable refinements have been made in the subdivision of the stratigraphical succession as a result of the present survey; many faults are now recognised. South of Pinhoe, the succession beneath the Lower Marls (=Aylesbeare Mudstone of this report) was divided on the 1:63 360-scale map into two formations: "Lower Sandstone" above and "Breccia and Conglomerate" below. The Lower Sandstone is essentially the Dawlish Sandstone Formation of this report, but the underlying sequence has now been divided into three: Whipton Formation at the base, overlain by Alphington Breccia and Heavitree Breccia. The division into two breccias has not been made on the adjacent 1:50 000-scale geological sheet 339 (Newton Abbot) on which the breccias are classified as (undivided) Teignmouth Breccia.

North-east of Exeter the Heavitree Breccia passes laterally and upwards into sandy mudstone and clayey fine-grained sandstone of the Monkerton Member.

Perhaps the most striking feature of the New Red Sandstone stratigraphy of the Exeter area is the marked northward thinning and eventual disappearance of the breccia formations south of Pinhoe against a block of Crackington Formation which probably formed a ridge, possibly fault-controlled, against which the breccias were banked. Not until Dawlish Sandstone times was the ridge overtopped, the lower New Red Sandstone formations being overlapped by the Dawlish Sandstone.

North of Broadclyst the Dawlish Sandstone thickens rapidly into the southern part of the Crediton trough, and is divisible into five alternating sandstone and mudstone members (in ascending order: Brampford Speke Sandstone, Bussell's Mudstone, Belfield Sandstone, Poltimore Mudstone, and Broadclyst Sandstone). The Dawlish Sandstone (Brampford Speke Sandstone Member) is underlain in the north-west of the project area, west of Brampford Speke, by breccias that contain murchisonite and thus may correlate with the Heavitree Breccia south of Exeter. These breccias apparently pass laterally in the subcrop into silty sandstone with a few breccia beds (Shute Sandstone of Edwards, (1984c)) in a manner analogous to the lateral passage from Heavitree Breccia into Monkerton Member in the area north-east of Exeter.

4.2 Whipton Formation

The name Whipton Formation has been given to the oldest sequence of Permian sediments in the Exeter district. The formation comprises poorly sorted, commonly clay-rich, sandstone with breccias, mudstones and siltstones. The type section of the Whipton Formation is the stream section [9435 9419 to 9446 9406] along the western boundary of the grounds of Northbrook School. Here, beds of silty breccia and gritty clayey sand rest with marked unconformity on a southerly-dipping surface of silicified iron- and manganese-stained Crackington Formation. The basal breccia consists of about 0.3m of coarse, subangular, cobbles of indurated sandstone and shale in a ferruginous cement. The sequence passes upwards through sands with subordinate breccias, into a predominantly argillaceous sequence. Minor east-west faulting is common throughout the section.

Sandstones are generally very weakly cemented at outcrop, red or reddish brown, and vary in grain size from coarse and gritty to silty or, in places, clayey fine-grained sand. Some clay is commonly present, though relatively clean sands locally occur. The degree of sorting varies from poor to moderate. Bedding is typically parallel; small-scale cross-bedding is rarely developed. The breccias form the basal parts of sandstone units and commonly grade upwards into gritty sandstones. The thickness of the breccia units seldom exceeds 1m, and is commonly much less. Basal contacts are sharp and may show channelling into the underlying finer-grained sediment. Clast size is variable, with coarse breccias being subordinate to finer gritty units. Culm sandstone and slate predominate in the clast populations, with a very minor amount of quartz-porphyry and other igneous debris; in this they differ from the overlying Alphington Breccia. The breccia matrix may be red, rather coarse-grained sand or brownish red, more argillaceous material. Except for the coarser units the breccias are matrix-supported. The red or purplish brown mudstones and less common siltstones may form units up to several metres in thickness with prominent green and grey-green reduction zones. More usually, the argillaceous beds are relatively thin and locally occur as discontinuous lenses within the sandstones.

The estimated thickness of the Whipton Formation in the type area is 60m, but the formation thins towards the west, and in

Exeter city centre it is represented by only about 20m of red sand and mudstone. West of the R. Exe, in the St Thomas area, the Whipton Formation consists of mudstones, fine-grained sandstones and thin breccia beds. West of the Exe Fault a rapid lateral passage occurs into a sandy sequence, about 10m thick. In this latter area the Whipton Formation rests on lavas of the Exeter Volcanic Series. The upper part of the formation passes upwards from predominantly fine-grained clastic sediments into a more breccia-dominated sequence.

4.3 Teignmouth Breccia Formation

The name Teignmouth Breccia in its present context was first used by Ussher (1902) when he referred to the "Teignmouth and Dawlish breccias". This name was later modified to Teignmouth Breccias (Laming, 1968). The name was further modified to Teignmouth Breccia Formation by Bristow (1984a) based on work in the Exminster area where the breccias are divisible into a lower Alphington Breccia, rich in Culm shale, readily distinguishable on lithology and by topographical features from the overlying Heavitree Breccia which contains abundant fragments of the potassium feldspar murchisonite. This two-fold division was first recognized by Ormerod (1875), although he only specifically mentioned the upper unit (his Murchisonite Bed). Within and south of the Exeter city area the Teignmouth Breccia Formation consists mainly of two members, but to the north the Heavitree Breccia passes laterally into a third member, dominantly a very sandy mudstone, the Monkerton Member.

There is general agreement (eg. Laming, in Durrance and

Laming, 1982) that the Teignmouth Breccia, like other breccias of the south Devon New Red Sandstone, was deposited as alluvial fans adjacent to a mountain-front. Deposition was mainly by sheet-flooding during occasional heavy rainstorms in a semi- arid region; the sheet-floods spread muddy or sandy gravel fairly evenly over the surface of the fan, giving rise to regular planar-bedding that is characteristic of the breccias. In the Whipton-Pinhoe area, the Heavitree Breccia interfingers with sandstones and mudstones containing thin breccia beds (Monkerton Member) which probably represent the finer-grained more distal portions of the gravel fan. Farther south, in the Exminster-Kenn area, the Heavitree Breccia interfingers with and is overlain by sand of the Dawlish Sandstone; the sands are thought to have been mainly deposited from sand-laden streams draining out from the permeable gravel at the foot of the fan after floods,but some of the sand beds may have been blown into place by strong winds.

4.3.1 Alphington Breccia

The Alphington Breccia, which consists of mudstone-rich breccias, crops out in the west and north-west of the Exeter district from [90 85] about 2km W of Kenn in the south to the Whipton area in the east of Exeter. The Breccia underlies the villages of Shillingford St George [905 880] , Shillingford Abbot [911 888] , Alphington [915 800] and much of the south-eastern part of Exeter.

Although Ormerod (1875) recognized that these breccias were distinct from his overlying Murchisonite Beds, he did not give them a separate name. The name Alphington Breccia was subsequently introduced by Laming (in Smith and others, 1974), but without definition, or subsequent amplification (Laming in: Durrance and Laming, 1982). The Alphington Breccia is, at least locally, a correlative of the lower part of the Teignmouth Breccia of the Newton Abbot (339) Sheet (1976).

The Alphington Breccia is poorly cemented and this feature, combined with its high content of shale, which causes it to weather to a clay, gives rise to a more rounded topography than that of the Heavitree Breccia.

The base of the Breccia is not exposed within the present district, but is recognized by the incoming of thick breccia beds. West of Exeter, where the Alphington Breccia overlies the Whipton Formation, the junction is gradational over about 10m. Because of the lack of cement the Alphington Breccia has not been quarried for building stone and there are few artificial exposures. Soils over the Alphington Breccia are generally clayey and contain fragments of Culm sandstone, black chert, slate and quartz porphyry. Where seen in roadside exposures the breccias are poorly sorted with fragments mostly up to 4cm across, but some are up to 0.3m across. They are mostly matrix-supported in a fine- to medium-grained sand; local thin seams (up to 0.1m) of fine- and medium-grained sandstone occur. There are local occurrences of murchisonite feldspar and granitoid fragments, particularly in the upper part, but they form a very small proportion of the total.

Heavy minerals from the Alphington Breccia (Table 3) are high in zircon and with moderate amounts of rutile, indicating derivation largely from older sediments, but tourmaline of Type E

HORIZON		Mineral species, percentage of grains: AMPHIBOLE	ANATASE	APATITE	CASSITERITE	EPIDOTE	GARNET	MONAZITE	PYROXENE	RUTILE	SPHENE	STAUROLITE	TOURMALINE	ZIRCON	TOURMALINE TYPES (Morton, 1982) Percentages of grains: A	B	C	D	E	F
ALPHINGTON BRECCIA	9120 8912		1.5				1.5			17.0		0.5	24.0	55.5	24	4	6	36	30	0
HEAVITREE BRECCIA	9202 8785	1.5	0.5	16.5			13.5			3.5		2.0	46.5	16.0	24	2	10	44	20	0
" "	9170 8705			18.5			17.0			1.0		2.0	59.5	2.0	8	4	6	50	32	0
SAND IN " "	9450 8683		2.5					R		11.0		1.5	31.5	53.5	28	4	16	34	18	0
MONKERTON MEMBER	9649 9380		2.5				0.5			13.5		1.0	50.0	32.5	20	6	16	30	26	2
DAWLISH SANDSTONE FORMATION	9444 8634		2.0				0.5			8.5			42.5	46.5	34	2	14	30	20	0
UNDIVIDED	9422 8810	R	0.5				1.0	2.0		9.5		0.5	50.0	36.5	40	4	12	28	16	0
"	0144 9915		1.0	0.5						16.6		6.0	16.5	59.5	34	4	18	36	6	2
"	0290 0005		2.0	3.0						19.0		3.5	15.5	57.0	30	2	20	36	8	4
"	9653 9327		6.0				0.5			14.0		1.0	41.5	37.0	36	6	14	20	22	2
"	9815 9345		1.0				0.5			12.5	R	0.5	17.5	68.0	36	4	12	30	14	4
"	9858 9265		1.5				0.5	0.5		18.5		0.5	26.5	52.0	30	2	14	36	18	0
BELFIELD SANDSTONE MEMBER	9820 9936		1.5	7.0	22.0		2.0			8.0		3.5	13.0	43.0	26	2	10	52	10	0
	9681 9893		0.5					1.0		8.0		5.5	12.0	73.0	28	2	14	34	22	0
	9594 9780		1.0				0.5		R	15.5		11.0	12.0	60.0	32	2	10	44	10	2
BROADCLYST SANDSTONE MEMBER	9915 9560		0.5	0.5						11.0		1.0	20.0	67.0	32	0	6	54	6	2
" "	9830 9812		2.0	0.5			0.5			19.5		3.0	8.0	66.5	32	2	12	44	10	0
" "	9821 9617		2.5						R	7.0		2.0	29.0	59.5	34	2	8	40	16	0
" "	983 974		2.0	11.5		0.5				8.0		2.5	16.0	59.5	38	2	16	36	8	0
" "	983 974		0.5	3.0						13.5		4.0	10.0	69.0	30	2	18	46	6	2
" "	9886 9838		0.5	24.5			0.5		1.0	13.0		1.5	15.5	43.5	30	2	14	46	6	2
SAND IN AYLESBEARE MUDSTONE	0382 9704		0.5	10.5			38.0			2.0		2.0	17.0	30.0	46	2	8	38	6	0
" "	0410 9522		0.5	2.5			6.5			4.5		4.5	60.0	21.0	50	0	10	34	6	0

Table 3. Heavy minerals from the Permian of the Exeter project area

R .... rare

(Morton, 1982) indicates some tapping of aureole or vein material. However, it should be stressed that at this stage no significance should be placed on the relative abundances of the minerals in Table 3 as an aid to correlation as too few samples have been examined.

The maximum thickness is estimated to exceed 240m in the Shillingford area in the south-west. Northwards the Member gradually thins until last seen in the Whipton area [around 950 928]. East of Whipton the Alphington Breccia has either died out or been overstepped by the Monkerton Member.

The beds are gently folded with dips generally less than 10^{o} giving rise to long dip-slopes generally inclined to the E,SE, SSE or ENE.

Detailed descriptions of exposures in the Alphington Breccia are given by Bristow (1984a) and Scrivener (1984).

