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Procedure for the assessment of limestone resources

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Field and laboratory studies for a regional assessment of limestone resources have involved trials of various techniques and procedures, which are described and illustrated by examples. The integration and presentation of geological and resource data by means of an assessment map and report are outlined. The results of such systematic surveys will provide the essential factual basis for land-use planning and should assist the rational long-term development of national limestone resources.

Bibliographical reference

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The first twelve reports on the assessment of British sand and gravel resources appeared in the Report Series of the Institute of Geological Sciences as a subseries. Report No. 13 onwards appear in the Mineral Assessment Report Series of the Institute. Details of published reports appear at the end of this report.

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Introduction

In recent years concern for environmental planning has made it clear that more detailed and comprehensive information on limestone resources is required. This information will assist central and local government in land-use planning and in the formulation of national policies, which will help to ensure the future availability of supplies to all industries for which limestone is an essential raw material. Ideally the information provided should cover all the properties which are important in the commodity's various uses. For example, crushing strength affects its use as aggregate, and trace-element composition, particularly lead and arsenic content, will affect the selection of limestone for incorporation in animal foodstuffs.

In response to a recommendation of the Inter-Departmental Mineral Resources Consultative Committee, a small team was set up within the Mineral Assessment Unit of the Institute to investigate the possibility of producing regional resource data for limestone and this account presents the results of the pilot study which began in 1970. The Carboniferous limestones of the Peak District of Derbyshire and Staffordshire were selected for study as 6-in geological mapping was proceeding, and the area supports an industry which in 1974 (Healing and Harrison, 1975) produced more than 20 million tonnes of limestone and dolomite, over 19 per cent of total production in Great Britain. The vicinity of the village of Monyash within the Peak District National Park (Fig. 1) was selected for the study.

It is believed that, with appropriate changes of emphasis, the principles and techniques that have emerged during this study can be applied successfully to other areas of varying geological complexity.

The assessment of the limestone resources in any area can be divided into four elements: planning (including desk study), field and laboratory programmes and the preparation of results for publication.

Planning

Before field investigations into the mineral resources of an area begin, the following preliminary tasks should be completed:

1 Literature survey
2 Examination of existing borehole records
3 Assembly of existing data on reserves/resources in consultation with the quarrying industry
4 Formulation of appropriate drilling and sampling programmes.

Field programme

SAMPLING

For resource assessment purposes, material for study must adequately represent the variations of those parameters which influence the suitability of a rock for different uses. To achieve this objective, an optimum sampling interval must be established for each survey area.

Detailed logging of both boreholes and exposed sections has shown that the complete limestone sequence must be sampled by boreholes in order to obtain adequate lithological correlations. Exposed rocks can be used to provide supplementary information only, because even the best sections may be incomplete or inaccessible.

BOREHOLES

Cores of at least 74 mm diameter produced by commercial drilling companies and some small diameter (22 mm) cores obtained with lightweight equipment were used for this study. A number of different drilling rigs were used to obtain cores by air- and water-flush techniques. An initial comparison of these two methods shows that good core recovery in chert-free rocks is obtained more quickly by the air-flush method whereas, in cherty rocks, more acceptable results are given, although slower progress is made, by the water-flush method; this despite the problems of water supply and lost circulation in limestone terrains. More recently the use of wire-line equipment has proved superior to both these methods and has given better core recovery and rates of progress in all ground conditions.

In much commercial drilling it is standard practice to 'open hole' (using a rock-bit) from the surface to depths of about 5 m. During this study the water-flush boreholes were drilled in this way, and a portable lightweight rig used subsequently to obtain core from the unsampled uppermost few metres.

ROCK SECTIONS

Initially it was hoped that the collection of samples from extensive quarry and natural sections could be substituted for borehole cores. To test this a borehole was drilled 400 m from a section in a railway cutting. Although the correlation between the insoluble residue values is reasonably good (Fig. 2), it is subject to errors of interpretation unless supported by detailed knowledge of the

