SAVING LYME REGIS FROM THE SEA: RECENT GEOLOGICAL INVESTIGATIONS AT LYME REGIS, DORSET

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The south coast resort of Lyme Regis is threatened by a combination of marine erosion and large landslips. The geological factors that influence the rapid rates of marine erosion and consequential cliff and slope movements in coastal areas such as this are difficult to determine. Individual sites within the town can be adversely affected by processes and events that occur in much larger adjacent onshore and offshore areas. However, coastal sites have the advantage of being amenable to a wide range of data-collection methods which can be combined to provide the detailed three-dimensional geological and geomorphological models on which to base proposals for remedial works. Multidisciplinary studies carried out at Lyme Regis in advance of detailed site investigations of the most threatened areas have included topographical surveys and the preparation of large-scale geological maps in the onshore area along with sidescan-sonar, bathymetric and seismic-reflection surveys in the offshore area.

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INTRODUCTION

The foundations of the present-day town of Lyme Regis (population 5000) were probably laid in the twelfth century when a community was established around a church (built in 1145) on a small knoll at the eastern end of the town adjacent to the River Lim. This was linked by a track to a small natural harbour some 700 m to the south west (Figure 1) that was protected from the prevailing south westerly gales by a series of limestone ledges. These were supplemented by a stone wall (The Cobb) at some time before 1250 (Fowles, 1991). The path between the town and the harbour ran along a sea front of low, degraded cliffs in mudstones that were prone to landslip and rapid marine erosion, and the area was not built on. The Victorian fashion for seaside resorts caused the town to expand, and areas that had previously been avoided because of the risk of erosion or instability were developed.

The present-day shape of Lyme Regis remains much the same as its medieval forerunner, with an eastern centre around the Church and a western area around the harbour, but with much inland addition on the valley slopes of the River Lim. As a result, much of the present-day town is built on landslip systems of various ages, and parts of the coastal zone face the double threat of marine erosion and the reactivation of old landslips. There has already been substantial disruption and damage in some parts of the town (Arber, 1941; Conway, 1977; Lee, 1992).

The problem of erosion and instability along the sea front has been exacerbated by man-made changes to the natural coastline. The most obvious example was the Victorian and early 20th century quarrying of the protective limestone ledges for cement-manufacture and building stone. The workings at the foot of Church Cliffs, at the eastern end of the town, eventually endangered the knoll that had been the focus of the original Lyme Regis settlement. Changes to the shape and height of The Cobb and later harbour walls interfered with the west-to-east longshore drift and at times starved the beaches of shingle. This, in turn, probably contributed to the reactivation of the sea-front (Lister Gardens) landslip and the large Spittles/Black Ven landslip on the eastern edge of the town, partly by removing the toe weights of old slips and partly by allowing increased marine erosion.

Various remedial works have been carried out since Victorian times, including the use of groynes, sea walls and rock armour to protect the developments along the sea front, and drainage works in the areas prone to landslip. None of these has been lastingly successful and the time has now come when a comprehensive strategy has to be developed if Lyme Regis is to remain as a desirable residential and tourist town. The neighbouring coastline contains several examples of the results of piecemeal sea-defence works that have been costly and only temporarily successful. The solutions of yesterday have become the problems of today, and of tomorrow.

However, it is by no means obvious what the best solution might be at Lyme Regis. Piecemeal protection of the esplanade would not only detract from the natural charm of the town, but it could also change the beach regime beneath and adjacent to the Spittles/Black Ven landslip and trigger dormant landslips that could eat their way back into the town. The financial, legal and planning implications of any works could obviously be serious.

In 1995, West Dorset District Council (WDDC), in its role as coast-protection authority, initiated studies designed to obtain the data necessary to enable possible long-term engineering solutions to be devised and evaluated. In addition to engineering, hydrological and geomorphological studies, a major part of the work included detailed geological surveys of the town and those adjacent onshore and offshore areas that might be affected by any future sea-defence works. The primary aim of the studies was to understand the underlying mechanisms and geological and geomorphological controls on landslipping and marine erosion, and the inter-relationship between them. The WDDC study coincided with the re-survey of the British Geological Survey's (BGS) 1:50,000-scale Geological Sheet 326 (Sidmouth) at the 1:10,000-scale. This included Lyme Regis and the adjacent areas, and WDDC and BGS were, therefore, able to combine their researches on the geology, stratigraphy and structure of the coastal-engineering study area.

The general geology of Lyme Regis has been known since the time of De la Beche (1826). Much of the town is built on mudstones and limestones of the Blue Lias Formation and Charmouth Mudstone Formation (which is divided into four members) of the Lias Group (Figure 2). These solid deposits are overlain by a highly variable thickness of stony sand and clay (Head deposits) derived largely from the Cretaceous Upper Greensand. The highest parts of the town extend onto the Cretaceous outcrop.