4.3.2 Heavitree Breccia

The Heavitree Breccia crops out in a broad arc that sweeps from Coryton Cove [961 760] on the coast near Dawlish, into the present district through Exminster, then across the River Exe in the Countess Wear [945 895] area of Exeter, towards its type locality at Heavitree [9490 9204] . North of Heavitree the breccia thins rapidly and passes laterally into the dominantly arenaceous Monkerton Member. The Heavitree Breccia is last seen in the Hill Barton area [954 930].

These breccias were first noted by De la Beche (1839) who referred to the "conglomerates of Heavitree". This was modified to the Heavitree Conglomerate by Murchison(1867), and to

Heavitree Breccia by Ussher (1902).

The Heavitree Breccia is distinguished from the older Permian breccias of Devon by the marked influx of fragments of murchisonite feldspar. The presence of murchisonite, although not specifically named until 1827 by Levy, has been recognized by many workers from the time of Berger (1811) onwards. Ormerod (1875) introduced the name Murchisonite Beds for all the Devon breccias containing significant amounts of murchisonite. Since that time many local names have been introduced; the inferred stratigraphical position of these local units has varied (Table 2). Worth (1890) introduced the name Exminster conglomerates for the breccias in the Exminster area [around 940 870]; this name was modified tc Exminster Breccias by Laming (in: Smith and others, 1974, table VI). Ussher (1902) appeared to use the term Heavitree Breccia synonymously with "Teignmouth and Dawlish breccias", but restricted the use of the former name to the Exeter area. Murchisonite-rich beds in the Crediton Trough were named the St Cyres Beds, from the type area of Newton St Cyres [88 98], to the north-west of the present area, by Hutchins (1963). Laming (1968) initially thought that the Kennford Breccias [type area around 916 866], together with the Exminster Breccias (in Smith and others, 1974, table IV), were younger than the Heavitree Breccia, but later (in: Smith and others, 1974, p.29;in: Durrance and Laming, 1982) he considered that these two deposits, together with the St Cyres Beds, were contemporaneous. The present study supports this latter conclusion.

Murchisonite-rich beds at the top of the Teignmouth Breccias have been recognized by Laming (in: Durrance and Laming, 1982) at Coryton Cove, and named the Coryton Breccias, but they have not been differentiated on the Newton Abbot 1:50 000 Geological (339) Sheet (1976). References to the Heavitree Breccia in this report relate to the outcrops from Kenn [920 850] northwards.

The outcrop has a characteristic topography of steep scarp faces and longer dip slopes, and is more rugged than that of the Alphington Breccia. The outcrop of the Heavitree Breccia is broken by faulting, particularly in the south

The base of the Heavitree Breccia is defined by the marked influx of murchisonite feldspar fragments. The breccia is well cemented, possibly calcareously, in places; the basal beds form a prominent scarp above the Alphington Breccia over the whole length of the outcrop within the project area. Additionally the boundary between these two breccias can be reliably placed using either a scintillation gamma ratemeter, or a gamma-ray spectrometer. A marked increase in the potassium-derived count (from the feldspar crystals) occurs when passing from the Alphington Breccia to the Heavitree Breccia.

In the extreme south of the present district the upper limit of the Heavitree Breccia is difficult to define. Within the Heavitree Breccia there are several thick (up to 5m) beds of sandstone, and within the Dawlish Sandstone there are several thick (up to 5m) beds of breccia. The outcrop of both units is broken by faulting, and the stratigraphical relationships of strata within any one block cannot always be determined. In places [947 859] where thick (up to 15m), murchisonite-rich breccia, overlying thick sandstone, forms the top of the local sequence, this may be part of the Exe Breccia which is widely developed on the Newton Abbot (339) Sheet to the south. There the Exe Breccia overlies the Dawlish Sandstone and underlies the Exmouth Mudstone and Sandstone. Because of the limited area mapped, and because of faulting, the exact stratigraphical position of these breccias remains uncertain. In the present survey they are regarded as lenses of breccia within the Dawlish Sandstone.

The Heavitree Breccia is dominantly fine grained with fragments generally less than 8cm across, but some exceed 0.3m. The clasts include sandstone, slate, vein quartz, hornfels, porphyritic spilite, porphyritic granite, fine-grained tourmaline granite, microgranite, dolerite, lava, lamprophyre, fragments of murchisonite and a minor proportion of Culm shale; calcite fragments have been recorded in the Heavitree quarry (Berger, 1811). A bulk sample from the Matford Park Quarry [936 890] had a calcium carbonate content of 5.3% by weight; another sample from a quarry [9384 8875] opposite the former Limekiln Lane Cottages, had a carbonate content of only 1%. In neither of these samples is it known whether the calcium carbonate is present as cement or as limestone clasts. A detailed list of the clast rock types from the Heavitree Breccia of the Exminster area is given by Worth (1890).

The clasts are commonly matrix supported; the matrix consists of poorly sorted, fine-, medium- and coarse-grained, commonly very clayey, sands. Bedding is planar and bedding planes persist over long distances (500 to 600m where seen in long sections). Bedding units, which vary in thickness from 0.3 to 3m, are usually picked out by change in clast size, or absence of clasts; larger clasts are more common at the base of bedded units. Fining upward sequences occur locally and are particularly evident in the Starved Oak Cross Borehole No 2 [SX 9130 9879] (Scrivener, 1983), but most units are ungraded. Cross bedding has only been recorded in the Heavitree area. Vertical, carrot-shaped sand-filled pipes, up to 1m high and 10cm across at the top, are common in the Heavitree quarry. Smaller pipes, up to 0.5m high and up to 8cm across, occur near Kennford. In both localities the pipes cut, but terminate at the top of, individual bedding units. They occur at several levels at Heavitree, but are limited to one level at Kennford [9060 8714]. They have an irregular spacing of, on average, one every 2m. Their three dimensional shape is unknown. Possibly they represent infilled desiccation cracks as suggested by Ussher (1902, p.24), but more probably they are dewatering structures. Thin interbeds of sand and sandstone occur in many localities, but it is only in the Exminster Hill area [around 945 869] that they are thick enough to map. Here three interbeds of medium-grained sandstone occur within the breccia. A sample from one of these sandstones when sieved proved to be positively skewed, moderately well sorted and medium grained. The grains are dominantly rounded with some sub-rounded; an estimated 5% of the grains are feldspar.

The heavy minerals from the matrix of the breccia (Table 3) are high in apatite and stavrolite, garnet and very high in tourmaline, with an abundance of Type E of Morton, (1982), but low in rutile and zircon when compared with the residues from the

Alphington Breccia.

The thickness of the Heavitree Breccia is not known with certainty, but is estimated to be about 300m at its maximum in the south. In the area between Countess Wear and Heavitree the maximum thickness is estimated to be about 135m. From Heavitree northwards the Breccia thins rapidly to disappear as a mappable unit just north of Hill Barton. In the Starved Oak Cross No 2 Borehole [9130 9879] 38.6m of breccia with murchisonite fragments was proved, above 3m of sandstone and mudstone (Scrivener, 1983). It is not known whether these bottom 3m of strata are part of an underlying formation, or a bed within the breccia.

The Heavitree Breccia is particularly well exposed in the Exminster area. Because it is locally moderately well cemented it has been extensively quarried for building stone (Bristow, 1984a, table 4). The old quarries still retain vertical faces up to 35m high. Additionally there are near vertical faces up to 30m high and 500m long in the M5 Motorway and A30 road cuttings. Exposures show the Heavitree Breccia to be lithologically relatively uniform. Most exposures differ only in the thickness of the beds, clast size and the relative proportions of the various clasts. Detailed descriptions of the sections are given in Bristow (1984a); Bristow and Williams (1984) and Scrivener (1983; 1984).

A radiometric age determination on biotite from a granite cobble from the breccia at Kennford gave a date of 281 $\pm$ 7 million years (Rundle, 1981). This date, which lies close to the

Carboniferous/Permian boundary, provides the only direct evidence for the age of the Heavitree Breccia; it must be younger than 281 million years.

The breccia weathers to a gravelly, clayey soil with blocks of granite and tourmalinised quartz porphyry one of the commonest stones on the surface. Weathering may extend down to almost 8m (Bristow, 1984a).

4.3.3 Monkerton Member

The Monkerton Member crops out north-east of Exeter from Hill Barton in the west [956 928], through Monkerton [965 938], the type area, to just beyond the M5 Motorway in the east [974 939].

The Member consists of a variable sequence of clayey, dominantly fine-grained, but locally medium- or coarse-grained, sandstone, sandy mudstone, silty mudstone and thin breccia.

In the Hill Barton area the Monkerton Member overlies a thin remnant of the Heavitree Breccia. Hereabouts there appears to be a fairly rapid upward passage from breccia into a dominantly argillaceous sequence. The boundary is not marked by a feature. North of the Hill Barton Fault the Heavitree Breccia has passed laterally into the Monkerton Member, and the Monkerton Member rests directly on the Whipton Formation. The Member is absent east of the Pinhoe Fault, although possibly the thick clay units near Mosshayne Farm [around 980 947] and under the Alluvium of the River Clyst [around 983 942] may in part be its lateral equivalent.

Details of sections within the Monkerton Member can be found in Bristow and Williams (1984).

The maximum thickness of the Monkerton Member is about 40m. Heavy mineral analysis of one sample from the Monkerton area [9649 9380] shows it to be high in rutile, zircon and tourmaline, but low in garnet and with no apatite (Table 3). Apart from the tourmaline content these figures are in marked contrast to those of the Heavitree Breccia, its lateral equivalent, of the Exminster area. Possibly the input of material derived from the aureole of the Dartmoor Granite has been diluted by sand from a different source. Samples from the type area were barren of palynomorphs.

4.3.4 Shute Sandstone

Breccias with murchisonite fragments mapped as Heavitree Breccia that crop out west of Brampford Speke and which were encountered in the Starved Oak Cross No.2 Borehole [SX 9130 9879] are thought to pass northwards in the subcrop into silty sandstone with a few breccia lenses. In the adjacent Thorverton district these sandstones have been named the Shute Sandstone (Edwards, 1984c).

4.4 Dawlish Sandstone Formation

The Dawlish Sandstone occupies a north-north-easterly trending belt about 5km wide, extending from the Exe estuary in the south to Broadclyst in the north. Northwards from Broadclyst the constituent members of the Formation expand to the west into the Crediton Trough. South of Broadclyst the Formation consists of sands and sandstones, mainly cross-bedded, largely uncemented, with intercalated thin lenses and beds of breccia and mudstone. The mudstone content increases towards the north, and in the vicinity of Broadclyst the Formation becomes divisible into five members, including two major mudstones. These subdivisions persist into the Crediton Trough.

The Dawlish Sandstone is the equivalent of Ussher's Lower Sandstone (see Table 2). The name Dawlish Sandstones was introduced by Ussher (1913); this term embraced the earlier-named Exminster Sandstone (Ussher, 1902). The name was modified to Dawlish Sands by Laming (1966); Laming (1968) later used the term Clyst Sands for the sands and sandstones of the Exeter area, and regarded them as the lateral equivalent of the Dawlish Sands. It was subsequently thought (Smith and others, 1974) that the Clyst Sands occurred at a higher stratigraphical level than the Dawlish Sands, being separated from them, in part, by the Langstone Breccias and the Exminster Breccias. On the Newton Abbot (339) Geological Sheet (1976) the term Dawlish Sandstone has been employed. During the initial work of the present survey, a thick sequence of alternating mudstones and sandstones that overlies the Heavitree Breccia, was named the Exeter Formation (Bristow, 1983; Scrivener, 1983). As a wider area has now been surveyed it is evident that the Exeter Formation, Exminster Sandstone, Clyst Sands and Dawlish Sandstone occupy the same stratigraphical position and can be united under one name. Exminster Sandstone has priority, but because Dawlish Sandstone is in widespread use it is proposed to retain it, in the slightly modified form, Dawlish Sandstone Formation, for all the occurrences of sand and sandstone between the Heavitree Breccia and the Exmouth Mudstone and Sandstone. The Dawlish Sandstone Formation overlies and interdigitates with the Heavitree Breccia throughout most of the present district except in the area south of Pinhoe where the Monkerton Member forms the top of the Teignmouth Breccia Formation. In that area, the passage from the argillaceous silty sandstones of the Monkerton Member to the Dawlish Sandstone takes place within a metre or so of strata. At Pinhoe the Dawlish Sandstone rests unconformably on the Crackington Formation.

