BRITISH GEOLOGICAL SURVEY

THE ENGINEERING GEOLOGY OF THE SIDMOUTH DISTRICT 1 : 50 000 GEOLOGICAL SHEET 326/340

TECHNICAL REPORT WN/98/1

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INTRODUCTION

This description of the engineering geology of the district around Sidmouth (Fig. 1) was based on the lithostratigraphical units shown in Table 1. They may be subject to amendment as the remapping proceeds. The account also includes information from a geotechnical database compiled by the Coastal and Engineering Geology Group of the BGS.

The geotechnical database was compiled from reports of site investigations for trunk roads, motorways and other construction projects carried out in or near the district which were held by the BGS in the National Geoscience Data Collection. Additional information was obtained from scientific papers published on the geology, engineering geology and the earth surface processes that had affected the area.

The geotechnical samples and their geotechnical parameters were obtained for the requirements of particular construction projects, and the sampling and geotechnical testing done on the samples were governed by the technical requirements of those projects. Therefore, the data that were abstracted from site investigation reports and entered into the geotechnical database do not necessarily represent all the lithostratigraphical units of the area. Also the values shown may not be representative of the variation in properties within a lithostratigraphical unit. However, there was sufficient information to give a guide to the likely behaviour of most of the lithostratigraphical units that had been mapped.

The geotechnical data were abstracted from good quality site investigation reports and entered into a computer database using Microsoft Access The data were split into subsets on the basis of lithostratigraphical unit and the subsets analysed statistically to provide summary statistics and X-Y plots. The results of this analysis enabled the lithostratigraphical units to be described in terms of their geotechnical properties and likely behaviour in engineering operations.

ENGINEERING GEOLOGY OF BEDROCK MATERIALS

The Chalk

No geotechnical data from site investigations were found for the Chalk in the district but the stone from the chalk mines in the Middle Chalk at Beer has been used for many years as a dimension stone. Although soft and easily worked when first quarried it hardens on drying to give a harder more durable stone. Watson (1911) quotes a bulk density of 2.11 Mg/m^3 and a strength of 16.22 MPa which is stronger than that of other UK chalks used for dimension stone which he lists.

The engineering behaviour of chalk in construction is strongly influenced by weathering that may extend to depths of several metres and the weathering grade should be identified in site investigations. The classification of Chalk in terms of its behaviour and properties for engineering purposes has been the object of much effort by many workers and the resulting schemes are strongly linked to its state of weathering. The first major scheme was that of Ward et al. (1968) based on work at Mundford in Norfolk but it was stressed at the time that it applied specifically to the Mundford site. Subsequently it has been widely adopted despite this caveat. Some of the inadequacies of the original scheme have been addressed by others and it has proved useful for the Upper and Middle Chalk (Wakeling 1969; Jenner and Burfitt 1975). Essentially Chalk is graded on the basis of fracture spacing and dilation to give six grades. Grades I to IV are 'structured chalk' in which the original structure of joints, fractures and bedding can be identified. Grade V and VI are 'structure-less chalk' in which the structure has been destroyed leaving, initially, a wide range of sizes of chalk lumps in a subordinate, fine matrix (grade V) and, ultimately, a remoulded matrix-dominated assemblage of coarse and fine chalk fragments with a similar behaviour to a cohesive soil (grade VI).

Lord et al. (1994) proposed a comprehensive classification of Chalk, which included weathering, based on intact dry density, discontinuity aperture and discontinuity. The Chalk is initially classified as structureless or fissured. The structureless Chalk is subdivided on the basis of the comminuted matrix being more or less than 35%. The fissured Chalk is subdivided on the basis of a field assessment of density (later refined by laboratory determined density), discontinuity spacing and discontinuity aperture.

The description and classification of weathering for engineering purposes was addressed by the Geological Society's Engineering Group Working Party (Anon., 1995) and they proposed the use of five approaches depending on the nature of the material. Chalk may be described using either "Approach 4", which is based on material and mass features, or "Approach 5" which is for special cases not following the patterns covered by the other four approaches.

Sampling chalk is made difficult by its open structure of poorly-cemented, component grains which renders it highly sensitive to mechanical disturbance. Thus, sampling by techniques such as the Standard Penetration Test, U100s or thin-wall driven samplers result in remoulding and fracturing to a greater or lesser extent, which will be reflected in the results of any strength tests which are done on those samples. Better samples may be obtained using rotary coring with sample quality improving as more protection is given to the core by using core barrel liners or triple tube coring methods. Adequate protection of the core and samples against mechanical damage and drying out is particularly important in the case of weak rocks and particularly those which are sensitive to irreversible changes on drying, such as chalk.

However, despite the high quality of samples that may be obtained by advanced coring methods, the test results obtained in the laboratory will not be able to allow for the fracturing in the rock mass. Consequently, in situ testing, such as large diameter plate tests, may offer the best method to establish the strength characteristics of chalk. However, for many engineering purposes visual description of in situ chalk with SPT and index test results can be used to assess the character of chalk (Howland 1991; Fookes and Martin, 1977).

Generally, unweathered Chalk offers good foundation conditions with good bearing capacity and low, rapid settlement. However, the possibility of natural solution cavities, which may be empty or filled with material of contrasting geotechnical properties, must be considered. Artificial cavities from chalk or flint mining may also be present. The high natural water content may lead to slurrying and high positive pore water pressures if chalk is over-compacted in earthworks or haul roads. Flints may cause a high rate of wear on plant such as excavators and tunnelling machines.

Active instability of natural slopes in chalk is usually only associated with coastal cliffs either being actively eroded at their base or recently abandoned and in the process of degrading to a stable angle. Sea cliffs are commonly in excess of 65° and may be vertical or overhanging where erosion is active at the base. Inland, the maximum slope angle for stable slopes is generally found to be between 30° to 35° (Clark and Small, 1982). Slopes in excess of this may be expected to degrade until they reach this angle and slopes in excess of about 45° are unlikely to maintain a permanent cover of vegetation

Upper Greensand

Index tests in the database indicate a median moisture content of 23% with a range of 8 to 40%, a median bulk density of 2.02Mg/m^3 with a range of 1.91 to 2.10 Mg/m^3 and a median dry density of 1.75 Mg/m^3 with a range of 1.49 to 1.76 Mg/m^3. Plasticity data for the clayey material indicate it to be an inorganic clay of medium plasticity with a few values extending into low and high plasticity (Fig.2). Particle size analysis data in the database indicate that the Upper Greensand is predominately a well-sorted, clayey, silty, fine- to medium-grained sand (Fig. 3). Standard Penetration Test data in the data base give a median 'N' value of 26 indicating a medium relative density but ranging from 6 (loose) to about 65 (very dense). When plotted against depth a clear trend of increasing density with depth was seen, especially in the predominantly sandy lithologies (Fig. 4). The silty and clayey lithologies also show an increase in SPT 'N' value with depth (Fig.5, Fig.6) but with a few tests giving a steeper increase in value with depth. Few strength values are present in the database and effective stress values (4) indicate a median value for c' of 27.5 with a median phi' of 30.5^{O}. Brunsden (1996) quotes phi' value for sandy material in the range 33 to 35^{0} range, with residual phi values as low as 12^{0}, and cohesions of 6 to 23kPa in the lower part which contains more clay. Compaction tests (7) indicate a median value for maximum dry density value of 1.80 Mg/m^3 at an optimum moisture content of 13%. A median California Bearing Ratio value of 3.5 was calculated from six tests on silty sand.

The fine-grained sands and silty lithologies of the Upper Greensand may be susceptible to frost heave to the detriment of shallowly founded structures such as paths and light roads. Excavations should be possible by digging . The Upper Greensand has a bad reputation, locally, as a running sand and its liquefaction may be a contributory factor to landslide activity in the area (Brunsden, 1996). Excavations below the water table may encounter running sand conditions and require close-boarded support or other support.

Gault

The Gault clay is thinner and more sandy in the south west of England than to the north and east, in East Anglia, and in south east England. This is reflected both by the lack of geotechnical data in the database and in the geotechnical properties of those samples which had been recorded (Forster et al.,1994). The descriptions of samples recorded in the database are silty, sandy clays with a median value for moisture content of 20% (64 samples); plasticity indices (2 samples) indicated an inorganic clay of intermediate plasticity with a median plastic limit value of 19% and a median liquid limit of 38%. These values were similar to Area 1 (>100 samples) of Forster et al. (1994) which gave median values for moisture content of 24%, plastic limit of 24% and liquid limit of 52%. This data set extended to the north-east as far as Trowbridge where the proportion of clay in the Gault clay was believed to increase.

Middle Lias

No geotechnical values for the Middle Lias were available for the database.

Lower Lias

Index tests for the Lower Lias in the geotechnical database indicate a median moisture content of 34% with a range of 20 to 44%, a median bulk density of 1.88 Mg/m^3 with a range of 1.77 to 2.22 Mg/m^3 and a median dry density of 1.45 Mg/m^3 with a range of 1.33 to 1.63 Mg/m^3. Plasticity data indicate it to be an inorganic, silty clay of intermediate to very high plasticity (Fig.7). Particle size analysis data for two samples in the database indicate that the Lower Lias was a very silty clay with a little sand but the samples may not be representative of the material as a whole. Standard Penetration Test data in the data base give a median 'N' value of 41 (hard) but ranged from 24 (very stiff) to 52 (hard). When plotted against depth, a trend of increasing density with depth was found but, with few results available, it was not possible to determine a significant relationship (Fig.8). Few strength values were in the database and effective stress values indicated a wide range of values, depending on lithology, from c' = 0, phi' = 17^0 (calcareous silty mudstone) to cu' = 27 kPa, phi' = 35^0 (silty clay). Compaction tests (7) indicated a median value for maximum dry density of 1.77 Mg/m^3 at an optimum moisture content of 17%. A median California Bearing Ratio value of 2 was found for five tests on silty clay and calcareous silty mudstone.

Penarth Group

Little geotechnical information was found for the Penarth Group in the area and only six SPT 'N' values were recorded in the database. These ranged from 'N' = 38 to 'N' = 161 which reflects the wide range in lithology, from silty mudstone through calcareous silty mudstone to limestone, which was found in this Group.

Westbury Formation

The Westbury Formation is poorly exposed in the area but was sampled at a beach-level exposure at Culverhole Point by Pitts and Brunsden (1987) who described it as a very stiff to hard, grey to black, laminated and occasionally fissured, variably carbonaceous pyritic and selenitic shale. The main clay minerals identified were illite and kaolinite with calcite and minor quartz. They reported its geotechnical properties as; bulk density 2.045 Mg/m^3, moisture content 23%, residual cohesion $c'_r = 4kPa$ and residual $\phi'_r = 4.5^0$

Mercia Mudstone Group

Index tests indicated a median moisture content of 23 % with a range of 7 to 36 %, a median bulk density of 2.01 Mg/m^3 with a range of 1.83 to 2.19 Mg/m^3 and a median dry density of 1.55 Mg/m^3 with a range of 1.49 to 1.69 Mg/m^3. Plasticity data for the Mercia Mudstone Group indicated it to comprise inorganic clay of low to intermediate plasticity but with two values, for the Blue Anchor Formation, in the very high plasticity range (Fig.9). Particle size analysis data (4 tests) in the database indicated that the Mercia Mudstone was predominately a silty clay with a little sand but one test indicated it to be a well-graded sandy, silty, clayey gravel which was likely to be due to a poor disaggregation of the sample since the lithological description was 'silty clay'. Standard Penetration Test data in the database had a median 'N' value of 46 (hard) but ranged from 3 (soft) to about 161 (hard). When plotted against depth a clear, but diffuse, trend of increasing 'N' value with depth was seen (Fig. 10). Few strength values were represented in the database, but undrained cohesion values (33) had a median value of 95 kPa (range 26 – 365) and showed little correlation with depth (Fig. 11) perhaps due to the cemented nature of the mudstone. Effective stress values (13) had a median value for c' of 50 kPa (range 20 – 155) and a median phi' of 15^O (range 0 – 29). Compaction tests (3) indicated a median value for maximum dry density of 1.76 Mg/m^3 at an optimum moisture content of 16 %. Three California Bearing Ratio tests in the database gave a wide range of values, namely 1.5, 3.5 and 21.

Sherwood Sandstone Group

Otter Sandstone

The Otter Sandstone is generally a moderately weak, reddish brown or yellowish brown, silty, fine- to medium-grained sandstone which weathers to a very dense, silty, fine- to medium-grained sand. Index tests indicated a median moisture content of 12 % with a range of 6 to 24. No density data were found and the Otter Sandstone was not plastic. Particle size analysis data in the database (30 tests) indicated that the Otter Sandstone was predominately a well-sorted, silty, medium- to fine-grained sand with a little clay. However, two samples were well-graded, sandy silt and well-graded, sandy gravel (Fig.12). Standard Penetration Test data in the database had a median 'N' value of 29 (medium dense) but ranged from 4 (loose) to 54 (very dense). When plotted against depth a clear, but diffuse, trend of increasing 'N' value with depth was seen (Fig. 13)

Although moderately weak the Otter Sandstone may form steep, stable, natural slopes of up to 45° where they are protected from basal erosion, and stable vertical faces up to 12 m high have been cut by the River Otter. Higher sea cliffs are seen at Ladram Bay [SY 850 095] (Fig.33) and west of Sidmouth by Chit Rocks [SY120 860]. To the east of Sidmouth at the mouth of the river Sid other vertical faces have developed but, where they were subject to marine erosion at their base, active rock falls were present. In the Exeter area road cuttings, up to 15 m deep, have been excavated successfully at angles of 30° to 40°. Older road cuts with near-vertical faces appeared to remain stable up to 3 m high, but where they were between 3 and 8 m high the faces showed isolated instability due to loose blocks and overhangs as a result of weathering and erosion.

The finer-grained sands and silty lithologies of the Otter Sandstone may be susceptible to frost heave to the detriment of shallowly founded structures such as paths and light roads.

Excavations in weathered material should be possible by digging, but in well-cemented areas more vigorous methods such as ripping may be required. Excavations below the water table may encounter running sand conditions and require close-boarded support or other support measures. The thin mudstone and conglomerate beds may act as minor aquicludes and may give rise to perched water tables to the detriment of slope stability, or cause face instability in cuttings.

Budleigh Salterton Pebble Beds

The Budleigh Salterton Pebble Beds are brown or red-brown, medium dense to very dense, silty, sandy gravels with well-rounded, pebbles, cobbles and boulders mainly of quartzite. Beds of cross-bedded silty sand and pebbly sand, commonly lenticular, occur within the gravel.

Geotechnical data in the database were mainly from cone penetration tests (CPT) which may be misleading due to the possibility of the cone tip impacting on large cobbles giving anomalously high N values. The median value for N was 32 (dense) with a range of 15 (medium dense) to 58 (very dense). Generally, the relationship between CPT and depth was one of increase with depth but very diffuse due to the coarse nature of the material (Fig.14). Particle size distribution data indicate the Budleigh Salterton Pebble Beds to be sandy, cobbly gravels with some silt. The grading ranges from well-graded to well-sorted (Fig 15).

The Budleigh Salterton Pebble Beds do not form natural slopes greater than 12°, except where cut by rivers, when slopes up to 25° may form, or sea cliffs which may stand close to the vertical. Artificial slopes, in excavations such as quarry faces, may also stand near to vertical. Weathering causes debris to accumulate below such faces forming a scree slope. The erosion of steep cut slopes may be caused by seepage from perched water tables in the Pebble Beds due to thin beds of silty sand acting as aquicludes.

Excavations in the Pebble Beds should be possible by heavy excavating equipment, although where they are worked for aggregate in the Exeter area, techniques intermediate between hard rock quarrying and sand and gravel extraction are used. Excavations below the water table would suffer rapid inflow of water and, in the sandier lithologies, running sand conditions.

A spring line may occur at the base of the Pebble Beds at the junction with the Littleham Mudstone Formation. This may cause slope instability on susceptible mudstone slopes below the Pebble Beds.