Woodward and Ussher (1911), Lang (1914, 1924, 1926, 1932, 1936), Hesselbo and Jenkyns (1995) and Callomon and

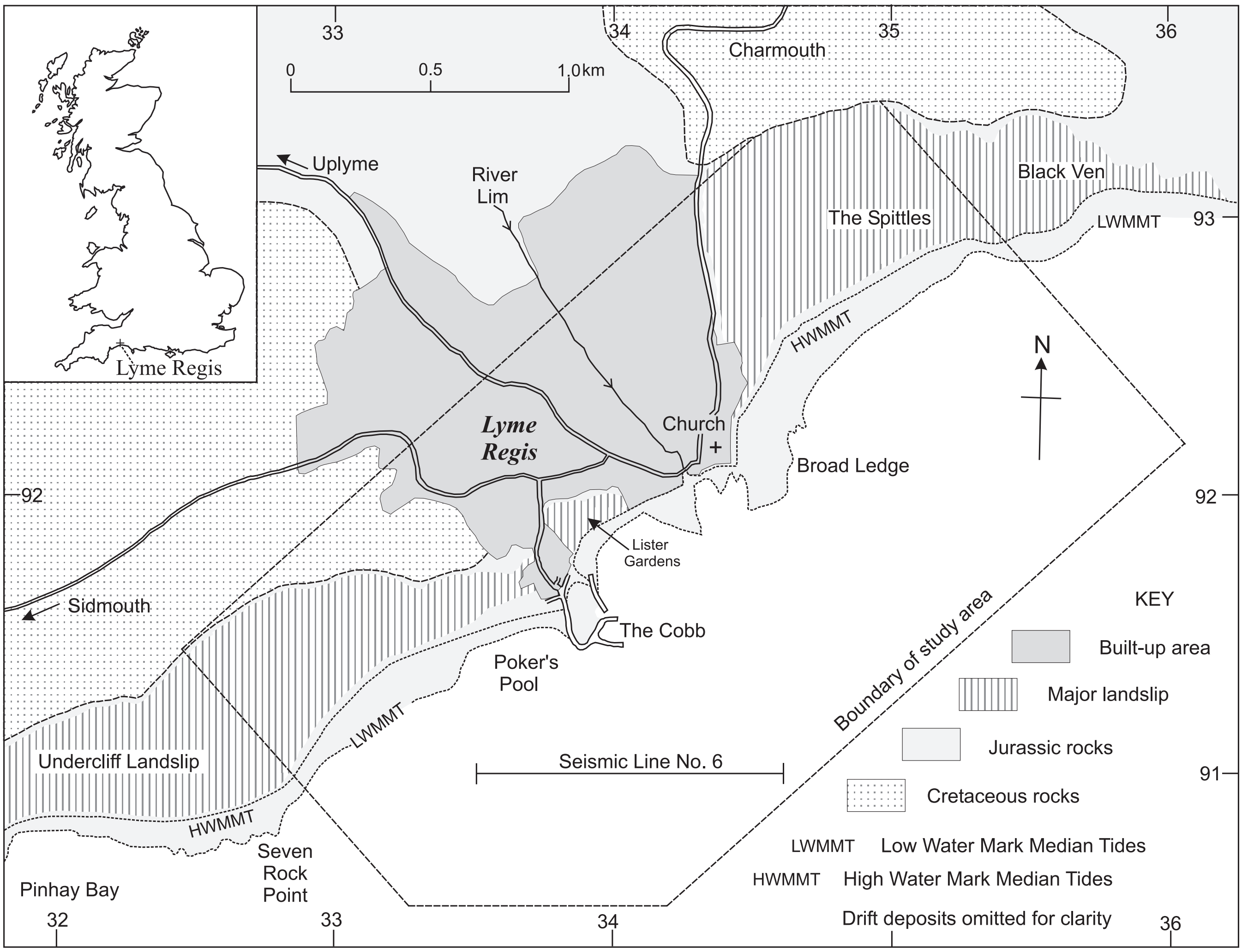


***Figure 1**. Geographical and simplified geological map of the study area.*

Cope (1995) have provided descriptions which, taken together, provide a detailed stratigraphy of the Lias of the study area. Many of the individual limestone beds within the mudstone-dominated succession were named by the quarry workers who won the stone for building and for lime and cement manufacture. These names were retained by Lang and subsequent workers. In addition, Lang allocated bed numbers to the whole of the succession, and these have continued to be used to the present day (Figure 2).

METHODOLOGY

The site-investigation of large coastal sites that involve unstable ground and active marine erosion, such as that at Lyme Regis, is commonly prohibitively expensive to carry out by conventional mapping and drilling/trenching methods alone. However, such sites are amenable to the use of interactive multidisciplinary surveys that can provide a wealth of detailed geological information at low cost.

The BGS survey of Lyme Regis and the surrounding area included an examination of the cliff, foreshore sections and inland sections, feature mapping combined with hand-augering, air-photograph interpretation, and an examination of earlier map, borehole and published geological data. The works commissioned by WDDC included large-scale colour aerial photography of the cliff and intertidal areas; bathymetric, seismic-reflection and sidescan-sonar surveys of the intertidal area and the subtidal area fronting and adjacent to the town; a programme of trial pits and continuously cored boreholes and the installation of borehole instrumentation to monitor groundwater pressures and slope movements within the town itself.

Aerial photogrammetric mapping

Analytical stereoplotting equipment and specially commissioned aerial photographs were used to prepare 1:500-scale topographical base maps for the study area with ground surface contours at 0.5 m intervals. The results were also used to produce Digital Terrain Models (DTMs) that pick out many of the features formed by the underlying geology.