The Dawlish Sandstone Formation consists of red-stained, chiefly cross-bedded sands, usually uncemented, with breccia and mudstone intercalations. In places a poorly-developed clayey calcareous cement loosely binds the sands to form sandrock or sandstone. Locally the sandstone is bonded by a ferruginous cement to form hard beds of carstone. Around Exminster the sandstone (the Exminster Sandstone of Ussher, 1902) is characteristically yellow in colour and, apart from the basal beds, is free from breccias and mudstones, in all other areas it is red or reddish brown stained. South of Exminster, however, thick beds of breccia occur throughout the Dawlish Sandstone.

The sorting and grain-size of the Dawlish Sandstone vary across the outcrop. Over most of the project area the sands are poorly to moderately sorted, dominantly fine-, locally medium-, and rarely coarse-grained. The bulk of the sand is less than well-rounded; some millet-seed grains with frosted surfaces, however, are found, and well-rounded grains are characteristic of the coarser fraction of many of the sands. In the Clyst Honiton area analysed samples have a bimodal grain-size distribution, with that part of the distribution coarser than 0.5mm being very well-sorted and composed of rounded to well-rounded quartz and feldspar grains. In the Bishops Court Quarry area, however, the sands are dominatly medium-grained, well sorted to moderately well-sorted.

The results of heavy mineral analyses are included in Table 3. Too few samples have been examined to establish regional variations, but from the samples studied there is a decrease in the tourmaline content north-eastwards across the district. This decrease indicates a diminishing input, or dilution from another source, of granite-aureole material. Apatite is present only in samples of the Dawlish Sandstone from the north-east. A sample from the Belfield Sandstone is unique amongst all the samples examined in its high cassiterite content (22% of the heavy minerals).

In the northern part of the present area, where the formation is subdivided, the Brampford Speke Sandstone Member consists of medium- to coarse-grained reddish brown sandstone, locally cross-bedded, with thin interbeds of breccia and mudstone. The sandstones are moderately well sorted, the bulk of the grains are subrounded to subangular and a small proportion are well-rounded. Planar cross-bedding occurs at some localities, elsewhere parallel lamination or massive bedding is present.

The Bussell's Mudstone Member is composed of brown mudstone and fine-grained argillaceous sandstone. Non-argillaceous sandstone beds occur locally within the Member.

The Belfield Sandstone Member is made up of fine-, medium-and coarse-grained sandstones, locally pebbly. The base of the Member rests abruptly on the Bussell's Mudstone and the basal beds are more pebbly than the higher strata and contain thin breccia beds. The higher beds are much finer-grained and enclose red mudstones up to 3.8m thick.

The Poltimore Mudstone Member is about 15m thick and rests abruptly on the Belfield Sandstone. It comprises red clay, sandy clay and clayey fine-grained sand.

The Broadclyst Sandstone Member is the highest member in the Formation and is lithologically similar to the Belfield Sandstone, but includes several relatively thick red clays that are locally mappable. The sandstones were formerly an important source of building stone.

The only fossils recorded from the Dawlish Sandstone from the present district are reptilian footprints (Clayden, 1908) and annelid and crustacean tracks and "Posidonia" (Shapter, 1842) in the Broadclyst Sandstone north of Broadclyst (Bristow, 1983).

The depositional environment of the main mass of the Dawlish Sandstone Formation is open to some doubt. It is thought that the cross-bedding is usually of fluviatile origin, with foresets dipping at up to 20^{o} and some planar-bedded sets and cosets. Some large-scale cross-bedded sets and cosets up to 7m thick and with foresets dipping at 25^{o} to 30^{o} suggest an aeolian origin, although the sand is mostly less than well-rounded. Some millet-seed grains are, however, found in these sands of aeolian aspect, and well-rounded grains are characteristic of the coarser fraction of many of the sands. Taking into account the sorting (dominantly moderate), the positive skewness and grain roundness (dominantly subrounded to rounded) the balance of the evidence suggests fluviatile deposition, with the coarser, well-rounded grains derived from aeolian deposits. Current-direction measurements from Bishops Court Quarry suggest derivation predominantly from the south-east.

4.5 Aylesbeare Mudstone

About 75 km^2 of the Exeter project area is underlain by a 400m-thick sequence of reddish brown clays and mudstones, with impersistent, mostly thin, sandstone beds, comprising the Aylesbeare Mudstone. The outcrop of the formation (Figure 2) lies mainly in the east of the project area, and extends northwards from around Woodbury, where it is about 5 km wide, to around Aylesbeare and Whimple. The sequence was called Lower Marls by Ussher (1902) but renamed Exmouth Beds by Laming (1966); Smith and others (1974) introduced the term Aylesbeare Group for the same strata. The evolution of the nomenclature is summarised in Table 2. The Aylesbeare Group has been reduced to formational status in this and other reports for the Exeter project because geological mapping has shown that it is unlikely to be possible to subdivide it into component formations. The predominant lithology of the formation has also been indicated in the new formation name, which is thus Aylesbeare Mudstone Formation (usually shortened to Aylesbeare Mudstone in text references). The type area was named by Smith and others (1974) as the village of Aylesbeare, but owing to the lack of inland exposure, the best type section is the sea-cliff between Exmouth and Budleigh Salterton, outside the present district.

Ussher (1902, 1913) recognized that the Lower Marls consisted of two members, the lower of which comprised "marls with sandstones, intercalated at irregular intervals", upon which rested a member of "marls without sandstone". He found it impossible, however, to trace the boundary between the two members inland. The lower member was named the Exmouth Sandstones and the upper member the Littleham Beds by Laming (1968); the same subdivisions were called Exmouth Formation and Littleham Mudstones in Smith and others (1974).

It has proved possible to divide the Aylesbeare Mudstone into two members in that part of the project area south of Aylesbeare. The upper member is named the Littleham Mudstone, the lower is termed the Exmouth Mudstone and Sandstone. The latter term is preferred to Exmouth Sandstone-and-Mudstone used in the district to the south (Selwood and others, 1984), which gives the erroneous impression that sandstone is the dominant component of the member.

In the Exeter district, the base of the Aylesbeare Mudstone is taken at a sharp lithological change from the sandstone of the underlying Dawlish Sandstone to mudstone. The junction is nowhere well exposed, but can readily be traced inland by features and augering. Locally, near Topsham, a lens of breccia occurs at the junction of the Exmouth Mudstone and Sandstone with the Dawlish Sandstone, and its presence foreshadows the situation in the Exmouth area to the south, where Exe Breccia intervenes between the Dawlish Sandstone and the Exmouth Mudstone and Sandstone (Selwood and others, 1984).

The highest bed of the Exmouth Mudstone and Sandstone in the coastal section is a 19-m-thick sandstone that forms Straight Point [SY 037 795], and which is referred to informally as the Straight Point Sandstone. The base of the Littleham Mudstone is taken at the junction of this sandstone and the mudstones that overlie it. When traced inland, the sandstone does not form a single continuous bed, but is lenticular. In view of the lack of continuity of sandstones, it cannot be stated categorically that the topmost mapped sandstone of the Exmouth Mudstone and Sandstone occurs everywhere at the same stratigraphical level as the Straight Point Sandstone. A moderately persistent sandstone defines the top of the Exmouth Mudstone and Sandstone from near the southern margin of the project area to Perkin's Village near Aylesbeare (Figure 2). North of there, the sandstone beds are fewer and more impersistent, and cannot be satisfactorily correlated, and the Aylesbeare Mudstone is not subdivided into members. Sandstone beds in the Exmouth Mudstone and Sandstone are concentrated in the upper one-third of the member, and the lower part contains relatively few very impersistent sandstones.

Exposures of the Aylesbeare Mudstone are generally poor, the mudstones readily weathering to red clay; natural exposures occur mainly in stream banks beneath Alluvium or Head. The sandstones are more resistant to weathering, and steep-sided topographical features are commonly related to the presence of a sandstone bed or beds, which may, however, be too thin to be shown on the 1:10 000-scale map.

Mudstones, the predominant lithology of the formation, are generally massive and structureless in outcrop, with a characteristic blocky-weathering habit. They are normally moderate reddish brown in colour, but commonly contain spherical pale greenish grey 'reduction' spots, irregular patches, and bands. The reddish brown colour of the mudstones is due to ferric oxide, usually hematite, as a coating to grains and as finely divided material in the clay-mineral matrix. The mudstones consist predominantly of silt- and very fine-grained sand-sized grains of angular to subangular quartz (with a few feldspar grains) set in a hematite-stained clay matrix. Generally the mudstones are structureless, although a few thin impersistent silty laminae occur at some levels. Henson (1971) attributed the lack of structure of the mudstones to intensive bioturbation.

Henson (1971) used a sedimentation balance to analyse the grain-size distributions of mudstones from the Littleham Mudstone and the Exmouth Mudstone and Sandstone of the coastal exposures. No sample was analysed from outcrops in the Exeter project area, but the lithologies are so similar and uniform that Henson's analyses are probably applicable to the project area. The mudstones of the Exmouth Mudstone and Sandstone were found to contain usually between 4 and 8% of very fine-grained sand (up to 11% recorded), the remainder comprising sub-equal proportions of silt and clay-grade material (40 to 55% for each grade). The overall mean diameter for the particles within the mudstones was 0.004mm. The Littleham Mudstone samples as a whole contained somewhat smaller amounts of very fine-grained sand (usually between 2 and 5%, with up to 7% recorded). The silt content varies between 30 and 53% and the clay content between 40 and 70%. The overall mean diameter for the particles within the mudstones was 0.0027mm indicating that the Littleham Mudstone as a whole is finer-grained than the Exmouth Mudstone and Sandstone.

The silty mudstones of the Aylesbeare Mudstone were called marls in the past (Ussher, 1902, 1913), but generally the term is restricted to clays or mudstones containing between 35 and 65% calcium carbonate (Pettijohn, 1957, p.410). Typical Aylesbeare Mudstone samples collected during the resurvey of the Exeter district contain between 3.9 and 12% calcium carbonate and are thus marly clay or marly mudstone in Pettijohn's classification. The widespread presence of disused marl-pits on the Aylesbeare Mudstone outcrop indicates that the calcareous content was sufficiently high for the mudstone to be of value for the long-discontinued agricultural practice of marling.

The clay mineralogy of the Aylesbeare Mudstone of the Exeter district has not been examined; Henson noted that samples of the formation from the coastal exposures were composed mainly of illite with subordinate amounts of kaolinite and chlorite.

Concentrations of dark grey nodules that contain high proportions of metallic elements including vanadium, uranium, copper, and nickel occur near the base of the Littleham Mudstone (Carter, 1931; Perutz, 1939; Harrison, 1975; Durrance and George, 1976; Durrance and others, 1980). The nodules are surrounded by olive "haloes", the radii of which increase with the radius of the contained nodule. The best-known locality is at Littleham Cove [SY 040 803]. During the resurvey of the Exeter project area, nodules similar to those from the coastal exposures were collected from a locality [SY0331 9154 to 0335 9154], near Aylesbeare; nodule-bearing strata are also reported from localities [SY0134 8496] near Coombe Farm near the south-west corner of the project area (Dr H.Bateson, oral communication, 1984). These occurrences, both from near the base of the member, suggest that the nodule-bearing strata extend northwards for at least 11km from the coastal sections.

The nodules are post-depositional since layers in them can be seen to cut across bedding in the surrounding rocks. Harrison (1975) considered that precipitation of mineralised solutions occurred mainly at permeable/impermeable interfaces, the ultimate source of the solutions being hot springs associated with waning phases of the metalliferous mineralization of south-west England. However, Durrance and George (1976) suggested that precipitation took place around fragments of contempcraneous plant material.

The origin of the haloes of the nodules is also uncertain. Perutz (1939) thought that they were formed by the diffusion of radon from the nodules, a suggestion disproved by irradiation experiments (Harrison, 1975). Henson (1971), referring to the work of Bloomfield (1964) who showed that considerable quantities of iron are mobilised in organic complexes and could be removed in circulating ground water, considered that the iron deficiency of the bleached haloes could be readily explained by the removal of the iron in complexes with the organic material around which the nodule formed, suggesting a direct link between concentrations of organic material in anaerobic conditions and the formation of the nodules. Durrance and others (1978) proposed that the "reduction" spots of the Aylesbeare Mudstone were caused by the inhibition of oxidation in sediments buried beneath about 1000m of overburden.

