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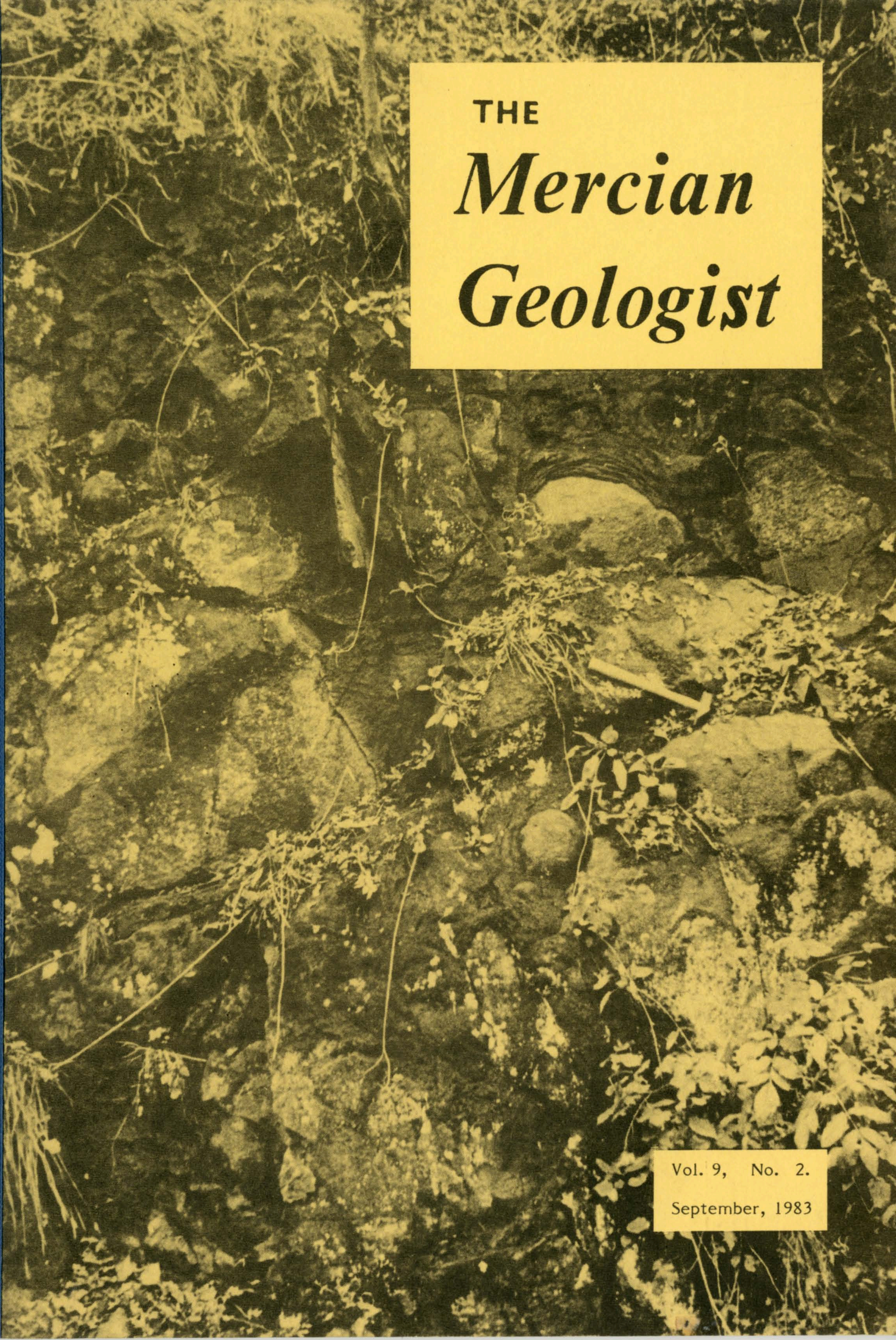

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Address for Correspondence,

General information, membership details:	The Secretary, East Midlands Geological Society, 311 Mansfield Road, Redhill, Arnold, Nottingham Tel. No. (0602)267442

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Front Cover: The Lower Miller's Dale Lava, Tideswell Dale Picnic Site.
Photograph by P. R. Ineson.

REGIONAL GEOCHEMICAL MAPS OF THE UNITED KINGDOM ENVIRONMENTAL AND ECONOMIC APPLICATIONS

Foundation Lecture, 6th February, 1982

by

Jane A. Plant

Introduction

In the mid-1960s, pollution was already a matter of national concern, and while predictions of future world shortages of metalliferous minerals had been made, no comprehensive data existed on either the background levels of metals in the environment, or on the metalliferous mineral potential in Britain. Consideration of these issues at national level clearly required a basis of sound factual information. The Institute of Geological Sciences (IGS), therefore initiated a programme, subsequently sponsored by the Department of Industry, to prepare a series of regional geochemical maps (IGS, 1978a; 1978b; 1979; 1982) at a scale of 1:250,000 showing the surface distribution of trace elements of economic and environmental significance. Sixteen trace elements were included in the original programme: this has recently been increased to twenty five elements. From the outset of the programme, geochemical, geological and topographic data have been collected in computer-readable digital form so that it is possible to investigate the information inter-actively using automated data processing methods.

The geochemical mapping programme is aimed at providing information for several specific purposes including:

1. Mineral exploration — to identify occurrences of metalliferous minerals of potential economic significance.
2. Pollution studies — to provide reliable information on the natural and artificial levels of elements (including heavy metals) so that realistic assessments of contamination can be made.
3. Agriculture and medical geography — to provide data which can be used directly in statistical studies of the epidemiology of degenerative diseases of man, animals and crops.
4. Geological mapping — to provide information on lithological, compositional and structural variations which are difficult to detect by visual mapping procedures.
5. Studies of the geochemical aspects of crustal development and ore-forming processes — to develop quantitative metallogenic models for exploration in the United Kingdom and overseas.

In this paper, the methods of preparing geochemical maps are described, and some economic and environmental applications of the data are discussed with reference to examples of regional geochemical maps of Scotland.

Geochemical Mapping

Sampling

Research and development in support of the geochemical mapping programme was carried out, and the first series of maps prepared for the Northern Highlands of Scotland (Plant, 1971; Plant & Moore, 1979). This area was selected because the relative lack of contamination enables information on natural levels of elements to be obtained and compared with that of areas such as the Midland Valley of Scotland or industrialised regions of England and Wales.

Several different types of sampling media were considered — principally rocks, soils and stream sediments. Rocks are unsuitable for a regional survey of Great Britain because of the limited and variable amount of solid outcrop; the occurrence of areas of deep weathering; the difficulty of representing heterogenous assemblages such as the Lewisian or Dalradian by statistically valid sampling models; and the difficulty of obtaining samples from potentially mineralised faults and structures which are frequently areas of low topography infilled with thick overburden. Soil sampling also presents considerable problems because of the variation in soil types across Britain; the limited soil cover in upland areas; the wide variation of pH and Eh in soils, which critically affects the solubility and concentration of metals (Baas, Becking *et al.*, 1960); and the difficulty of ensuring consistent sampling of specific soil horizons by non-expert sampling teams.

Both rock and soil samples provide information of limited areal significance and large numbers of samples must be collected, prepared and analysed to represent even relatively small areas. Regional geochemical mapping based on either sample type would thus be slow and costly.

The Institute's geochemical atlases are therefore based on stream sediment samples which have clear advantages in systematic regional geochemical mapping. Each sample approximates to a composite sample of weathering products upstream of the sampling point, and hence reflects the average concentration of elements in the stream catchment basin (Hawkes & Webb, 1962). Many studies of the application of stream sediment sampling to exploration geochemistry (see, e.g., Webb *et al.*, 1968) and environmental geochemistry (see, e.g., Thornton & Webb, 1974) have shown that analysis of the minus 80 mesh size fraction of 'grab' samples of stream sediment provides an effective method of broadscale geochemical mapping where individual values are averaged by statistical procedures (Howarth & Lowenstein, 1971; Webb & Howarth, 1979). These methods, are not sufficiently precise and accurate, however, for the Institute's geochemical maps which show point source data at a scale of 1:250,000 and new highly reproducible field and laboratory procedures based on studies of natural streams were therefore developed. Study of the distribution of trace elements in relation to the size fraction of sediment, showed for example, that several elements, including cobalt, copper, iron, manganese, molybdenum, uranium and zinc are concentrated in the finest size fraction of the sediment, particularly over areas of mineralisation; but the recovery of this material by dry screening is not quantitative owing to its agglomeration to form larger particles during drying, which are then screened out in varying amounts. A system of wet screening on site, which uses the minimum of water, is therefore employed routinely to collect the fraction of sediment smaller than 150 μm, which is the finest fraction which it is practical to collect.