Drilling

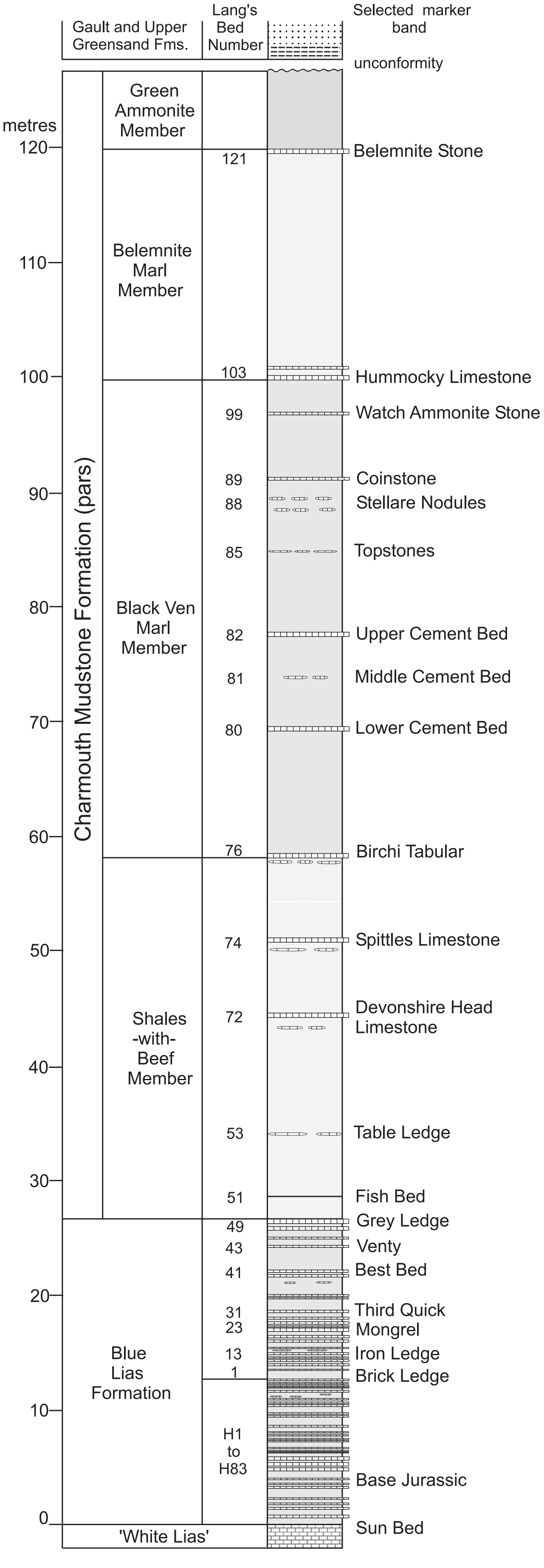
A search of the archives of local government departments, consultants and others produced 250 borehole logs from 45 ground investigations in the study area. Seventy nine continuously cored boreholes were drilled to depths of 5 to 55 m for the present study to fill gaps in the data cover, and to explore particular areas such as the sea front in greater detail (Clark *et al*., 2000). All the new holes were gamma-ray logged to assist in their correlation. Taken together, the borehole data combined with the other surveys described below enabled detailed structure contour maps of the key geological marker beds to be drawn for the onshore area.

Cliff measurements

An initial reconnaissance of the cliffs to the east and west of the town showed that there is strong stratigraphical control on the major landslips in which the basal shear surfaces tend to occur in mudstones on top of, or just above, competent limestone beds within the Lias. The stability of the landslips was particularly sensitive to small changes in the amount and direction of dip, and some of the minor faults (with displacements of less than 2 m) also appeared to influence the extent and characteristics of individual landslips. In addition, it was clear from the shapes of the foreshore outcrops that the water depths in the intertidal and adjacent offshore areas were strongly influenced by the lithostratigraphy and structure, and that these had a direct bearing on the rates of erosion of the adjacent coastline. These observations confirmed the need for detailed descriptions of the lithostratigraphy and structures exposed in the cliffs and on the extensive foreshore rock platforms.

Measurements made of the Blue Lias Formation sections with a 5 m tape in the near-vertical cliffs at Devonshire Head and Church Cliffs, 2 km apart, proved to be in good agreement. In contrast, measurements made in the Charmouth Mudstone at Devonshire Head and at the Spittles and Black Ven, where the beds crop out on 30° to 40° slopes separated by broad debris-covered benches, were in such poor agreement that it was not possible to determine whether or not there were lateral variations in the sequence. No reliable thicknesses could be measured on the foreshore where the outcrops of the individual limestone beds have very irregular surfaces.

In order to get precise measurements, the positions and elevations of selected marker beds exposed in the cliffs and foreshore were determined to centimetre accuracy using a prism target and electronic distance measurement (Total Station Survey). In the more vegetated parts of the landslip, where line of sight could not be achieved, a Global Positioning Satellite (GPS) survey was used. Some of the marker beds in the cliffs are visible from the foreshore, but access to them was too difficult to carry out either a Total-Station or a GPS survey. Theodolite sitings were used in combination with the large-scale contour maps to obtain plan positions and elevations to an estimated accuracy of +/- 0.5 m.