The Aylesbeare Mudstone contains thin (generally <1.0m) beds of pale olive calcareous silty sandstone and sandy siltstone. Inland they are too thin and too poorly exposed to map, but in coastal exposures they are laterally persistent for distances of over 400m. Henson (1971) found that the rock consists of subangular to angular quartz grains, with less abundant feldspar and metaquartzite grains, in a clay matrix that is similar in composition to that of mudstones in the formation; a patchy intergranular calcite cement is commonly present.

Sandstones in the Aylesbeare Mudstone are generally reddish brown in colour, medium- to fine-grained, uncemented or weakly cemented where weathered at outcrop. Most samples are moderately sorted or moderately well sorted. Statistical grain size parameters are given in Edwards (1984a, table 3; 1984b, table 3) and Bristow (1984b). Silt and clay contents of the sandstones together comprise less than 6% in most samples, although one contained 11% of silt and clay. The sandstone is composed predominantly of subangular to subrounded quartz and metaquartzite grains, with an estimated 15% to 25% of the total sample weight consisting of feldspar. The sandstones are classified as sub-arkoses and arkoses in the classification of Folk (1968).

Mapping indicates that the sandstones of the Aylesbeare Mudstone form disconnected lenses which may, however, occur at approximately the same stratigraphical level. Between Woodbury and Woodbury Salterton the Straight Point Sandstone is persistent for about 3 km but north of Woodbury Salterton is absent or too thin to map until it thickens rapidly to about 30m at Windmill Hill, Higher Greendale. The sandstones are commonly cross-bedded, but exposures are too few for many measurements of cross-bedding direction and dip, or for the vertical sequence of sedimentary structures to be established. However, examination of well-exposed sandstone beds in the cliffs near Exmouth by Henson (1971) showed that the thicker beds contained fining-upward sequences; the base of each sequence is a sharp, probably erosional, surface which is overlain by plane-bedded and large-scale cross-bedded sandstones, the grain size of which decreases upwards. The Straight Point Sandstone cored in the BGS Blackhill Borehole [SY 0320 8547] consists of a 10m-thick bed of reddish brown cross-bedded sandstone that fines upwards from a sharp base.

Cross-bedding measurements have only been possible in the Exeter project area at Windmill Hill, Higher Greendale, where foresets dip to the ESE and SSE. Henson (1971) measured 63 foresets in the coastal exposures of sandstone beds in the Exmouth Mudstone and Sandstone and found that the distribution was bipolar, the mode to the north being much larger than that to the south. Most fluviatile sequences have unimodal palaeocurrent patterns; Henson attributed the bipolar pattern to the "lateral migration of meandering streams, in which case the true current direction is normal to the axis of the bimodal distribution." The larger northern mode was considered to result from a basin which had a steeper gradient south to north than west to east, indicating a basin elongated east to west with a high land area to the south. The net transport of sediment was towards the north-east.

The geology of the source area of the Aylesbeare Mudstone, as indicated by the types of sand grains, was probably a gneissic basement, possibly with an intrusive granite, partly overlain by a low-grade metamorphosed sedimentary cover (Henson, 1971).

Henson (1970, 1971, 1973), in his studies of the coastal exposures of the Aylesbeare Mudstone, considered that the formation was deposited by rivers in a flood-plain complex. Thus, the thick sandstones of the Exmouth Mudstone and Sandstone were formed in river channels by the deposition of bed-load sediment on advancing dunes or ripples, aggregated into point bars. Such deposits show a characteristic upward decrease in grain size. The thinner (generally < 1m) silty sand beds that occur intercalated in a predominantly mudstone sequence were considered to have formed in the inter-channel area as crevasse splay deposits that spilled out onto the flood-plain during floods. The red mudstones of the formation were deposited on the flood-plain; they show no clear evidence of subaerial exposure, however, and there are no recorded examples of suncracks, calcretes, ferricretes, or evidence of soil formation.

There are no recorded fossils in the Aylesbeare Mudstone of the Exeter project area. Laming (1966) found one poorly preserved plant fragment, possibly a macerated calamite, in sandstone west of Orcombe Point. The same author, and Henson (1971), noted the occurrence of burrows in the sandstones.

Spores recovered from the Aylesbeare Mudstone are all derived, of Devonian and Carboniferous ages (Warrington, 1971).

The Aylesbeare Mudstone is estimated to be 350m thick in the Whimple area (Bristow, 1984b) and 400m thick in the Woodbury area; taken with Henson's estimate of a coastal thickness of up to 530m (but Laming (1966) estimated 450m for the same sequence) there is some evidence for a northward thinning of the sequence.

The clearest facies change in the formation is the decrease in number and thickness of the intercalated channel sandstones north of Aylesbeare (Figure 2). This change may coincide with the incoming of many thin gypsum bands and nodules which, although not recorded at outcrop, were penetrated in a borehole [SY 0659 9111] near Venn Ottery Common, about 1.5km east of the Exeter project area.

4.6 Budleigh Salterton Pebble Beds

The Budleigh Salterton Pebble Beds are one of the most distinctive and widely known of the Permo-Triassic formations of south-west England, owing to their striking textural and compositional differences from the underlying and overlying formations. Their outcrop extends from the south coast at Budleigh Salterton northwards to near Watchet on the north coast.In the southern part of the outcrop (between Uffculme and Budleigh Salterton) the formation consists of uncemented gravel made up of well-rounded pebbles, cobbles, and boulders in a coarse - to fine-grained gravel and silty sand matrix; lenticular beds of sand occur within the gravels. The purple-coloured metaquartzite pebbles contained in the gravels have long attracted attention since they contain an Ordovician and Devonian shelly fauna (Vicary and Salter, 1864; Davidson, 1870; 1880). Between the coast and Uffculme there is a reduction in the mean size of the pebbles.

The pebble beds have an outcrop area of about 5 km^2 in the south-eastern corner of the Exeter project area, where they underlie much of the heathland of Colaton Raleigh, Woodbury, and Bicton Commons (Figure 2). The formation comprises up to 30m of uncemented gravel with sand beds. The base is sharply defined on the underlying Littleham Mudstone, and because of the better resistance to weathering of the pebble beds they form a prominent scarp feature on the mudstones. Resistivity surveys (Henson, 1971, fig.6.6; Sherrell, 1970, fig.7) have shown that the pebble beds base has an irregular topography; Henson noted that ridges and troughs were developed along E-W and NW-SE axes. He considered (1971,p.214) that the irregular basal topography of the pebble beds was the result of incompetent folding during early Alpine movements, rather than channelling of the pebble beds into the Littleham Mudstone; however there is no satisfactory evidence to decide either way at present.

About 90% of the pebbles, cobbles and boulders in the deposit consist of well-rounded metaquartzite up to 0.45m in diameter. the remainder consist of schorl, vein quartz, porphyries and occasional sandstone. They occur within a matrix of about 65% coarse to fine gravel, 20% to 30% sand, and 5% to 12% silt and clay (Henson, 1971, p.185). The gravels generally show a poorly developed horizontal (or very low angle) stratification, caused mainly by changes in grain size, sorting and the amount of matrix. Large-scale cross-bedding of the gravels is less common. Beds of fine- to medium-grained sand, commonly cross-bedded, occur within the gravels at all levels. The sand beds are lenticular, generally 1 to 2m thick, but up to 4m thick at some localities. In the excellent exposures at Blackhill Quarry [SY 031852], sand beds are more persistent in NNE-SSW trending faces than in NNW-SSE-trending faces where they are more lenticular in shape, suggesting the presence of sand channels oriented in a NNE-SSW direction. Poorly developed pebble imbrication and measurements of cross-bedding indicated to Henson (1971) that the gravels and sands were transported towards the north between NW and NE.

The maximum thickness of the formation in the project area is around 30m, compared to 26m in the Budleigh Salterton coastal exposures (Henson, 1971). No major lateral lithological variation of the pebble beds has been noted, but some vertical variation is apparent. Locally, the basal 2m contain abundant fragments of reddish brown mudstone derived from the Littleham Mudstone. Henson (1971) noted that the mean size of the coarse fraction of the formation decreased upwards, but this has yet to be demonstrated by detailed work. Henson (1971) also considered that cross-bedded sand beds are commoner with the upper one-third, but at Blackhill Quarry there appears to be no obvious change in the proportions of sand beds at different stratigraphical levels in the formation. Grain-size analyses of samples from four sand beds (2m, 5m, 10m, and 23m above the base of the formation) at Blackhill Quarry shows that samples from lower in the formation are finer-grained than higher in the formation (Edwards, 1984b, figure 4). These results should be treated with caution in view of the small number of samples studied.

Henson (1970) noted that the top of the Budleigh Salterton Pebble Beds on the coast was marked by a 70-mm-thick layer of wind-faceted pebbles (ventifacts), representing a desert pavement. A similar ventifact layer has been described by Leonard and others (1982) from the east side of Woodbury Common. Ploughing revealed a tightly-interlocking pavement of wind-faceted pebbles, commonly with polished surfaces; the undersides of pebbles were etched and pitted by solution of intergranular quartz. The presence of the ventifacts suggests a hiatus preceding deposition of the Otter Sandstone.

The sedimentary features of the Budleigh Salterton Pebble Beds indicate that they were deposited by braided rivers flowing from the south (Henson, 1971). The channels of such rivers are commonly overloaded with coarse-grained sediment which is deposited as bars in the centre of the channel, causing new channels to form around the bar. Continuous bar formation and channel switching produces a network of braided channels on the alluvial plain, on which there is no clearly defined overbank terrain as in the case of meandering rivers. As a consequence, the alluvium of braided rivers consists predominantly of channel lag gravels and of cross-bedded channel bar and braid bar sands. Fine-grained sediments are rare and generally occur infilling abandoned channels; desiccation cracks have been recorded from such deposits (Henson, 1971, p.188). The nature of the braided river depositional mechanism explains the marked vertical and lateral variation in the proportions of sand and gravel, the lenticularity of the sand and gravel beds, and the general lack of fine-grained sediments.

Many modern braided river systems occur on piedmont fans at the edges of mountains where gradients are steep, large amounts of coarse-grained sediment are available, and discharge is commonly erratic; this was probably the setting in which the pebble beds were deposited.

The pebbles contained in the formation provide considerable information about its source areas. The metaquartzites contain Ordovician and Devonian brachiopods, trilobites, and bivalves which occur in south-west England only as exotic blocks in the Roseland and Meneage breccias. Early authors (Salter in Vicary and Salter 1864; Davidson, 1870; 1880) matched the faunas to those in quartzites exposed in Brittany, so that those areas or northward extensions of those areas into the English Channel were proposed as the source of the pebble beds pebbles (Ussher, 1879). It is, however, unlikely, as Laming (in Durrance and Laming, 1982) has pointed out, that a river capable of transporting cobbles up to 0.4m across would be able to move them as much as 250 km from one side of a desert basin to another. He considered that a more likely source might have been a Palaeozoic ridge in the vicinity of Start Point. Whatever their origin, the high degree of rounding of the pebbles could not have been acquired during a single depositional cycle, and their roundness was probably built up during several periods cf reworking. Other pebble types in the Budleigh Salterton Pebble Beds include contact metamorphic rocks indicating that material was also being derived into the formation from the aureole of the Dartmoor Granite.

Thus the pebbles indicate a general southern derivation for the formation. This is supported by imbrication and cross-bedding data (Henson, 1971), and by the orientation of sand beds in Blackhill Quarry (see above).

4.7 Otter Sandstone

The Otter Sandstone (Upper Sandstones of earlier authors) overlies the Budleigh Salterton Pebble Beds and closely follows the outcrop of that formation from the south coast near Budleigh Salterton to near Minehead on the north coast. The two formations together comprise the Sherwood Sandstone Group of Warrington and others (1980).

Vertebrate remains (amphibian and reptilian) from the Otter Sandstone of East Devon were thought to be possibly of Anisian (early Mid Triassic) age on the basis of the presence of a form of Rhynchosaurus regarded as more primitive than representatives of that genus from the Central Midlands and the Cheshire Basin (Walker, 1969).