In areas of upland Britain (much of Scotland, Wales, the Lake District and parts of southwest England) elemental levels in stream sediments can be enhanced relative to bedrock because of coprecipitation with hydrous manganic and ferric oxides (Nichol *et al.*, 1967). This occurs where reduced, acid water bearing iron and manganese from peat flows into streams where the pH is higher and the water is in equilibrium with atmospheric oxygen. Collection of samples containing quantities of these precipitates results in elemental values which may not only be spuriously high, but which are also highly variable. Studies of natural stream channels indicate that the problem is most serious in first order tributaries where the proportion of water in the channel which is derived directly from peat is at a maximum. Furthermore, the precipitates are enriched in the top few centimetres of the sediment profile where the pH and Eh tend to be higher. Sampling of high order streams draining large catchments fails to detect local anomalies associated with mineralisation, however, owing to rapid downstream dilution. A minimum sampling density of 1 per 2km^2 based on second or third order stream samples immediately above confluences is therefore used for the standard procedure. In this, the top few centimetres of sediment are removed before sample collection, particularly where manganic/ferric precipitates are observed. A heavy mineral concentrate is also prepared by panning at a proportion of sample sites and a 30ml water sample is taken at all sites (Plant & Rhind, 1974; IGS, 1978a).

Field parties normally include a proportion of non-professional sample collectors, usually students, and care has to be taken to ensure that samples are not collected from sites that differ from the location recorded on the map. Also, non-standard sampling procedures may be used. To reduce these errors, professional staff of the Institute maintain close supervision with a minimum staff:student ratio of 1:5. Students work in pairs and are interchanged on a daily basis to minimise the likelihood of sampling bias arising from the development and use of modified procedures. Each sampling team of twelve is assigned an area which is irregularly shaped, with boundaries that do not follow mapped geology. Hence variation in element levels related to sampling teams can be identified by overlaying sampling areas over plots of the geochemical data.

In the field or headquarters laboratory, damp sediment samples contained in Kraft paper bags are dried at approximately 95 °C in large electric ovens equipped with fans. Sediments containing appreciable clay-fraction material dry in lumps which are difficult to disaggregate. Trials with freeze-drying produced a friable powder with almost all samples tested, and routine drying by this method is being introduced.

Analysis

In order to satisfy the analytical requirements of the programme it is necessary to employ rapid, inexpensive, multi-element methods and the d.c. arc emission technique is still regarded as the most appropriate means of providing the required analytical data. Emission spectrography depends on the principle that atoms excited in the high temperature of an electric arc emit light, each element producing characteristic wavelengths. By splitting the light into its component wavelengths (using a diffraction grating or prism) the elements present in the sample can be determined. In the initial stages of the survey, a spectrographic technique with a Hilger Large Quartz instrument with photographic recording, was employed. Element concentrations were estimated by visual comparison of spectral lines from the samples with standard spectra by use of a Jarrell-Ash spectrum-projector comparator. In 1975, a major change was made in the analytical system and all regional geochemical survey samples were subsequently analysed by using direct-reading spectrometry. The spectrometer, a Jarrell-Ash 1.5 m Atomcounter, incorporating forty channels, is on-line to an IBM 1130 computer: options for data output include lineprinter, card punch, or magnetic tape.

A 100 mg sub-sample of ignited material of a grain size finer than 53 μm is mixed with an equal mass of spectroscopic buffer comprising a 1:1 mixture of pelletable graphite and sodium fluoride containing indium, europium and platinum as internal standards. A 30 mg pellet of the mixture is arced for 99 seconds at 12.5A with the use of anode excitation in a jet of argon:oxygen (75:25) to improve stability, to suppress CN band emission and to reduce general background radiation.

The importance of adequately researching interelement effects and introducing appropriate computer correction procedures for direct-reading spectrographic analysis is shown in Table 1 where apparent levels of lead are doubled by interference from manganese. The type and magnitude of interferences vary according to the spectral lines used and for different instruments. Calibration of the data obtained by direct-reading spectrograph in the Institute's laboratories is performed by polynomial regression on data obtained for synthetic reference materials (Date, 1978). The trace elements that are corrected for major element interferences are shown in table 1.

Table 1 Direct-reading spectrometry: matrix correction

analyte	interfering element	approximate effect
Ga	Mn	-
Ge	Mn	-
Sn	Mn	-
Pb	Mn	-
B	Fe	20% Fe = 20 parts B ppm
Zr	Fe	20% Fe = 200 parts Zr ppm
V	Ca	-
Mo	Ca	20% Ca = 30 parts Mo ppm
Li(2)	Ca	-
Sn	Mg	-

Based in part on A. R. Date and J. S. Coats (pers. comm.)

The relative standard deviation of ten determinations over five months is 10% or better for seventeen elements and 25% or better for eight elements at average concentration levels for the sediments. Results obtained from the spectrometer are routinely checked against determinations performed by analytical procedures based on different principles such as atomic absorption spectrophotometry (table 2) and neutron activation analysis on in-house standard samples.

Sensitivity for uranium by emission spectrometry is inadequate for the purposes of regional surveying and a delayed neutron method based on that of Amiel (1962) is used for both sediment and stream water samples. The method has a detection limit of about 1ppm in sediment.

Table 2 Jarrell-Ash 1.5m atomcounter: major element interference correction
(Pb 405.7nm: correction for Mn interference)

[Mn]	[Pb] ppm uncorrected	[Pb] ppm corrected	[PB]* ppm
5.2	206	165	140
5.4	61	16	20
5.6	82	34	50
5.6	64	17	50
6.0	54	0	20
6.6	87	23	60
9.5	116	20	30
5.4	86	49	50
5.2	84	50	60
7.9	178	100	80
7.1	76	13	20
15.3	162	31	40
mean	105	43	52

*Results from atomic absorption spectrophotometry

Error control and data processing

A constant check on errors is necessary to obviate false trends or anomalies on geochemical maps. A system to monitor error in sampling and analysis is therefore used (Plant *et al.*, 1975). Monitoring systematic error in field sampling or analysis is based on a system of randomised sample site numbers (Plant, 1973) with standards to monitor analytical error between batches of samples. Some sources of systematic error are shown in table 3. Standard stream sediment samples prepared in-house and rock standards calibrated against international standard materials are used to monitor analytical accuracy. These are also randomly numbered and are not distinguishable to the analyst. The accuracy of the data for cobalt, manganese, vanadium, molybdenum and barium, which can be determined by instrumental neutron activation analysis (Plant *et al.*, 1976), is established by analysis of randomly selected samples by this technique, and samples of deionised water are included in batches of water samples to be analysed for uranium by the delayed neutron method to serve as blanks.

Sampling and analytical precision is monitored by using a procedure based on analysis of variance. Duplicate samples are collected a few metres from the routine samples at approximately 2% of the sites and the between-site variance (geochemical variation) and the within site variance (total error, including errors in sampling, sample preparation and analysis) are determined by a method based on a single-factor analysis of variance model (Koch & Link, 1971).

Table 3 Some sources of systematic error

Sample preparation:	Cause
Sieving	Contamination of background samples following preparation of anomalous samples
Grinding	Within-batch contamination from external source
Analytical methods:	
Instrumental methods	Changes in conditions between determination of standards.
Methods depending on visual comparison, e.g., photographic emission spectrography	Tendency to read high or low depending on previous determination Within-batch contamination from external source

Table 4 Sources of typographic error in geochemical data processing
(From 2000 samples from Orkney and Shetland)

	percentage error
(1) recording National Grid Reference	8.9
(2) punching from field data cards	1.2
(3) plotting maps of sample sites	5.2
(4) digitising sample sites from maps	0.7
(5) punching and sequence error in analytical data	4.0
total	20.0

From M. D. Forrest and R. T. Mogdridge (pers. comm.)