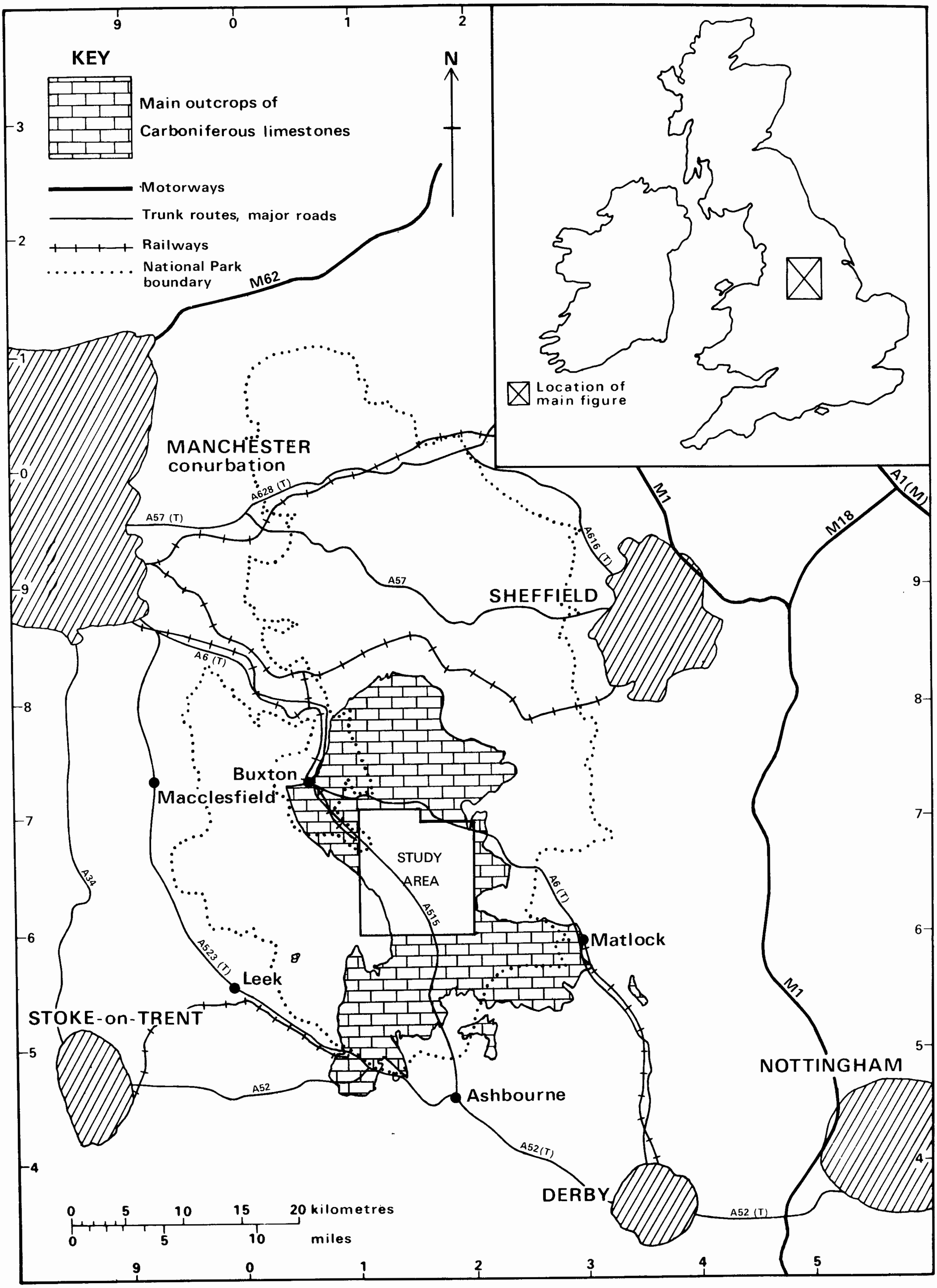


Fig. 1. Locality map

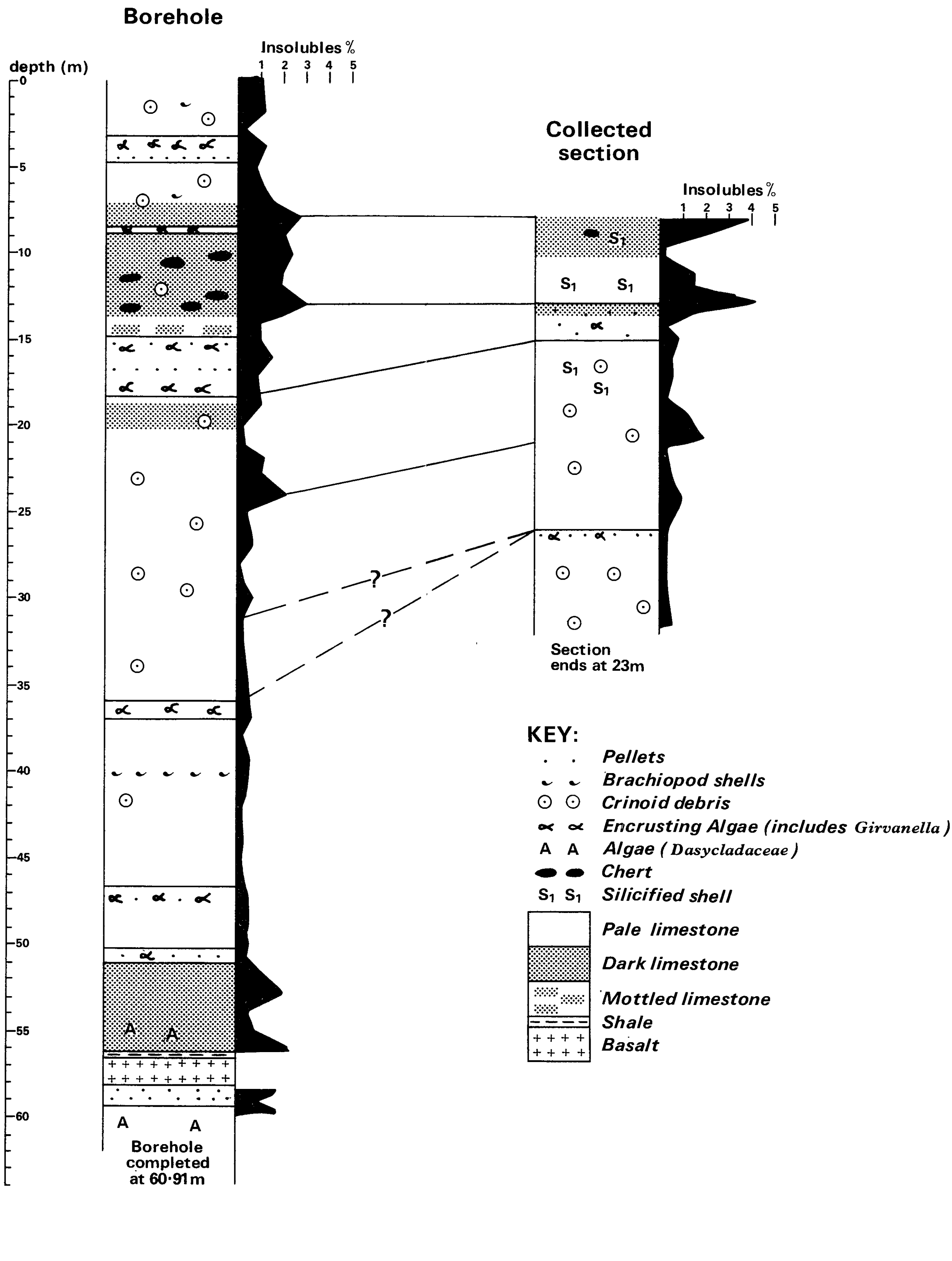


Fig. 2. Correlation between a borehole and a collected section

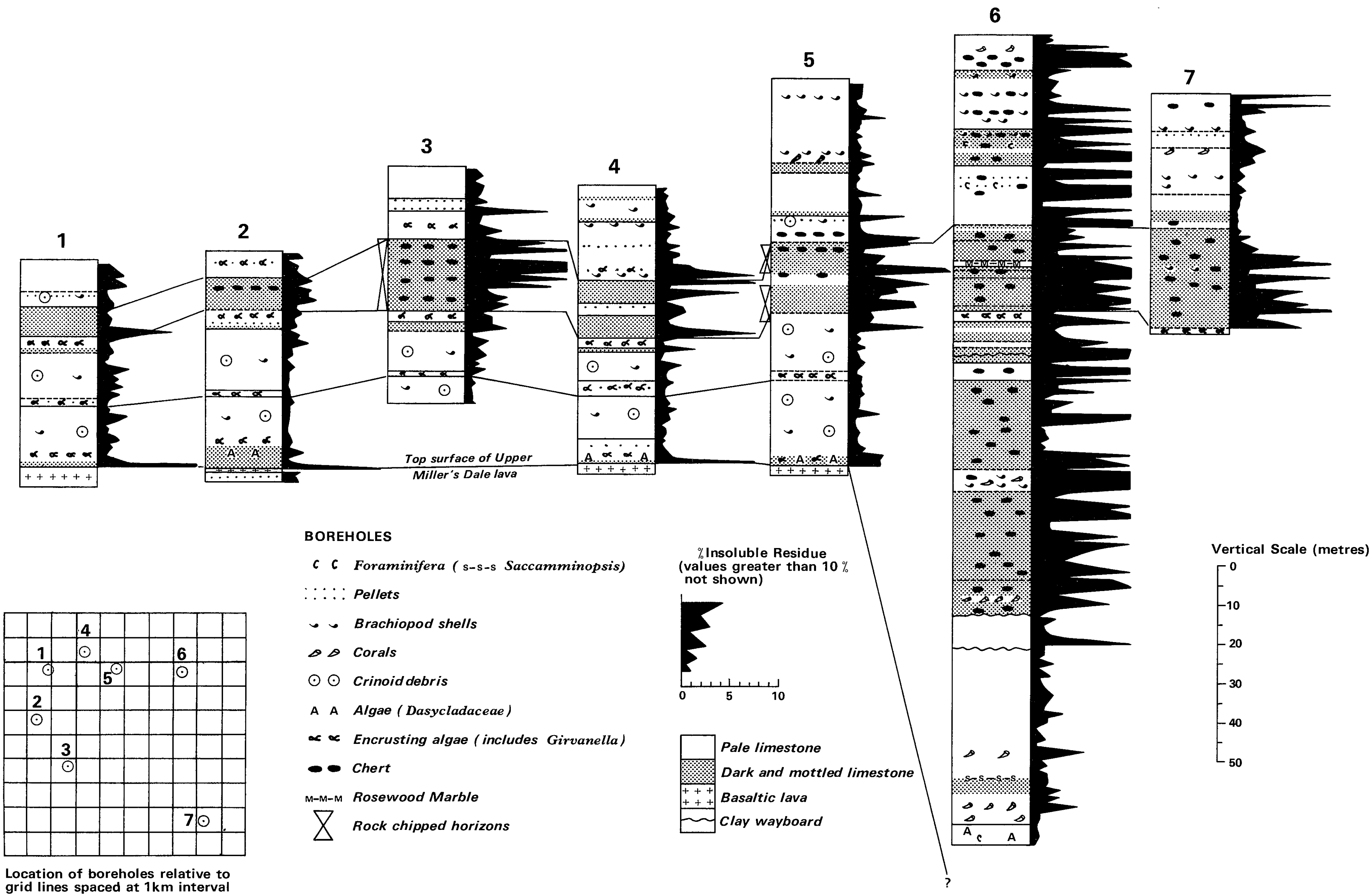


Fig. 3 Generalised borehole logs in the Monsal Dale Limestones
(illustrating the relationship between lithology and insoluble residue)

lithostratigraphy. Since the recognition of beds less than half a metre thick is of paramount importance in establishing lithological correlations, problems arise in using sections because of their irregular geographical distribution and, more particularly, the occurrence of numerous small gaps in even the best examples. Other problems include the inaccessibility of some cliff and quarry faces and the danger and cost of handling the large blocks of stone necessary to obtain fresh material. It has been concluded that resource assessment should be based upon a complete succession established by drilling and augmented by samples from sections. The number of boreholes required will depend upon the geographical and stratigraphical distribution of the sections and the structural and sedimentary complexity of the area.

SPACING OF THE SAMPLING POINTS

Although particular emphasis during this study has been placed upon the regional variation of calcium carbonate content within the rocks, other properties were recorded. For example, in addition to lithostratigraphy, insoluble residue and loss-on-ignition, which relate directly to carbonate content, other data recorded include strength index, non-carbonate mineralogy, trace-element content and colour values. To map the distribution of all these properties adequately would require a different sampling grid for each, determined by either a specifically designed experiment or prior knowledge of similar rocks from comparable areas. For some the frequency of sampling required could be prohibitively expensive. Because of the financial restraints on a publicly funded resource investigation, the minimum sampling interval compatible with producing useful results must be established. This has been determined by comparing the results from boreholes with spacings ranging from 1 to 6 km. Fig. 3 shows an optimum correlation using irregularly spaced boreholes and demonstrates that boreholes up to 6 km apart may be satisfactorily linked by means of lithology and insoluble residue data. It is concluded that the lithological, mineralogical, chemical and physical variation of the rocks studied would have been adequately detected by boreholes spaced approximately 6 km apart. However, optimum conditions rarely apply and a 3-km interval was chosen to provide an increased number of data points. From this it follows that 11 or 12 equally spaced boreholes would be required to cover the area of one 1:25 000 sheet (100 km^2) with limestones of similar lithological variation.