In East Devon, "the formation comprises micaceous sands, calcareous sands and fine- to medium-grained sandstone which is generally red and sometimes yellowish in colour, and contains horizons of small pebbles as well as horizons of clay and marl" (Sherrell, 1970, p.258). Henson (1970) described two divisions of the formation, characterised by different sedimentary structures. The lower part consists of plane-bedded graded units with occasional cross-bedded sets with interbedded coarse- and fine-grained beds; the upper part contains cyclothemic sequences which consist of the following upward-fining succession: scoured surface; intraformational conglomerate: large-scale cross-bedded medium-grained sand; small-scale cross-bedded medium- and fine-grained sand.

The formation was 143m thick in a borehole at Greatwell, near Ottery St Mary (Sherrell, 1970, p.258). Only about the lowermost 15m of the formation are present in the Exeter project area, forming a small outcrop (<1km^2) in the south-eastern corner. It consists of reddish brown to yellowish brown micaceous sands and very weakly cemented sandstones that are predominantly fine- to medium-grained. The sands consist largely of quartz, metaquartzite, and feldspar grains, with flakes of muscovite, in a hematite-stained silt and clay matrix that is normally 5% or less of the total sample weight. Most grains are subangular, but coarser grains are more rounded. The few exposures indicate that in the Exeter project area the sands are predominantly plane-bedded, with occasional sets and cosets of large- and small-scale cross-bedded sand. The base of the formation is not exposed in the Exeter project area, but is sharply defined on the Budleigh Salterton Pebble Beds. Reliable deductions about the depositional environment of the Otter Sandstone cannot be made from the limited data available in the Exeter project area. However, Henson (1971) has studied outcrops of the Otter Sandstone east of the project area, and concluded that the sands of the lower part of the formation were deposited in low-sinuosity braided rivers. The first deposits of the formation to be laid down encroached upon a stony desert surface littered with wind-faceted pebbles; the time interval between cessation of pebble beds deposition and initiation of Otter Sandstone deposition is uncertain.

Palaeocurrents responsible for depositing the formation flowed from south to north and have a unimodal distribution (Henson, 1971, p.226); the unimodal pattern and high consistency ratio were considered by Henson to be characteristic of braided river deposition.

The types of quartz, feldspar, and metaquartzite in the Otter Sandstone suggest that the formation was derived from the same sources as the pebble beds, except that hypabyssal or extrusive rock fragments have not been identified in the Otter Sandstone (Henson, 1971). Henson considered that the Otter Sandstone was the later product of the uplift responsible for the deposition of the pebble beds piedmont fan.

5. STRUCTURE

The Carboniferous rocks were folded and faulted during the Variscan Orogeny; their complex structure contrasts with the relatively simple structure and gentle dips of the New Red Sandstone. The Crackington Formation folds are tight, with approximately E-W-trending axes. They have steep (typically 60° to 80°) inverted southern limbs, and less steep, right-way-up northern limbs typically dipping about 45°. Thus the folds face south and are overturned to the south. They vary in wavelength from 0.5m or less to about 10m, but there is some evidence of large-scale folds with wavelengths of hundreds of metres. In areas close to major fractures, the structures may be disturbed, with vertical or near-vertical dips, or in places, contorted or shattered strata. The Carboniferous rocks are commonly affected by small-scale fractures, usually thrusts or strike faults which were synchronous with the Variscan folding. They are too small to be represented on the map.

Larger-scale faults in the Crackington Formation are E-W to ESE-WNW-trending and apparently post-date the main Variscan earth movements. These faults are cut by NNW-SSE-trending wrench faults with dextral displacements, which are part of a regional pattern of wrench faults described by Dearman (1963). They are thought to have been initiated in the Palaeozoic, but were reactivated particularly in the Tertiary.

The bulk of the New Red Sandstone sequence south of Broadclyst is tilted gently eastwards at 5° or less. Dips in the breccia formations south of Exeter and west of the River Exe are steeper (up to 20^{o}) but this figure probably includes an original sedimentary dip that developed on the surfaces of alluvial fans. The New Red Sandstone strata are gently folded at a few localities, for example in the Exminster district where the Heavitree Breccia forms a broad eastward-plunging faulted syncline, and in the Brampford Speke district where members of the Dawlish Sandstone are involved in a broad syncline in the southern part of the Crediton trough.

Two main fault trends are discernible in the New Red Sandstone rocks south of Broadclyst. In the Pinhoe district (Bristow and Williams, 1984) and in the Exminster district (Bristow, 1984a), SE - or ESE-trending faults are displaced by later ESE-, ENE- or E-trending faults.

Few faults can be detected in the Aylesbeare Mudstone outcrop because of the lack of lithological contrast. Some faults cutting sandstones within the formation near Woodbury trend NW-SE to NNW-SSE. Faults cutting the Budleigh Salterton Pebble Beds in the south-east of the project area trend between E-W and ESE-WNW, downthrowing to the south.

An important feature of the Whipton-Pinhoe area is the likelihood that Permian sedimentation was influenced by contemporaneous fault movements. The Monkerton Member is present only to the end of the Mincinglake Fault and the Whipton Formation, Alphington Breccia, Monkerton Member, and Heavitree Breccia are confined to the west side of the Pinhoe Fault (Figure 2). The Hill Barton Fault may have influenced the deposition of the Heavitree Breccia and Monkerton Member as the Heavitree

Breccia is not found north of the fault and the Monkerton Member is much thinner on its south side. The ENE-WSW-trending Honiton Road Fault is presumed to have limited the deposition of the Monkerton Member which does not occur south of the fault.

The Permian-Carboniferous boundary at the southern margin of the Crediton trough between Longford and Huxham has been mapped at outcrop as a fault zone in which an E-W structure has been displaced by later movements. This reflects the view of De La Beche (1839) rather than that of Ussher (1902) who favoured a highly angular unconformity rather than a faulted boundary. In order to investigate this structure, two boreholes at Upton Pyne [9108 9783] and Huxham Barton [9474 9773] were drilled during autumn 1984. The Upton Pyne borehole proved 51m of sandy breccias disturbed at the base, in contact with shattered and brecciated sandstones and shales of the Crackington Formation: the dip of the contact proved is 40^{o} N. A somewhat shallower dip of 33^{o} N was proved at Huxham Barton where 39m of red sandstone with abundant minor fractures rested on weathered, but relatively unfractured Crackington Formation. These boreholes and the field evidence suggest that while some degree of fracturing is present at this Permian - Carboniferous boundary, it is much less marked in the eastern part near Huxham, where the junction is probably an unconformity.

6. QUATERNARY (DRIFT) DEPOSITS

6.1 Head

Head deposits comprise structureless or poorly stratified mixtures of clay, silt, sand and stones which are believed to have moved downslope by solifluction (soil-flow) under periglacial conditions. In south-west England the term is also used by BGS to include weathered bedrock (regolith) which has moved little or not at all. Three generations of Head have been mapped in the present district: Blanket Head and Regolith, Older Head, and Valley Head. In many areas it is impossible to distinguish transported material from weathered rock debris that formed and remained in situ and, in the absence of exposure, neither its thickness nor its original position can be determined. This material is shown on the map as Blanket Head and Regolith and varies in thickness up to 3m.

Blanket Head and Regolith is particularly well-developed on the Crackington Formation. A typical profile commences at the surface in brown clay with indurated sandstone fragments and passes downwards into yellow or pale grey clay with sandstone and shale fragments resting on weathered-in-situ shale and sandstone.

Deposits mapped as Older Head occupy much of the upland area in the ground east of the River Clyst (Figure 3). The surfaces of the deposits have a low relief and dip gently westward away from the pebble beds ridge. The Head consists of pebbles and cobbles, chiefly of metaquartzite derived from the pebble beds, set in a matrix of silty and sandy clay varying to fine-grained clayey silty sand. The pebble content varies, thus the deposit varies from stony clay to clayey gravel. The Older Head is believed to have originated as an extensive solifluction sheet which spread downslope in periglacial conditions from the higher ground to the east, from which it derived pebbles and cobbles. The present outcrops are probably the dissected remains of a formerly more widespread sheet. The thickness of the Older Head is usually less than 3m but exceptionally may reach 4m.

Valley Head consists of locally derived rock debris, so that its composition varies with the composition of the particular solid formation upon which it rests. Thus the deposit may comprise every variation between sandy and silty clay, and clayey and silty sand, with a variable pebble content. The Valley Head occupies the valley sides and bottoms, and probably formed by a combination of solifluction, soil creep and slopewash. In the areas in the eastern part of the present district it is largely derived from the Older Head, and reflects its composition. The thickness of the Valley Head deposits rarely exceeds 2m.

6.2 River Terrace Deposits

River Terrace Deposits are extensively developed in the valleys of the Exe, Clyst, Creedy and Culm and their tributaries. Eight levels have been mapped: a few terraces have been mapped as River Terrace Deposits undifferentiated where there is insufficient evidence to allow their correlation. The levels of the bases of the deposits range from 0.5m to 36m above the present floodplain. The upper surfaces of the terraces are commonly eroded and degraded; in places this has made separation of contiguous terraces difficult or impossible. It has, however, proved possible to correlate the River Terrace Deposits of the various river-systems, so that the same numbering system is applied throughout the present district.

The composition of the deposits is very variable, and is clearly related to the catchment area of the depositing stream. Thus the terraces of the Exe and Culm are predominantly composed of pebbles and cobbles of rounded Culm sandstone, with rounded quartz, quartzite, and lava pebbles and a few flints, set in a matrix of fairly coarse-grained sand, which itself contains a varying amount of clay and silt. The lower terraces (Second and First) are usually predominantly sandy, but often contain a basal gravel course.

The River Terrace Deposits of the Clyst and its tributaries characteristically contain a high proportion of well-rounded metaquartzite cobbles and pebbles derived from the Budleigh Salterton Pebble Beds; Culm sandstone fragments are less common, otherwise the composition of these deposits is similar to those described above.

6.3 Alluvium and Alluvial Fan

Tracts of Alluvium are found in all the main river valleys in the district and along their larger tributaries. In most areas the Alluvium can be divided into a lower unit of sand and gravel and an upper unit of silty and sandy clay. In the lower reaches of the Exe valley the lower unit is composed of up to 7m of sandy gravel, thus forming a potential gravel resource. The alluvial clay fraction varies from brown and reddish brown silty and sandy clay where derived mainly from Permian rocks, to heavy brown clay where Carboniferous rocks provide the main source. A few small alluvial fans have been mapped on the sides of the Exe valley. The deposits consist of gravel with silt and clay.

6.4 Estuarine Alluvium.

About 4km of the southern part of the district are occupied by the intertidal Estuarine Alluvium of the Exe Estuary. The deposits are compcsed largely of mud which is in part stabilised by mussel colonies. A small area of sand is present adjacent to the river channel. On the west bank of the Exe and along the Clyst valley a total of about $5km^2$ of former salt marsh has been reclaimed from the estuary and is now pasture. Boreholes in this area have proved up to 5m of silty clay resting on up to 6m of gravel.

6.5 Peat

A small tract of peat overlying sand and gravel occurs near Southern Lake, Broadclyst.

7. ECONOMIC GEOLOGY

7.1 Soils

The soils of the Exeter area have been fully described in Clayden (1971), and the distribution of soil types is shown on the 1:63 360-scale soil map (Sheets 325 and 339). The main characteristics of the soils and their relationship to the geology of the project area can be summarised as follows.

Soils developed on the Crackington Formation or on shaly Head belong mainly to the Halstow series, with small areas of the Dunsford series. Not all soils on the Crackington Formation are poorly drained as is generally supposed: Dunsford soils are moderately well drained shallow brownish clay loam over shale on steeper slopes (for example, in Stoke Woods). Less well drained gleyed brown earths of the Halstow series occur on less steep sites; they occupy much of Ashclyst Forest in the NE of the project area.

Permo-Triassic breccias in the SW of the district carry mainly soils of the Crediton series, consisting of well drained gravelly loams.