The Pebble Beds are suitable for use as aggregate. The crushed quartzite has good wear and polishing resistance and the absence of colloidal silica makes it suitable for use as aggregate in concrete. They may be used as backfill in trenches and excavations below the water table, but will need the addition of cohesive soil for use in embankments.

Aylesbeare Mudstone Group

Littleham Mudstone Formation

The Littleham Mudstone Formation is a reddish brown, well-jointed, slightly calcareous silty mudstone in which the more strongly cemented beds form breaks in the slope angle of natural slopes and cliffs. The mudstone weathers to a fissured, plastic, silty clay.
Index tests indicated a median moisture content of 18 % with a range of 12 to 27 %, a median bulk density of 2.15 Mg/m^3 with a range of 1.66 to 2.21 Mg/m^3, a median dry density of 1.77 Mg/m^3 with a range of 1.62 to 1.87 Mg/m^3. Plasticity data for the Littleham Mudstone Formation indicated it to comprise inorganic clay of low to intermediate plasticity (Fig.16). Particle size analysis data (6 tests) in the database indicated that Littleham Mudstone Formation was predominately a silty clay with a little sand (Fig.17). Standard Penetration Test data in the database gave a median 'N' value of 32 (hard) but ranged from 16 (very stiff) to 55 (hard). When plotted against depth a clear trend of increasing 'N' value with depth was seen (Fig.18). Few strength values were present in the database; undrained cohesion values (10) had a median value of 99.5 kPa (range 43 – 225) and showed a general increase in value with increasing depth (Fig. 19).

ENGINEERING GEOLOGY OF SUPERFICIAL MATERIALS

River Terrace Deposits,

The coarse deposits laid down by rivers in the district have in the past been called valley gravel, river gravel and river terrace deposits according to age and topographical position. These deposits are of similar genesis and were considered together in terms of their geotechnical properties as River Terrace Deposits. The composition of gravel deposits and their geotechnical properties varies according to the rock types present in the source area. This was demonstrated by the wide range of lithological descriptions in the database. They were mainly gravels, sandy gravels and gravelly sands, but there may be significant amounts of finer deposits such as silty or sandy clay, and sandy or gravelly silt. Particle size distribution data (Fig. 20) illustrated their wide range of composition but showed relatively few samples with a significant proportion of fine material. Generally the curves indicated a quite well-graded distribution.

Cone and Standard Penetration Test data indicated a median 'N' value of 22 (medium dense) with a range of 4 (loose) to 74 (very dense). In most cases, the relationship of 'N' value with depth suggested a rapid increase in value with increasing depth but with a lot of scatter in the 0 to 4 m depth range (Fig.21). Plasticity data on the finer-grained material indicated it to be mainly inorganic, sandy clay of low plasticity.

Compressibility is expected to range from very low for the gravels to medium for the silts or clays and to take place rapidly on the gravels and at a medium rate on the silts and clays. The only exception would be if organic clay or peat were present, in which case high compressibility may prevail; consolidation will be fast for peat but slow for organic clay.

Excavations should be possible with normal digging equipment, but support may be required in the less dense material. Excavations below the water table may meet very high rates of water inflow and running sand.

The gravel deposits should give good foundation conditions, but the presence of pockets of material of contrasting properties (clays, silts, organic material) should be investigated; such pockets should be avoided, removed or otherwise dealt with to avoid differential settlement.

Head

Head is a term used to denote material which has moved down slope under gravity, by the processes of solifluction, soil creep and hillwash. Therefore it is in a more or less remoulded condition and composed of a variable mixture of the bedrock and superficial lithologies up slope of its position. It is likely to be inhomogeneous with regard to its lithology and its geotechnical properties.

Although it is related to its source material, the behaviour of Head is not accurately predictable unless it lithological composition has been mapped in detail. In the east of the district two distinct heads were recognised by Conway (1979a): Cretaceous Head and Lias Head. The Cretaceous Head consisted of chert and flint gravel in a sandy clay matrix of moderate to high plasticity with low shear strength whereas the Lias Head consisted of clay or shale breccia in a remoulded clay matrix of very high plasticity and very low shear strength

Index test results in the database for undifferentiated Head indicated a median moisture content of 20 % with a range of 5 to 51 %, a median bulk density of 2.03 Mg/m^3 with a range of 1.83 to 2.03 Mg/m^3, a median dry density of 1.69 Mg/m^3 with a range of 1.38 to 1.86 Mg/m^3. Plasticity data for Head indicated it to comprise inorganic clay of low to intermediate plasticity with a few values falling in the high to very high ranges (Fig.22). Particle size analysis data (56 tests) indicated that Head comprised a very wide range of particle size distributions, even when the data was split according its lithological description into clayey head and sandy head (Figs 23, 24). Composition ranged from sandy silt to cobbly, sandy gravel. Standard Penetration Test data in the database for clayey head gave a median 'N' value of 17 (very stiff) but ranged from 1 (very soft) to 66 (hard). Sandy head had a median 'N' value of 29 (medium dense) with a range of 5 (loose) to 80 (very dense). When plotted against depth a diffuse trend of increasing 'N' value with depth was seen with a more rapid increase in 'N' value shown in clayey head (Fig. 25) than in sandy head (Fig. 26). Few strength values were present in the database but undrained cohesion values (15) had a median value of 65 kPa (range 15 – 250) and showed a general increase in value with increasing with depth (Fig. 27). Compaction tests (25) were similar for both sandy and clayey head and indicated a median value for maximum dry density value of 1.96 Mg/m^3 and 1.92 Mg/m^3 at an optimum moisture content of 10% and 11% respectively. A median California Bearing Ratio value of 2 was found for 17 tests in a wide range of lithologies from silty clay to silty, gravelly sand

Head is generally of low strength and may be excavated with digging machinery. It will require support in excavations and although commonly thin it may be several metres thick at the foot of slopes. It may contain perched water tables or water-bearing sands that will flow into excavations causing their collapse. Cretaceous Head offers adequate foundation conditions for small to medium sized structures where it contains a high proportion of gravel, but where it is clay-rich it offers poor foundation conditions, as does Lias Head.

The solifluction process which was active in the formation of Head deposits may leave relict shear surfaces within the Head which are potential surfaces on which movement may take place if the toe of the slope were excavated, the slope loaded, water introduced into the slope or the drainage of water from the slope impeded. Engineering works on slopes covered by thick Head should include a slope stability investigation at the site investigation stage. Lateral changes in lithology and hence geotechnical properties may give rise to uneven settlement of a structure and care must be taken to determine the bearing capacity when constructing on Head deposits. Where deposits are not excessively thick it may be desirable to remove them and place the foundation on bedrock.

Clay with Flints

Index test results in the database for Clay with Flints indicated a median moisture content of 22 % with a range of 12 to 44 %, a median bulk density of 1.87 Mg/m^3 with a range of 1.81 to 2.13 Mg/m^3 and a median dry density of 1.48 Mg/m^3 with a range of 1.34 to 1.84 Mg/m^3. Plasticity data for Clay with Flints indicate it to comprise inorganic clay of intermediate to high plasticity with a few values falling in the low range. Particle size analysis data (2 tests) indicated that Clay with Flints was a fairly well graded clayey, silty sandy gravel. But according to the lithological descriptions of other samples in the database it comprised a wide range of compositions from silty clay through clayey and sandy gravel to clayey gravel and cobbles. Cone and Standard Penetration Test data in the database for Clay with Flints gave a median 'N' value of 41 (dense/hard) but ranged from 16 (medium dense/very stiff) to 90 (very dense/hard). However, in an inhomogeneous and coarse material Cone and SPT values might be expected to be erratic. When plotted against depth a diffuse trend of increasing 'N' value with depth was apparent. Few strength values were present in the database; undrained cohesion values (8) had a median value of 84 kPa (range 49 – 160) and two values for effective cohesion were both 9 kPa. A single compaction test on a sample of silty clay indicated a median value for maximum dry density of 2.06 Mg/m^3 at an optimum moisture content of 9 % and a California Bearing Ratio value of 3.

Alluvium (excluding gravel)

Alluvium in the Sidmouth district ranged from a brown or reddish brown soft to stiff, normally consolidated silty or sandy clay to sandy gravel and some organic material. The median value for natural moisture was 26.5 % with a range of 8 to 156 % and bulk and dry density were 1.85 Mg/m^3 (range 1.73 – 2.13 Mg/m^3) and 1.35 Mg/m^3 (range 1.26 – 1.43 Mg/m^3) respectively. Plasticity data showed a wide range of values from sandy inorganic clay of low plasticity to inorganic clay of extremely high plasticity. Some values fell below the A-Line indicating silty or organic material. However, the bulk of the data fell in the low to high plasticity categories (Fig.28). Particle size data for the alluvium confirmed its wide compositional range (Fig.29).

Standard Penetration Test values gave a median N value of 6 (firm) and ranged from 2 (soft) to 56 (hard) but showed little correlation with depth. Few values (4) for undrained cohesion were recorded in the database (4) but two of these indicated the possible presence, in some areas, of a desiccated crust with a higher strength than material below it. A single value for effective cohesion was found of 47 kPa with a phi' of 0. Alluvium may be expected to have medium to high compressibility with a medium to slow rate of consolidation.

Alluvium may be easily excavated by normal digging methods, but excavations are likely to require support and precautions against running sand may be needed. Excessive water inflow may be met if underlying water-bearing gravels are penetrated. Very weak soft alluvium may be met below a stronger desiccated crust. The lower material would offer poor trafficability if the desiccated crust were removed or disrupted.

The Alluvium may contain minor ribbon-shaped or lenticular bodies of peat or sand which could cause differential settlement of structures founded across their edge.

Marine Deposits

Marine Deposits in the Sidmouth district ranges from normally consolidated, silty or sandy clay to sandy silts and clays with some peat. The median value for natural moisture was 35% with a range of 23 to 91% and bulk and dry density were 1.84 Mg/m^3 (1.46 – 2.04 Mg/m^3) and 1.42 Mg/m^3 (0.76 – 1.66 Mg/m^3) respectively. Plasticity data indicated it to be a sandy, inorganic clay of low to intermediate plasticity with some values falling below the A-Line indicating the presence of organic material. Particle size data for the alluvium confirmed its wide range of composition.

Standard Penetration Test values gave a median 'N' value of 7 (loose/firm) and ranged from 2 (very loose/soft) to 26 (medium dense/very stiff) and showed a very good correlation with depth (Fig. 30). Few values for undrained cohesion were recorded in the database (6) with a median value of 14.5 kPa (range 5-26 kPa). Effective stress data gave a median value for effective cohesion of 10.5 kPa with a phi' of 0^0 but ranged from 45 kPa with a phi' of 28^0 for a silty, clayey sand to 5 kPa with a phi' of 0^0 for a peaty silty clay. Marine Deposits may be expected to have medium to high compressibility with a medium to slow rate of consolidation.

Marine Deposits should be easily excavated by normal digging methods, but excavations are likely to require support and precautions against running sand may be needed. Excessive water inflow may be met if underlying water-bearing gravels are penetrated. Very weak soft material may be met below a stronger desiccated crust. The lower material would offer poor trafficability if the desiccated crust were removed or disrupted.

The Marine Deposits may contain minor ribbon-shaped or lenticular bodies of peat or sand which could cause differential settlement of structures founded across their edge

LANDSLIDES

The Sidmouth district contains lithological sequences and structures that predispose the area to slope instability. Inland, slopes have, in general, reached a mature configuration, which is in equilibrium with the current climatic conditions, and active slope instability due to natural processes is uncommon. However, along the coastal zone, which forms the southern margin of the district, where marine erosion is active there is an exceptional range of active landslides and slope movements that are recognised as classic examples of geomorphology.

Classification and description of landslides

A number of characteristic types of mass movement types were observed, identified and described on the Dorset Coast between Black Ven and Burton Bradstock by Conway (1976a) and between Axminster and Lyme Regis by Pitts (1979). The mass movements on the coast of the Sidmouth district can be divided into four broad categories:

1. Free falls under gravity.
2. Flows.
3. Translational movements, with failure occurring on a relatively planar shear surface, either deep or shallow, with regard to the ground surface.
4. Rotational movements, involving failure along a curved shear surface either at a shallow or deep level relative to the ground surface.

1. Free falls under gravity

Rock fall is the free descent of material from a steep slope under the influence of gravity alone, in which separation from the parent mass occurs chiefly as a result of movement on joints and fissures. Simple falls occur where material is undercut by erosion, and topples occur where material falls from a steep face with an outward rotation. Falls due to joint failure are common from weak, jointed sandstone such as the Otter Sandstone or from weak, jointed mudstone such as the Belemnite Marl. Dilation and detachment on joints and bedding planes are facilitated by stress relief, the swelling of clays on hydration, frost action due to the expansion of water when it freezes and wedging by roots of vegetation growing into cracks.

2. Flows

There are several modes of shallow, lateral transport of material which are active along the coast and they are essentially flows of a fluid or plastic nature. They may be observed as distinct individual movements or as changing from one mode to another with variation in moisture content, slope, weathering and the degradation of the materials concerned. Shallow, lateral, movement is the most common form of mass transport on the coast and is continually active, to a greater or lesser extent, in one form or another.

a. Seepage erosion

Seepage erosion is a form of movement in which soil particles are carried away by ground water seepage at a free face, leading to the undercutting of overlying strata, causing their eventual collapse, and to the consequent development of gullies. Seepage erosion resulting in gully formation is active along the entire length of the coast section within the district, and occurs commonly in the Cretaceous sands and the Lias clays.

In the case of the Upper Greensand the downward movement of percolating ground water is impeded by horizons of secondary cementation within the sequence causing highly seasonal springs to be thrown out at the cliff faces. Cementation is in the form of iron oxide or silica towards the base of the Chert Beds and calcium carbonate in the Foxmold. In these circumstances the soft sandstone and loose sand are rapidly eroded to form gullies and the degradation of the cliff profile is accelerated. Gullies which develop as a result of the ground water being thrown out towards the bottom of the Chert Beds erode back to form funnel-like embayments in the cliff top. The process of head erosion is accelerated by the removal of the sandy clay matrix leading to falls of coarse chert-rich material that forms debris cones at the foot of the gullies.

Seepage erosion in the Lias clays occurs where thick accumulations of debris on cliff terraces become saturated and water is thrown out at the junction of the debris with the in-situ clays or at a limestone band within fissured clays. Thick deposits of head overlying Lias clays also result in minor seepage erosion producing denticulation of the cliff top. The formation of gullies in Lias clays is rapid, largely because the weathered surface layer (which may be up to a metre thick) is susceptible to erosion. The orientation of the faces of the gullies may be controlled by joint planes.

Parallel gullies often develop on cliff faces in fairly close proximity to one another and their funnel shaped heads intersect. The effect of this is the formation of a series of conical buttresses separated by deeply incised gullies. When this happens failure of a buttress can occur resulting in the formation of a rotational slide.

b. Wash

The term wash is applied to highly mobile, seasonal down slope movements of arenaceous and argillaceous debris by unchannelled flows of surface water. The movement of material in this manner is greatest on slopes of less than 50^0. Accumulations of debris transported in this manner may be up to 0.5 m thick and extend 10 m from the foot of the slope. Another aspect of wash is the festooning of debris over undercliff terrace faces. Although of minor importance as far as the movement of material is concerned, wash has in some circumstances an effect on the stability of other materials. Where, for example, a clay wash is carried over a face of porous sand it can form an effective non-porous seal. This may allow an increase in pore water pressure within the sands, possibly greater than the water table at the surface condition, with a consequent significant reduction in their shear strength. On clay slopes wash grades into sheet flow and similarly sand wash grades into sand runs.

c. Mudflows

Mudflow is a slow moving, seasonal down slope movement of argillaceous debris, on a surface at shallow depth, taking place by liquid and /or plastic flow of the material. The flows erode their own channels or flow tracks. The bulk of the material making up a flow comprises angular fragments and on drying, when much of the water has been lost, it assumes the lithological characteristics of a clay breccia.