Individual limestone beds not shown to scale

***Figure 2**. Generalised vertical section for the solid deposits of the Lyme Regis area.*

Foreshore mapping

Although Lang (1914, 1924) had published detailed large-scale maps of the Blue Lias Formation and Shales-with-Beef Member outcrops on the foreshore between Seven Rock Point and Charmouth, these contained too many misidentifications of the limestone beds to provide the structural data needed to understand the failure mechanisms of the coastal landslips. In addition, Lang's maps only covered about 40% of the intertidal area within the coastal-engineering study area.

The foreshore and adjacent coastal strip between Seven Rock Point in the west and Black Ven in the east was photographed at low tide on four occasions between 1995 and 1997. Colour prints at 1:3000 scale were used to plot the outcrops of faults and the more prominent geological marker beds (mostly limestones) on the foreshore. Most of the photographs were taken at or close to low tide. None was taken at a low Spring tide, but on several sets the sea was so clear that it was possible to trace ledges from the intertidal into the subtidal area.

All the foreshore outcrops in the study area are in the Blue Lias Formation or the Shales-with-Beef Member. Those in the Blue Lias Formation consist of overlapping broad ledges of limestone which largely conceal the narrow outcrops of the intervening mudstones. The overlying Shales-with-Beef Member gives rise to a more subdued foreshore topography in which widely spaced ribs of limestone and 'beef' are largely surrounded by sand. The process of identifying the individual limestone beds in the foreshore exposures was greatly assisted by the advice of local fossil collectors. Following in the footsteps of the Philpot sisters and Mary Anning, the town still houses the greatest concentration of professional and amateur fossil collectors in Europe. Many of them have an unrivalled knowledge of the stratigraphy of the local Lias.

The air photographs enabled numerous small faults to be accurately plotted on the foreshore and beneath shallow water (Figure 3). Many of these are difficult to trace on the ground, partly because of their sinuous nature and partly because they occur as erosional gullies infilled with sand or stones. Few of these faults were recorded on the large-scale geological maps of the foreshore made by Lang (1914, 1924).

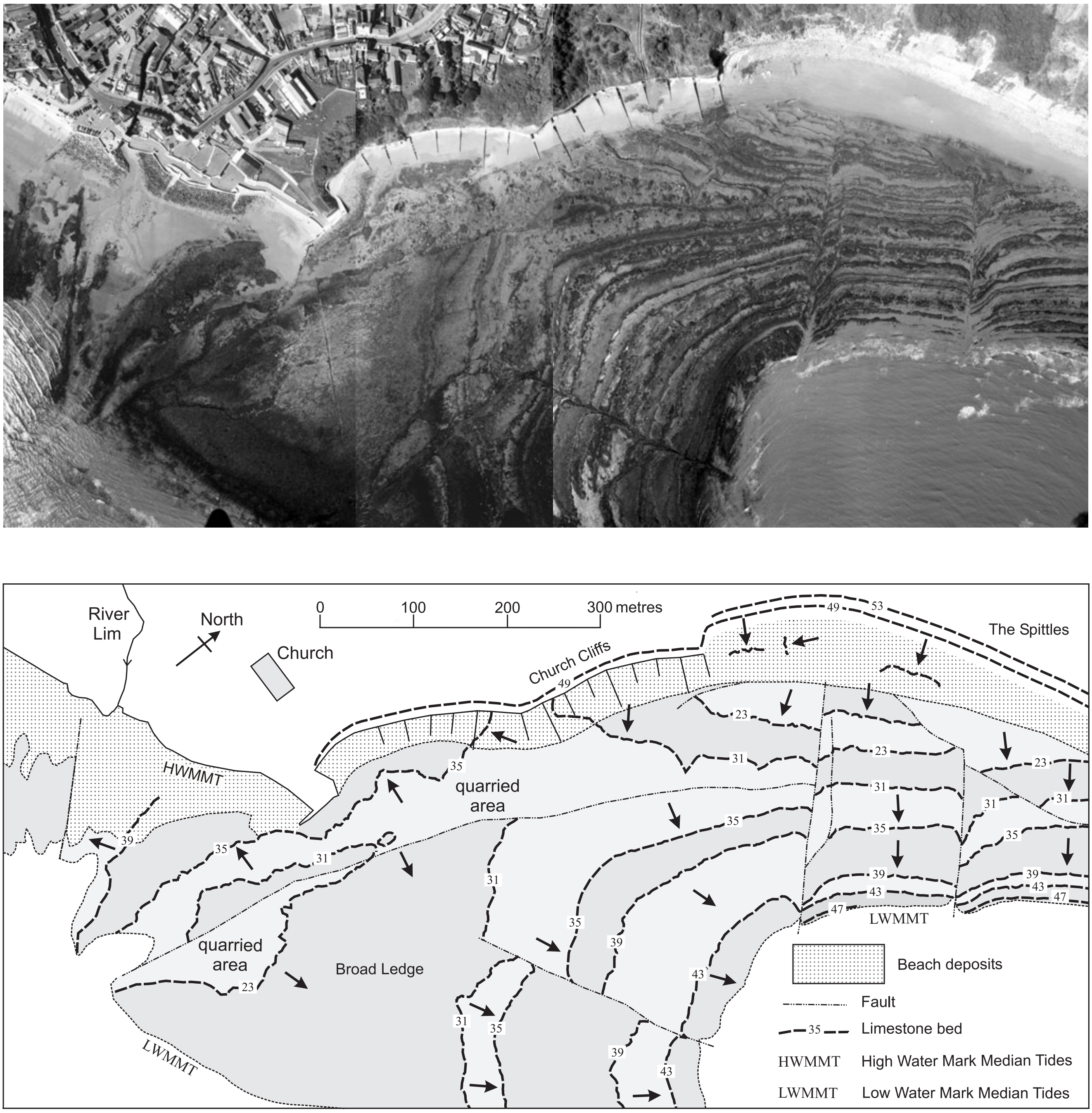


***Figure 3**. Aerial photograph and simplified geological interpretation of the Broad Bench area. Bed numbers as in Figure 2.*