Generally, material for lithological, mineralogical and insoluble residue determinations was obtained by sampling from every metre in exposed sections. In the case of a borehole, the core was sawn in two; one half was etched and used to prepare a detailed lithological log, and the other was crushed in metre-lengths to provide bulk samples for the determination of insoluble residues, chemical analyses, reflectance values and mechanical properties.

The area studied has a 250 m variation in topography and most boreholes were drilled to depths of about 61 m (approximately equivalent to the depth of the deepest working quarries at the time of survey); three deeper boreholes were drilled for stratigraphical purposes, the deepest being taken to almost 210 m. The combination of relief and the OD level of the topographically lowest borehole resulted in samples being obtained from a vertical interval of about 300 m.

For limestone resource assessment generally, the minimum depth to which drilling should be taken depends on the structure, stratigraphy and topography of the area being assessed, on the projected maximum quarrying depth and on the feasibility of mining; current surveys are based upon the need to collect data to depths of 100 m from the surface. The variation in structure and stratigraphy from one area to another suggests that the assessment of a 1:25 000 sheet should be conducted in two stages. The first should involve the drilling of key boreholes (say 5 or 6 on average) and the collecting and the laboratory processing of material from natural and quarry exposures. The need for further drilling, if any, in a second stage will be indicated by the results of the first.

FIELD LOGGING

A preliminary lithological log was prepared on site and was used as a reference aid and supplement to the laboratory log. Two simple strength tests were investigated in the field, a point-load strength test and a stamp-mill test, (Franklin and others, 1971; Protodyakonov, 1963; Brook and Misra, 1970) and it was concluded that the former was the more suitable. The structural homogeneity of the limestones was assessed by measuring the frequency of naturally occurring fractures such as joints and bedding planes, which was expressed quantitatively as a fracture-spacing index.

Laboratory programme

In the course of the feasibility study, laboratory tests were undertaken to examine the mineralogical, chemical and physical properties of the limestones. This information was used for classification, to determine regional trends and to indicate the suitability of the rocks for particular end uses.