The material feeding a mudflow may be contained in a discrete flow bowl or occur as unconfined accumulations on ledges or terraces. Desiccation crusts develop during dry periods and are fractured and heaved by subsequent movements giving rise to arcuate pressure ridges across the toe area. The area in front of mudflows, which is being actively eroded by the sea in the inter-tidal zone, is often marked by boulder arcs of resistant limestone blocks. These are useful indicators of the maximum extent of the flows and, where multiple arcs are present, give indications of episodic activity.

Primary mudflows usually occur on a small scale. However, after initial failure, mudslides often degenerate into secondary mudflows as they degrade and increase in moisture content. Some large mudslides have given rise to many generations of mudflows one on top of the other, frequently with flow movements in different directions.

d. Gully flows.

The term gully flow is used to describe a mudflow in which the movement of debris is confined to previously existing water-eroded channels or gullies, often following fault or joint planes. Material feeding a gully flow is usually derived from the sides of the channels but where the gully develops as a result of seepage erosion from the base of the debris accumulations on a ledge or terrace, this debris feeds the flow and back erosion produces funnel-shaped flow bowls

e. Sheet flows

This is a form of mudflow in which the movement of saturated debris is not canalised but flows downward as a sheet on a broad front. Sheet flows may develop from the coming together of several mudflows, but they usually occur as a result of the discharge of debris from an undercliff terrace. As the debris falls, or is pushed, over the cliff edge loose, weathered material from the cliff face is stripped off and incorporated into the sheet flow.

f. Sand runs

A sand run is a fairly rapid, seasonal, down slope movement of arenaceous debris taking place in the presence of free water. It may be restricted to gullies formed by seepage erosion or it may move on a broader front, as part of the breakdown of rotational slide blocks of Upper Greensand. Heavy rainfall events causing flash floods often result in a very rapid and extensive movement of sand. An example of this was observed during a survey of Black Ven in 1971, when a fifty five minute period of torrential rain mobilised a sand run which moved wooden survey pegs a distance of 40 m (Conway, 1976a).

3. Translational movements.

SHALLOW SEATED MOVEMENT

Mudslides

A mudslide is a down-slope movement of argillaceous material and is distinguished from a mudflow by its taking place by shearing on a discrete plane at a shallow depth. The bulk of the material making up the slide is a coherent mass; although it may be deformed it is not fragmented and may be characterised by rafts of vegetation on its surface. The supply area for the material of a mudslide is defined by a tear scar, often of arcuate form and the margins of the slide track by shear planes, sometimes accompanied by en echelon tension gashes and levees. Like mudflows, the eroded toe may be marked by boulder arcs in the inter-tidal zone.

Initially, the tear scars and lateral shear planes show well developed slickensiding but these are usually rapidly defaced due to the tendency of the shear planes to become paths of water flow. The supply of material may be from a single event failure or from a succession of small failures over a period of time. In the latter case movement often degenerates into a mudflow. Transition to a mudflow also occurs when a slide track develops a marked convex change of slope, as for example when passing over a hard bed, tension cracks form transversely, often through the full thickness of the slide. As a result of this the slide block is fragmented and the entry of water into the body of the slide is enhanced.

DEEP SEATED MOVEMENT

Lateral translation or spreading failure
In the western part of the district where thick Chalk cliffs rest on Gault and Upper Greensand very large scale lateral translational movements of coherent blocks of Chalk have occurred at infrequent intervals, notably at Bindon in 1839/40 and possibly at Hooken Cliff in 1790. The movements appear to be the result of sliding at the base of the Cretaceous strata on the seaward-inclined surface of the Triassic strata on which it rests unconformably. The causes of the movement are the removal of lateral support by the erosion of material by the sea forming an over steepened cliff face and high pore water pressure in the Gault and Upper Greensand at the base of the Cretaceous strata. Rotational failure of the sea cliff reduces lateral support even further and may restrict the drainage of water from the sands at the base causing pore water pressure to increase and large scale lateral spreading to start. Rotational failures into the void created behind the translated block result in the development of graben-like structures on its landward side.

4. Rotational movements
Rotational movements involve downward movement along a curved failure plane with rotation towards the slope about a horizontal axis. A rotational slide is a down slope movement of a coherent rock mass involving shear failure on a surface which is generally concave upward, so that some degree of backward rotation is imparted to the sliding mass and the detached blocks have a slopeward dip imparted to them as a result of this movement.

Two main categories of rotational slides are generally recognised:

a. Shallow slope failures where no significant part of the cliff top is involved in the movement

b. Deep slope failures where a significant part of the cliff top is involved

Shallow slope failure often occurs where head deposits rest on clays and, although they provide debris for other forms of instability, it is not a significant type of coastal landslide.

Deep slope failures are characteristic of the Chalk and the Upper Greensand cliffs. However they are also frequent on clay cliffs and are the first stage in the development of mudslides. Incipient failure is indicated by arcuate tension cracks, often extensive, forming from the edge of the cliff. They may be up to half a metre wide and several metres deep before the final movement occurs. Where deformation of the slide block occurs before failure the tension crack bounded block is often stepped.

Causes of landslides

The material which forms a slope is under a stress due to the force of gravity acting on it which is directed to move it down slope. The slope does not move if the shear strength of the material is greater than the imposed stress. A stable slope is one where the shear strength of the materials forming the slope is greater than the stress due to gravity. A slope becomes unstable when the balance is altered so that stress exceeds available strength, and movement ensues until the stress is reduced or material strength is increased.

Factors which increase stress

1. Removal of support
The removal of support from the bottom of a slope may be caused by marine erosion, seepage erosion, landsliding of the lower slope area, or by excavation during construction work. The result will be to concentrate the existing stress in the remaining part of the slope.

2. Loading the top of a slope
Loading at the top of a slope increases the potential total stress applied to the slope. It may be caused naturally by landslides, debris flows, rock or soil falls, depositing earth material onto the slope from an active area higher up the slope, or artificially by construction works or land fill operations. The growth of vegetation may give a net increase in mass and the saturation of the slope during seasonal rainfall or heavy rainfall events will also cause an increase in loading on the slope.

Factors which decrease strength

1. Increased pore water pressure
The strength of a soil material is dependent on the inter-particle friction of its component particles, which is proportional to the weight of the overlying mass that forces the particles together. Where there is pore water in the inter-particle spaces the pressure of the pore water must be subtracted from the overburden stress to determine the effective stress acting between the particles. Thus the higher the water table the lower the effective stress and the lower the shear strength. Where a water bearing soil is sealed by overlying impermeable strata, a confined condition is produced which may result in pore water pressure of greater magnitude than for an unconfined condition with a water table at the ground surface.

2. Weathering
Fresh mudrocks will decrease in strength when weathered as stress relief causes their physical disintegration, swelling occurs as water is absorbed by their component clay minerals and the beneficial effects of soil suction are lost. In granular rocks and soils the strengthening effect of inter-particle cements may be lost as the cementing agents are dissolved.

Structural effects

The geological structure of the slope and its surroundings may have a controlling effect on the incidence, nature and frequency of landslides. Discontinuities affect all geological materials at scales ranging from small to large and are found in the form of bedding planes, fissures in clay soils, jointing in rocks, faulting and unconformities. These disruptions in the continuity of the material provide paths for the flow of water into and through the ground and supply planes of weakness on which movement and detachment may take place.

Folds in strata may collect ground water and concentrate its flow along the troughs formed by synclinal aquicludes. If such a pathway is inclined to a free face or slope it will concentrate water at a spring or seep, raise pore water pressures and supply a source of water to drive mass moments. A structural control of this type is believed to operate at the eastern embayment of Black Ven. Where planes are inclined towards a free face or slope, block falls may occur or translational slides will be favoured as at Bindon. Where two such planes intersect wedge failures may take place.

Climatic effects

Rainfall is the most important aspect of climate in terms of controlling slope stability. Its effect may be very rapid such as the role of heavy rain in generating hillwash and sand runs, which are apparent at the time of the rain or soon after. However, the more important effect is seen over a longer time scale which gives time for rain to infiltrate the ground to a greater depth, saturating materials and causing a build up of pore water pressures which reduce the available shear strength of the slope forming materials. The effectiveness of the infiltration will be affected by other factors such as vegetation cover and the time of year, both of which will influence the amount of water lost by evaporation. It is also possible that a period of very dry weather, which has caused ground shrinkage and cracking, will allow infiltration quickly and to a greater depth and reduce losses due to runoff.

The figures for average, monthly rainfall from 1856 to 1996, collated from the Proceedings of the Dorset Natural History and Archaeological Society, show that the wettest months fall in the winter period (Fig.31). Annual rainfall is usually quoted for the calendar year from January to December. However, when considering the effect of rainfall on landslide activity, the effect of a wet winter period will be more marked than a wet summer since the rain falling during the summer may not penetrate into the ground being largely lost due to evaporation and transpiration. Therefore, the rainfall records for Dorset from 1856 to 1996 (Table 2) have been reorganised to show rainfall for successive twelve month periods from July to June (Fig. 32) and for winter rainfall from October to March rather than the more conventional statistics based on calendar years. In this way continuous periods of wet weather that will have raised the pore-water pressure levels in the ground have been high lighted.

The data (Table 3) show quite wide variations from the average rainfall with up to 149 % above average annual rainfall and up to 159 % of average winter rainfall. Landslide events had been indicated where a reference has been found in published literature (Table 4) but these events must be a very small percentage of actual events since only the large events or ones affecting the community would had been recorded. Few events were recorded before landslides were considered of interest for academic study. However, inspection of the records does indicate a correlation between periods of higher than average rainfall and landslide activity. The years 1961, 1977 and 1994 are years of both exceptionally high rainfall and several landslide events. When a broader view is taken, groups of years with high rainfall and an increased incidence of landslide events are often found, with the wet years preceding the landslide activity. The years 1935-1937 and 1939-1941 preceded activity in 1937/8 and 1942-1944. Longer wet periods occurred between the years 1955 to 1961, 1966 to 1971 and 1977 to 1983 which were in advance of periods of very marked landslide activity between 1956 to 1966, 1968 to 1978 and a lesser incidence between 1981 and 1984. Thus it would appear that the long term saturation of the slope forming material and the build up of pore water pressures over several years are necessary for episodes of major landslide activity and the effects of a single wet winter in isolation such as 1990 are less pronounced.

Coastal landslide distribution

The Triassic and Jurassic strata which outcrop on the coast of the district are generally inclined to the east at a low angle with a resulting apparent seaward component while the Cretaceous/Jurassic unconformity dips generally slightly east of south. The Cretaceous rocks (Gault, Chalk and Upper Greensand) overstep the underlying Jurassic and Triassic mudstones and limestones progressively westward as they dip gently to the south and east. Thus, a thick, water-bearing, poorly cemented or non-cohesive deposit overlies an impermeable mainly argillaceous deposit for most of the length of the coast from Sidmouth in the west to Charmouth in the east. Between Sidmouth and Budleigh Salterton on the western margin of the sheet the cliffs are composed of Mercia Mudstone and Otter Sandstone which are also prone to slope instability but of a lesser degree of intensity. Landslide activity, to the west of Budleigh Salterton at West Down Beacon, involving the Littleham Mudstone where it is overlain by the Budleigh Salterton Pebble Beds, has been studied by Kalaugher et al. (1987) and Grainger and Kalaugher (1994). They described the morphology and causes of the landslide (Kalaugher et al. 1987) and the influence of tides on its activity (Grainger and Kalaugher, 1994).

Budleigh Salterton to Hern Point Rock

Between Budleigh Salterton [SY 290 820] and Hern Point Rock [SY 101 856] the coastal cliffs comprise Otter Sandstone which is generally a medium- to thickly-bedded with widely- to very-widely spaced discontinuities, moderately weak to moderately strong, sandstone which forms near-vertical (70^0-90^0) cliffs at Ladram Bay [SY 098 852]. The cliffs show selective erosion of the weaker beds leaving the stronger beds standing proud of the cliff face. During a visit in October 1996 some undercutting of the cliff by basal erosion by the sea was seen, but scars from recent falls were not visible and no debris was present at the base of the cliff (Fig.33).

Hern Point Rock to Sidmouth

North east of Hern Point the cliff line rises and Mercia Mudstone overlies the Otter Sandstone until the Otter Sandstone dips below beach level [SY 105 861]. Opposite Big Picket Rock [SY 104 857] the Mercia Mudstone is itself capped by a small outlier of Upper Greensand and Clay with Flints which is repeated opposite Tortoise Shell Rocks [SY 108 865]. The Mercia Mudstone has a steep, planar, lower cliff section that stands close to the vertical (80^0-90^0) and a less steep upper slope which stands at about 40^0 and is deeply incised by v-shaped gullies (Fig. 34). The lower of these two facets is the result of erosion by the sea and the upper may be the remnant of a slope formed by mass wasting under terrestrial conditions. The capping of Upper Greensand does not appear to exercise a significant control on slope processes.

Shallow sloughing of weathered material from the mudstone cliffs and some activity from the gullies, probably related to surface water flow, were evident but no signs of large-scale mass movement were seen. At SY 113 868 a recent debris slide has cut back the cliff top to the side of the cliff top road which required the road to be diverted further inland. The cause of the slip may have been related to a roadside drain that was exposed in the side of the slip scar (Fig. 35).

On the western side of Sidmouth the Mercia Mudstone cliff has a single, steep facet but was displaced by a fault at Chit Rocks which brings the Otter Sandstone to the surface to form low cliffs on the west side of the town. The sandstone is medium- to thickly-bedded with wide- to very widely-spaced discontinuities and forms a steep cliff. The cliff has been protected from marine erosion by armour stones of granite and larvikite in front of a concrete sea wall and had been strengthened with concrete and masonry dentition where weaker beds had been selectively eroded in the cliff face. This work has been carried out owing to the proximity of buildings to the cliff edge (Fig.36).

Sidmouth to Branscombe Mouth

The cliff on the eastern side of the River Sid is formed of Otter Sandstone capped by Mercia Mudstone. Although the sandstone is medium- to thickly-bedded with wide- to very widely-spaced discontinuities, marine erosion at the base maintains a steep cliff face at about 80^0 and the fresh face was subject to joint-controlled rock falls (Fig. 37). Warning signs are prominently displayed at the entrance to the beach.

The Otter Sandstone dips below beach level to the east leaving the cliffs of Mercia Mudstone capped by Upper Greensand, except where it has been eroded by southward draining valleys at Salcombe and Weston Combe. Generally, the Mercia Mudstone maintains a high angle close to the vertical where erosion was active at its base. Slope instability was by rock or soil falls of weathered material such as the falls which closed the cliff path east of Sidmouth in October 1995 [SY 135 874] (Fig. 38). The upper part of the cliff is often at a lower angle (about 40^0 to 50^0) than the lower part. East of Salcombe the entire cliff appeared to be at this inclination, was more vegetated and appeared to be generally stable.

Beer Head to Seaton

The Mercia Mudstone dips below beach level between Branscombe and Beer Head and at the same time the Chalk above the Upper Greensand increases in thickness to become the dominant cliff forming material. In general, the Chalk forms a very steep, nearly vertical, cliff with occasional minor rock falls. But a major landslide occurred in March 1790 at Hooken Cliff when between 3 and 4 hectares of land on the cliff top moved seaward by 200 metres and dropped between 60 and 80 m (Arber 1940). During its movement the slipped mass became broken, forming pinnacles, some of which are visible today, but they did not appear to be tilted backwards in a rotational failure mode. However, contemporary reports indicate that the sea bottom was uplifted by about 7 m to form an offshore reef. It is not clear whether this was the result of a lateral movement piling up material in front of its seaward face, or was the toe of a rotational landslide that has subsequently been removed by erosion. The cause of the movement would appear to have been the build up of pore water pressure in the underlying Upper Greensand which may had been associated with the cessation of a stream which emerged from half way up the cliff two years prior to the failure.