Locational information for up to 10,000 sample sites and analytical data for up to 30 elemental determinations for each of the sites are processed each year, making a total of 300,000 items of information. An analysis of the sources of typographic error for 2,000 early samples taken from Orkney and Shetland by M. D. Forrest and R. T. Mogdridge (personal communication) showed that the initial error rate associated with recording and card punching of analytical or locational information was approximately 20% (table 4). The percentage of locational error could be reduced to less than 1%, however, where sample site locations were entered into computer records by digitising from maps of sample sites, while the error associated with transcription of analytical data could be eliminated by recording data directly onto a magnetic disc for processing and storage. Automated methods of data capture are, therefore, used routinely to prepare corrected data sets for all regions mapped; these are stored on magnetic disc for plotting and for statistical analysis.

Data presentation and statistical analysis

Map presentation and statistical analysis were aimed initially at preparing interpretations of individual elements in relation to the geology and surface features of each of the 1:250,000 map sheet regions covered. Multivariate statistical analysis of data sets for larger regions is being used increasingly, however, for specific studies (see below). The geochemical atlases, which are the principal publication of the programme, include geochemical maps for up to 25 chemical elements. The distribution of each element is shown on separate maps by lines originating from the sample location, with a length proportional to the element concentration. The geochemical data are plotted in black over a modern compilation of the geology prepared as a single colour plot. In addition, contour maps at 1:750,000 are included in the geochemical atlases to indicate more regional geochemical trends. Proportional point source symbols were adopted as the principal method of presentation by the Institute since contouring or smoothing procedures remove local variation from the data and the choice of parameters such as class intervals or cell size for averaging affect the patterns represented. Also, it is considered essential to distinguish general increases in background levels from apparent increases produced by averaging a few very high values with several low values.

Geochemical atlases have been published for Shetland, Orkney, South Orkney and Caithness, and Sutherland (IGS, 1978a, 1978b, 1979, 1982) and provisional geochemical data for the Scottish Highlands generally are available in computer-readable form through the National Geochemical Data Bank. Geochemical mapping of southern Scotland and the English Lake District is in progress and it is intended to extend the programme over the rest of Scotland and England and Wales.

A summary of chemical elements available in the published geochemical atlases and provisional data in computer-readable form is given in table 5.

Table 5 Summary of chemical elements available in IGS geochemical atlases or provisional computer-readable lists

Published atlases	**Elements**
Shetland	Ba, Be, B, Cr, Co, Cu, Fe, Pb, Mn, Mo, Ni, U, V, Zn, Zr
Orkney	Ba, Be, B, Cr, Co, Cu, Fe_2O_3, Pb, Mn, Mo, Ni, U, V, Zn, Zr
South Orkney and Caithness	Ba, Be, B, Cr, Co, Cu, Fe, Pb, Mn, Mo, Ni, Sr (partial data), Ti (partial data), U, V, Zn, Zr
Sutherland	Be, B, Cr, Co, Cu, Fe, Pb, Mn, Mo, Ni, U, V, Zn, Zr
In press	
Lewis/Little Minch	Ba, Be, Bi, B, Ca, Cr, Co, Cu, Fe, K, La, Pb, Li, Mg, Mn, Mo, Ni, Sr, Ti, U, V, Y, Zn, Zr
Great Glen	Ba, Be, B, Ca, Cr, Co, Cu, Fe, K, La, Pb, Li, MgO, Mn, Mo, Ni, Sr, Ti, U, V, Y, Zn, Zr
Provisional maps available for purchase through NGDB	
Argyll–Tiree Moray/Buchan Tay/Forth	Ba, Be, Bi, B, Ca, Cr, Co, Cu, Fe, K, La, Pb, Li, Mg, Mn, Mo, Ni, Sr, Ti, U,V, Y, Zn, Zr F

Metalliferous mineral resources and economic geology

High concentrations of chemical elements in stream sediments and water may provide direct indications of metalliferous mineral occurrences of potential economic significance. In Scotland, uranium-lead mineralisation in the Yesnaby-Stromness area of Orkney (Michie & Cooper, 1979), uranium-lead-fluorine mineralisation in the Helmsdale-Ousdale area of Sutherland (Gallagher *et al.*, 1971) and barium-fluorine-lead and molybdenum mineralisation near Lairg in Sutherland (Gallagher, 1970) are three such examples. The most important new discovery of metalliferous minerals located by geochemical reconnaissance to date is the stratabound barium-lead-zinc deposit in the Middle Dalradian rocks of Perthshire, (Coates *et al.*, 1980; Coats, Smith *et al.*, 1981). The mineralised zone at the type locality near Aberfeldy has a thickness of about 100 m, with total reserves of barium of 2 million tons; additional occurrences of stratabound sulphide mineralisation have been found in adjacent areas of the Middle Dalradian at Tyndrum and elsewhere (Smith, Gallagher *et al.*, 1981).

The applications of the regional geochemical data to the identification of metalliferous minerals may be less direct, however, and one of their most important is in helping to understand ore genesis and to develop exploration criteria based on metallogenic models. The feasibility of restricting mining activity to areas where it will have least environmental impact depends on the availability of adequate supplies of metal. This in turn depends on a scientific understanding of ore genesis and the development of effective exploration methods.

An investigation into the controls of uranium provinces which was based on the geochemical map of uranium in northern Scotland (plate10) is an example of such a study. Uranium provinces are regions of the Earth's crust which contain elevated levels of uranium and in which there may be evidence of repeated episodes of uranium mineralisation; an understanding of the genesis of uranium provinces is thus of value both for exploration and resource evaluation purposes. Studies of the geochemical map of uranium in Northern Scotland in the light of metallogenic and geological data helped to identify the precise tectonic setting in which uranium mineralisation took place (Watson & Plant, 1979); this was a relatively short period of time during the lower Old Red Sandstone which was characterised by granite magmatism and deep faulting associated with uplift and stabilisation (cratonisation) of the Caledonian mountain belt. Further enrichment occurred in the Lower Middle Old Red Sandstone with secondary sedimentary enrichment in Middle Old Red Sandstone lacustrine facies sediments. The tectonic setting of cratonisation following orogenesis in which uranium enrichment occurred in Scotland has been shown to be applicable to uranium provinces elsewhere (Watson *et al.*, 1982; Simpson *et al.*, 1979).

The regional geochemical map of uranium also provided the first indications of high levels of heat-producing elements (uranium, thorium, potassium) over the Cairngorm granite and helped to identify Caledonian granites with potential as sources of geothermal energy (Plant, 1978; Brown *et al.*, 1979). These granites appear to have more potential as 'hot rock' geothermal energy sources than the Tertiary granites which had previously been suggested as the most promising source of such energy in Scotland (Garnish, 1976).

Identification of the regional geochemical, geophysical and geological signatures of metalliferous granites (containing high magmatic contents of metals, predominantly in silicate minerals) and mineralised granites (in which metals have been redistributed into secondary ore minerals) have also enabled exploration criteria to be developed for porphyry copper, porphyry molybdenum-tungsten, and tin-uranium granites (*sensu lato*) (Plant *et al.*, 1981). Tin-uranium granites, for example, have geochemical signatures characterised by low potassium: rubidium, strontium: yttrium and high rubidium: strontium, uranium: thorium, potassium: barium ratios, and by rare-earth element (REE) patterns that are REE enriched with marked negative europium anomalies.

Research into the metallogenesis of the Dalradian barium-lead-zinc mineralisation is also leading to an improved understanding of this type of exhalative stratabound deposit which may lead to new discoveries in the British Caledonides and elsewhere. Exploration criteria derived from these studies can be used to screen datasets held in computer-readable form both for exploration and resource evaluation.