The following procedures were followed:

1 Petrographical logging
2 Carbonate determination by:
   a insoluble residue measurements
   b volumetric determination of carbonate
   c loss-on-ignition
3 Mineralogical examination of the insoluble residue using petrographical and X-ray methods
4 Use of stains to determine carbonate mineralogy
5 Automated chemical analyses of powdered samples
6 Measurements of the colour reflectance of powdered samples and etched limestone
7 Comparison of mechanical testing methods:
   a point-load test
   b stamp-mill test
   c aggregate-impact value test

DETAILED PETROGRAPHICAL LOGGING

To examine the limestone samples, all material from boreholes and sections was sawn and etched in hydrochloric acid to remove saw marks and to clean the surface. This proved to be a highly satisfactory way of revealing lithology. Acetate peels were prepared at this stage, for use as a logging aid and as a record of the original samples.

The samples were examined systematically using a binocular microscope and thin sections were made when required. The petrographical terms used are based on Folk's classification (Folk, 1959; 1961) (Table 1). The results were presented as written and graphical logs (Fig. 4) and were the basis of a correlation of the rock sequence.

If the rock contains significant (> 25 per cent) quantities of allochems, which are not mentioned in the main rock name, they may be shown as qualifiers before the rock name and have a capital letter, eg Crinoidal biosparite. Subordinate diagnostic allochems also precede the main rock name; these are differentiated by use of small initial letters, eg algal Brachiopod biosparite. Folk's grain-size classification has also been adopted and may be incorporated into the rock type (eg Biosparrudite, Biomicarenite etc).

The pure mineral dolomite ($CaMg(CO_3)_2$), contains 21.9 per cent MgO and 30.4 per cent CaO(= 54.3 per cent $CaCO_3$). Rocks containing more than 10 per cent of dolomite are classified as follows:

10–50 per cent Dolomitic limestone
51–90 per cent Calcitic dolomite
>90 per cent Dolomite rock (commonly referred to as dolomite)

In the first category, the use of Folk's terminology is not precluded, eg Dolomitic biosparite.

SYSTEMATIC CARBONATE DETERMINATION

Carbonate content is fundamental to a wide range of limestone uses. A simple method for determining the carbonate content of large numbers of samples had, therefore, to be selected. Ideally the method should be rapid, accurate, easy to use (preferably by semi-skilled staff), not subject to operator error and should be capable of giving reproducible results.

Insoluble residue

This method for the determination of carbonate content is widely used in industry and has the merit of providing samples of the non-carbonate fraction for mineralogical examination. Initially in this study, chip samples were taken at metre intervals and the proportion of chert was calculated separately by direct measurements on the core. It was subsequently decided that sampling would be more representative if the core were crushed in metre lengths and subsamples taken for each test using a laboratory splitter.

RESOURCE BLOCK A

Sheet number site ref

Surface level + 385.3m (+ 1264 ft)

Reich (airflush), 74 mm diameter

March 1971

		Thickness (metres)	Depth (metres)
Topsoil		1.00	1.00
Limestone	Openhole to 1.10m. algal biosparrudite, dark grey at base, abundant Girvanella encrusting crinoid and brachiopod debris, subordinate foraminifera and pellets	3.18	4.18
	Crinoid Brachiopod biomicrosparite, mottled from 10.55m, massively-bedded, Girvanella encrustations to 5.50m, subordinate foraminifera, bryozoa and finely comminuted debris throughout, scattered quartz	8.20	12.38
	algal biomicrosparite, mainly coarse calcarenite (consisting of crinoid and shell debris) grading to fine calcarenite from 14.30m, abundant Girvanella and Coelosporella	2.27	14.65
	algal pelsparite, locally iron-stained; 4cm-Clay wayboard at 15.65m	1.52	16.17
	Brachiopod Crinoid biomicrosparite, coarse calcarenite to fine calcirudite, locally jointed	3.43.	19.60
	Biospelsparite with well-sorted brachiopod and crinoid debris in beds alternating between fine and coarse calcarenite, Girvanella and Coelosporella occur below 23.20m	6.90	26.50
	algal pelsparite, local Girvanella with subordinate crinoid and shell debris, pyrite present in increasing amounts towards base	3.01	29.51
Altered Lava	Pale grey-green, firable at top with amygdales and pyrite streaks	1.49	31.00
altered Lava	Amygdales become less common at depth	2.16+	33.16

Borehole completed at 33.16m

A
NW 13

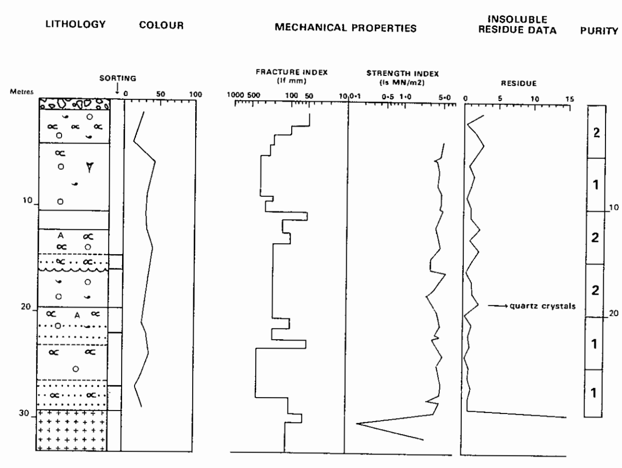


Fig. 4. Example of a written and graphical log

Because it was established that there is good agreement (Fig. 5) with the residues calculated from conventional chemical analyses, minor discrepancies falling within the errors of the various analytical methods employed, the number of more expensive chemical analyses can be reduced. The distribution of insoluble residues from several boreholes, shown in Fig. 3, indicates the additional usefulness of this method as a correlation tool.

Volumetric determination of carbonate
British Standard 1795 (1965) gives a description of this method in which carbonate content is determined from powders. This method is more rapid than the insoluble residue technique and results were found to be reproducible, but the scope for operator error is similar in both cases.

Loss-on-ignition
Following an established technique (Galle and Runnels, 1960), selected powdered samples were heated to 550°C to drive off carbonaceous material and water, and the temperature then raised to 1000°C to release CO_2. The loss of weight during the second ignition can be used to calculate the percentage $CaCO_3$. The method gives relatively accurate results, even with the darker coloured rocks, which contain considerable impurities. This technique gives reproducible results and is simple and rapid. However, it is impractical for the large number of determinations required.

The insoluble residue method has the advantage of providing information on the nature of the mineralogy of the non-carbonate fraction, and is suitable for large batch work. It was therefore decided to use this method. Recent research (Molinia, 1974) has shown that filtration may be used to determine insoluble residues. Microcellulose filters are used to trap the residue from a sample of powdered limestone of known weight which has been dissolved in N/10 hydrochloric acid. This method combines the advantages of the classical method of insoluble residue determination with a very high throughput. It has therefore been adopted for use in more recent surveys.