Bathymetric survey

A bathymetric survey was carried out over a 2.8 km length of coast out to the -13 m OD contour, between 750 m and 1500 m from high-water mark. East-west survey lines 10 m apart gave depth soundings with a nominal accuracy of +/-0.1 m. The resolution of the resulting dataset was sufficiently high to generate computerised seabed images that show the principal faults and marker bands (Figure 4, after Badman *et al*., 2000).

Side-scan sonar survey

A side-scan sonar survey made over the same area as the bathymetric survey showed numerous seabed features in detail, including the distribution of rock outcrops and sediment cover. Grab samples and video recordings were used to verify the interpretations at selected sites. Bare rock pavements of Blue Lias Formation were recorded in which individual limestone beds and faults are recognised. In contrast, the Shales-with-Beef Member outcrops are largely overlain by sand with, locally, trains of gravel megaripples.

Seismic-reflection profiling survey

Seismic-reflection traverses were made along 22 sub-parallel, roughly E-W tracks at high tide in the central part of the study area. In order to minimise the cost of the survey, multiple reflections were not processed out, with the result that the effective interpretable base to the sections varies from about 5 to 40 m, depending on the water depth and geology. This was adequate for the required interpretation of the stratigraphy and geological structure. Two-way-travel times were not converted to depths because the thicknesses between the principal marker bands were already accurately known from the cliff and borehole measurements.

In the area surveyed, the rock outcrops (and subcrops beneath a veneer of recent sediment) consist of the highest part of the Blue Lias Formation and the full thickness of the Shales-with-Beef