Comparison of a photograph of Hooken Cliff (Fig. 39) dating from about 1900 (Rowe, 1903) with Fig. 40 shows that some steepening of the cliff profile in front of the pinnacle had taken place by rock fall since the earlier photograph was taken. However, much of the topography of the area has remained unchanged over a period of 90 years.

Seaton to Lyme Regis

The coast between Seaton and Lyme Regis encompasses many large scale landslides which have been studied and described in detail by Pitts (1979,1981,1983a, 1983b, 1986), Pitts and Brunsden (1987), Grainger, Tubb and Neilson (1985), Grainger and Kalaugher (1995), and Grainger, Kalaugher and Kirk (1996).

At the western end of the section, at Haven Cliff, the cliff is formed of Mercia Mudstone capped by Upper Greensand and Gault. The Mercia Mudstone stands at a steep angle and fails by soil fall as weathered material sloughs from the face of the Mercia Mudstone cliff (Fig. 41). The Upper Greensand fails by multiple retrogressive rotational failures which are the result of pore water pressure build up at the junction of the permeable Upper Greensand on the underlying impermeable Gault and Mercia Mudstone. The repeated failure and erosion of the sands and clayey silts forms a bench on the top of the more resistant Mercia Mudstone. Additional, failed material accumulates on the bench and degrades before moving seaward over the bench as sand runs and mudflows to form debris accumulations at the base of the Mercia Mudstone cliff (Fig. 42). Where debris accumulation is rapid or the cliff is protected from sea erosion by beach deposits the Mercia Mudstone sea cliff may be completely buried under debris, but where erosion is more active the debris is rapidly removed.

Where the Chalk becomes thicker to the east and forms a significant part of the cliff the style of landsliding changes to predominantly multiple retrogressive rotational failures. Large-scale, slipped blocks of Chalk on Upper Greensand, with shear zones passing below them through weaker impermeable formations, are controlled by the underlying structure and succession as strata of progressively younger age are encountered eastwards, below the unconformity. Significantly weak strata are the Penarth Group, Shales-with-Beef and Blue Lias. The landslides are very complex and their causes and detailed development are still to be fully understood. Their geomorphology and recent activity had been studied extensively by Arber (1940, 1973), Pitts (1979, 1981, 1983a, 1983b, 1986), Pitts and Brunsden (1987) and Grainger et al (1985,1996). In general, the landslides form a stepped profile of steep Chalk scarps with back-tilted surfaces at their foot and, at their seaward lower slopes, mudslide and mudflow activity involving the underlying sands, silts and mudstones. In some cases, most notably the Bindon landslide of 1839/40, the initial rotational failure caused a lateral slide of a massive intact block which moved seaward maintaining a horizontal orientation. Rotational failures into the space behind left a wide graben structure on its landward side (Fig. 43).

Lyme Regis

Although some slope instabilities have occurred in Lyme Regis due to water seepage at the junction of the Cretaceous Upper Greensand with the Lias clay, such as those at the disused railway station [SY 33926] (Arber, 1973), most of the instabilities are associated with the outcrop of the Lower Lias on which much of Lyme Regis was built.

The steep slopes between the Cobb and Broad Street are the remnants of a former sea cliff composed of the Shales-with-Beef and have been the site of many slope failures. Notable failures were: -

- The Cliff House slide during stabilisation works west of Longmoor Gardens in 1962 which was preceded by minor movements in 1926 and 1947 and took the form of a rotational failure degrading into a mudflow (Conway, 1976a).
- The Library Cottage mudflow of 1971 (Arber, 1973).
- Numerous slope movement in the vicinity of Cobb Road in the 1920s, 1948, 1959, 1962-

65, 1983 and 1989 (Hawkins, 1991).

To the east of the town, Church Cliff suffered a series of rockfalls which destroyed part of the churchyard in 1843,1844, 1849 and 1862, but these have been attributed to the removal of limestone from the foreshore reefs and lower cliffs to supply the local cement works rather than to entirely natural processes. The removal of the material accelerated erosion by the sea with a consequent increase in cliff instability. Cliff recession rates, based on the work of Humby (1951), of 1 m/yr for the period 1841 to 1928 and 0.65 m/yr for the period 1928 to 1951 resulting in a total cliff retreat of 100 m were quoted by Conway (1974). Conway also calculated a rate of 0.65m/yr for the period 1913 to 1951 based on the maps of Lang (1914). The erosion was so serious that a sea wall was constructed in 1910, but deteriorated to the extent that it needed to be rebuilt in 1957 (Conway, 1976a).

Although East Cliff was protected by a sea wall, landslide activity started on the land above it at the end of 1973 and peaked, initially, in May 1974. Changes in the ground water regime up slope of the cliff had caused saturation of the previously stable head-covered slope. Movement continued for several years on the slope and destroyed two houses and damaged a recently constructed car park before it was stabilised by remedial works. This emphasised the fact that marine erosion is only one factor involved in coastal slope instability. The landslide activity and the early stabilisation works were described by Conway (1974,1976b,1977a) and Conway and Culshaw (1976).

Lyme Regis to Black Ven

The coast between Lyme Regis and Charmouth contains one of the largest and most currently active landslide complexes in Britain. The Black Ven landslide complex has been described by Brunsden (1969), Arber (1941,1973) described and mapped by Conway (1974, 1976 sheet 1) and recently studied by Chandler and Brunsden (1995). The coastal slope comprises Cretaceous sands and cherts that lie unconformably on Lower Lias clays with beds of limestone. The coastal slope has evolved into a series of terraces formed at the level of harder clays or limestones by repeated landslide activity. The build up of pore water pressure at the base of the permeable Cretaceous sands promotes rotational failure in the sands that accumulate on the top of the uppermost bench formed by the relatively hard Belemnite Marl. The material becomes saturated by water issuing from the base of the Cretaceous strata and flows over the front of the bench plucking blocks of material from the face and incorporating softened and weathered clay as it descends to the next lowest bench where the process is repeated. The material that accumulates on the lower terraces comprises blocks of softening clay, limestone and chert in a remoulded silty, sandy, clay matrix. At the foot of the slope, this material forms a debris apron that spreads across the beach and is removed by the sea. Periodically areas of the coast stabilise and become vegetated, forming a series of terraces densely covered by scrubby vegetation and backed by steep scarp slopes. Episodes of major activity take place periodically and may be related to climate and the occurrence of a series of wetter than average years or steepening of the cliff profile by marine erosion (Chandler and Brunsden, 1995).

A major episode of activity started in the winter of 1956/7 and culminated in February 1958 when twin mudflows feeding debris aprons spread across the beach below adjacent back scarps in the Cretaceous strata at the top of the cliff. This complex became known as the Black Ven Mudslide, after the stretch of the coast between Lyme Regis and Charmouth which was generally known as Black Ven. Another significant episode of movement, to the west of the Black Ven mudslide, started in 1986 with most activity occurring in 1994. This landslide was centred in the cliff section called the Spittles.

Landslide Chronology

The Sidmouth district is a rural area with a relatively low population and since most of the landslides occur on the coast only those occurring in recent years are likely to had been noticed and recorded. In former times, before recreational use of the cliffs and beaches became popular and the study of landslides became important, the results of landslide events, if noticed at all, would only had been seen by farmers, fishermen or the coastguards and would had been unlikely to have been significant to their activities. Thus only very large magnitude events, such as the Bindon Landslide of 1839/40 and the Hooken Cliff slide of 1790, would had been noted and recorded. The listing of landslide events (Table 4) was compiled from published sources and reflects this diminishing record back through time.

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TABLES
1 - 4

Table 1. The lithostratigraphical units of the Sidmouth district

Solid geological divisions

- The Chalk
- Upper Greensand
- Gault
- Middle Lias
- Lower Lias
- Penarth Group
  - Westbury Formation
- Mercia Mudstone
  - Blue Anchor Formation
- Sherwood Sandstone
  - Otter Sandstone
  - Budleigh Salterton Pebble Bed
- Aylesbeare Mudstone Group
  - Littleham Mudstone Formation

Superficial geological divisions

- River Terrace Deposits
- Head
- Clay with Flints
- Alluvium
- Marine Deposits.

Note: The nomenclature and classification of the lithostratigraphical units in the district are likely to be modified as the survey of the district proceeds.

Table 2. Annual rainfall, in millimetres, for Dorset calculated on a July to June twelve month period for the years 1856 to 1996

Rainfall percentage above average			Landslide site in reference
x	= 100% to 110%		Every L represents reference(s) in the literature to one site
xx	= 110% to 120%		
xxx	=120% to 130%	893	Average annual rainfall July to June
xxxx	= 130% to 140%	528	Average winter rainfall Oct/March
xxxxx	=140% to 150%		

Year	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June	Year	Annual total July -june	% of Ave. rainfall	Above Ave rainfall	Recorded landslide events	Oct/March total rainfall	% age of Ave rainfall	Above ave rainfall
1997																				
1996	21	77	33	85	160	34							1997							
1995	26	10	146	76	137	102	90	99	73	54	63	39	1996	915	105	x		577	113	xx
1994	30	64	95	126	119	126	188	131	55	39	47	10	1995	1030	118	xx		745	146	xxxxx
1993	70	38	141	134	79	179	129	118	80	58	94	22	1994	1142	131	xxxx	LLLL	719	141	xxxxx
1992	56	125	97	50	161	110	119	11	49	93	56	75	1993	1002	115	xx		500	98	
1991	67	25	93	102	67	29	35	49	60	96	16	35	1992	674	77			342	67	
1990	27	31	49	95	58	75	114	48	110	69	12	120	1991	808	93			500	98	
1989	24	45	56	106	60	191	135	182	10	37	22	48	1990	916	105	x		684	134	xxxx
1988	84	81	41	109	36	28	39	97	105	82	17	27	1989	745	85			414	81	
1987	43	23	48	173	79	64	168	79	102	41	51	28	1988	897	103	x		663	130	xxx
1986	48	114	36	86	152	145	13	81	84	76	23	76	1987	935	107	x		561	110	x
1985	51	117	36	41	58	170	155	8	69	71	97	33	1986	904	104	x	L	500	98	
1984	23	41	79	97	150	109	89	43	69	51	38	58	1985	846	97			556	109	x
1983	13	25	86	79	43	104	163	48	61	5	69	28	1984	724	83		L	498	98	
1982	58	69	58	160	145	107	97	23	51	89	97	64	1983	1016	117	xx	L	582	114	xx
1981	51	18	157	102	46	124	53	66	119	25	43	91	1982	897	103	x	L	511	100	
1980	61	66	71	119	61	61	46	58	160	46	104	48	1981	902	103	x	LL	505	99	
1979	41	79	25	79	48	183	64	99	114	25	28	132	1980	917	105	x		587	115	xx
1978	119	43	20	8	33	198	104	84	122	61	140	41	1979	973	112	xx		549	108	x
1977	43	117	41	61	89	140	114	122	86	56	43	38	1978	950	109	x	L	612	120	xx
1976	18	15	188	206	132	124	99	147	99	28	61	81	1977	1199	138	xxxx	LLL	808	159	xxxxxx
1975	43	56	130	28	89	30	15	48	56	5	28	5	1976	533	61		LLLL	267	52	
1974	38	124	191	58	180	71	142	25	91	51	25	5	1975	1003	115	xx	LL	569	112	xx
1973	53	41	66	56	36	71	145	155	43	10	56	71	1974	803	92		L	505	99	
1972	38	46	30	46	117	147	51	25	20	51	74	48	1973	693	80		LL	406	80	
1971	20	69	10	53	74	41	135	119	104	79	81	74	1972	859	98		LLL	526	103	x
1970	53	66	89	30	208	36	160	28	64	48	30	130	1971	942	108	x	LLL	526	103	x
1969	61	36	48	8	140	99	175	86	53	53	38	33	1970	831	95		LLL	561	110	x
1968	51	56	163	122	64	102	122	64	81	38	104	38	1969	1003	115	xx	LLLL	554	109	x
1967	43	53	122	198	53	64	74	66	33	69	66	114	1968	955	110	x	LL	488	96	
1966	56	104	28	193	89	91	109	104	74	38	132	28	1967	1046	120	xx		660	130	xxx
1965	104	79	102	28	135	150	84	140	28	122	58	46	1966	1074	123	xxx	L	564	111	xx
1964	20	18	33	74	66	107	114	5	91	38	51	64	1965	681	78		L	457	90	
1963	43	102	71	58	180	48	15	30	112	51	97	36	1964	843	97	x	L	445	87	
1962	38	117	86	43	109	66	20	53	117	97	38	74	1963	859	98		LL	409	80	
1961	38	51	81	140	56	107	142	13	41	53	64	8	1962	792	91		LL	498	98	
1960	102	135	142	257	155	104	135	86	3	122	33	25	1961	1298	149	xxxxx	LLLLL	739	145	xxxxx
1959	43	53	5	94	124	239	99	94	61	66	46	51	1960	975	112	xx	L	711	140	xxxx
1958	58	79	137	89	81	127	140	10	104	74	33	33	1959	965	111	xx	L	551	108	x
1957	102	84	91	74	66	79	104	89	41	18	69	99	1958	914	105	x	LL	452	89	
1956	74	114	145	53	23	157	89	117	76	8	58	56	1957	970	111	xx	LL	516	101	x
1955	97	18	41	94	99	150	130	5	25	38	18	61	1956	775	89		L	503	99	
1954	81	84	99	81	180	89	99	64	41	20	114	69	1955	1021	117	xx		554	109	x
1953	86	52	85	98	53	23	51	91	117	5	58	79	1954	799	92			433	85	