MINERALOGY OF THE NON-CARBONATE FRACTION

Initial mineralogical determination of the insoluble residue was by optical microscopy, followed by analysis using an X-ray diffractometer. Results have indicated the presence of chert, clay-grade quartz, baryte, pyrite and various clay minerals, all of which are important in determining possible uses for the rock. As the insoluble residues are now retained on filters they can be readily stored and used for X-ray studies when necessary.

STAINING

The staining of limestones to determine their carbonate mineralogy is a well-established technique (Dickson, 1966), which is used primarily to determine the presence of dolomite, ferrodolomite and ferrocalcite. This process is now used only where dolomitisation is suggested by the petrographical study.

CHEMICAL ANALYSES

Detailed chemical analyses are necessary when a range of industrial uses is being considered. Most uses are governed by total carbonate content and by the proportions of various other elements and minerals, which may be beneficial or deleterious. For example, limestones containing metals that impart colour are unsuitable for use in the manufacture of good quality glass; lead and arsenic must be monitored in rocks used in the production of animal feedstuffs or for sugar refining. The samples selected for full chemical analysis were taken to represent the full range of rock types present, as indicated by the laboratory logs and the carbonate determinations. Analyses were made using direct electron excitation X-ray spectrometry for Na_2O, MgO, Al_2O_3, SiO_2, P_2O_5, SO_3, K_2O, CaO, Fe_2O_3 and F; other elements were determined by atomic absorption spectrophotometry (Roberts and Davis, 1977). These provided a 'background' level of trace-element chemistry but, because of the relatively wide spacing of boreholes, localised variations in the concentration of industrially significant elements will not be recorded. Table 2 shows a typical analysis for an assessment borehole.

COLOUR MEASUREMENT

Objective colour measurements are a valuable aid to correlation between cores. In addition, colour determines whether powdered limestone can be used as a whitening agent. Discs of powdered ($<63\mu$) very high purity limestone (Table 5) were prepared using a Leitz Elrepho press and their reflectance was measured with a reflectance spectrophotometer. A white magnesium carbonate standard (percentage reflectance = 100) was used to calibrate the equipment. The following three systems of colour measurement were tried using different filters.

1 Filters approximating to X Y and Z wavelengths (Kaye and Labey, 1973) were used to calculate the Commission Internationale de L'Eclairage (C.I.E.) coordinates. Unfortunately, a plot of X and Y on the chromaticity chart locates all the samples in the same area near the source, because all the samples are grey or white in colour.

2 The colour index (CI) system was evaluated according to the formula

$$\frac{\text{Red - Blue}}{\text{Green}} \times 100 = \text{CI}$$

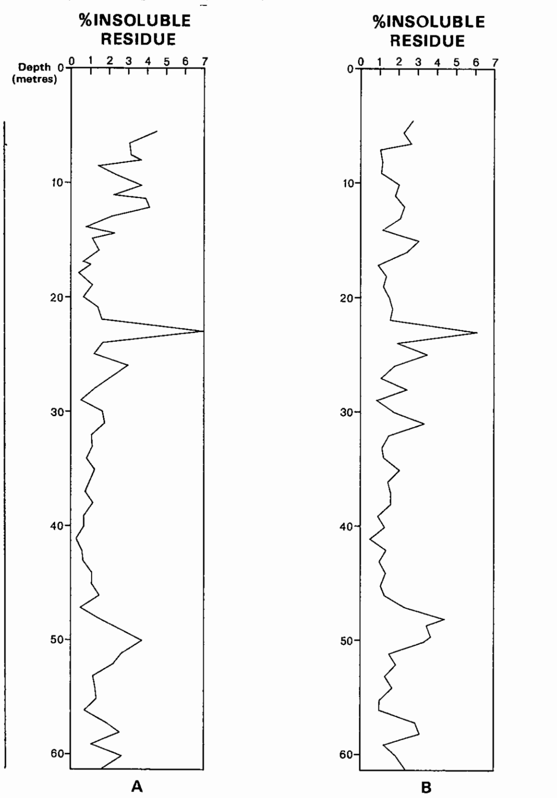
This index is used in industry to distinguish between whites but it was found to be incapable of separating shades of grey.

3 Tri-colour reflectance measurements using filters with wave-lengths of 660 nm, 520 nm and 470 nm were made both of powders and etched rock surfaces.

The tri-colour reflectance method gave a scatter of results which allowed a reasonable classification of the samples measured and it was concluded that this system was the most suitable for limestone assessment work. A summary of values obtained by this method on very high purity

Table 1. Classification of limestone rocks (based on Folk, 1959)

Volumetric Allochem Composition	LIMESTONES: >10% Allochems, Allochemical Rocks — Sparry calcite cement> micocrystalline ooze	LIMESTONES: >10% Allochems, Allochemical Rocks — Microcrystalline ooze > sparry calcite cement	LIMESTONES: <10% Allochems, Microcrystalline Rocks — 1-10% allochems	LIMESTONES: <10% Allochems, Microcrystalline Rocks — <1% allochems
>25% Intraclasts	Intrasparite	Intramicrite (rare)	Intraclasts: Intraclastic micrite (rare)	Micrite
<25% Intraclasts; >25% oolites	Oosparite	Oomicrite (rare)	Oolites Oolitic micrite (rare)	
<25% Intraclasts; <25% oolites; Volume ratio of Fossils: Pellets >3:1	Biosparite	Biomicrite	Fossils: Fossiliferous Micrite	
<25% Intraclasts; <25% oolites; Volume ratio of Fossils: Pellets 3:1 to 1:3	Biopelsparite	Biopelmicrite	Pellets: Pelletiferous Micrite	
<25% Intraclasts; <25% oolites; Volume ratio of Fossils: Pellets <1:3	Pelsparite	Pelmicrite		



A Insoluble residue determined experimentally by the acid-digestion technique

B Insoluble residue calculated from chemical analyses

Fig. 5. Insoluble residue curves determined by acid-digestion and by calculation from chemical analyses. (Sampling interval 1 m throughout; controlled by lithological change in B.)