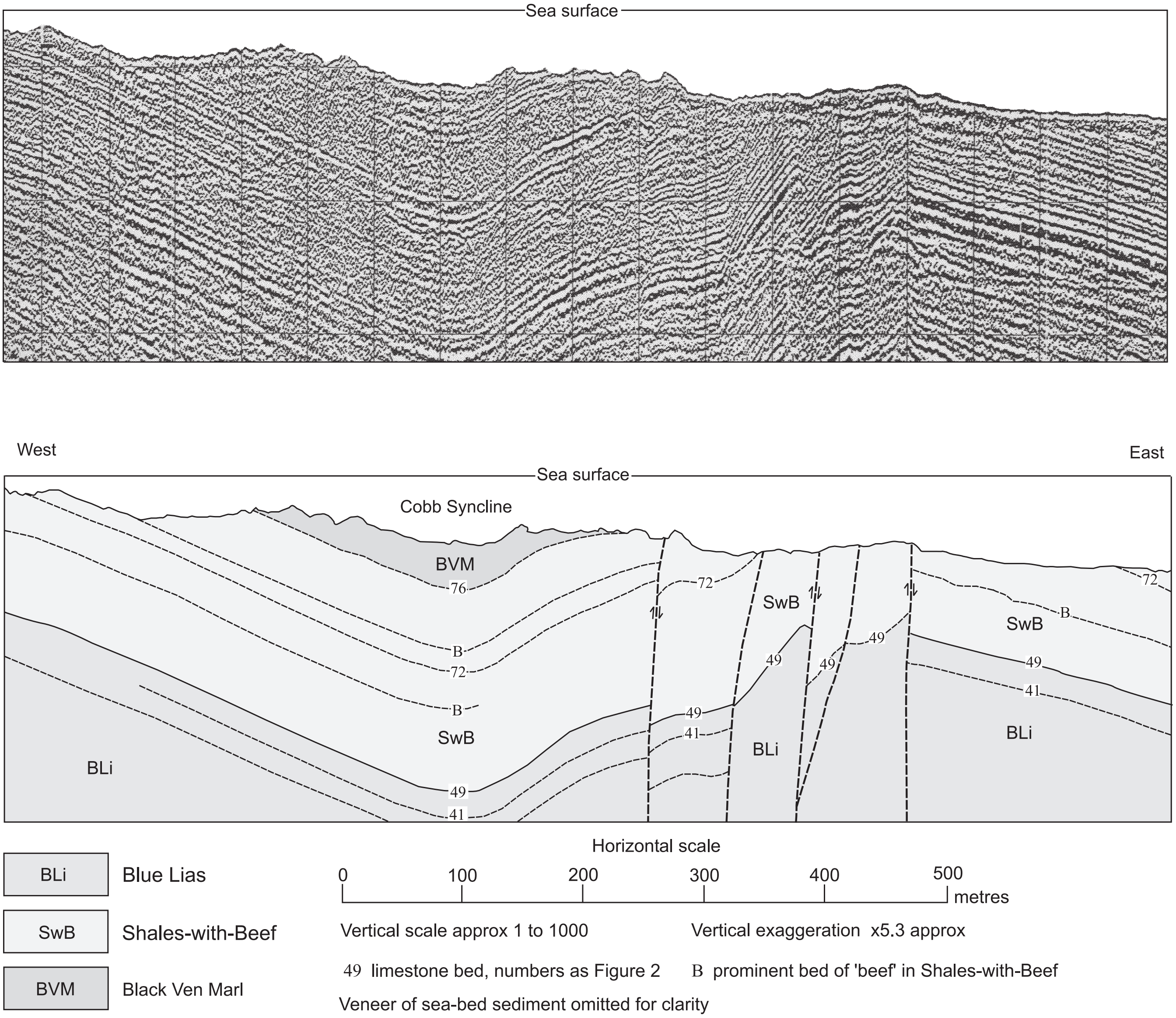


***Figure 5**. Seismic-reflection profile and simplified geological interpretation along Seismic Line No. 6.*

Member. The closely spaced limestones in the Blue Lias Formation produced strong reflections that give the formation a distinctively 'well-bedded' seismic signature (Figure 5). The junction with the Shales-with-Beef Member is particularly clear in all the sections. Within the overlying mudstones the principal limestone beds, notably the Devonshire Head, Spittles and Birchi Tabular limestones gave strong individual reflections that could be matched with sea-bed ledges recorded on the bathymetric (Figure 4) and sidescan-sonar surveys.

The seismic-reflection survey proved to be especially useful for identifying folding and faulting within the Lias. These structures had proved to be particularly difficult to recognise in the intertidal area where the more fractured rocks are either sand covered or represented by debris-filled gullies. The survey also identified a large offshore area of disturbed materials, part of the toe of an ancient landslip that was previously unsuspected (Figure 6).

GEOLOGICAL RESULTS

The geological results of the combined surveys are summarised in a 1:5000-scale map of the study area, a revised detailed vertical section for the stratigraphy, large-scale structure contour maps for the tops of the Blue Lias Formation and Shales-with-Beef Member in the offshore and onshore areas, and correlations between the various exposure and borehole sections. The stratigraphy of the study area proved be laterally more variable than was anticipated from the published geological accounts. It also contained several marker beds that can be recognised in the gamma-ray logs and are well exposed in the cliffs, but which had not previously been recorded.

To the east and west of the town, the foreshore and low cliffs expose fresh sections in the upper part of the Blue Lias Formation (beds 13 to 49 of Lang, 1924) and the lower part of the Shales-with-Beef Member (beds 50 to 64 of Lang 1914, 1926) (Figure 6). More weathered sections that are not subjected to marine erosion occur to the east of the town in the Spittles and Black Ven landslips. These expose the full sequence of the Charmouth Mudstone unconformably overlain by the Gault and Upper Greensand. A westerly overstep of the Cretaceous rocks cuts out the upper part of the Charmouth Mudstone on the west side of the town.

The outcrop of the Blue Lias Formation is confined to the foreshore and low cliffs on the eastern and western edges of the town, and to a narrow strip along the Lim Valley. The formation consists of interbedded dense, fine-grained limestones and organic-rich and carbonate-rich mudstones. It can be roughly divided into two parts in the Lyme Regis area. A lower 18 m (referred to by Lang, 1924, as beds H1 to H31) composed of tabular and nodular beds of limestone mostly 20 to 40 cm thick