1952	22	94	114	123	102	81	25	51	17	72	74	66	1953	840	96			399	78			
1951	48	139	107	28	252	84	65	20	85	53	74	32	1952	988	113	xx		534	105	x		
1950	134	103	115	36	173	72	99	155	110	69	71	13	1951	1152	132	xxxx		646	127	xxx		
1949	25	38	112	193	114	51	20	158	49	67	42	27	1950	895	103	x		585	115	xx		
1948	38	109	76	76	58	152	23	41	38	51	64	15	1949	742	85			389	76			
1947	43	25	38	28	56	89	170	36	30	48	79	61	1948	704	81		L	409	80			
1946	33	122	142	38	178	122	91	48	218	69	58	53	1947	1173	135	xxxx	L	696	137	xxxx		
1945	38	56	84	109	38	127	99	76	36	69	102	102	1946	935	107	x		485	95			
1944	86	66	48	117	178	74	64	66	30	20	71	84	1945	904	104	x		528	104	x		
1943	64	66	69	119	69	91	71	15	8	51	13	61	1944	696	80		L	373	73			
1942	38	122	74	112	46	137	196	36	25	25	74	33	1943	917	105	x	L	551	108	x		
1941	46	104	30	33	58	71	119	8	74	51	112	10	1942	716	82		L	363	71			
1940	66	2	46	109	223	83	119	112	89	58	66	56	1941	1030	118	xx		736	144	xxxxx		
1939	112	71	25	159	203	58	72	105	77	64	71	17	1940	1034	119	xx		674	132	xxxx		
1938	102	85	59	105	162	112	175	56	29	58	15	92	1939	1051	121	xxx		640	126	xxx		
1937	88	34	83	113	74	106	99	28	6	2	57	37	1938	725	83		L	425	83			
1936	151	4	68	45	87	98	128	165	120	76	79	34	1937	1054	121	xxx	L	643	126	xxx		
1935	8	62	101	91	169	155	165	81	134	68	19	51	1936	1104	127	xxx		795	156	xxxxxx		
1934	2	105	75	69	39	260	20	93	34	104	42	112	1935	956	110	x		515	101	x		
1933	53	64	47	67	25	27	73	4	65	84	27	28	1934	561	64			260	51			
1932	77	33	87	169	51	35	60	133	92	54	55	31	1933	877	101	x		540	106	x		
1931	121	93	62	9	120	29	53	2	60	64	100	69	1932	781	90			273	54			
1930	49	92	105	71	159	119	62	59	34	67	88	84	1931	990	114	xx		505	99			
1929	41	51	11	88	221	149	130	29	34	70	57	13	1930	895	103	x		652	128	xxx		
1928							51	53	7	25	65	51	1929		0				0			
1927	67	83	189	68	84	114							1928		0				0			
1926	35	22	19	93	245	170	58	76	72	55	24	62	1927	930	107	x		714	140	xxxx		
1925	88	88	84	105	82	112	109	47	10	71	44	70	1926	910	104	x	L	465	91			
1924							105	89	13	45	91	0	1925		0				0			
1923	39	36	84	130	41	89							1924		0				0			
1922	113	70	40	46	52	117	35	147	37	68	53	16	1923	794	91			435	85			
1921	12	58	21	31	80	42	127	59	76	86	20	20	1922	633	73		LL	416	82			
1920	145	38	49	59	37	115	89	8	54	33	59	14	1921	698	80		L	361	71			
1919	66	86	44	54	59	132	129	18	95	117	47	67	1920	914	105	x	LL	488	96			
1918	121	52	175	52	64	88	151	116	135	59	33	18	1919	1066	122	xxx		607	119	xx		
1917	74	101	48	93	35	38	104	52	49	44	47	24	1918	709	81			371	73			
1916	19	124	58	132	119	123	28	34	78	28	51	38	1917	832	95			514	101	x		
1915	111	40	55	173	68	213	25	150	85	21	67	65	1916	1072	123	xxx		713	140	xxxx		
1914	131	85	71	97	103	151	98	130	22	31	63	30	1915	1011	116	xx		600	118	xx		
1913	6	40	100	107	88	44	18	104	138	34	40	48	1914	766	88			499	98			
1912	57	178	16	116	34	143	161	23	67	80	59	11	1913	943	108	x		543	107	x		
1911	5	11	33	97	111	213	112	99	149	3	44	101	1912	978	112	xx		781	153	xxxxxx		
1910	75	110	6	108	123	155	30	50	73	55	21	47	1911	855	98		L	540	106	x		
1909	91	64	45	156	22	145	84	100	16	53	70	56	1910	902	103	x		523	103	x		
1908	39	98	81	117	25	108	29	9	127	46	27	100	1909	805	92			415	81			
1907							30	54	81	68	40	9	1908		0		L		0			
1906													1907		0				0			
1905	14	88	45	62	127	29							1906		0				0			
1904	129	119	58	54	44	91	22	15	130	61	13	46	1905	781	90			356	70			
1903	105	104	109	163	36	84	109	113	48	29	86	28	1904	1013	116	xx		553	109	x		
1902	51	97	66	81	97	54	88	38	99	75	59	45	1903	849	97			457	90			
1901	55	47	98	67	21	169	25	42	52	45	45	90	1902	756	87			376	74			
1900	27	54	19	62	100	156	81	36	59	87	43	39	1901	764	88			495	97			
1899	50	29	65	58	127	97	135	118	34	41	47	86	1900	886	102	x		568	112	xx		
1898	3	35	37	143	128	108	119	105	12	98	27	38	1899	852	98			614	121	xxx		

1897	29	117	71	32	23	168	22	48	44	40	96	22	1898	713	82			337	66	
1896	27	55	166	70	30	131	56	99	118	94	42	84	1897	971	111	xx		503	99	
1895	64	70	9	101	158	94	29	14	76	13	2	58	1896	689	79			473	93	
1894	134	71	77	108	193	75	126	1	78	62	9	39	1895	973	112	xx		581	114	xx
1893	118	28	51	107	48	87	107	80	45	61	50	55	1894	836	96			473	93	
1892	66	86	75	136	96	49	60	110	11	3	23	28	1893	743	85			463	91	
1891	57	155	51	230	114	124	50	38	19	26	21	33	1892	916	105	x		573	113	xx
1890	79	74	48	27	72	43	79	1	76	22	61	52	1891	634	73			298	59	
1889	65	77	33	138	43	68	105	23	36	84	52	69	1890	791	91			412	81	
1888	108	56	36	58	200	75	23	50	65	65	38	48	1889	822	94			471	92	
1887	22	59	72	59	93	69	37	24	97	43	53	82	1888	710	81			379	74	
1886	73	29	72	114	100	180	87	23	36	24	47	20	1887	805	92			540	106	x
1885	7	30	117	115	101	48	93	19	91	56	92	18	1886	787	90		L	468	92	
1884	69	38	50	29	48	103	77	108	42	65	84	46	1885	759	87			407	80	
1883	71	23	133	74	104	22	99	76	78	58	31	89	1884	860	99			453	89	
1882	96	61	80	207	113	94	97	128	31	29	52	66	1883	1052	121	xxx		669	131	xxxx
1881	47	160	57	49	142	93	43	51	26	124	51	102	1882	944	108	x		404	79	
1880	98	29	98	164	95	122	62	117	75	26	24	68	1881	977	112	xx		634	124	xxx
1879	104	150	108	31	7	24	19	114	34	53	24	54	1880	722	83			228	45	
1878	47	99	43	97	66	57	122	117	15	81	68	146	1879	958	110	x		473	93	
1877	82	88	74	64	218	49	46	60	45	99	125	41	1878	991	114	xx		482	95	
1876	19	97	148	72	121	240	187	37	53	99	66	28	1877	1165	134	xxxx		709	139	xxxx
1875	104	55	85	183	121	33	37	85	85	74	9	46	1876	916	105	x		544	107	x
1874	40	61	91	136	79	103	122	58	18	27	61	61	1875	858	98			517	101	x
1873	41	88	42	63	109	9	58	62	14	46	16	62	1874	611	70			315	62	
1872	100	29	45	172	146	128	99	81	77	20	22	45	1873	963	110	x		702	138	xxxx
1871	101	20	114	70	33	64	151	64	76	55	48	105	1872	901	103	x		458	90	
1870	17	21	25	89	47	98	76	57	45	126	25	52	1871	678	78			412	81	
1869	10	6	100	52	53	111	44	57	49	13	37	19	1870	551	63			366	72	
1868	12	117	86	84	72	175	117	78	57	28	120	29	1869	976	112	xx		583	114	xx
1867	96	57	46	71	39	49	96	49	35	51	41	10	1868	639	73			338	66	
1866	32	63	188	56	48	68	115	66	95	66	47	27	1867	870	100			448	88	
1865	90	128	0	196	135	107	131	95	57	47	56	40	1866	1083	124	xxx		722	142	xxxxx
1864	12	19	74	41	65	82	117	94	33	18	61	44	1865	661	76			432	85	
1863	18	87	105	157	55	71	86	40	57	33	21	30	1864	760	87			465	91	
1862	57	42	45	140	26	76	100	29	56	34	47	103	1863	753	86			426	84	
1861	102	18	69	43	116	46	70	27	136	69	71	58	1862	826	95		L	438	86	
1860	41	102	61	37	83	132	15	100	87	13	25	118	1861	814	93			454	89	
1859	45	92	58	84	83	67	98	25	69	60	83	140	1860	904	104	x		425	83	
1858	61	42	50	37	53	83	35	56	45	57	20	17	1859	556	64			309	61	
1857	88	14	57	124	37	19	12	48	24	77	46	25	1858	572	66			264	52	
1856	23	92	83	92	26	62	82	30	89	89	53	58	1857	779	89			381	75	
							93	52	42	111	49	49	1856		0					
												Total		115952.71				509.421444		
										Average annual rainfall July to June				872						

Table 3. Annual rainfall for Dorset, in millimetres, calculated on a July to June twelve month period and an October to March winter period for the years 1856 to 1996

Year	Annual total July -June	% of ave. rainfall	Above ave rainfall	Recorded landslide events	Oct/March total rainfall	% age rainfall	Above ave rainfall
1996	915	105	x		577	113	xx
1995	1030	118	xx		745	146	xxxxx
1994	1142	131	xxxx	LLLL	719	141	xxxxx
1993	1002	115	xx		500	98	
1992	674	77			342	67	
1991	808	93			500	98	
1990	916	105	x		684	134	xxxx
1989	745	85			414	81	
1988	897	103	x		663	130	xxx
1987	935	107	x		561	110	x
1986	904	104	x	L	500	98	
1985	846	97			556	109	x
1984	724	83		L	498	98	
1983	1016	117	xx	L	582	114	xx
1982	897	103	x	L	511	100	
1981	902	103	x	LL	505	99	
1980	917	105	x		587	115	xx
1979	973	112	xx		549	108	x
1978	950	109	x	L	612	120	xx
1977	1199	138	xxxx	LLL	808	159	xxxxxx
1976	533	61		LLLL	267	52	
1975	1003	115	xx	LL	569	112	xx
1974	803	92		L	505	99	
1973	693	80		LL	406	80	
1972	859	98		LLL	526	103	x
1971	942	108	x	LLL	526	103	x
1970	831	95		LLL	561	110	x
1969	1003	115	xx	LLLL	554	109	x
1968	955	110	x	LL	488	96	
1967	1046	120	xx		660	130	xxx
1966	1074	123	xxx	L	564	111	xx
1965	681	78		L	457	90	
1964	843	97	x	L	445	87	
1963	859	98		LL	409	80	
1962	792	91		LL	498	98	
1961	1298	149	xxxxx	LLLLL	739	145	xxxxx
1960	975	112	xx	L	711	140	xxxx
1959	965	111	xx	L	551	108	x
1958	914	105	x	LL	452	89	
1957	970	111	xx	LL	516	101	x
1956	775	89		L	503	99	
1955	1021	117	xx		554	109	x
1954	799	92			433	85	
1953	840	96			399	78	
1952	988	113	xx		534	105	x
1951	1152	132	xxxx		646	127	xxx
1950	895	103	x		585	115	xx
1949	742	85			389	76	
1948	704	81		L	409	80	
1947	1173	135	xxxx		696	137	xxxx
1946	935	107	x		485	95	
1945	904	104	x		528	104	x
1944	696	80		L	373	73	

1943	917	105	x	L	551	108	x	
1942	716	82		L	363	71		
1941	1030	118	xx		736	144	xxxxx	
1940	1034	119	xx		674	132	xxxx	
1939	1051	121	xxx		640	126	xxx	
1938	725	83		L	425	83		
1937	1054	121	xxx	L	643	126	xxx	
1936	1104	127	xxx		795	156	xxxxxx	
1935	956	110	x		515	101	x	
1934	561	64			260	51		
1933	877	101	x		540	106	x	
1932	781	90			273	54		
1931	990	114	xx		505	99		
1930	895	103	x		652	128	xxx	
1929		0				0		
1928		0				0		
1927	930	107	x		714	140	xxxx	
1926	910	104	x		465	91		
1925		0				0		
1924		0				0		
1923	794	91			435	85		
1922	633	73		L	416	82		
1921	698	80		L	361	71		
1920	914	105	x	LL	488	96		
1919	1066	122	xxx		607	119	xx	
1918	709	81			371	73		
1917	832	95			514	101	x	
1916	1072	123	xxx		713	140	xxxx	
1915	1011	116	xx		600	118	xx	
1914	766	88			499	98		
1913	943	108	x		543	107	x	
1912	978	112	xx		781	153	xxxxxx	
1911	855	98		L	540	106	x	
1910	902	103	x		523	103	x	
1909	805	92			415	81		
1908		0		L		0		
1907		0				0		
1906		0				0		
1905	781	90			356	70		
1904	1013	116	xx		553	109	x	
1903	849	97			457	90		
1902	756	87			376	74		
1901	764	88			495	97		
1900	886	102	x		568	112	xx	
1899	852	98			614	121	xxx	
1898	713	82			337	66		
1897	971	111	xx		503	99		
1896	689	79			473	93		
1895	973	112	xx		581	114	xx	
1894	836	96			473	93		
1893	743	85			463	91		
1892	916	105	x		573	113	xx	
1891	634	73			298	59		
1890	791	91			412	81		
1889	822	94			471	92		
1888	710	81			379	74		
1887	805	92			540	106	x	
1886	787	90		L	468	92		
1885	759	87			407	80		
1884	860	99			453	89		

1883	1052	121	xxx			669	131	xxxx	
1882	944	108	x			404	79		
1881	977	112	xx			634	124	xxx	
1880	722	83				228	45		
1879	958	110	x			473	93		
1878	991	114	xx			482	95		
1877	1165	134	xxxx			709	139	xxxx	
1876	916	105	x			544	107	x	
1875	858	98				517	101	x	
1874	611	70				315	62		
1873	963	110	x			702	138	xxxx	
1872	901	103	x			458	90		
1871	678	78				412	81		
1870	551	63				366	72		
1869	976	112	xx			583	114	xx	
1868	639	73				338	66		
1867	870	100				448	88		
1866	1083	124	xxx			722	142	xxxxx	
1865	661	76				432	85		
1864	760	87				465	91		
1863	753	86				426	84		
1862	826	95				438	86		
1861	814	93				454	89		
1860	904	104	x			425	83		
1859	556	64				309	61		
1858	572	66				264	52		
1857	779	89				381	75		
1856		0							
893	Average annual rainfall July to June								
528	Average winter rainfall Oct/March								
Rainfall percentage above average									
x	= 100% to 110%								
xx	= 110% to 120%								
xxx	=120% to 130%								
xxxx	= 130% to 140%								
xxxxx	=140% to 150%								
Landslide site in reference									
Every L represents reference(s) in the literature to one site									

Table 4. Chronology of recorded landslides in the Sidmouth district between Budleigh Salterton and Black Ven.