New occurrences of metalliferous minerals, particularly those which have not been worked previously, also enable research into geochemical and geophysical methods of exploration to be carried out (e.g., Plant, 1971; Leake & Aucott, 1973; Parker, 1980) and provide field conditions suitable for developing and testing instruments (Miller & Loosemore, 1972; Grout & Gallagher, 1980).

Geological mapping

The geochemical maps prepared to date have provided much new information which amplifies the conventional geological map of Scotland. For example, different groups of Caledonian granites (Plant *et al.*, 1981) and major divisions in the Lewisian basement assemblage (IGS, in press) are identified by the new geochemical data. One of the most important new findings is the change which is identified by regional geochemical and geophysical data across the Moine-Dalradian boundary (plates 11 and 12) and it has been suggested (Plant *et al.*, 1983) that the boundary coincides with a deep discontinuity in the crust which affected the sedimentary, metamorphic, and magmatic development of the Caledonian orogeny. The boundary is thought to represent the southeastern margin of a former continental slab containing a thick layer of 'Old Moine', the Dalradian accumulating on a thinned Lewisian-like basement in an incipient ocean basin adjacent to the edge of this continental slab. Dalradian stratabound mineral deposits and volcanics characterise the palaeo-oceanic rift (Plant *et al.*, 1983).

Pollution

The level of contamination over the regions of northern Scotland mapped to date is generally low for all elements determined with the exception of isolated tin-copper-lead anomalies near to settlements, or localised increases in pH in areas of intensive agriculture. In some areas of recent afforestation or intensive agriculture, increased levels of uranium may occur (IGS, 1979; Michie & Cooper, 1979) which may be attributable to the use of phosphate fertilisers (Spalding and Sackett, 1972). With these exceptions the regional data provide an important source of background information on the natural levels of chemical elements in the environment and on their distribution and dispersion. The levels of many elements show marked variations regionally and locally, for example copper, cobalt and chromium concentrations range from <10 to >200 ppm, <15 to >200 ppm and <50 to >1% (10,000 ppm) respectively over a distance of less than 10 miles in Shetland (IGS, 1978a). Further examples of marked changes in natural levels of trace elements are described by Plant and Moore (1979) and many examples can be found in individual geochemical atlases in the IGS series.

Medical geography and agriculture

In recent years there has been growing concern about the effects on human health of heavy metal contamination such as that reported from Japan for cadmium and mercury. It is also recognised increasingly that certain degenerative diseases in man, animals and crops may be attributable to entirely naturally occurring concentrations or deficiencies of trace elements (Royal Society, 1983).

Two main groups of trace elements are of particular importance for health. Firstly, those identified as essential to animal life, which according to Underwood (1977), are the first row transition elements—iron, manganese (both normally considered as major and minor rather than trace elements in geochemistry), nickel, copper, vanadium, zinc, cobalt and chromium; together with molybdenum, tin, selenium, iodine and fluorine. The disorders associated with deficiency of these elements are given in table 6 (after Mills, 1979). Boron is known to be essential for higher plants, but has not yet been shown to be necessary for animals. Secondly, 'toxic elements' such as lead, cadmium and mercury and some of the daughter products of uranium, which are known to have adverse physiological significance at relatively low levels. All trace elements are toxic if ingested or inhaled at sufficiently high levels for long enough periods of time. Selenium, fluorine and molybdenum provide examples of elements which show a relatively narrow concentration range (of the order of a few ppm) between deficiency and toxic levels.

Ideally, trace element maps for application to agriculture or human health investigations would be based on systematic analysis of soil or vegetation samples or direct analysis of dust. In Britain, such an approach has to date proved impracticable because of the cost and time required. Information is available for parts of Scotland (Swaine, 1955; Mitchell, 1971) but in England, Wales and northern Ireland there are few systematic data on either total or 'available' levels of trace elements in soils. There are even fewer published data on regional variations of the levels of trace elements in pasture herbage and food crops. Some surveys of trace elements and heavy metal contaminants in food for human consumption based on random samples, and the analysis of total diets, have been published (Hamilton & Minski, 1972; Hubbard & Lindsay, 1975) and information on the intake of mercury, lead, cadmium and arsenic has been assessed (HMSO, 1971, 1972, 1973). Surveys of this type do not, however, provide information which enables epidemiological or public health studies to be made and the regional geochemical data for Scotland and Northern England, prepared by the IGS, and for England and Wales, prepared by the Applied Geochemistry Research Group of Imperial College, provide the only systematic data sets for regional studies of the health of livestock or humans.

Table 6 Major clinical and pathological defects in essential trace element deficiencies (after Mills, 1979)

Deficiency	Gross pathological responses	Species**
copper	defective melanin production: hair, wool	ro, ru, pr, m
	defective keratinization: hair, wool	b, ro, ru, m
	cardiac hypertrophy	ro, p, ru
	skeletal and vascular defects	all
	ataxia, myelin aplasia	ru (sheep)
	anaemia	all
	foetal resorption	ro
cobalt	anorexia	ru
	anaemia	ru
selenium	myopathy, cardiac and skeletal	
	myoglobinuria	ru
	liver necrosis	ro, b, p
zinc	anorexia	all
	parakeratosis/hyperkeratosis	all
	foetal malformation	ro
	perinatal mortality	ro
manganese	skeletal and cartilage defects	b, ro, ru
	ataxia	ro
	reproductive failure	ro, ru
silicon	skeletal and cartilage defects	b, ro
iodine	thyroid hyperplasia	all
	reproductive failure	all
	hair, wool loss	all
chromium	corneal opacity, impaired glucose tolerance (diabetic-like syndrome)*	pr
nickel	perinatal mortality	ro, p
molybdenum	defective keratinization	b
fluorine	perinatal mortality, anaemia	b
vanadium	skeletal defects	b
	reproductive failure	ro

*C. F. Mills, pers. comm.

**Key to species: ro, laboratory rodents; b, bird, p, pig; ru, ruminant; pr, laboratory primate; m, man.

Note: With the exception of chromium, deficiency of all of the above elements ultimately results in growth failure. Growth inhibition has also been reported for arsenic and cadmium deficiencies but no gross lesions have yet been described.

Research has been undertaken by Imperial College into the applications of geochemical maps to problems of crops and the health and productivity of agricultural animals in parts of England and Wales (e.g. Thornton, 1974; Thornton & Kinnburgh, 1978). For example, it has been shown that soils with 5 ppm molybdenum can be associated with scouring, loss of production and growth retardation in cattle due to reduced copper absorption and utilisation, and in Derbyshire, molybdenum anomalies in stream sediment led to the recognition of areas totalling c. 150 km^2 in which over 75% of the cattle were hypocupraemic (Thomson *et al.*, 1972). Subsequent copper supplementation trials showed responses in live-weight gain in young cattle ranging form 14 to 32 kg per animal over a 6-month grazing season.

Areas of high molybdenum are also identified on regional geochemical maps of Scotland, particularly over the lacustrine facies sediments of the Middle Old Red Sandstone of Caithness and Southwest Orkney, where levels are in the range of 6-20 ppm molybdenum (IGS, 1979, map 15). Alkaline ground waters in these areas may further increase the availability of this element. In addition, important local anomalies with values ›100 ppm molybdenum are associated with mineralisation and occur, for example, in the Lairg area of Sutherland (IGS, 1982). Preliminary comparisons of areas of high molybdenum with data on the health of livestock in collaboration with the Veterinary Advisory Services for Scotland and with the Rowett Institute of Animal Health, Aberdeen, suggest a similar association between molybdenum levels and animal health and productivity to that identified in England and Wales.

Regional variations in the prevalence of human disease are also recognised in Britain (e.g. Howe, 1970), although relationships with the distribution of trace elements in the environment are in most cases empirical and, in general, less well-founded than diseases in farm animals. Moreover, there are many difficulties in relating biological and geochemical activity of trace elements to their total concentrations and these are particularly important in studies of the association between human health and trace element levels. Some of the inorganic factors that affect the solubility and hence the availability of trace elements to plants and animals are discussed by Plant and Moore (1979).