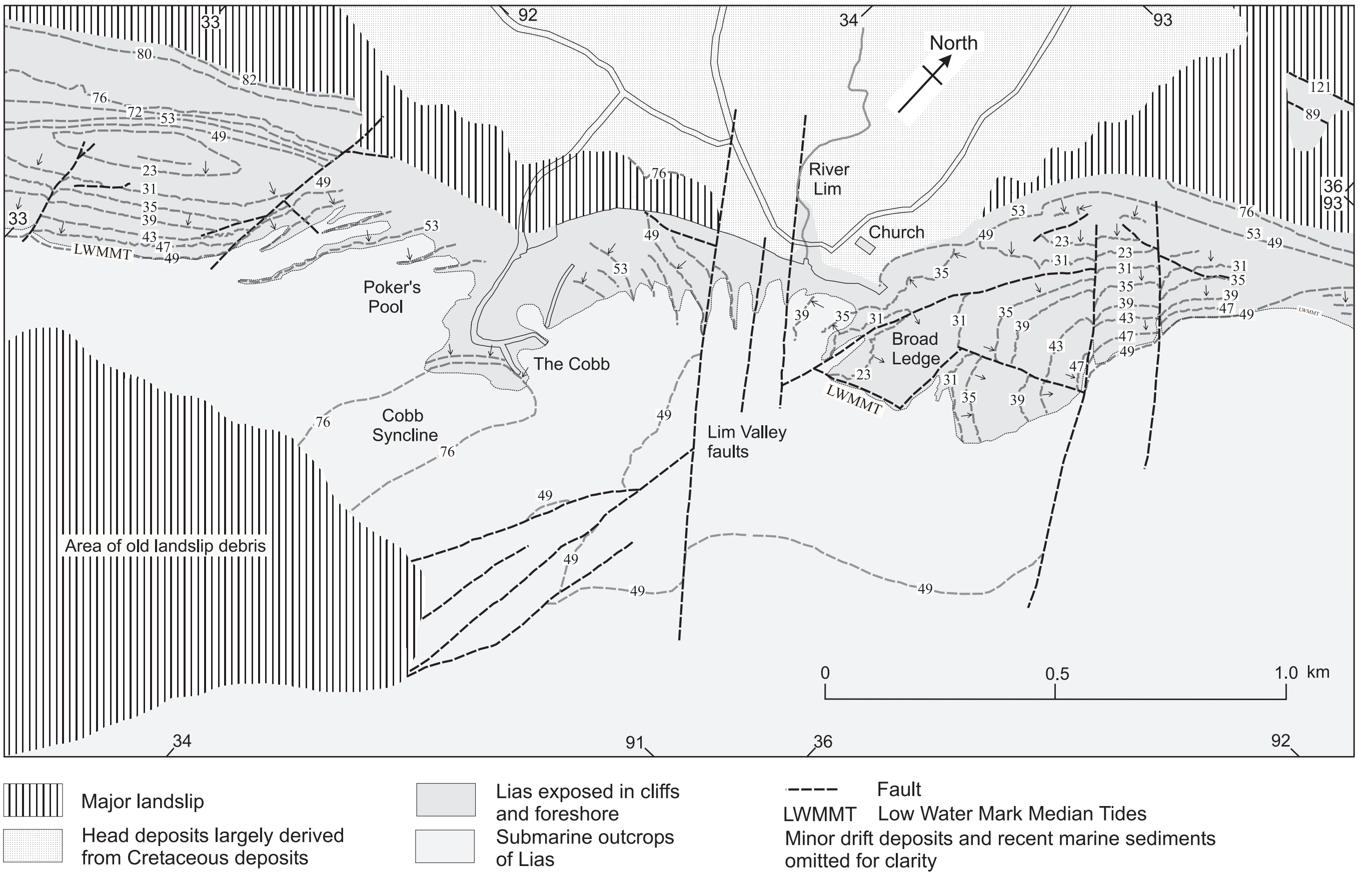


Figure 6*. Geological sketch map of the Lyme Regis area.*

separated by beds of mudstone mostly 10 to 40 cm thick, overlain by 8 to 10 m (Lang's beds 32 to 49) of mudstone with nine tabular beds of limestone 20 to 60 cm thick and with several horizons of discontinuous limestone concretions. These higher limestones form Broad Ledge and Church Cliffs that protected the earliest settlement at Lyme.

The Charmouth Mudstone Formation underlies most of the town. It consists of about 95 m of pale, medium and dark grey mudstones, calcareous mudstones and organic-rich mudstones that contain few limestone beds. The formation has been divided into four members, each of which has a lithologically distinctive limestone bed at its base or top. In ascending order, the Shales-with-Beef Member is capped by the Birchi Tabular stone band (Bed 76), the Black Ven Marl Member by the Hummocky Limestone (Bed 103), and the Belemnite Marl Member by the Belemnite Stone (Bed 121). The highest member, the Green Ammonite Member, has a small outcrop on the eastern edge of the study area.

The lower part of the Shales-with-Beef Member is exposed in the cliffs at Devonshire Head [SY332 915] and the whole of the member (32 m thick) is exposed at the Spittles [SY 350 929] and on Black Ven. The member occupies a shallow syncline on the foreshore and formerly formed low, slipped cliffs (now landscaped to form Lister Gardens) [SY 3385 9190]. Beds of 'beef' (fibrous calcite) form ledges in Poker's Pool [SY 336 914], and on either side of the harbour walls. A prominent outcrop of the Birchi Tabular Bed in the axis of the syncline forms the foundation for the outermost wall of The Cobb.

The Black Ven Marl at Black Ven consists of 42 m of mudstones and calcareous mudstones with concentrations of thin beds of fissile, organic-rich mudstone at several levels. The member contains several laterally persistent tabular limestone beds, notably the Birchi Tabular at the base, the Lower and Upper Cement beds. As with the Shales-with-Beef Member, the Black Ven Marl is susceptible to landslip and has been extensively mobilised by collapse of the overlying Gault and Upper Greensand.

The Belemnite Marl Member consists of 20 m of rhythmic alternations of more- and less calcareous, pale grey and dark grey mudstones, mostly in couplets 0.35 to 0.40 m thick. The full thickness of the member is exposed above The Spittles and Black Ven in a cliff-like escarpment [SY 3575 9322 to 3500 9314] capped by the Belemnite Stone.

The Gault and Upper Greensand formations, unconformably overlain by a Tertiary erosion surface capped by Clay-with-flints, crop out on the high ground to the west and east of the town. The Gault, although thinner and more arenaceous than its more easterly equivalents, acts as a major zone of weakness when weathered. It causes the decalcified Upper Greensand to collapse and give rise to debris flows and large quantities of sand slurry that mobilise and combine with landslips and mud flows in the Liassic rocks to form some of the largest coastal landslips in Europe (Brunsden, 1969; Conway, 1977). The landslips have been especially active in the past 200 years, and in many cases can be seen to have reactivated older failure surfaces that were probably initiated by freeze-thaw processes during the periglacial climates of the late Pleistocene.

Many of these older slips in the urban area were covered by successive extensive solifluction sheets of sand with cherts (Head) derived from the decalcification of the Upper Greensand. These sheets of Head obscure not only the *in situ* Lias, but also older sheets of soliflucted and landslipped Lias debris. Inland, these have mostly become stabilised by natural and artificial drainage beneath the urban area, but they could become remobilised if inappropriately developed.