Year	Date	Place	References
1689		West of Lyme Regis, Humble Point.	Roberts 1840, Pitts1983a,1983b.
1765		Whitlands Cliff.	Roberts 1840, Wankyln 1927.
1790		Hooken Cliff.	Conybeare et al. 1840.
1790/1800		Dowlands.	Macfadyen 1970, Pitts 1981.
1828		Black Ven - Lyme/Charmouth road	Conway 1976a.
1828		Pinhay to Ware.	Macfadyen 1970, Pitts 1981.
1830		Axmouth (Haven Cliffs?).	Lang 1927.
1839		Black Ven - Lyme/Charmouth road	Conway 1976a.
1839	24/25th Dec.	Bindon.	Conybeare et al. 1840, Buckland 1840, Roberts 1840, Bickley 1911, Pitts1979.
1839		Dowlands - Goat Island.	Conybeare et al. 1840, Roberts 1840, Arber 1973.
1840	3rd Feb.	Whitlands, Humble Green.	Conybeare et al. 1840, Buckland 1840, Roberts 1840,Pitts1981.
1844		Lyme Regis Church Cliffs	Conway 1976a.
1849		Lyme Regis Church Cliffs	Conway 1976b.
1852		Black Ven - Lyme/Charmouth road	Conway 1976a.
1862		Lyme Regis Church Cliffs	Conway 1976b.
1886		Pinhay - The Great Cleft.	Rowe 1903, Woodward & Young1906, Arber 1940, Pitts 1981.
1908		East of Lyme Regis.	Cameron 1908.
1911	26th Sept.	Rousden Estate - Gamekeeper's Cottage.	Anon 1911, Pitts 1981.
1920		Charmouth - Higher Sea Lane.	Denness et al. 1975.
1922		Black Ven - Lyme/Charmouth road	Conway 1976a.
1920s		Lyme Regis, Cobb Road,Glenhome Flats.	Hawkins1991.
1926		Lyme Regis Cliff House	Conway 1976a.
1937		Black Ven - Coast Road.	Arber 1973.
1938		Charmouth - Higher Sea Lane.	Denness et al 1975, Conway 1979b.
1942		Stonebarrow.	Lang 1943.
1943		Black Ven - Raffey.	Lang 1944.
1944		Black Ven - Devil's Bellows.	Lang 1945.
1947		Lyme Regis Cliff House	Conway 1976a.
1948		Lyme Regis - Stile Lane.	Conway 1972, Hawkins1991.
1956/7		Black Ven.	Conway 1974.
1957/8	9/10th Feb.	Black Ven.	Brunsden 1969.
1958		Black Ven - Roman Road.	Lang 1959, Conway 1974.
1959		Lyme Regis, Cobb Road, RAF base.	Hawkins1991.
1960	November	Pinhay Bay seaward of Lynch Cottage.	Wallace 1966, Pitts 1981.
1961		Bindon.	Arber 1973.
1961		Culverhole Cliffs.	Pitts 1981.
1961		Dowlands.	Pitts 1981.
1961	March	Pinhay - Bindon.	Arber 1973.
1961	28Feb / 7Mar.	Humble Point	Macfadyen 1970, Arber 1973, Pitts1979.
1962		Lyme Regis - Cliff House.	Arber 1973.
1963		Pinhay Bay.	Macfadyen 1970.
1962/5		Lyme Regis, Cobb Road -chalet sites.	Hawkins1991.
1966		Pinhay Bay.	Arber 1971,1973.
1968	13th May	Charmouth - Higher Sea Lane.	Denness et al 1975, Conway 1979.
1968/9		Ware Cliff - Ware Lane.	Arber 1973, Pitts 1981.
1969		Charlton Bay	Pitts1979,1981, Arber 1973
1969		Black Ven - Raffey.	Arber 1973.
1969/73		Black Ven.	Brunsden 1974, Brunsden & Goudie 81, Chandler and Brunsden 1995.
1970		Lyme Regis - Pine Walk.	Arber 1973.
1971		Lyme Regis - Library Cottage.	Arber 1973, Conway 1976.
1972		Ware Lane - fields.	Pitts 1981.
1970/76		Lyme Regis - East Cliff.	Conway1979.
1975		Pinhay Pumping Station.	Grainger et al. 1985.
1976/7		Rousdon - Pinhay Undercliff.	Pitts 1981.
1976/7		Rousdon Undercliff.	Pitts 1981.
1976/7		Culverhole Cliffs.	Pitts1981.
1978		East Cliff.	Chandler & Brunsden 1995.
1981	May	Higher Sea Lane.	Anon 1981.
1981		Ware cliffs - Underhill Farm.	Pitts 1981.
1982		Pinhay - access road.	Grainger et al. 1985.
1983		Pinhay Pumping Station.	Grainger et al. 1985.
1984		Pinhay Pumping Station.	Grainger et al. 1985.
1986	Feb	Spittles west of Black Ven.	Chandler & Brunsden 1995.
1994		Spittles west of Black Ven rapid expansion.	Chandler & Brunsden 1995.
1994	Aug	Black Ven.	Chandler & Brunsden 1995.
1994	Feb	Pinhay Bay.	Grainger & Kalaugher 1995.

FIGURES
1 - 43

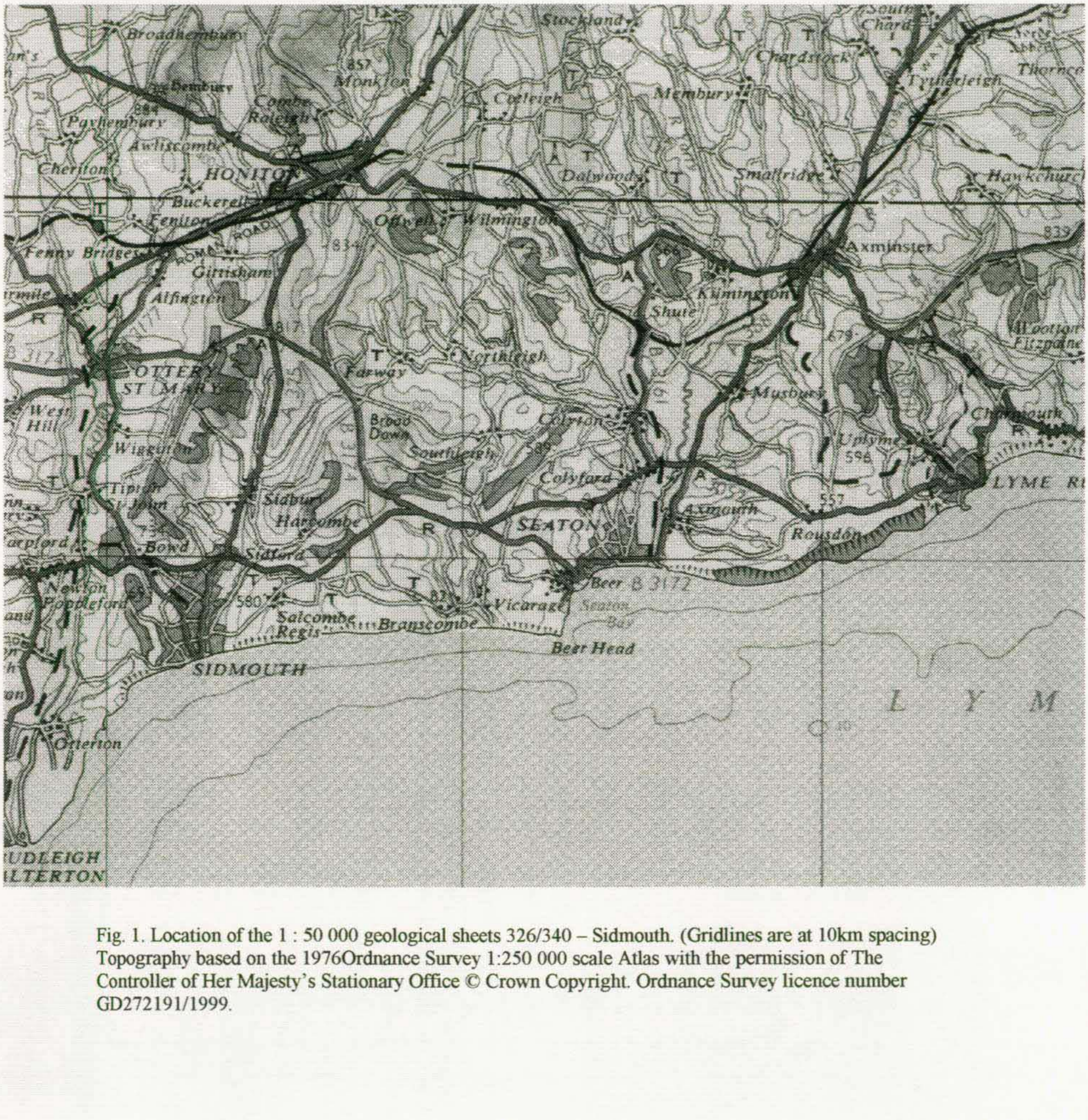


Fig. 1. Location of the 1 : 50 000 geological sheets 326/340 – Sidmouth. (Gridlines are at 10km spacing) Topography based on the 1976Ordnance Survey 1:250 000 scale Atlas with the permission of The Controller of Her Majesty's Stationary Office © Crown Copyright. Ordnance Survey licence number GD272191/1999.

Fig. 2. Upper Greensand - plasticity

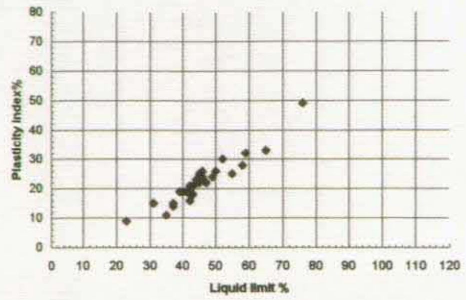


Fig. 3. Upper Greensand - Particle size distribution

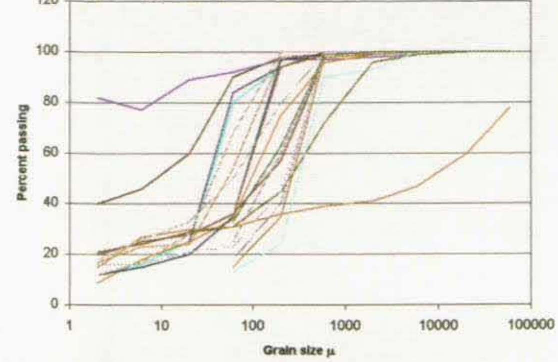


Fig. 4. Upper Greensand - sandy material SPT v Depth

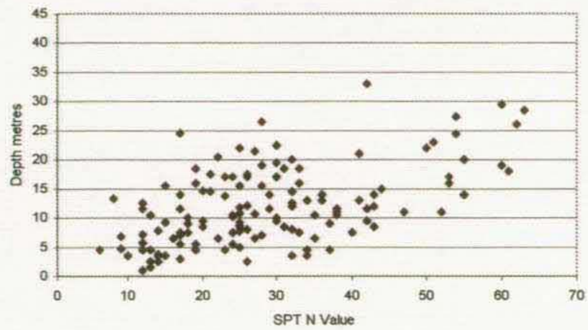


Fig. 5. Upper Greensand silty material - SPT v Depth

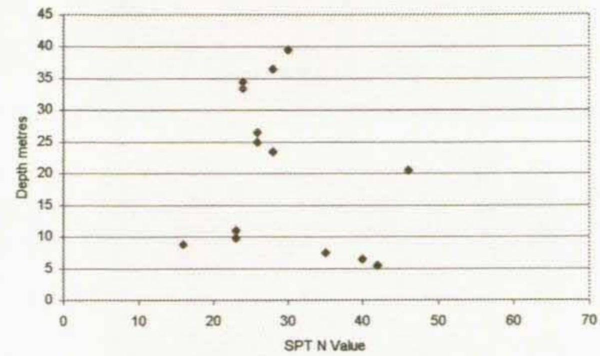


Fig. 6. Upper Greensand clayey material - SPT v Depth

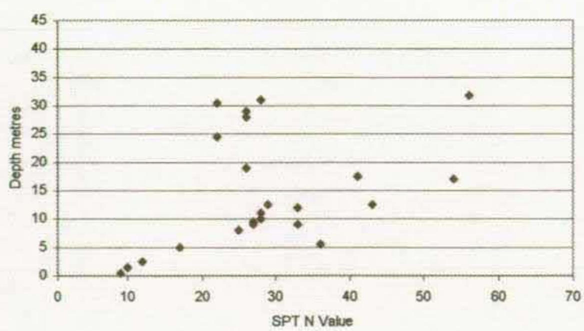


Fig. 7. Lower Lias - plasticity

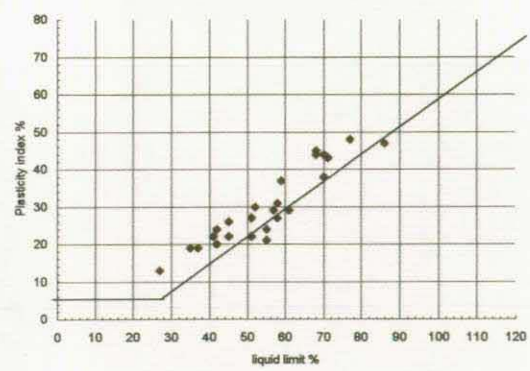


Fig. 8. Lower Lias - SPT v Depth

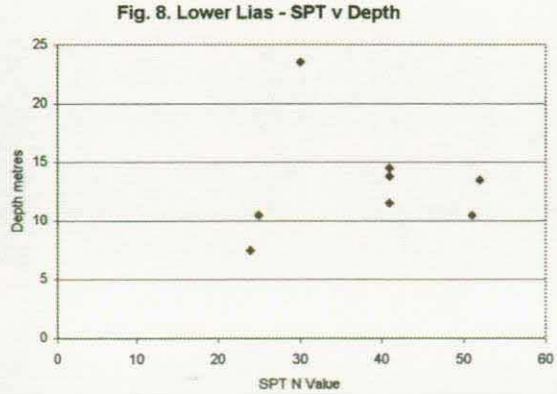
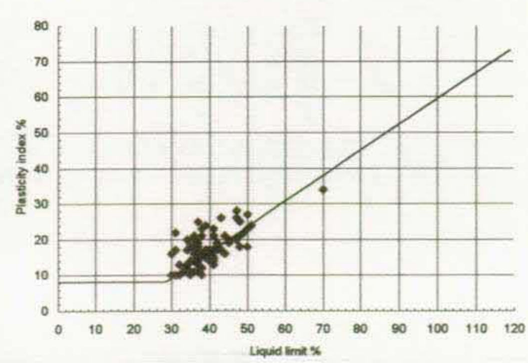