Table 2. Chemical analysis of an assessment borehole

RESOURCE BLOCK 00
Nat. Grid Ref.
Locality

Chemical analyses, major elements (results expressed as percentage oxides)

Depth (m)	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	Fe_2O_3	F	Loss on ignition at 1050° C
1.10	0.01	0.38	0.13	1.54	0.04	0.32	0.02	54.20	tr	0.03	43.33
3.90	0.01	0.34	0.09	1.63	0.03	0.35	0.02	54.35	tr	0.00	43.16
5.85	0.00	0.21	0.03	0.45	0.04	0.36	0.01	55.20	tr	0.00	43.71
9.00	0.00	0.22	0.05	1.49	0.04	0.32	0.01	54.40	tr	0.01	43.09
11.00	0.00	0.22	0.04	0.98	0.05	0.34	0.01	55.15	tr	0.02	43.51
12.00	0.00	0.23	0.06	1.25	0.05	0.32	0.01	54.75	tr	0.04	43.22
14.00	0.00	0.22	0.03	1.01	0.04	0.32	0.01	55.15	tr	0.00	43.26
16.00	0.00	0.23	0.03	0.83	0.03	0.26	0.01	55.10	tr	0.00	43.49
19.00	0.03	0.25	0.04	1.39	0.04	0.37	0.01	54.65	tr	0.00	43.31
21.00	0.00	0.23	0.04	0.62	0.03	0.30	0.01	55.00	tr	0.01	43.69
22.00	0.00	0.25	0.03	0.63	0.03	0.26	0.01	55.00	tr	0.00	43.74
24.00	0.00	0.20	0.01	0.40	0.03	0.23	0.01	55.10	tr	0.00	43.82
26.00	0.00	0.29	0.20	0.55	0.03	0.26	0.02	54.65	tr	0.00	43.73
27.00	0.00	0.31	0.12	1.00	0.03	0.22	0.01	54.60	tr	0.00	43.52
28.90	0.00	0.27	0.23	0.58	0.03	0.23	0.03	54.40	0.48	0.00	43.43

tr = trace

Trace elements (p.p.m.)

Depth (m)	Mn	Cu	Zn	Pb	Fe_2O_3	As
1.10	320	15	30	0	180	0
3.90	215	10	20	0	150	
5.85	100	10	10	0	110	
9.00	95	25	20	30	385	5
11.00	85	15	10	0	110	
12.00	110	10	10	0	150	0
14.00	105	10	10	0	85	
16.00	105	10	10	30	235	
19.00	140	10	10	0	225	
21.00	175	60	30	0	160	
22.00	180	5	10	0	220	
24.00	170	5	10	10	115	
26.00	265	10	10	0	860	
27.00	400	5	10	160	390	
28.90	850	5	10	50	Maj	

Maj = Major

Table 3. Examples of reflectance results from very high purity rocks

Division	$CaCO_3$ per cent	Mean reflectance percentage (standard deviation) 660 nm	520 nm	470 nm
Bee Low Limestones	>98.5	81(3)	73(3)	72(2)
" " "		84(5)	79(6)	78(7)
Woo Dale Limestones		81(3)	73(3)	73(3)
Monsal Dale Limestones		86(1)	72(2)	77(3)
" " "		82(3)	74(3)	72(4)
" " "		83(2)	75(4)	72(3)
" " "		82(2)	76(3)	74(3)

powders is given in Table 3.

MECHANICAL TESTING METHODS

Point-load test

Samples representing a wide range of limestone lithologies were taken at 1-m intervals from borehole cores and tested diametrally to failure between conical platens. The point-load strength index (Is) determined by this method gives a measure of tensile rock strength. The histogram (Fig. 6) plotted from all the observations shows a slightly skewed normal distribution with a mode between 4.0 and 4.5 MN/m^2, but a mean below 4.0 MN/m^2. This indicates either that the limestones have a fairly uniform strength or that the testing method is insensitive to lithological variation. The particular value of this test is that it may be carried out easily and cheaply in the field. Research by the Engineering Geology Unit of the Institute has failed to confirm the relationship claimed (Franklin and others, 1971) between Is values and compressive strength. However, there are indications (Dr N. Brook, personal communication) that laboratory tests for compressive strength have a low reproducibility and are therefore unlikely to produce results which correlate well with those of other tests.

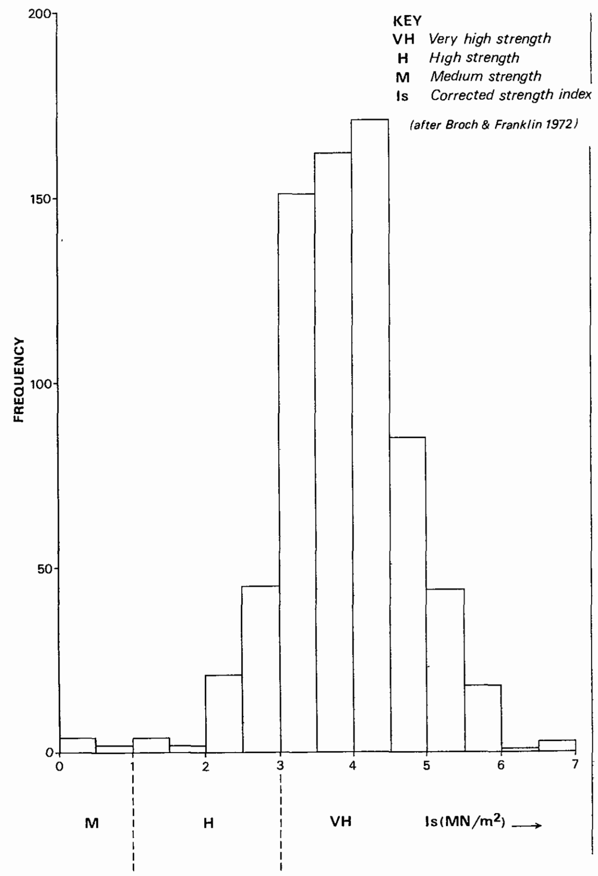


Fig. 6. Histogram of point-load strength test index values

Stamp-mill test

This test involves the comminution of rock samples in a mortar using a falling weight and was applied in this study to rock cylinders and chippings. The number of blows needed to produce 25 per cent fines ($<500\mu$) was determined and this value is defined as the rock impact hardness number (RIHN) (Brook and Misra, 1970). It was found that the values obtained were reproducible and could be correlated with particular lithologies (Table 4; Fig. 7). In particular there was a strong correlation between grain size of allochems and RIHN.