Much of the Dawlish Sandstone outcrop, together with thicker sand beds in the Aylesbeare Mudstone, and the Otter Sandstone outcrop, are occupied mainly by brown earths of the Bridgnorth Series, consisting of sandy loam and loamy sand. The Crannymoor series forms small pockets of humus-iron podzols within areas of Bridgnorth soils. Small areas of the Bromsgrove series - loamy or silty brown earths - occur north of Broadclyst, partly on the Bussells Mudstone outcrop. Most of the outcrop of the Aylesbeare Mudstone is overlain by Older Head or a thin surface layer containing metaquartzite pebbles. This surface layer gives rise to imperfectly or poorly drained gleyed brown earths of the Whimple series, with smaller areas of the more strongly gleyed Brinsea series. The tcpmost horizons of the Whimple soils are reddish brown stony silt-loam or clay loam, generally about 40 cm thick, overlying about 35cm of stoneless silty clay. Brinsea series soils are distinguished from Whimple series soils by the presence of a brown or yellowish-brown horizon which is usually mottled. Clayden (1971) considered that Brinsea soils were related to the presence of thicker and coarser-textured Head than that on which Whimple soils formed, but no such relationship is clear from the recent survey.

Areas of Kiddens series soils have been mapped by the Soil Survey as narrow belts along the foot of the pebble beds scarp, and on the Littleham Mudstone inliers of Colaton Raleigh Common and Bicton Common. The Kiddens series was described by Clayden (1971) as"a somewhat heterogeneous group of strongly gleyed soils in loamy and sometimes gravelly Head over a fine-textured substratum".

The pebble beds outcrop is occupied by soils of the Budleigh Complex, classed as humus-iron podzols. A typical profile (Clayden, 1971, pp. 78-79) consists of about 25cm of pale brownish grey gravelly sandy loam, on about 10cm of dark reddish brown extremely stony loam, on a horizon of pale yellowish brown extremely stony loam normally 5 to 10cm thick, but up to 20 cm in places. At its base is commonly a very thin irregular layer of iron-pan resting on _in situ_ pebble beds.

Estuarine Alluvium of the R. Exe and R. Clyst is occupied by the Exminster series, consisting of ground-water gley soils in non-calcareous clayey or silty alluvium occupying marshes. Alluvium of the project area carries a variety of alluvial soil types including the Exe series along the River Exe; the Clyst series along the River Clyst; and Mixed Bottomlands. The Exe series consists of well drained brown warp soils on the silty Alluvium of the Exe. The Clyst Series consists of gleyed brown warp soils in reddish brown clayey Alluvium. The soils along the higher reaches of the Clyst and its tributaries are in more mixed parent materials and are more variable; they are mapped as Mixed Bottomlands. The Cutton series of loamy and coarse loamy humic or peaty gley soils occupies small areas in Alluvium or Peat on the Dawlish Sandstone outcrop.

7.2 Sand and gravel

The sandstones of the Crackington Formation are a potential source of aggregate in some parts of Devon, and their properties as skid-resistant road surfacing material has been commended by Hawkes and Hosking (1972). Unfortunately, the ratio of shale to sandstone in the present district would prevent efficient extraction of suitable material.

The Heavitree Breccia, where poorly cemented, could be a possible source of gravel. Generally, however, it is too clayey (Bristow, 1984a, table 5) for exploitation as an aggregate, but it could be used for road base or for local tracks.

The Dawlish Sandstone is a source of building sand. Because of its thickness (commonly in excess of 80m) and its wide outcrop the overall resource volume is extremely large. However, the overall grain size (fine) and the variable grain size, with numerous interbeds of breccia in the south, and mudstones in the north, partly diminish its economic potential. The only working quarry within the district is Bishops Court Quarry [965 914] wherein the weakly-cemented sands are passed over a coarse screen to remove the iron-cemented material and sold in an ungraded condition for use in the building industry.

Grading figures for the Dawlish Sandstone of the area between Clyst Honiton and south of Exminster are included in Bristow and Williams (1984) and Bristow (1984a).

The Budleigh Salterton Pebble Beds form a large potential resource of sand and gravel; about 250 000 tonnes per year are extracted from the ECC Blackhill Quarry [SY 031 852]. It is estimated that where the pebble beds average 30m in thickness they are likely to yield between 105 000 and 125 000 tons of sand and gravel per acre (Report of Planning Enquiry,1968, para 36). The deposit contains 10 to 13% by weight of silt and clay; about 50% of the processed material is sand. The deposit is dug from the face by mechanical shovels and transported to a processing plant where it is screened and washed. The sand and crushed pebbles and cobbles are used for surface chippings, concrete aggregate, high-grade concrete sand and sand for tile manufacture. The fines are transferred to settling ponds. When full, the ponds are left to dry out before being covered with quarry waste prior to restoration.

The pebble beds are part of the unconfined portion of the important Triassic aquifer, from which supplies of groundwater for public supply are extracted by boreholes along the River Otter (Sherrell, 1970). Quarrying is potentially capable of adversely affecting yields from this aquifer by reducing the area available for infiltration, or by increasing run-off.

The Otter Sandstone is a potential sand resource of considerable volume, but it is not worked at present. Sand from near the base of the formation was extracted from a now infilled small pit [SY 0424 8518], at Tucker's Plants; the uses of the worked sand are not known. Grading analyses of samples of the Otter Sandstone are given in Edwards (1984b, table 5).

The patches of older River Terrace Deposits within the district could provide a local source of gravel, but their generally limited outcrop area combined with their thinness, would preclude large-scale exploitation. The younger terrace spreads are more extensive and are potentially a better resource. Second Terrace Deposits have been worked in the area [9800 9443] north of Hayes Farm, Clyst Honiton (Bristow, 1984b), and in the Culm Valley near Bussell's Farm [9551 9976] (Bristow, 1983). At both localities the pits are about 2m deep. No figure is available for the thickness of the gravel in these areas; in the Culm Valley the gravel may exceed 3m in thickness, whereas at Clyst Honiton it probably does not exceed 2m. Grading figures for the Second Terrace Deposits from the spread [985 9403] north-east of Clyst Honiton are given in Bristow and Williams (1984, table 3.).

The thickest and most extensive potential gravel resource in the district is the alluvial gravel of the rivers Clyst, Culm and

Exe. In the Clyst Valley the thickness varies from 1.0 to 2.7m, with an average (based on 11 boreholes) of 1.95m. Grading figures for the deposits in this area are included in Bristow and Williams (1984, table 3). An estimated 3.5 million cubic metres of alluvial gravel is present in the stretch of the Clyst between Clyst Honiton and its confluence with the Exe.

In the Culm Valley only two boreholes have penetrated the alluvial gravels and these proved thicknesses of 4.3m [9454 9883] and 4.9m [9551 9976] (Scrivener, 1983; Bristow, 1983). If these figures are representative then some 9 million cubic metres of alluvial gravel are present within the Culm Valley of the present district.

The alluvial gravels of the River Exe within the urban area have a mean thickness of 2.24m (Scrivener, 1984), whereas downstream in the Exminster area the mean thickness is 3.6m (Bristow, 1984a). Grading figures for this latter area show the deposits to have a gravel content that varies between 82 and 89% (Bristow, 1984a). The estimated resource of alluvial gravel of the Exe within the present district is 80 million cubic metres.

In calculating the above potential resources factors such as urban sterilization, which might restrict their exploitation, have not been taken into account.

7.3 Building stone

The Heavitree Breccia for hundreds of years provided a ready source of accessible and easily worked building stone. Examples of the breccia can be seen in the walls of many of the barns, older cottages and field boundaries throughout the district. The breccia, however, is only weakly to moderately cemented; Berger (1811) noted that the breccia hardened on exposure. Nevertheless on weathering the breccia is liable to crumble, particularly on faces exposed to rain. In former times the breccia was commonly faced with cob; nowadays many examples of breccia are protected by plaster or a concrete render. There are now no commercially worked pits in this stone, but its former widespread exploitation is evident from the many old pits throughout the district (see Bristow, 1984a, table 4). Some small-scale domestic extraction continues, mostly to provide hard core.

The Permian lavas have also provided building stone and extensive use of this material has been made since early times in the Exeter urban area; no quarry is active at the present day. The Rougemont basalt which forms the eminence in the centre of the old city was used as a source of building stone. In more recent times the principal sources of stone were the quarries west of Exeter and outside the present district, for example, the substantial working at Pocombe [898 916]. The small existing demand for local basalt to repair old walls and buildings is met from stocks of previously used material.

7.4 Brick clay

The only working brick-pit in the Exeter area is at Pinhoe [956 946]. There the shales and sandstones of the Crackington Formation are extracted for the production of facing, engineering and paving bricks. Some 100 000 tons per year of shale and sandstone are currently extracted and crushed for an annual production of 35 million bricks (oral communication, Mr G Thompson, 1984).

The Whipton Formation and poorly cemented, finer-grained parts of the Alphington Breccia were formerly extensively worked for brickmaking in the Exeter city area (Scrivener, 1984).

There are numerous small pits scattered across the outcrop of the Aylesbeare Mudstone. Many of these were dug for marl, but some have utilized the mudstone for brick clay.

7.5 Marl

The outcrop of the Aylesbeare Mudstone of the Exeter district is liberally dotted with shallow, commonly water-filled, pits, ranging in size from a few metres across to about 0.5 hectares in area. About 380 such pits are present in the district. Some of the pits were dug for brickclay, or clay for making cob, or to create ponds for watering stock, but many were probably dug to obtain calcareous clay ("marl") to spread on the non-calcareous soils of the formation. Analyses of four samples of Aylesbeare Mudstone clays indicate contents of calcium carbonate that vary from 3.9 to 12.6% (mean 7.1%)(Bristow, 1984b; Edwards, 1984b). Ussher (writing before 1913) noted that the practice of marling had been discontinued by that date.

7.6 Lime

Shapter (1862,p.184) noted that the Heavitree Breccia north-west of Exeter is locally sufficiently calcareous to have been worked for lime, but no figure for the carbonate content is quoted. Two analyses for calcium carbonate from the Exminster district showed the Heavitree Breccia to contain between 1 and 5%

carbonate (Bristow, 1984a); it is not known whether these figures are representative. Within the present district an old lime kiln was noted at Kenn [9203 8530]; in the Exminster area the former Limekiln Lane Cottages [9382 8878] and Kiln Close Plantation [9300 8827] are witness to the former industry. All three localities lie close to old quarries in the Heavitree Breccia. It is possible, however, that the name Limekiln Lane Cottages is derived from a lime-burning industry based on Chalk brought up river by boat to the Matford area.

7.7 Metalliferous minerals

Manganese

Manganese ores were formerly worked in the district from Permian rocks close to their faulted junction with Carboniferous rocks. Mining activity took place between 1788 and 1849 with some later, unsuccessful prospecting (Scrivener and Beer in:Durrance and Laming, 1982). The ores were used in glassmaking and in the preparation of bleach. A small partly filled pit [9022 9771] near Langford, another [9462 9764] near Huxton Barton and a flooded drift [9112 9979] at Upton Pyne are the only recognizable traces of the former mining activity. Ussher (1902) noted, without giving details, the presence of manganese at Ratsloe [958 976]. Da La Beche (1839) considered that the ores were associated with fractures which splayed off a fault separating the Carboniferous and Permian rocks. There is no indication of the extent of these manganese deposits.

Vanadiferous nodules

Minerals recorded from vanadiferous nodules in the Aylesbeare Mudstone (see section 4.5, above) include native copper and silver, (?modderite, niccolite, rammelsbergite, coffinite, vanadian mica, malachite and freirinite (Harrison, 1975).

Carter (1931) used autoradiograph techniques to establish that the nodules were radioactive; he recorded 0.07% U_3O_8 from one nodule. Perutz (1939) recorded uranium contents of 0.3% and 0.5% by radiometric and chemical techniques respectively; Durrance and others (1980) thought that the chemically determined value was likely to be nearest the correct value. Harrison (1975) noted that the concretions radiometrically assay between 0.006 and 12.3% U_3O_8 (most values between 0.1 to 0.5% U_3O_8).

Carter (1931) recorded 13.96% V_2O_5 from the dark part of a nodule.

7.8 Made Ground

Within the Exeter urban area there are extensive tracts of Made Ground (Scrivener, 1984). Some of these are obscured by building developments while others, such as the former refuse tip in the Mincinglake valley and the areas of fill associated with flood prevention works in the Exe alluvial plain, are landscaped and used as recreation areas.