Fig.9. Mercia Mudstone Group - Plasticity



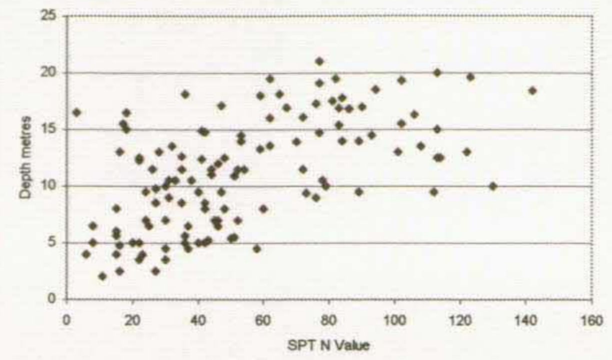


Fig. 10. Mercia Mudstone Group SPT v Depth

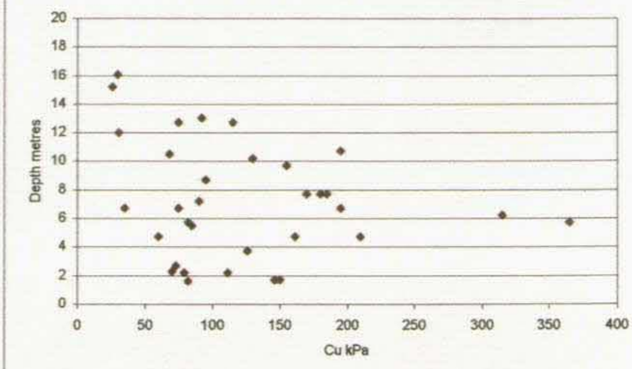


Fig. 11. Mercia Mudstone Group - Cu v depth

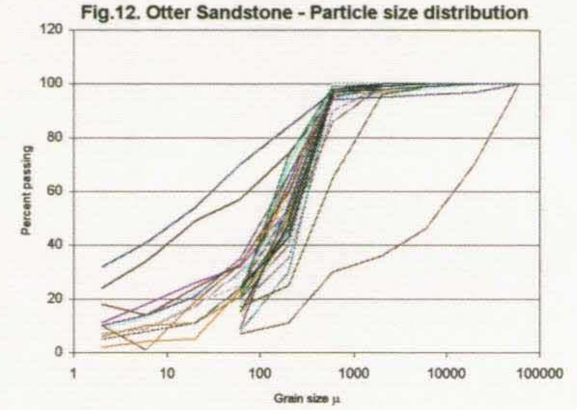


Fig.12. Otter Sandstone - Particle size distribution

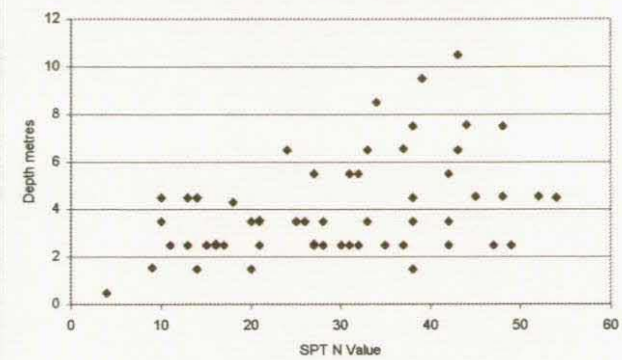


Fig.13. Otter Sandstone - SPT 'N' v Depth

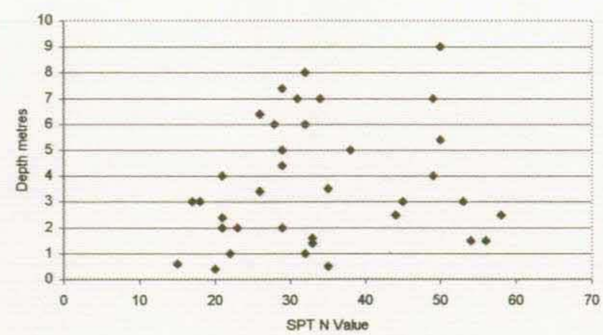


Fig. 14. Budleigh Salterton Pebble Beds CPT 'N' v Depth

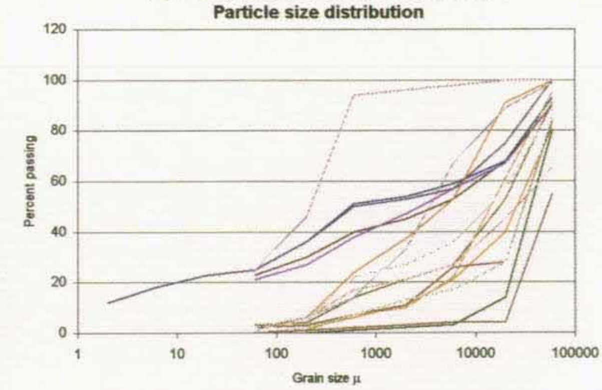


Fig. 15. Budleigh Salterton Pebble Beds Particle size distribution

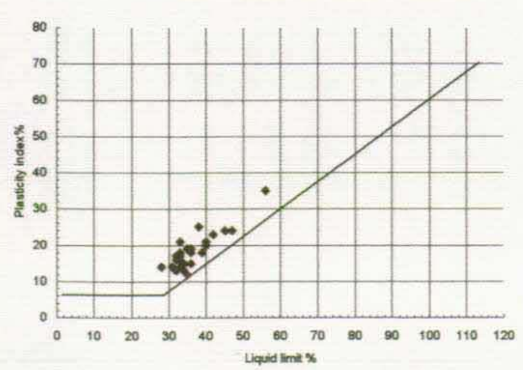


Fig. 16. Littleham Mudstone - plasticity

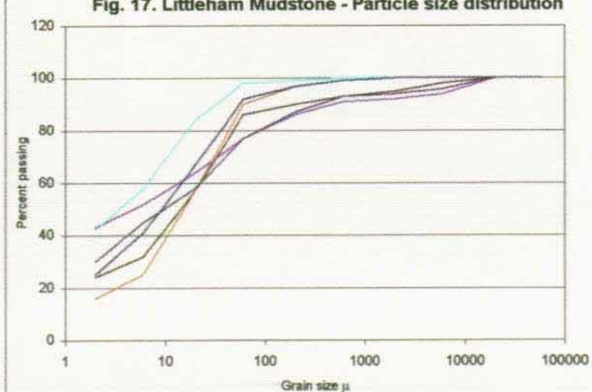


Fig. 17. Littleham Mudstone - Particle size distribution

Fig. 18. Littleham Mudstone SPT 'N' v Depth

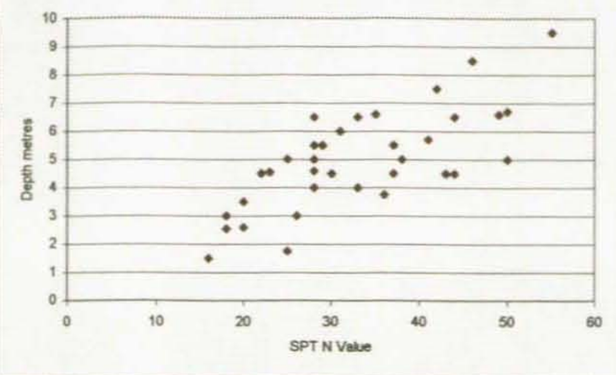


Fig. 19. Littleham Mudstone Cu v depth

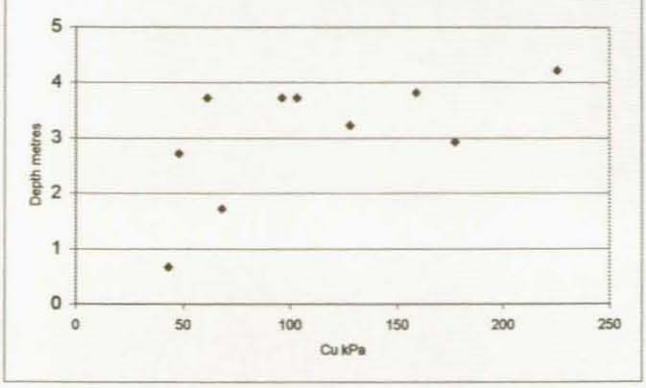


Fig. 20. River Terrace Deposits Particle size distribution.

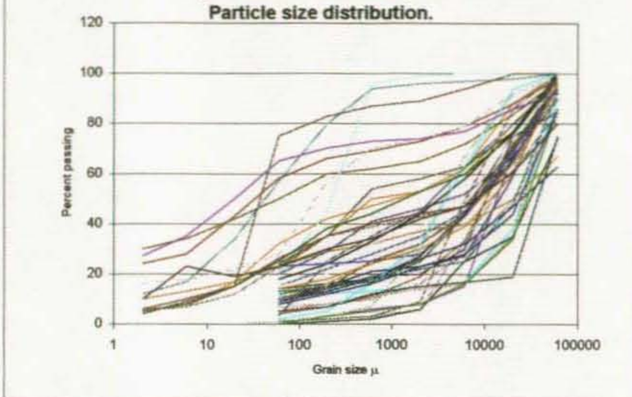


Fig. 21. River Terrace Deposits SPT and CPT 'N' v Depth

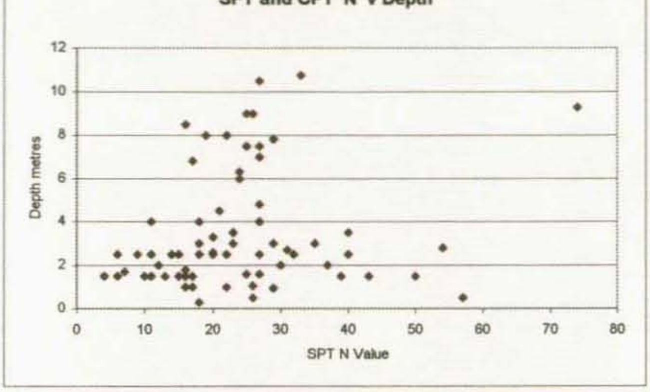


Fig. 22. Head - plasticity

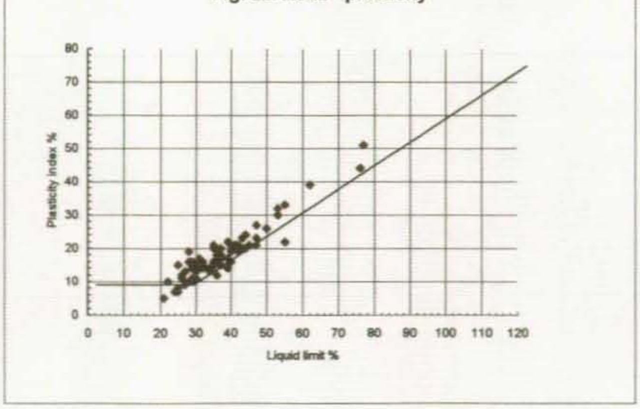


Fig. 23. CLayey Head - Particle size distribution -

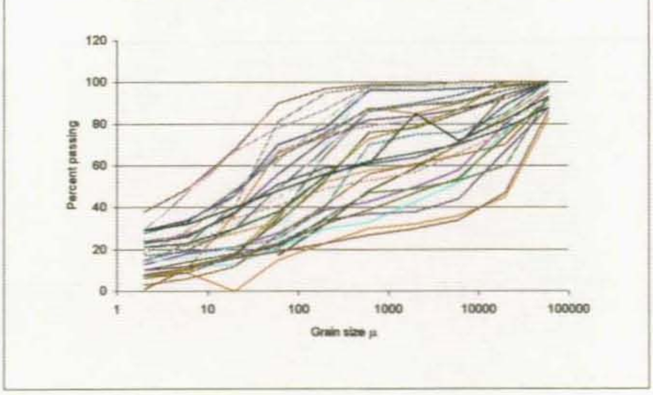


Fig. 24. Sandy Head - Particle size distribution

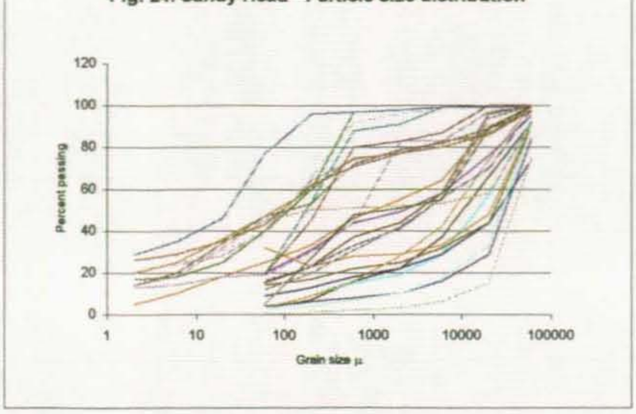


Fig. 25. Clayey Head SPT 'N' v Depth

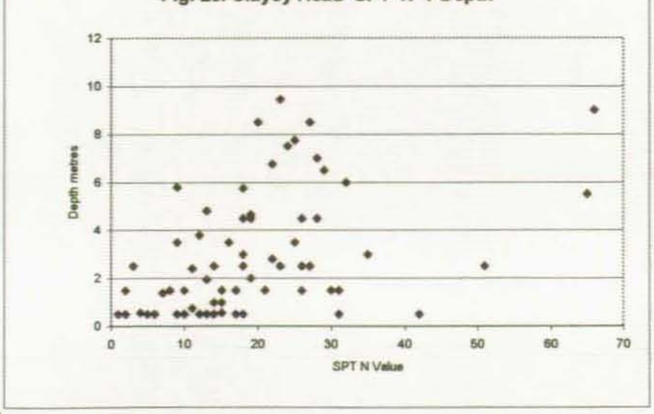


Fig. 26 Sandy gravelly Head SPT 'N' v Depth

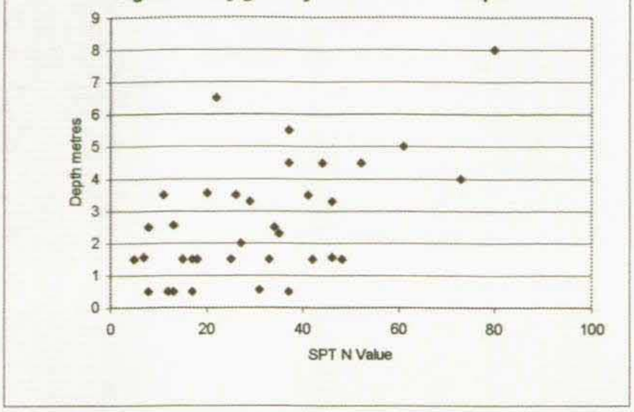


Fig. 27. Head - Cu v depth

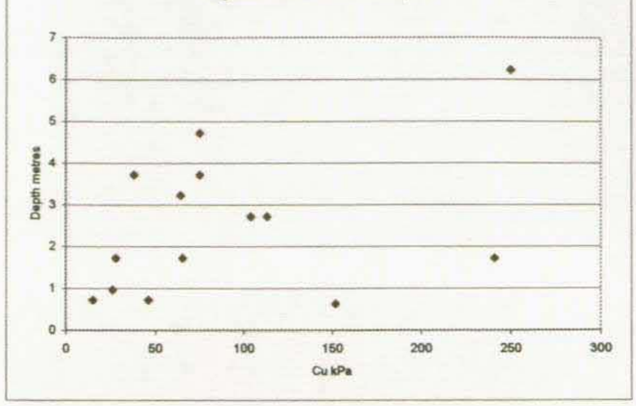


Fig. 28. Alluvium - plasticity

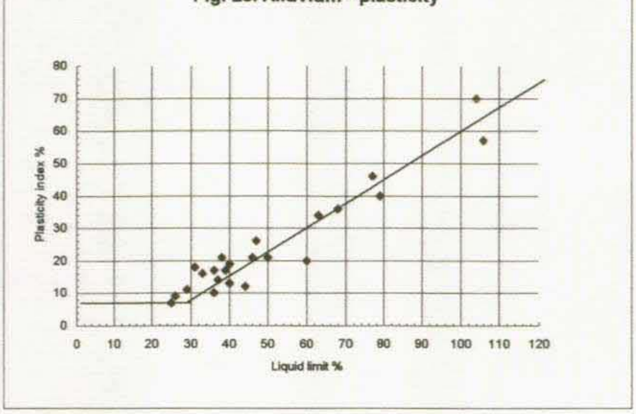


Fig. 29. Alluvium - Particle size distribution

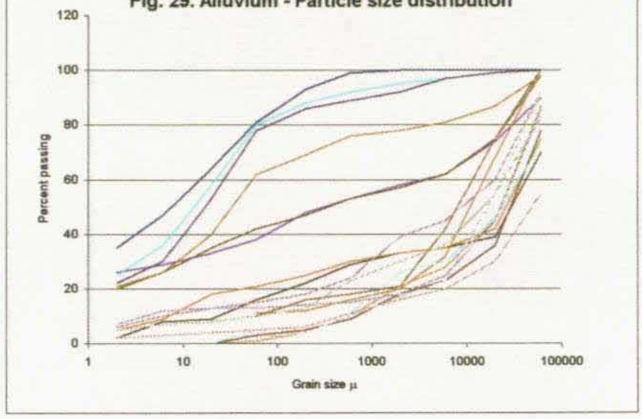


Fig. 30. Marine Deposits- SPT 'N' v Depth

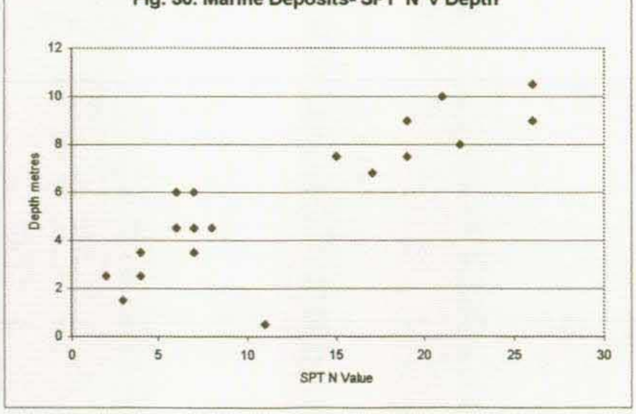


Fig. 31. Distribution of average monthly rainfall in Dorset 1856 to1996 showing the limitation in predicting landslide activity when calculating annual rainfall on a January to December calendar year.

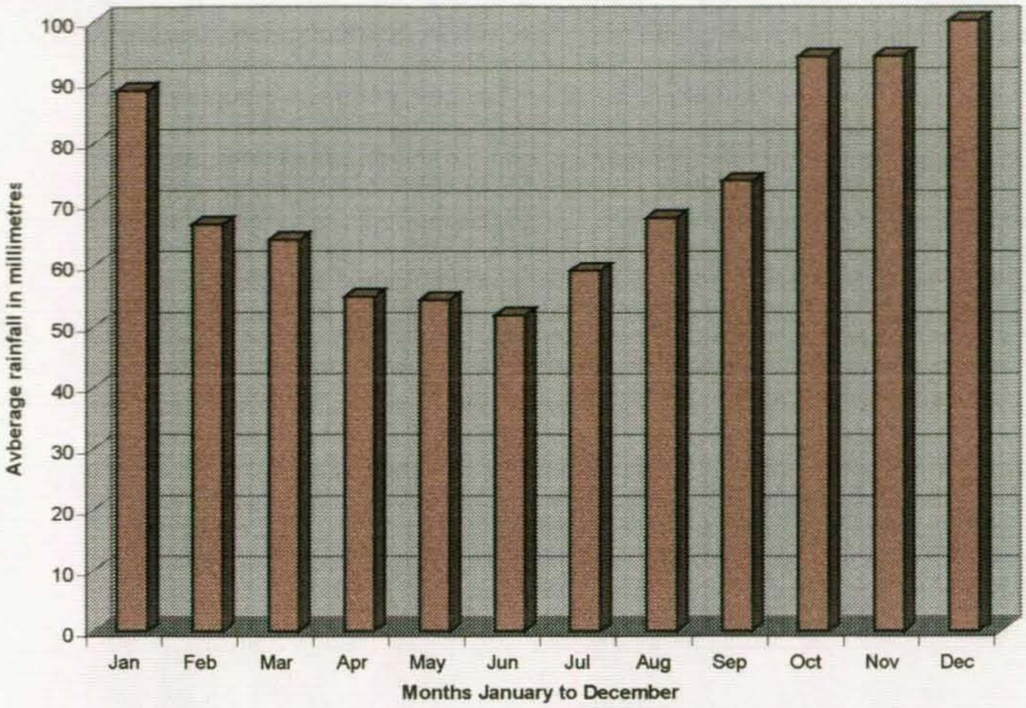


Fig.32. Distribution of average monthly rainfall in Dorset 1856 to 1996 showing how calculation of annual rainfall on a July to June basis highlights the winter rainfall.