In spite of these difficulties, the high cost of detailed geochemical/biochemical studies into the association between trace element levels and human health makes it essential to carry out regional statistically based studies to identify areas meriting such investigation. Inter-active graphical facilities such as the NERC I^2S system provide a powerful means of examining regional geochemical, epidemiological and other datasets to identify and quantify spatial associations; they also provide a means of formulating and constraining hypotheses on relationships between geochemistry and health. The Institute's regional geochemical data are sufficiently detailed and quantitative to serve as a basis for such studies from the broadscale down to the scale of individual farms and a study into the relationship between geochemistry and health in northeast Scotland has commenced, in collaboration with Aberdeen University, with funding from the European Economic Community.

Epidemiological research in relation to geochemistry has also recently been extended in the form of the National Heart Study directed by Professor A. G. Shaper of the Royal Free Hospital who, in collaboration with the Water Research Centre, is looking retrospectively at cardiovascular disease and a range of other diseases in over 250 towns, and comparing mortality and water hardness data. This work involves clinical studies in selected towns and follows the work of, e.g. Crawford *et al.* (1968) which showed that there is negative correlation between the prevalence of cardiovascular disease and water hardness.

Conclusions

The Institute of Geological Sciences' Regional Geochemical Reconnaissance Programme is providing systematic data on the levels of trace elements over Britain. The data, which are made available in published geochemical atlases and in computer-readable form suitable for study using interactive graphical devices, serve as a basis for applied and fundamental geochemical studies in the earth and environmental sciences.

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Dr J. Plant,
Institute of Geological Sciences,
Applied Geochemistry Unit,
154 Clerkenwell Road,
London
EC1R 5DU

Explanation of Plates 10—12

Plate 10

Geochemical map of uranium in northern Scotland.

Plate 11

Geochemical map of copper in northern Scotland.

Plate 12

Geochemical map of boron in northern Scotland.

Plate 10

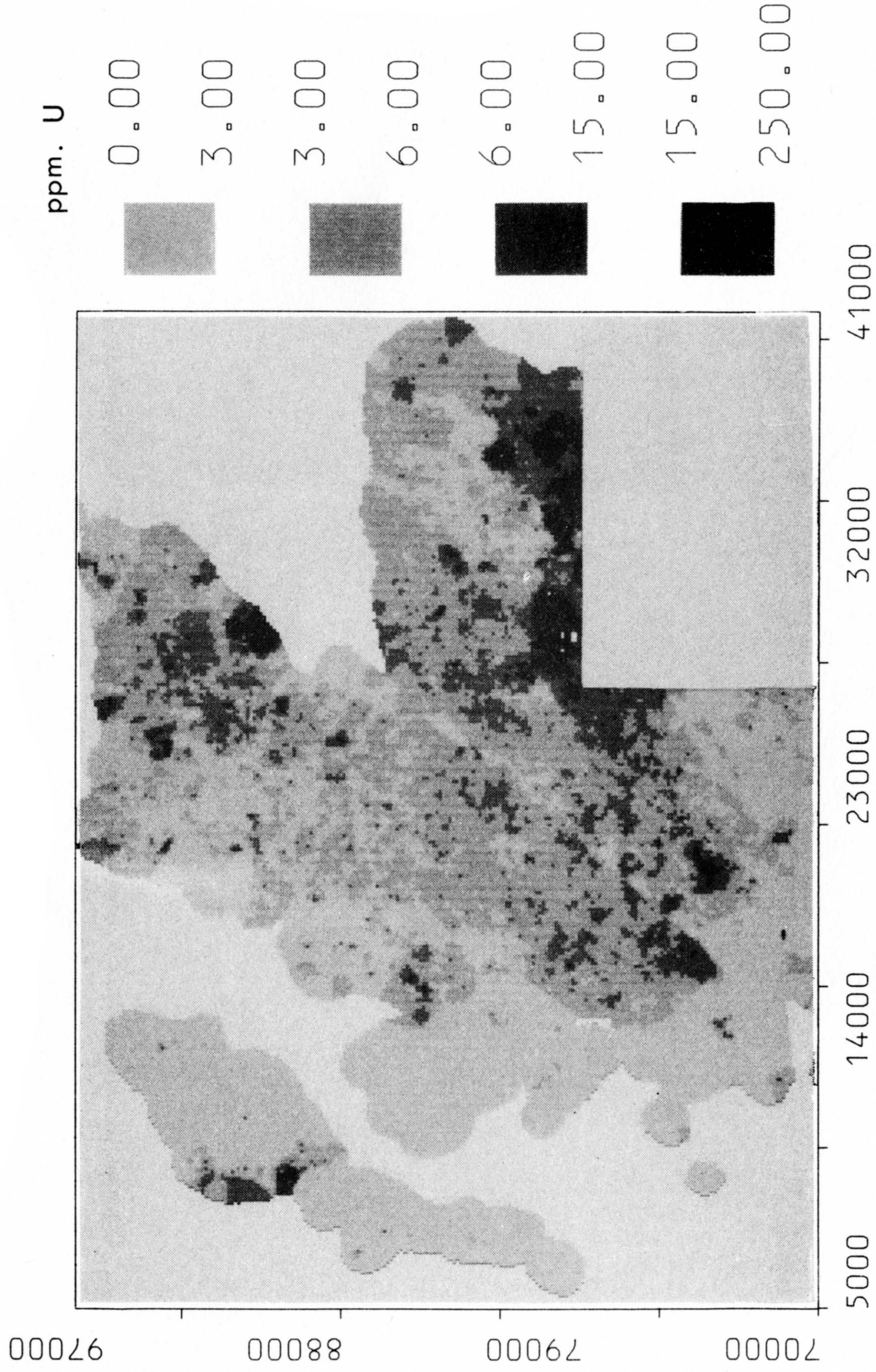
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Plate 11