Table 4. Mean rock impact hardness numbers (RIHN) for typical limestone lithologies

Lithology	Carbonate type	Mean RIHN
1	Dark Micrite	44.02
2	Pale Micrite	38.90
3	Dark Biomicrite	38.26
4	Sorted Fine Calcarenite	31.80
5	Sorted Medium Calcarenite	28.80
6	Pale Biomicrudite	28.00
7	Sorted Coarse Calcarenite and Fine Rudite	25.42
8	Dolomite	23.44

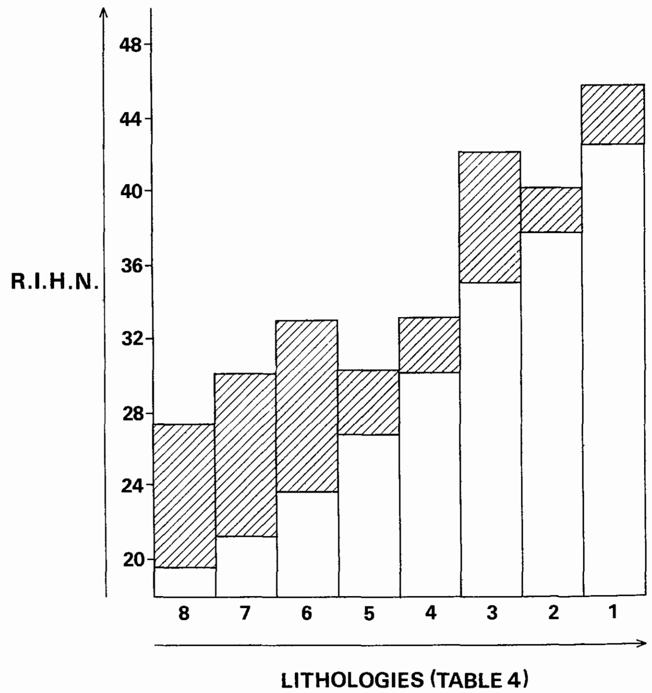


Fig. 7. Range of rock impact hardness numbers (RIHN) for typical limestone lithologies

Current research at Leeds University (Dr N. Brook, personal communication) suggests that plant and drill-bit wear can be related to RIHN; the index is, therefore, important commercially. Values can be converted to approximate equivalent values of compressive strength; in the samples tested maximum and minimum RIHN's of 15 and 44 correspond to compressive strengths of 80 and 196 MN/m^2 respectively.

Aggregate-impact value (AIV)
The AIV test is determined by measuring the percentage fines produced by a given number of blows. The method is described in British Standard 812 (1975) and is similar to that of the stamp-mill test. The repeatability and reproducibility of the AIV test makes it suitable for use in a regional assessment and since it is also used widely in industry, it has been adopted in all current surveys

Preparation of results for publication

Information is continually added to existing geological data from the detailed study and correlation of boreholes and sections, and an improved geological map results. Facies variations are defined spatially and stratigraphically and these in turn are related to the economically important parameters recorded.

When deciding the form the assessment map should take, it was necessary to consider which properties should be displayed and how best to show them in map form. Because the carbonate content is of paramount importance when considering most industrial uses, it was decided that the primary requirement is to illustrate its distribution. The categories selected are shown in Table 5.

Purity values are determined as follows. The insoluble residue measurements (=non-carbonate fraction) for individual boreholes and sections are grouped into sets representing limestone samples from the uppermost 10 m of rock and succeeding 5-m depth increments. For each set the mean, the standard deviation and confidence limits are calculated at the 95 per cent probability level, assuming a student's 't' distribution. The sum of the mean and positive confidence limit is subtracted from one hundred to obtain a conservative (= worst) estimate of the calcium carbonate content for each depth increment. This value is used to assign the limestone within each depth increment to one of the five categories.

RESOURCE MAP
Although the scale of map selected for the publication of these surveys is 1:25 000, it would be possible to adapt the field procedures and cartographical techniques described below to produce either small-scale reconnaissance maps or more detailed large-scale assessments.
Base map, including contours, is the Ordnance Survey 1:25 000 outline edition printed in grey. The geological boundaries are shown in green (both on the face of the map and in vertical and horizontal sections); faults and other structural features are shown in red. Mineral veins are indicated by lines of alternating red and black. Drift deposits are shown in black shading. Shades of blue are used to indicate the categories of limestone purity in the top 10 m.
Mineral resource information is shown in shades of blue for limestone and green for dolomite. The category shown reflects information on purity determined from boreholes, sections and spot samples, together with other relevant field observations (eg, presence or absence of chert); some data may be weighted, by eg, their area of

Table 5. Classification of limestones by calcium carbonate content

Category	Percentage $CaCO_3$	Possible industrial usage (grouped by minimum $CaCO_3$ specification)
1 Very high purity	>98.5	Steel, white glass (subject to trace elements), rubber, plastics, paint
2 High purity	97-98.5	Iron, ceramics, Portland Cement, whitings, chemical uses
3 Medium purity	93.5-97	Paper (subject to colour), animal feedstuffs (subject to level of poisonous trace elements)
4 Low Purity	85-93.5	Asphalt
5 Impure	<85	Mineral wool and natural cements (subject to the silica/clay mineral ratio)

NB All categories are suitable for aggregate use (subject to hardness etc.)

influence. Where more than one category of limestone occurs within the uppermost 10 m, ground where they overlap (zone of intermixing) is shown by alternating stripes of the appropriate colour, bounded by a dotted line (Fig. 8). This system is also used where 'solid' non-carbonate rocks dilute overall purity within 10 m of the surface. In areas where dolomites occur extensively, zones of intermixing with limestones can be shown.

horizontal sections (Fig. 10) are drawn to indicate the limestone purity at depth throughout the area. The calculated average purity to 10 m is shown, but below this depth the limestones are assigned categories of purity from an interpretation of structural, stratigraphical and lithological data.

A graphical section on the left-hand margin shows the thicknesses of the beds and their stratigraphical correlations. The symbols and conventions used are explained in the right-hand margin.

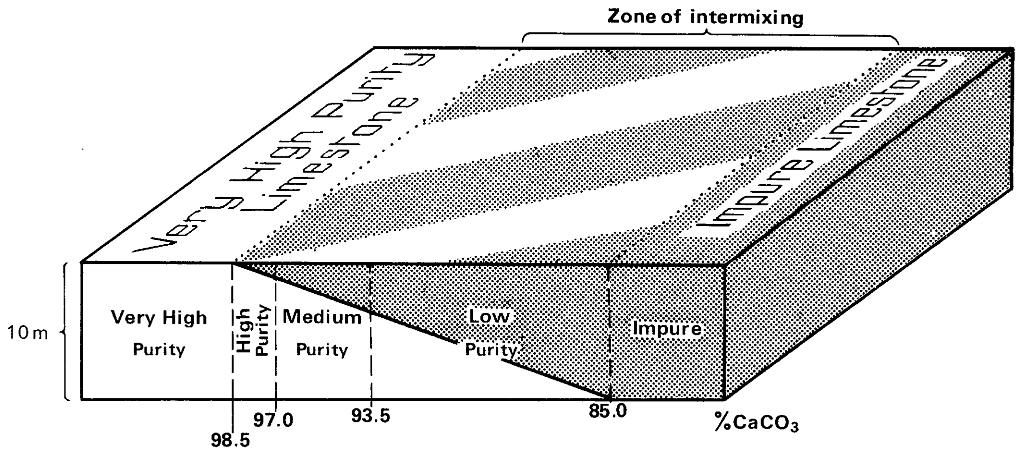


Fig. 8. Zones of intermixing produced at the contact of disparate qualities

On the map, tablets are used at borehole and section sites to display purity variations at depth. On the left-hand side of the tablet average purity is shown for each 5-m depth increment. Also shown are details of carbonate content and lithology, together with other relevant factors and the depths at which they occur (Fig. 9). On the first resource map the purity as indicated by the colour on the tablet may not always match the carbonate content on the graph, the discrepancy arising from a sampling procedure which excluded logged chert beds from the samples analysed. This practice has been discontinued in more recent surveys (see insoluble residue, p. 3) and the tablets will now show AIV (measured at 10-m intervals), together with rock colour and carbonate content.