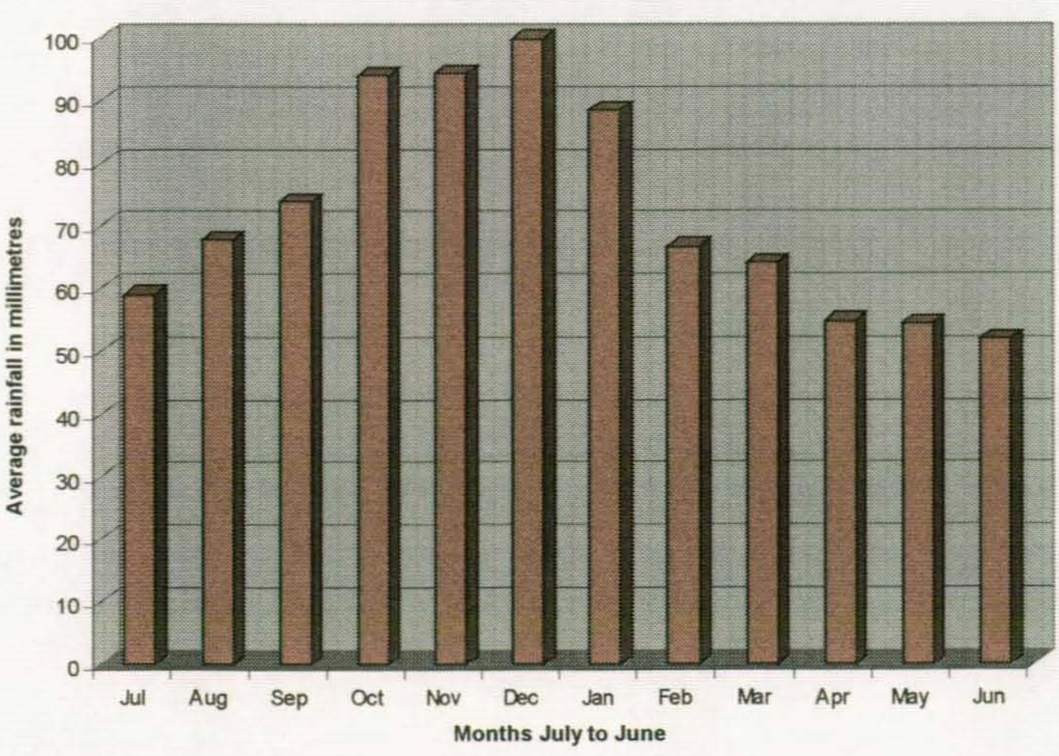


Fig. 33. Cliffs of Otter Sandstone at Ladram Bay.

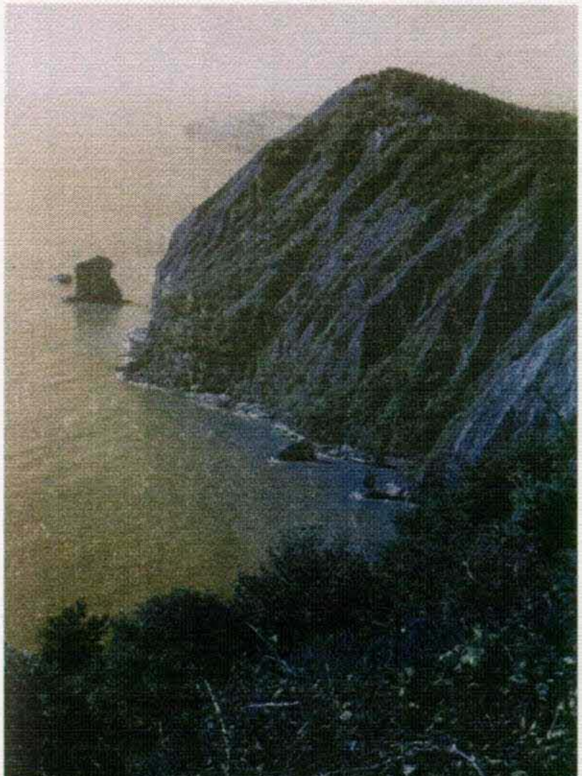


Fig. 34. Cliff at Big Picket Rock. A steep, lower cliff of Otter Sandstone stands close to the vertical. Above it is a less steep slope deeply incised by v-shaped gullies of Mercia Mudstone which is capped by Upper Greensand.

Fig. 35. A recent debris slide has cut back the cliff top west of Sidmouth [SY 1133 8685] to expose a roadside drain at the side of the cliff top road which may have been related to the cause of failure.

Fig. 36. Exotic armour stone protecting the sea wall and cliff in Otter Sandstone at Chit Rocks, Sidmouth.

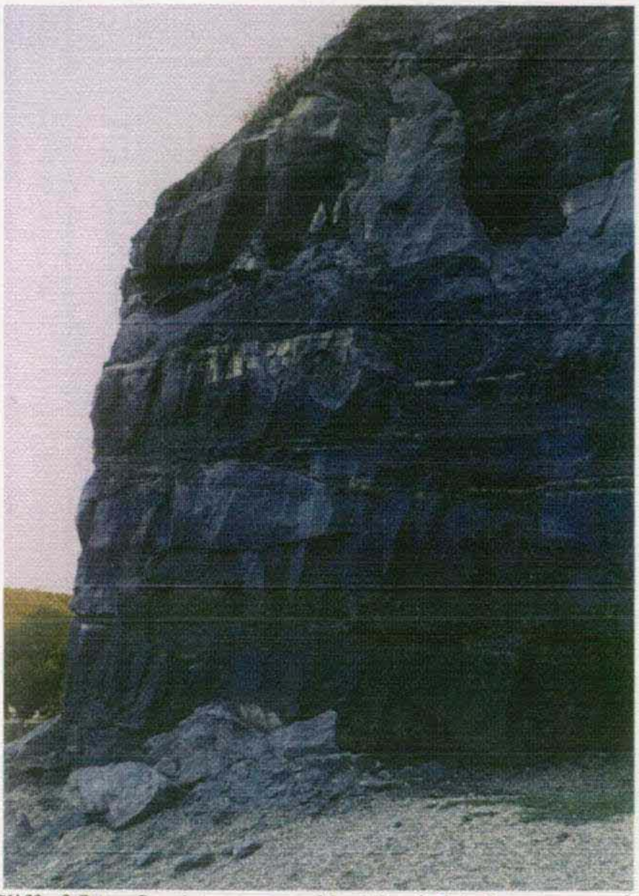


Fig. 37. Cliff of Otter Sandstone capped by Mercia Mudstone east of Sidmouth showing rockfall and undercutting by the sea.

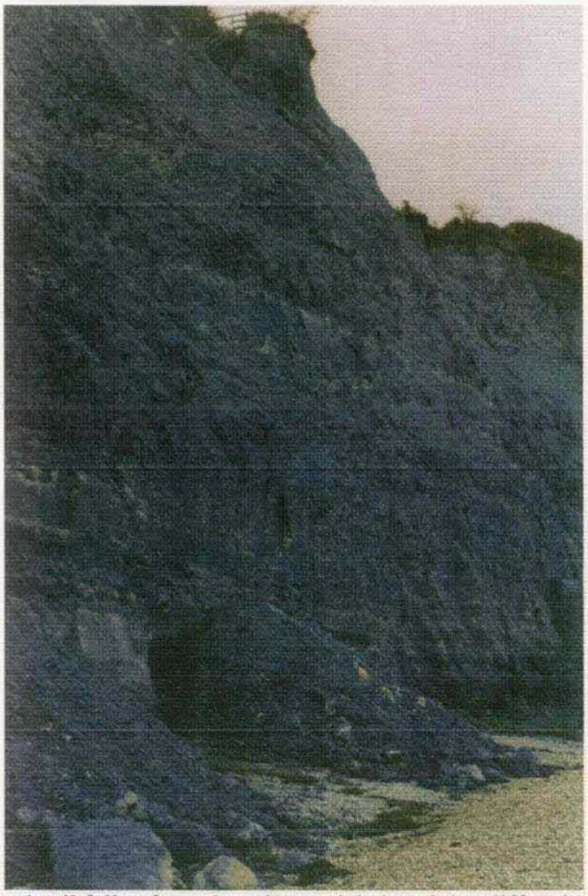


Fig. 38. Rock and soil falls of weathered material closed the cliff path east of Sidmouth in October 1995 [SY 135 874].

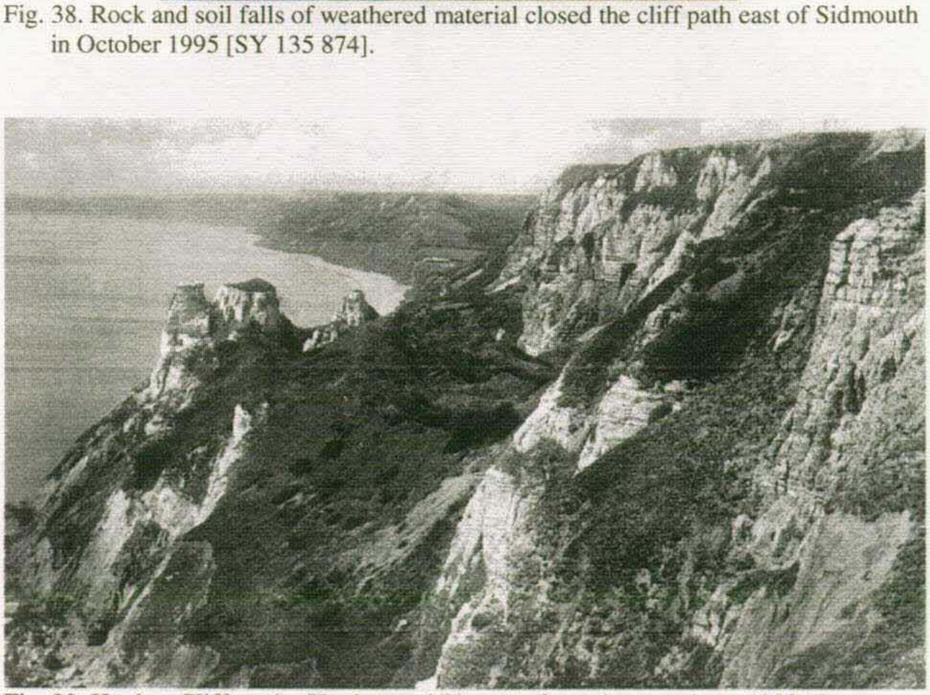


Fig. 39. Hooken Cliff, under Hooken and Pinnacle from the east about 1900 (Rowe, 1903).

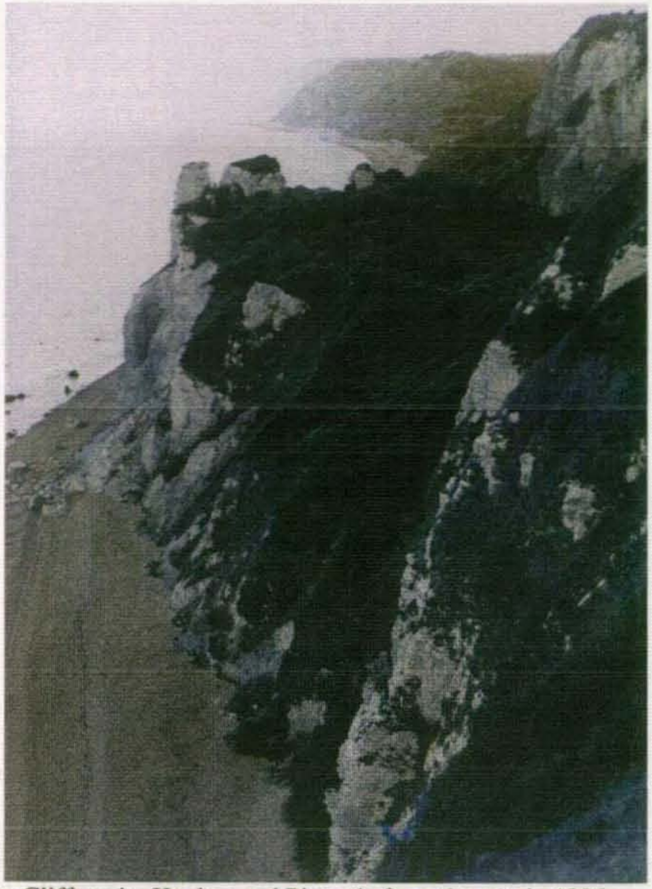


Fig. 40. Hooken Cliff, under Hooken and Pinnacle from the east in 1996.

Fig. 41. Mercia Mudstone stands at a steep angle and fails by soil fall as weathered material sloughs from the face of Haven Cliff.

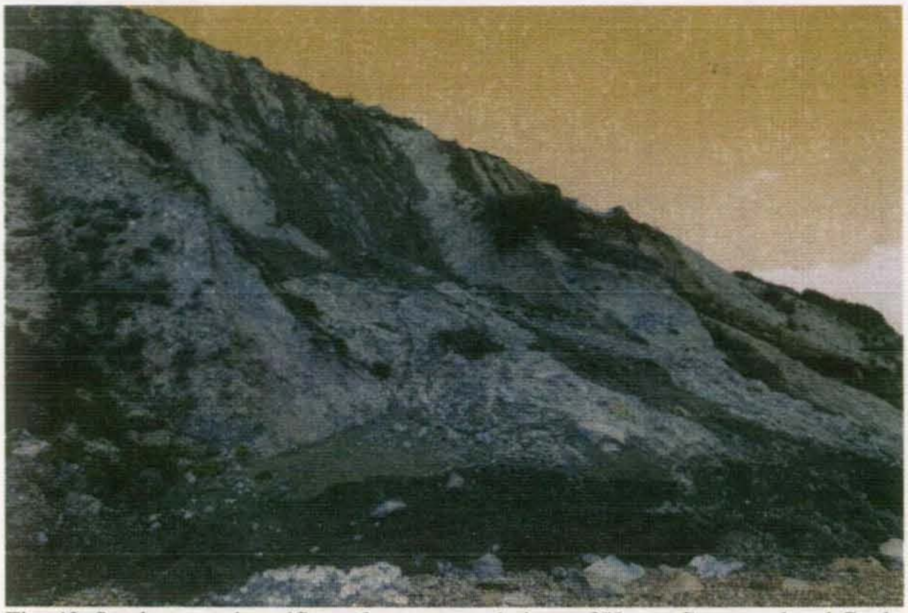


Fig. 42. Sand runs and mudflows from accumulations of Upper Greensand and Gault form debris accumulations at the base of the Mercia Mudstone cliff east of Seaton.

Fig. 43. Bindon landslide around 1885, after a drawing by A Geikie (Woodward and Ussher, 1911).