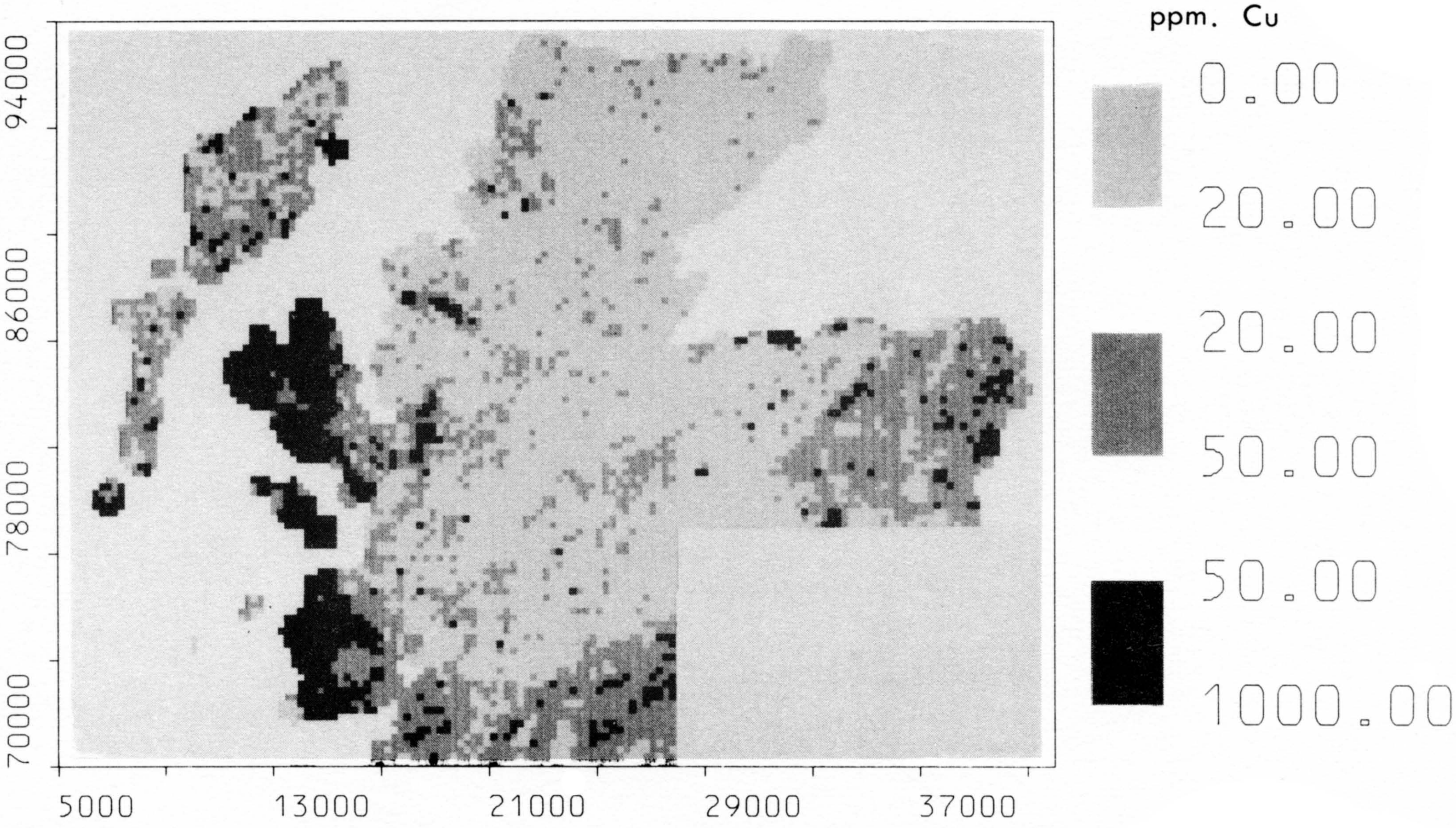
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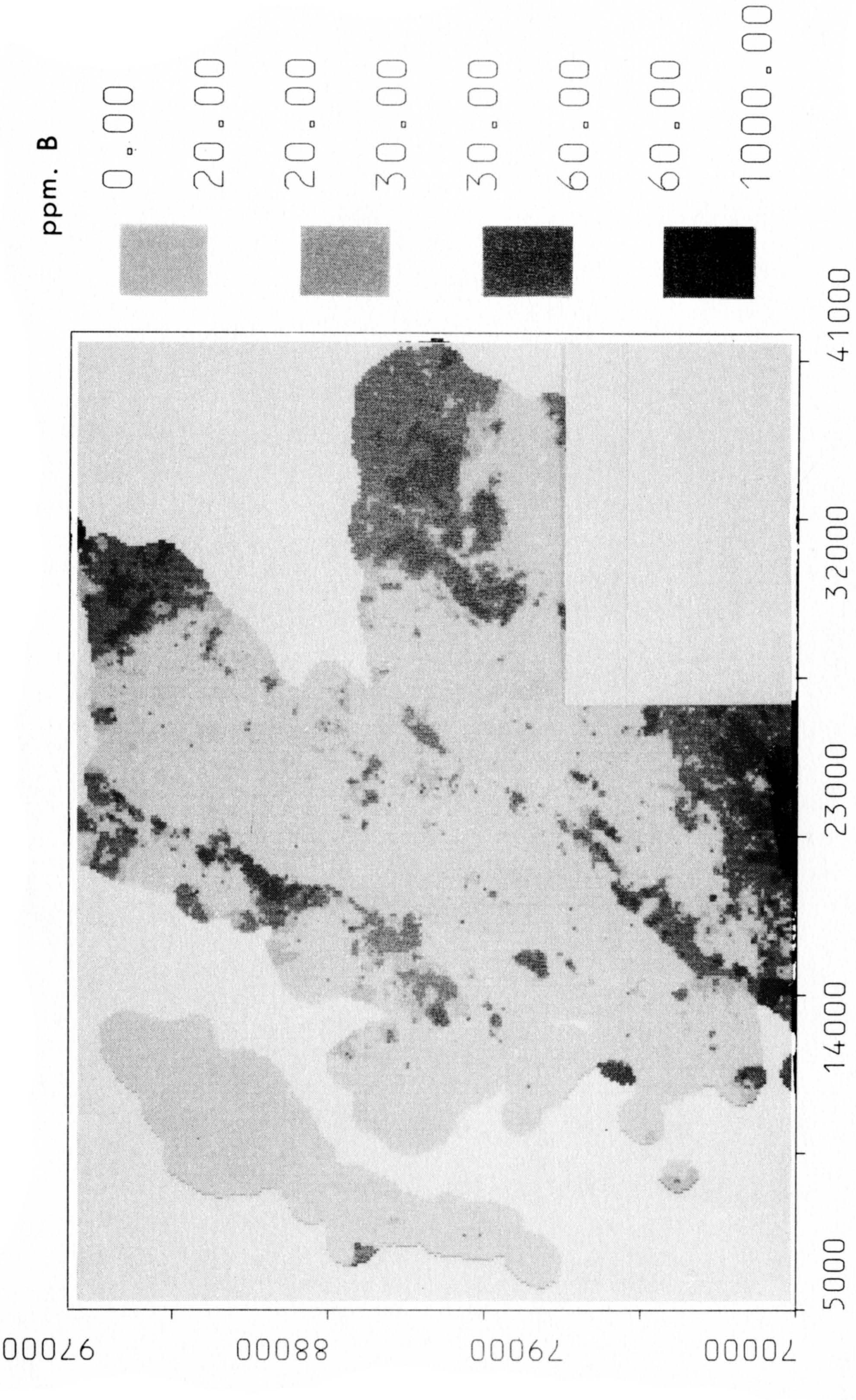
Plate 12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DINANTIAN EXTRUSIVE ACTIVITY IN THE SOUTH PENNINES

by

P. R. Ineson and S. G. Walters

Summary

Dinantian extrusive activity in the South Pennines (Derbyshire) occurred in the form of a number of small volcanoes. Basaltic magma emanated from central vents recorded in the vicinity of Hopton, Bonsall, Bakewell, Taddington and Litton and inferred around Ashover, Millclose Mine, Eyam and Castleton. Lava flows and sills associated with boss-like tuff cones and sheet deposits are related to phreatomagmatic activity. The extrusive activity may have occurred on an emergent carbonate platform, however, the interplay of sedimentation and emergence peripheral to the central areas of extrusion and uplift, gave rise to complex stratigraphical sequences.