Structural data. These data are derived from the initial geological survey, augmented by information obtained by assessment drilling.

Drift deposits. The boundaries of drift deposits which are more than 1.5 m thick are indicated in black, together with an appropriate symbol as used on the 1:50 000 geological maps of the Institute.

Resource blocks. The assessed area of limestone is subdivided into blocks, each not less than 1 km^2 in area, within which a single limestone category dominates at least the uppermost 10 m and commonly extends to greater depths.

Map margins. On the lower margin of the sheet,

REPORT

The map is an integral part of the report in which the aims, limitations and results of the survey are presented with a summary of the data recorded during the assessment. It contains an account of the regional and local stratigraphy, geochemistry and geotechnical properties of the limestones, supported by lithological and graphical logs and tables of chemical analyses in appendices (Fig. 4; Table 2). Descriptions of variations in the limestones found in each resource block amplify the quantitative assessment of the resources.

Further research

Compilations will be prepared to provide regional information based on the results of the survey. This will necessitate the development of computer programs to manipulate the vast amount of data collected during the survey.

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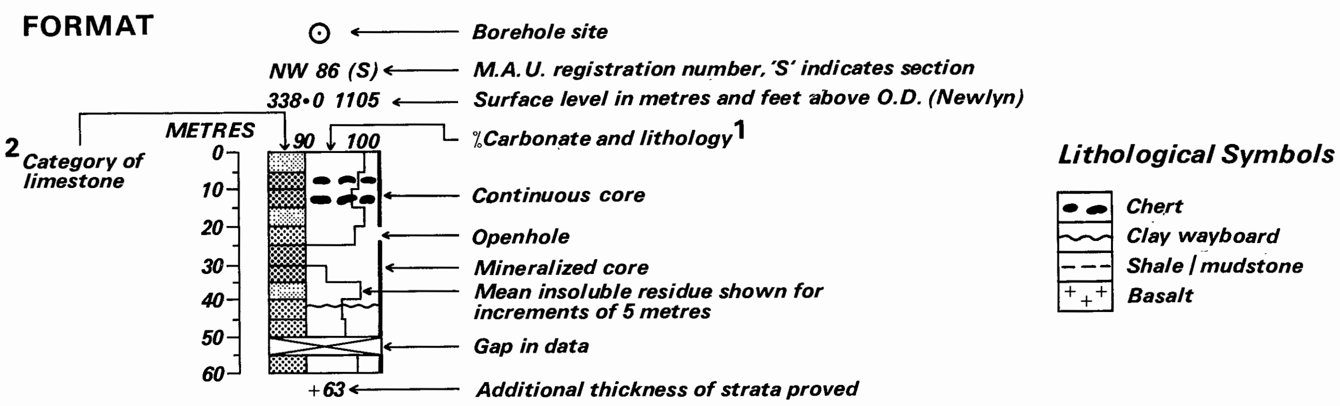

1. In later maps this will be aggregate impact value (A.I.V.) and lithology.
2. Shown by shades of blue on original

Fig. 9. Tablet showing borehole data as used on a limestone assessment map

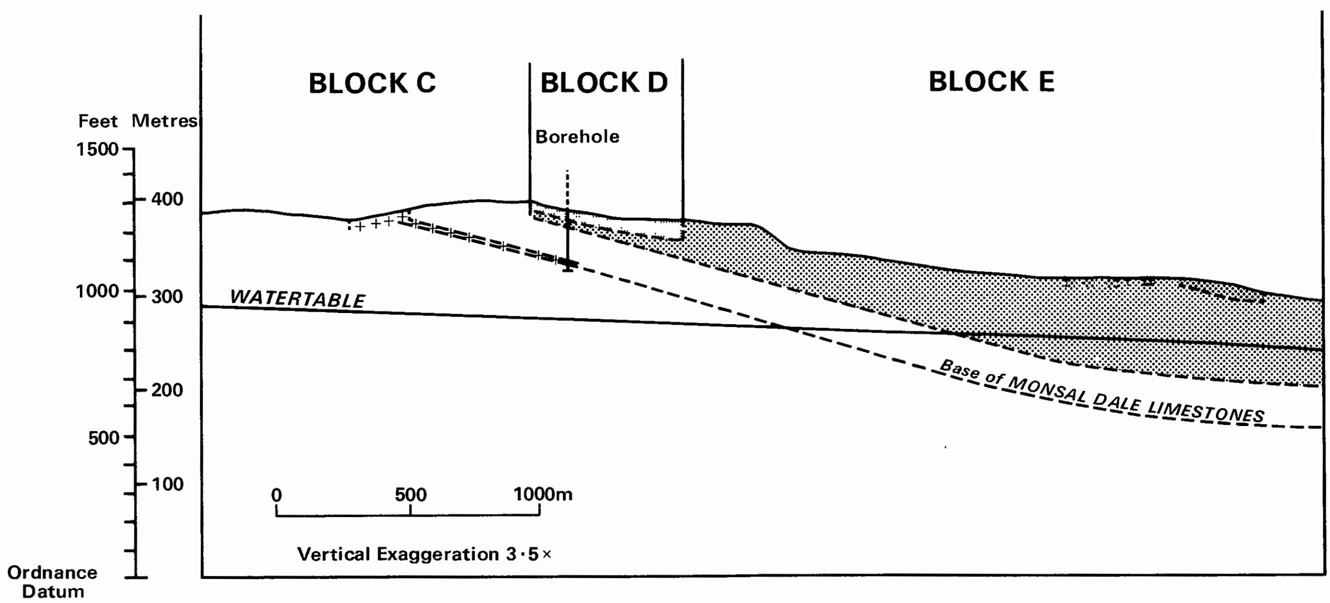

Fig. 10. Horizontal section showing generalised limestone categories at depth (additional geological lines, normally green on coloured sections, have been omitted for clarity)