In addition to the embankments along the M5 Motorway and the A 30 trunk road, substantial areas of low-lying ground [910 897, 919 889, 9120 8635 and 943 885] and some large valleys [918 881, 924 883 and 919 875] were built up or filled during the construction of the above two roads. It is presumed that most of the fill was derived from the cuts in the Heavitree Breccia and Dawlish Sandstone, but in the marshes at Exminster [943 885] some building material forms part of the fill. In this last area the made ground has a maximum thickness of about 2m. A considerably thicker infill is present in the large valleys; for most of these their original floor level is not known and the thickness of the fill can only be estimated: at Peamore [918 881] there appears to be about 3m of Made Ground; lower down this same valley [924 883] the maximum infill is estimated to be 5m; south of Peamore Garage [919875] there is probably up to 10m of fill in the deepest part of the valley.

7.9 Engineering Geology

The Crackington Formation over much of the Exeter district is mantled by extensive deposits of Valley Head and Blanket Head and Regolith. The formation of the regolith cover was accompanied by downhill mass movement which has practically ceased in the present climatic regime. No geotechnical data are available for the Crackington Formation nor for the extensive regolith developed on it. Stability of slopes on the Crackington Formation is gcverned by the extent and nature of the drift cover, as well as the structure and lithology of the underlying solid geology. Natural slopes developed on the formation do not exceed 26^{o}, with values between 10^{o} and 16^{o} common; most slopes appear stable. The steeper north-facing slopes in predominantly north-dipping shales and sandstones, commonly show small slips measuring a few metres across and probably affecting only the superficial deposits. Larger slips are less common, and are present on shallower slopes where the strata are more shaly, or where there is an abnormally deep weathering profile as in the areas close to the Permian/Carboniferous boundary (Scrivener, 1984). The only large landslip observed within the present district is at Ash Copse [962 953], Pinhoe. There an area about 150m by 200m on a 15^{o} - slope on the Crackington Formation has slipped to produce a hummocky surface. The slip occurs at the intersection of two faults, and these may have shattered the Crackington Formation and contributed to the initiation of the slip. The dip of the formation is not known at this locality, but if it is to the north or north-east then this would aid downhill mass movement.

Most slopes and cuttings in Crackington Formation of normal type appear to be inherently stable and steep road cuttings stand well though there may be local slippage of overlying superficial deposits. The river cliff section of the Exe adjacent to Bonhay Road [914 927] exposes a shaly sequence cut by low-angle fractures and this has, in places, required the support of stone revetments.

The Crackington Formation typically shows a deep weathering profile and exposures commonly show that shales in the uppermost 1.2m have been altered to a poorly structured clay, beneath which there is a gradation into more or less weathered shale. A cored borehole [9003 9457] near Exwick Barton proved 11.4m of weathered shale and sandstone beneath 2.6m of superficial deposits (Blanket Head and Regolith); The weathered material rests on shales and sandstones with iron-stained joints.

Much of the outcrop of the Whipton Formation is concealed beneath urban Exeter. Geotechnical data for the Whipton Formation are confined to one borehole [9704 9421] near Pinhoe. There the Whipton Formation contains low plasticity clays (Bristow, 1984, figure 4). Natural slopes are less than 4^{o} and it is probable that artificial cuttings in the formation would also have to be low angled. The railway cutting [9264 9346] near St James's Park Halt is angled at 30^{o} and has stood since its construction in the last century. It is cut, however, at the base of the Whipton Formation in a breccia-rich part of the sequence that is relatively well cemented. The near-vertical sides of the stream section [9417 9342] south of Polsloe Bridge shows much slippage in the more argillaceous parts of the sequence.

The Alphington Breccia consists of poorly cemented, shale-rich breccia which weathers to a clay soil. There is no geotechnical information for this member. Most natural slope angles are less than 8^{o}, but scarp slopes with slope angles of 15^{o} appear stable. Artificial cuts along the A 30 south-west of Exeter are generally low-angled at 25^{o} or less. Cuttings in the Alphington Breccia in urban Exeter are usually supported by revetments. The river cliff at the Quay [9144 9266] in Exeter stands well, but there is some evidence of erosion resulting in the accumulation of small debris cones.

The Heavitree Breccia has a weak to moderate cement over much of its outcrop. In the north, around Hill Barton, the cementation is confined to thin beds which give rise to ribs of cemented material within a sequence of poorly cemented breccias. Berger (1811) noted that the breccias hardened on exposure. Faces, many of which appear to be joint-controlled, in the many quarries in the breccia have remained vertical for decades. Where the breccia is exposed on lower-angled slopes, however, the faces are subject to erosion; gullies quickly develop on such faces leaving a talus cone at the foot. Joints with openings up to 10cm wide have been recorded near Exminster (Bristow, 1984a). In the Exminster area the outcrop of the Heavitree Breccia is crossed by several large faults, but none have been seen in section. Although the design of foundations in the breccia is unlikely to cause difficulties, their excavation might be hampered by their cement.

The Monkerton Member consists dominantly of clayey, fine-grained sandstone. No geotechnical data are available for this member. The principal outcrop is below the scarp of the Dawlish Sandstone south of Pinhoe where it forms gently sloping ground with a slope angle of less than 7°.

The Dawlish Sandstone comprises dominantly fine- and medium-grained, weakly cemented sandstone. Thin bands of red mudstone and breccia occur locally in the outcrops east of Exeter; thicker beds of breccia are present south of Exminster. Thin bands of ferruginous cement are developed in places. Natural slopes do not exceed about 13°. Despite their weak cement, vertical faces in the Dawlish Sandstone may be up to 15m high [Bishops Court Quarry, 964 914], although the top part of the face is liable to crumbling and rapid erosion by water. Old road cuttings [e.g.9747 9292 and 9900 9325], in the better-cemented sandstones have stable vertical faces 2m high. Newer road cuttings [e.g.969 935 and 965 913] have faces inclined between 30° and 40°. For the most part the Dawlish Sandstone is free-draining, but thin local seams of clay can give rise to perched water tables with associated springs. During the construction of the M5 Motorway steeply dipping joints, with openings up to 10cm wide, were noted in the cuttings [969 935].

The Aylesbeare Mudstone consists of reddish brown, weakly calcareous, overconsolidated, silty mudstone becoming a stiff, low to intermediate plasticity silty clay on weathering (Bristow, 1984b, figure 2; Edwards, 1984a, figure 3); thin bands of sand and weakly cemented sandstone occur in the lower part of the formation (the Exmouth Mudstone and Sandstone) south of Aylesbeare. The weathered zone has been observed in boreholes to extend to depths of 10m, but the depth of weathering is likely to be variable and probably on average is about 4m (Bristow, 1984b; Edwards, 1984a;b). Moisture contents are usually less than the plastic limit, so the liquidity index is usually negative for the weathered clay. Natural slope angles in the mudstones are less than 13^{o} in the present district; landslipping has been recorded at only one possible locality [0385 8723], near Woodbury Castle, in the present district. There, water seeping from the base of the Budleigh Salterton Pebble Beds has given rise to minor movement, resulting in a small area of hummocky ground in the underlying Littleham Mudstone. Although cuttings with angles up to 45^{o} have been constructed in the mudstone, care should be taken in their design, particularly where the mudstone is more deeply weathered. Where the formation contains water-bearing, uncemented sand, supports and/or dewatering may be necessary. For example, a trench [0127 8896] to 0130 8883] at Woodbury Salterton hit running sand and was only stabilized with the aid of continuous sheet-piling (Edwards, 1984b). Faces cut in sandstones of the Exmouth Mudstone and Sandstone such as road and quarry faces [0054 8731] near Woodbury are vertical and have been stable for over 40 years (Edwards, 1984b). Tests on soil samples from the Aylesbeare Mudstone show sulphate contents to be low, 0.01 to 0.02%.

The Budleigh Salterton Pebble Beds consist of generally medium dense to very dense, cobble and boulder gravel with beds of silty sand that are generally lenticular in form. Some of the disused quarry faces at Blackhill Quarry [SY031 852] are subvertical and over 10m high. With time such faces weather to a loose scree, commonly with an overhang at the top of the face where the gravel is held together by modern roots. Water seepages occur at levels above the zone of saturation in some faces, mainly at the top of the sand beds and perched water-tables may therefore, occur locally within the formation. Perched water-tables may also occur locally at the junction with the underlying Aylesbeare Mudstone.

The Otter Sandstone consists of generally very dense, micaceous, fine- to medium-grained sand, or very weakly cemented sandstone. Exposures within the district show sub-vertical, apparently stable, faces that are weathering steadily. Layers of clay may occur locally and give rise to local perched water-tables. Excavations below the water-table in the Otter Sandstone may encounter running sand.

Site investigations for light structures on gentle slopes on the argillaceous formations (Crackington Formation, Whipton

Formation, Alphington Breccia, Monkerton Member and the Aylesbeare Mudstone) could be limited in scope to proving the depth to unweathered mudstones and to confirming the strength and settlement characteristics of weathered mudstone. The presence of water-bearing sands, if present, should be proved and their effects on the proposed works predicted.

Geotechnical data for the Quaternary deposits are limited and not necessarily comprehensive or representative. Plasticity data for the Alluvium and Head are plotted in individual 1:10 000 sheet reports. The results show the clays to be of low to intermediate plasticity. However, the borehole logs show the bulk of the alluvial deposits to consist of gravelly sandy clays or clayey sands and gravels, locally organic. The organic content of the upper, clayey, part of the Alluvium is generally low, but some samples of peaty silty clay contain as much as 24% of organic material.

Site-investigations in the Quaternary deposits will need to be more extensive than in the solid deposits to prove the nature, depth and variability of the deposits in relation to the structures proposed. Particular problems may be experienced where soft silty clays are encountered.

7.10 Water Resources

7.10.1 Triassic System

The Otter Sandstone and Budleigh Salterton Pebble Beds together form the major aquifer of the area, although it occupies only a small part of the extreme south-east. The two formations are in hydraulic continuity, although different values of hydraulic conductivity may be assigned to each (Sherrell, 1970). Much of East Devon's water supply is abstracted from the aquifer via boreholes in the Otter valley, east of the present area. The importance cf the East Devon Commons (east of Woodbury) is that they form part of the unconfined area of the aquifer. Cradock-Hartopp and others (1982) noted that the Otter Sandstone at outcrop yields an excellent quality, moderately hard water. Pebble beds water is acidic, with low total dissolved solids, calcium and bicarbonate contents, and is therefore potentially corrosive; it can maintain high levels of trace metals in solution. The only known well-test is recorded by Sherrell (1970): a shaft "at Blackhill" 9.14m deep, with a saturated thickness of 2.43m gave a value for the coefficient of transmissibility of 153 500 litres/day/metre thus indicating hydraulic conductivity as being about 63 200 litres/day/metre. The test, however, was conducted for 6 hours only.

7.10.2 Permian System

Aylesbeare Mudstone.

The Aylesbeare Mudstone largely acts as an aquiclude. It does however yield sufficient water for small private supplies, but is nowhere used for public water supply. Yields are generally less than 1 litre/second (l/s) from the Littleham Mudstone and from the Aylesbeare Mudstone undivided, but higher yields arise from the sandier strata of the Exmouth Mudstone and Sandstone; one bcrehole near Woodbury yielded 6.3 l/s (Edwards, 1984a).

Dawlish Sandstone Formation

The Dawlish Sandstone forms an important clastic aquifer which is confined beneath the Aylesbeare Mudstone over much of the present area. Thin beds of mudstone probably act as aquitards and give rise to local layered aquifer systems but fissuring allows inter-aquifer movement. Cradock-Hartopp and others (1982) noted water of generally good quality with total hardness (predominantly carbonate) averaging about 200 milligrams/litre (mg/l) chloride and sulphate falling within the range 15-25 mg/l, and iron rarely being detected. Nitrate levels, however, are locally high and were considered likely to increase because catchment areas are intensively cultivated. Within the sandstones, up to 40 per cent of the transmissivity is attributable to intergranular permeability. Yields are variable, the highest in the present area outside the Crediton Trough being from a well at Exeter Airport, which yielded 12.8 l/s for a drawdown of 29.3m after 6 days. In the area of the Crediton Trough, where the Dawlish Sandstone is divided into five members, the mudstone members and beds within the Formation are aquitards, and give rise to a layered aquifer system interconnected by fissures. Additionally, the Brampford Speke Sandstone and underlying breccias act as a single major aquifer in the area of Brampford Speke. High yields occur hereabouts; water production boreholes in the vicinity of the village provided test yields ranging up to 41.0 l/s from the Sandstone and underlying breccias for a drawdown of 26.8m over 14 days.