Introduction

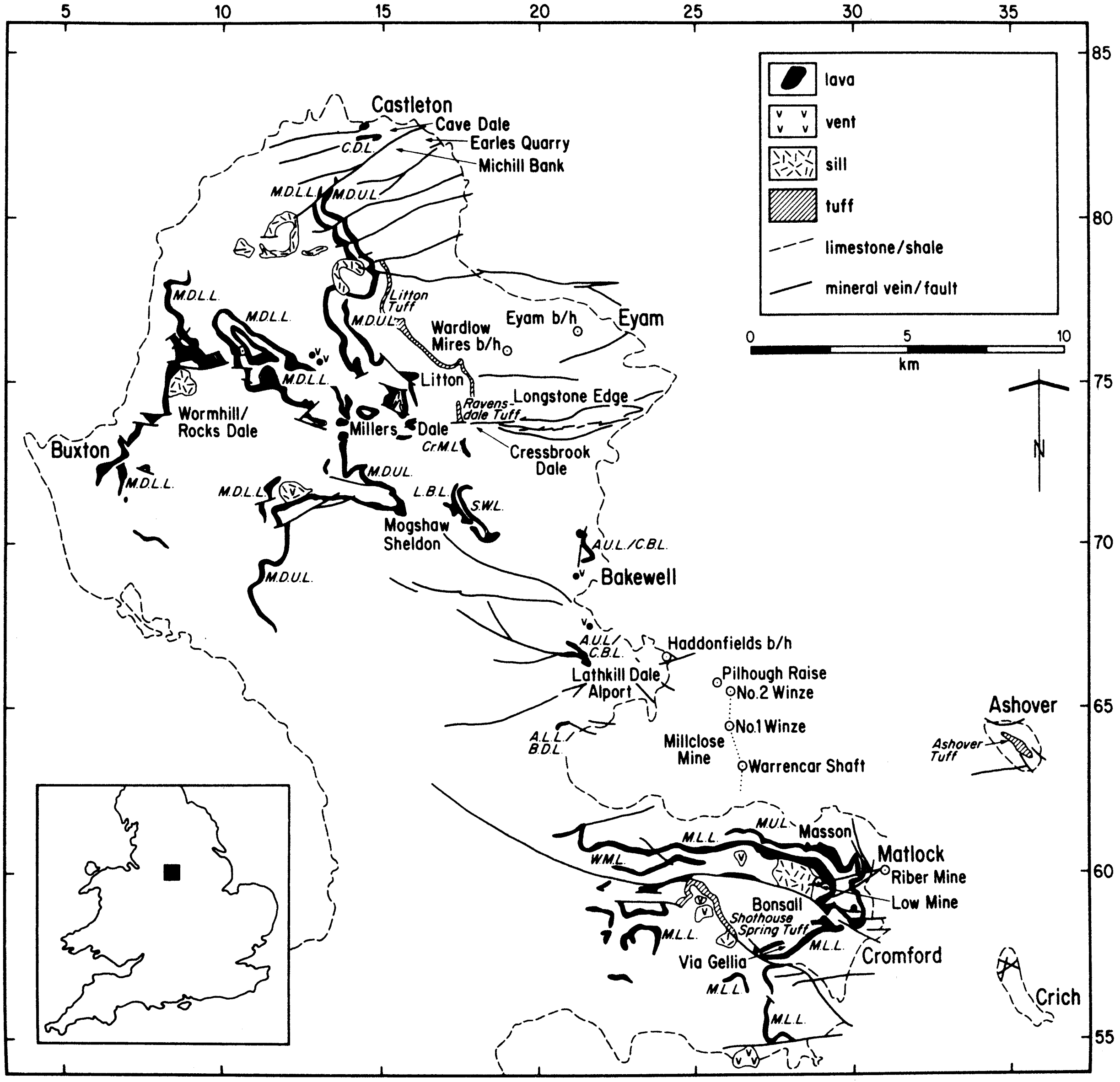
The Dinantian limestones of the South Pennines contain contemporaneous lava flows and tuff horizons together with sills, vents and rare dykes. Arnold-Bemrose (1894; 1907) provided detailed accounts of the petrography and field relationships, while Geikie (1897) enumerated the rock types. Stratigraphical complexities and subsurface distribution of the igneous rocks have been provided by Traill (1940) and Shirley (1950), general compilations by the Institute of Geological Sciences (Smith *et al.*, 1967; Stevenson & Gaunt, 1971) as well as 1:25,000 maps (Inst. geol. Sci., 1969; 1970; 1975a and b; 1976a and b; 1977). Kelman (1980) described the volcanics at Ashover while Walters and Ineson (1981) reviewed the distribution and correlation of these horizons. Text-figs. 1 and 2 show this distribution and correlation.

The terms 'lava' or 'tuff' have been, and still are, used to denote a mappable stratigraphical unit, i.e. the Miller's Dale Upper Lava or the Litton Tuff. The individual 'lavas' may contain separate lava flows as well as pyroclastic material and, in some cases, thin sedimentary intercalations. Walters and Ineson (1981) illustrated their circular to ovate outlines and indicated that the most extensive units have diameters of between 10 and 12 km with a maximum thickness of 100m. In profile they are comparable with the small basaltic shield volcanoes described by MacDonald (1972). In extent and volume they are less than, for example, the Icelandic eruptions which may extend to a diameter of 30 km and a height of 1000m, and are more comparable to the small shield eruptions centred on the Faroes which Noe-Nygaard (1968) designated as 'scutulum type'. These have a maximum diameter of 20 km and a maximum height of 250m.

As no general synthesis of the extrusive igneous activity centred on the South Pennines has been produced since Arnold-Bemrose's papers, and as recent mining and exploratory boreholes have provided new information, this paper describes the various styles of extrusive activity and erects palaeoenvironmental reconstructions.

Lavas

Nichols (1936) and Walker (1970) classified lava flows, on the basis of their internal structures and relationships, into composite, simple, compound and multiple types. A composite 'lava' is capable of subdivision into a number of distinct flows, or sets of flow units, each separated by an appreciable time interval which was sufficient for the onset of weathering or resumption of sedimentation, or marked by a period of pyroclastic activity. Simple lava flows occur as extensive flood-like extrusions and each flow is divided into an upper and a lower vesicular margin with a massive interior. If a simple flow is overlain by another lava, the whole assemblage is composite. Compound lavas are identified by having 'flow units' comparable to simple flows, the individual

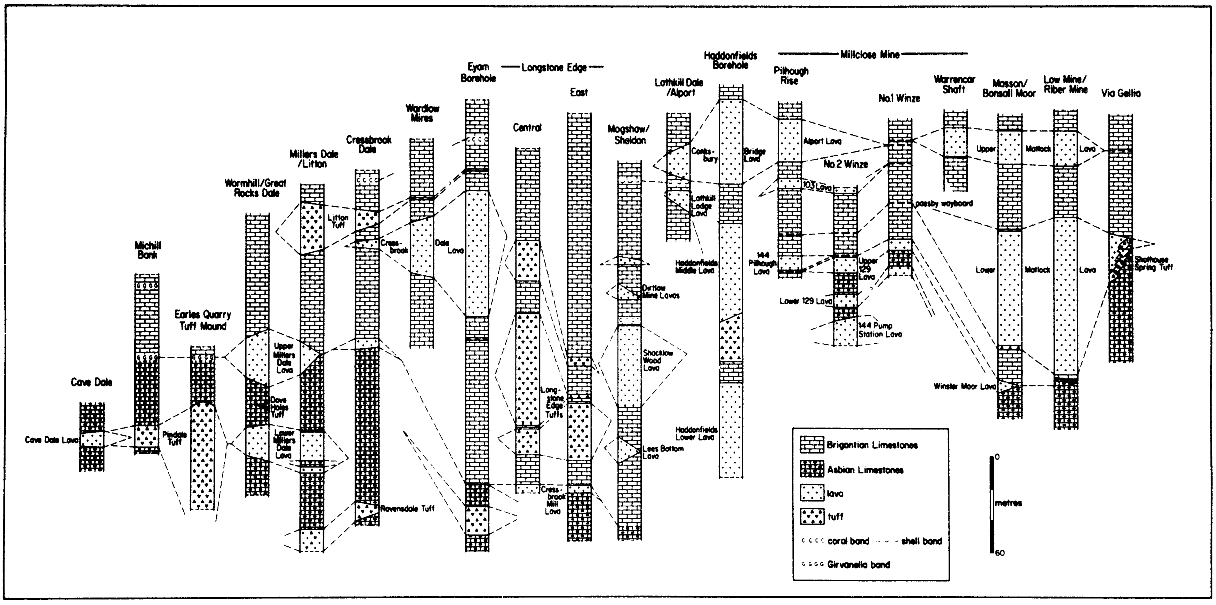


Text-fig.1. Distribution of the igneous horizons in the South Pennines.

units however are not laterally extensive. The controlling factor in differentiating simple and compound lavas is the effusion rate (Walker, 1970) where simple flows result from the more rapid effusion of material, while in compound lavas the time interval between successive units is only sufficient for a skin to form on the lower unit before it is inundated. Multiple flows are a variant of compound flows in which the time interval is such that no discrete divisions are evident, however the units are recognised by variations in the concentration, shape and size of the vesicular horizons.

The Eyam Borehole (Dunham, 1973) and the Wardlow Mires Borehole (Stevenson & Gaunt, 1971) intersected the Cressbrook Dale Lava which is poorly exposed at outcrop. Variations in the vesicular nature of the lava (text-fig. 3) indicate that it is a compound lava, for sharp contacts between highly vesicular and haematised lava as well as a 0.1m thick tuff, divides the lava into two effusive episodes.

In contrast, the Miller's Dale Lava and the Matlock Lava (text-fig. 1) are composite lavas where the 'simple' individual flow units rarely exceed 10 m in thickness. In the thinner flows rapid cooling has preserved a vesicular central zone, while in thicker flows the slower cooling has given rise to coarse holocrystalline centres characterised by fresh granular augite with a subophitic texture. An example of this type of lava is the Miller's Dale Lower Lava, the internal structures of which are shown in text-fig. 4. Boreholes at SK 103754 and SK 099762 intersected



Text-fig.2. A correlation of the igneous horizons in the South Pennines.