The landslipped areas to the west and east of the town have a well-defined stepped topography in which debris-covered benches are separated by small escarpments that are capped by thin beds of limestone within the Lias. This morphology is especially well developed at Black Ven, where it has been shown to be directly controlled by the underlying stratigraphy. Similar, but less distinct, topographical benches are present in the built-up area of the town, and it has been suggested that these also indicate the positions of harder beds within the Lias (Arber, 1941). The present study has confirmed this.

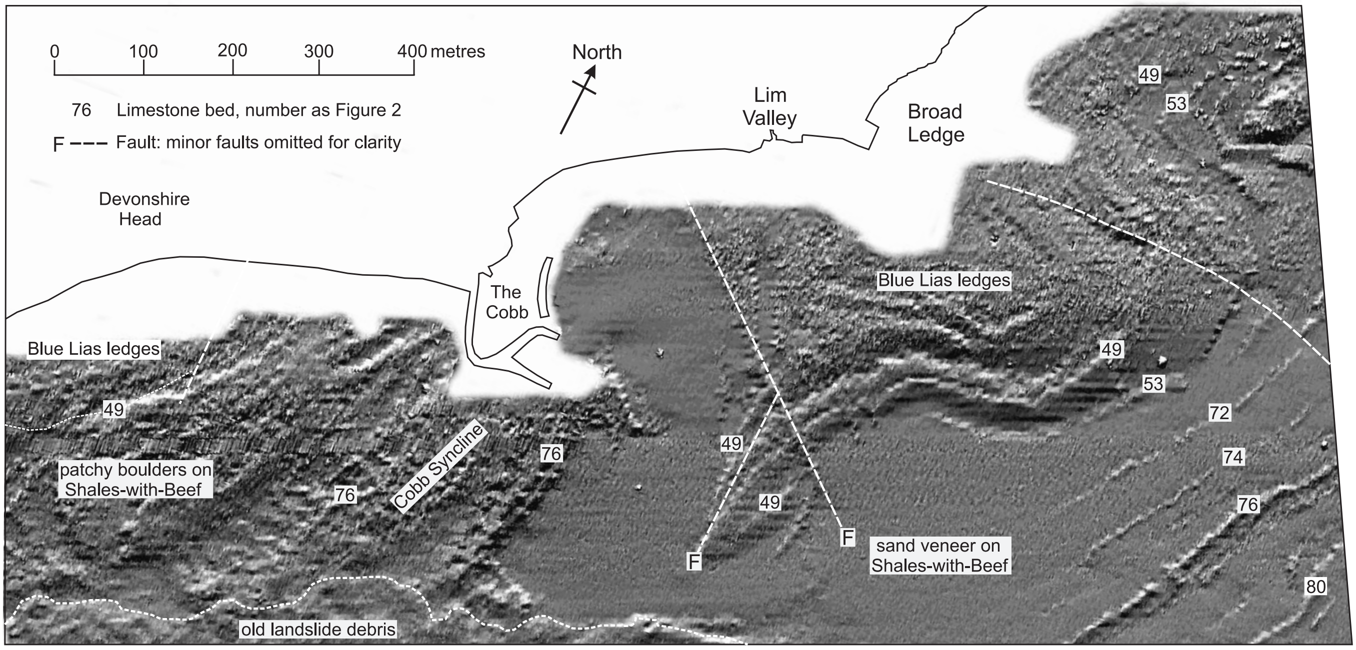


Figure 4. *Computer-generated shaded relief map of seabed topography (after Badman et al., 2000).*

The geological structure proved to be more complex than that shown in the published literature. What had previously been supposed to be a gently undulating easterly dip in the Blue Lias Formation in the central part of the town proved to be a seaward plunging, fault-bounded syncline that brings the full thickness of the weak Shales-with-Beef Member mudstones down to sea level in that area. In addition, thirty faults were identified in an area that had previously been considered to have few faults. Almost all of these have apparent throws of less than 2 m, but they have a marked effect on the dips of the strata in the blocks between the faults, and on the outcrop patterns on the foreshore. This, in turn, has an effect on the shape of coastline and the offshore topography, and on the susceptibility of particular cliffs and coastal slopes to landslip.

The eastward termination of the cliffs at Devonshire Head, the position of the Lim Valley, the shape of Church Cliffs and the most active zone of failure in the Black Ven Landslip are all related to faults. Not surprisingly, the growth of the town itself is closely linked to the geological structure. For example, the builders of The Cobb not only took advantage of a natural reef formed by a prominent limestone bed, they did so at a point where it was adjacent to a smooth-floored deep-water channel on the outcrop of the Shales-with-Beef Member (Figure 4).

CONCLUSIONS

The data obtained from overlapping onshore and offshore surveys has enabled the stratigraphy and geological structure of the area at and adjacent to Lyme Regis to be described in detail. These data form the basis for an understanding of the geological factors that influence the stability of landslips and the rates of marine erosion in and around the town. They form an integral part of a much larger study designed to recommend remedial engineering works that will safeguard the future of the town. In addition to the geological information that they provided, the seabed surveys also yielded data that is relevant to the marine processes that affect coastal erosion.

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