7.10.3 Carboniferous System

The outcrop of the Crackington Formation north of Exeter provides some small local supplies, but yields are low, ranging up to a maximum of 0.44 l/s.

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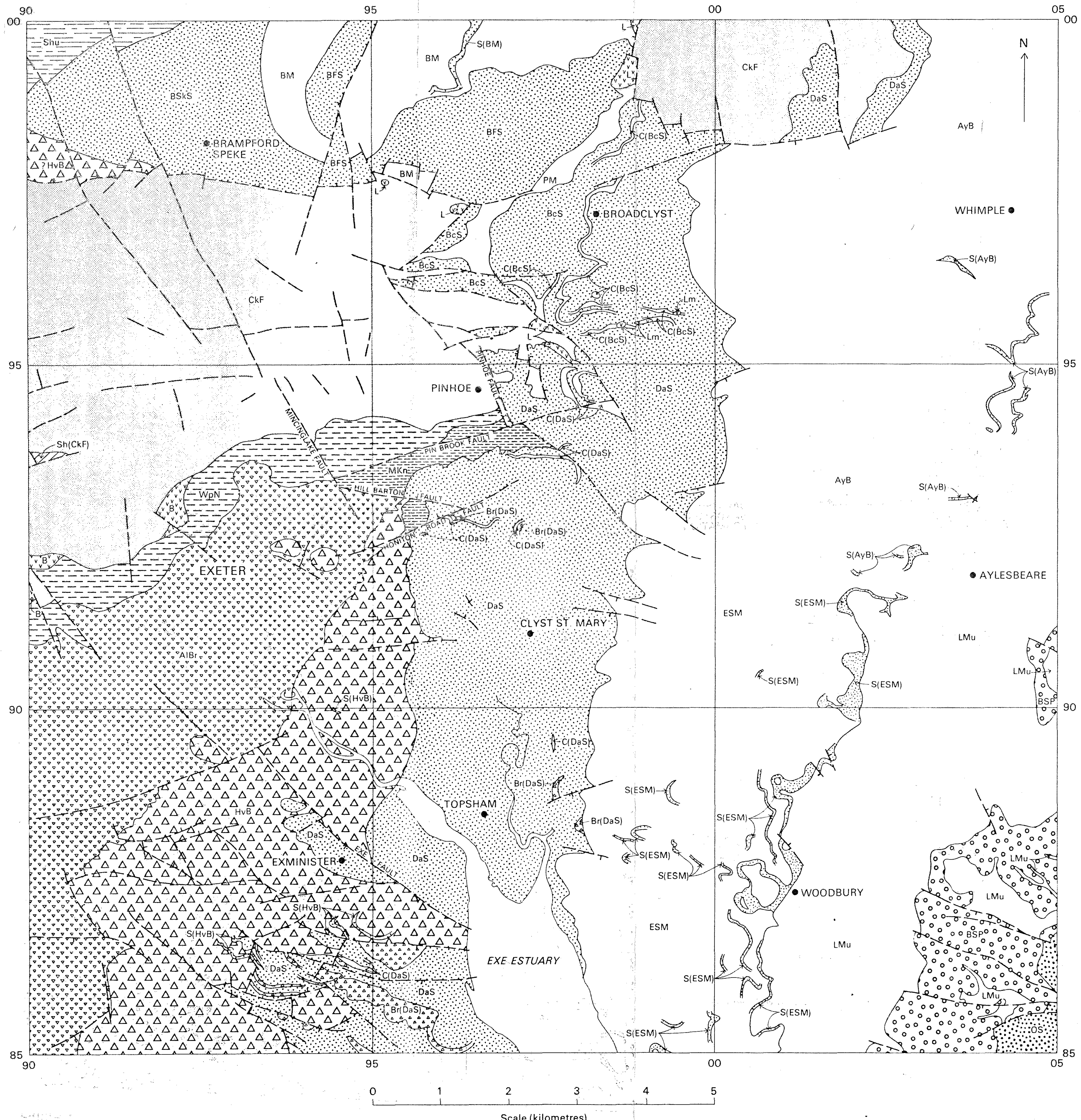
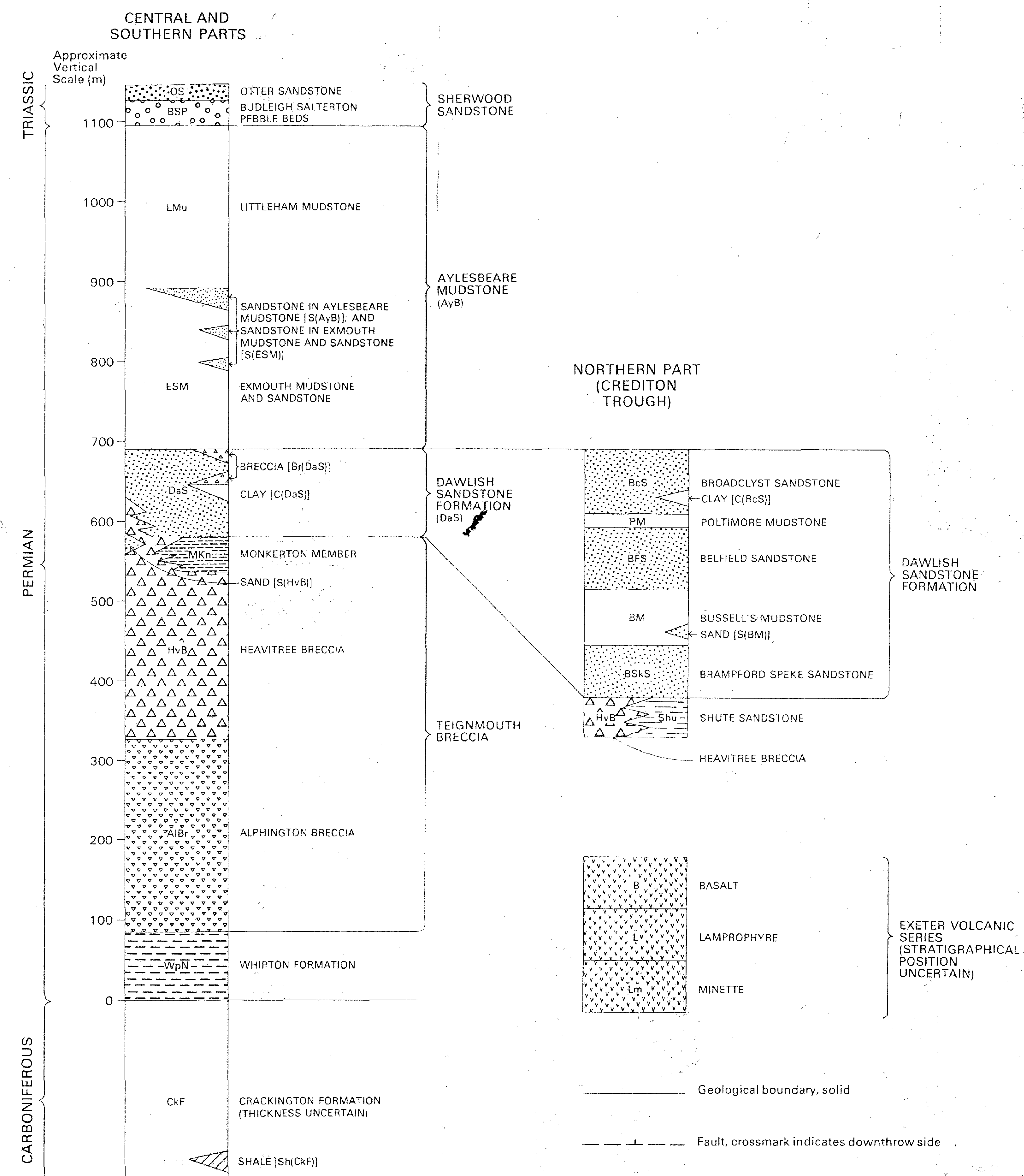
Figure 2 Solid geology of Exeter and its environs

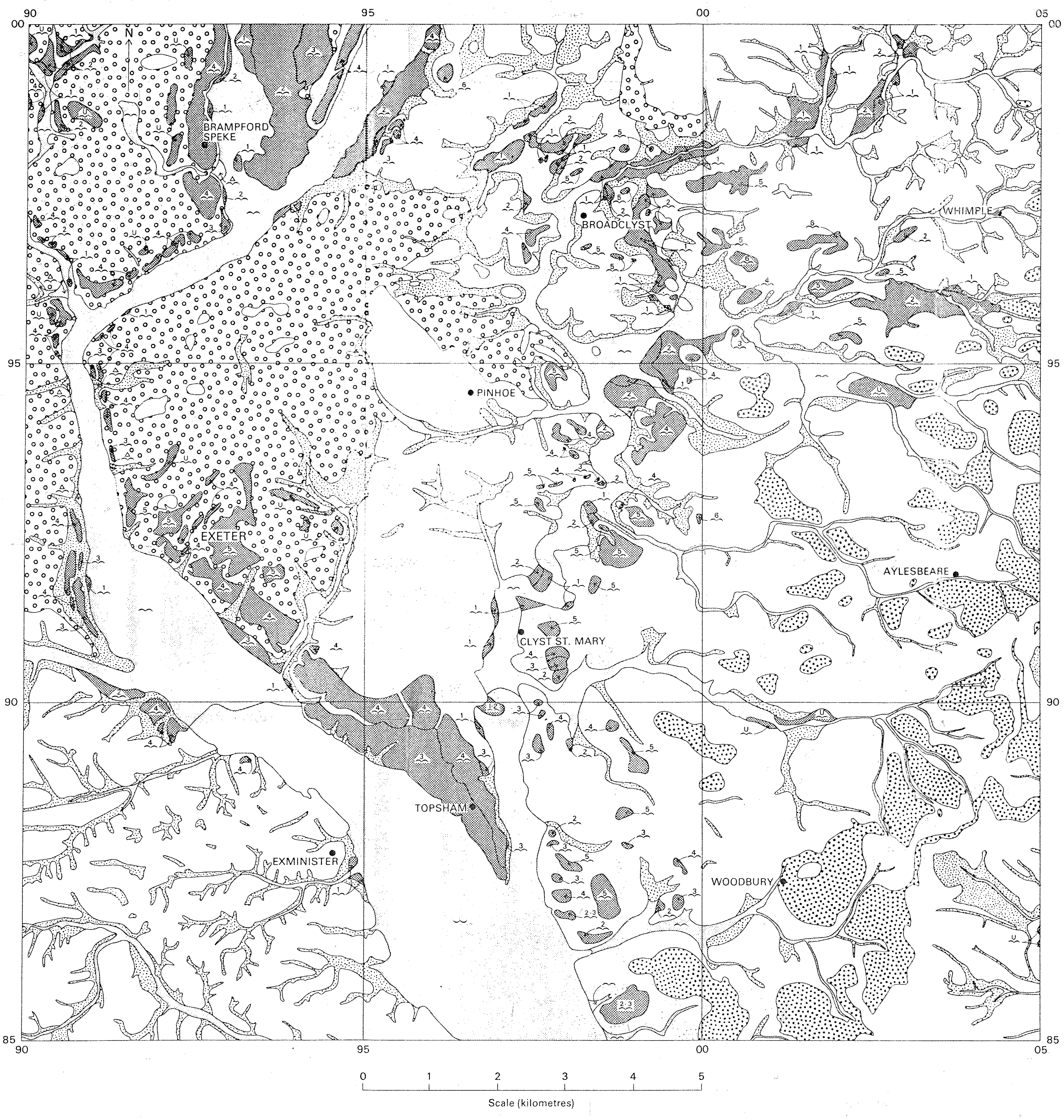


Key to ornaments and symbols



WAVG843

Figure 3. Quaternary ('Drift') geology of Exeter and its environs



Key to ornaments and symbols

QUATERNARY

- Alluvium
- Alluvial Fan
- Peat
- River Terrace Deposits, as numbered
- River Terrace Deposits, undifferentiated
- Estuarine Alluvium
- Valley Head
- Older Head
- Blanket Head and Regolith
- Geological boundary, drift

WAVG 843