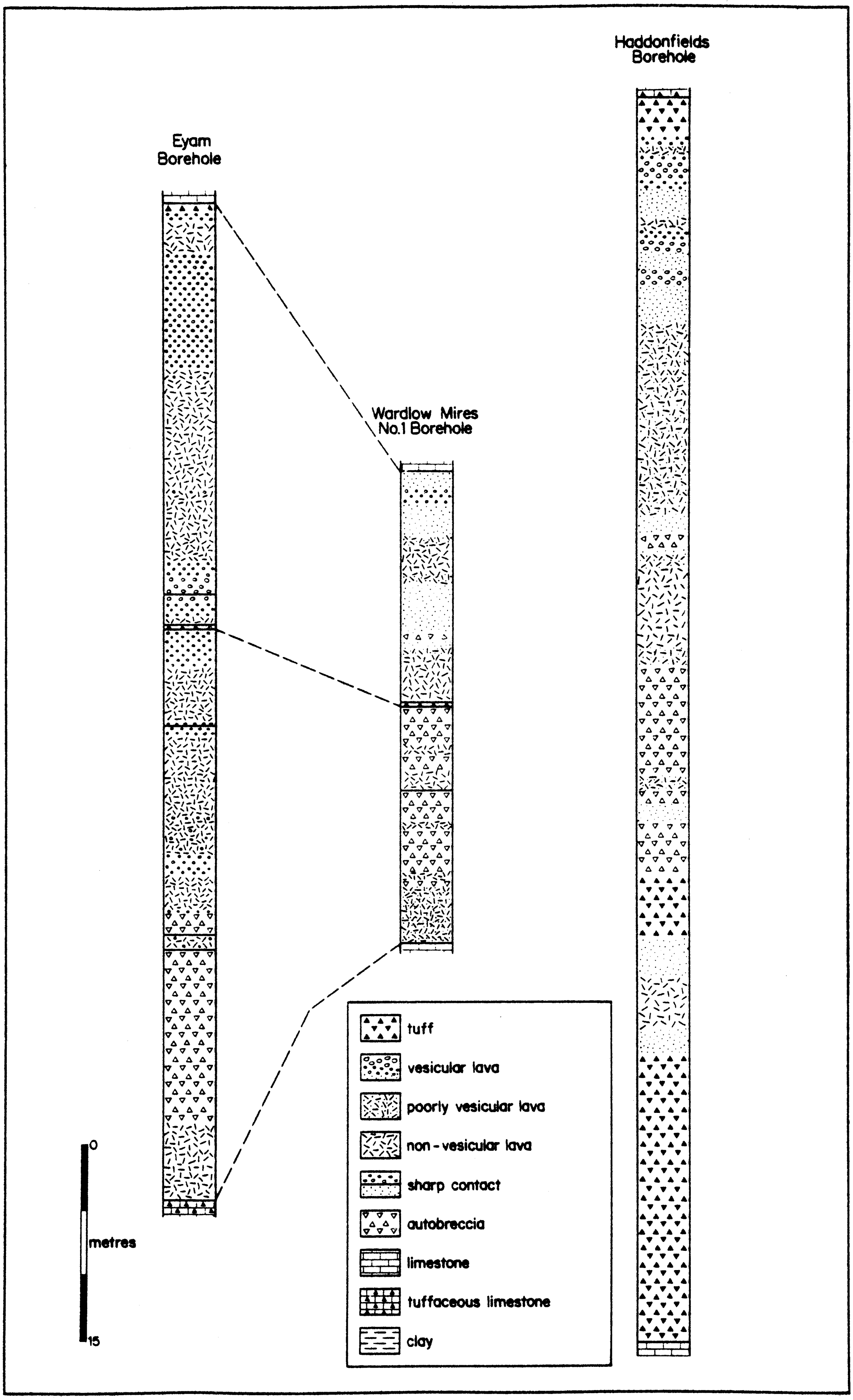
the lava and the cores showed that it is divisible into three extrusive events with a tuffaceous upper unit, while the two lower and relatively thicker units display coarse holocrystalline centres. The three flows exhibit uniform petrography in both the vesicular and the non-vesicular types. Pseudomorphed olivine microphenocrysts are set in a medium grained groundmass with occasional resorbed plagioclase phenocrysts and rare clinopyroxene microphenocrysts. Interstitial relict glass altering to clay aggregates occurs and results in a texture similar to that shown by the Haddonfields Lower Lava (text-fig. 3). Sections of the lava are exposed in three small quarries at SK 098761, near Buxton Bridge.

The Matlock Lower Lava is another example of a composite flow. The Bonsall Basalt Quarry (SK 284575) and Groaning Tor Adit (SK 283572) expose a flow unit approximately 12 m thick. The lava reaches its maximum thickness in the Masson Hill area (text-fig. 1) where a series of boreholes on Great Rake proved 99 m of lavas and tuffs (Walters, 1981). Three flows, characterised by vesicular upper and lower surfaces and separated by ash or decomposed clay, were recognised. The lower two units contain marmorised limestone and angular basaltic fragments with an agglomeratic texture. The upper unit is exposed in the opencast site on Masson Hill which has been described by Dunham (1952) and Ixer (1975).

Limestone and ash intercalations

Thin limestone and ash layers occur between flow units. Stevenson and Gaunt (1971) reported a 12 ft (3.7 m) limestone separating two flow units of the Miller's Dale Lava encountered in the Litton Dale Borehole (SK 160750). In an opencast site near Tides Low (SK 146782) the Lower Lava shows an upper flow unit, with highly vesicular margins, resting on 3 m of limestone which in turn overlies a lower but less vesicular blocky lava flow. Similar intercalations have been recorded in the Miller's Dale Upper Lava on Bole Hill (SK 108757) by the Institute of Geological Sciences (1976a) while Arnold-Bemrose (1894) reported coarse ash layers in a section of the lava at the Miller's Dale Lime Works Quarry (SK 140730) that enabled him to subdivide it into at least two units.

These examples are distinguished from the penecontemporaneous deposition of limestone with lava at the edge of a flow as described by Smith *et al.* (1967, p.18) for the Matlock Lower Lava. In that ash and limestone intercalations are not present in compound or multiple lava flows (Walker, 1970), certain lavas in the South Pennines are classed as composite flows, a suggestion initially made by Stevenson and Gaunt (1971).



Text-fig.3. Borehole sections of the Cressbrook Dale Lava in the Eyam, Wardlow Mires No.1 and Haddonfield Boreholes.

Breccias and pseudobreccias

Breccias were recorded by Ramsbottom *et al.* (1962) in the cores of the Ashover Borehole and by Walters in Ineson (1981) in the cores of the Eyam, Wardlow Mires No.1 and Haddonfields Boreholes (see text-figs. 1 and 3). The lateral extent of these breccias is not known in detail. The Haddonfields (No.11) Borehole (SK 237658) penetrated volcanics, in which breccias associated with the 'Middle Lava' overlie a sequence of inclined and graded tuffs (text-fig. 2). Walters and Ineson (1981) used this and Traill's (1940) information from Millclose Mine to suggest that in the vicinity of Rowsley a major volcanic centre may be concealed beneath the Namurian cover.

The breccias show characteristics of subaerial autobrecciation (Parsons, 1969), where friction or internal disruption of a flow produces 'monolithologic autoclastic volcanic breccias with angular, lithic unsorted fragments, usually with a central zone or lens of non-brecciated materials'. In the South Pennines the fragments are composed of either non-vesicular basalt which has been iron-stained and altered or occasionally shows evidence of chilling. The clasts are ill-sorted, and in the Cressbrook Dale Lava (text-fig. 3), the majority of the fragments do not exceed 50 mm in diameter but blocks up to a metre across are present. There is no fine grained material between the blocks and the voids are infilled with silica and chlorites while reaction rims between matrix and blocks are not seen (see plate13; fig. A). An additional feature of these breccias is that they interdigitate with unbrecciated, non-vesicular lava and appear to be related to areas of maximum lava development and local cone structures. As brecciation of a lava is a function of temperature, viscosity and strain rates as well as the rate of degassing and extrusion (MacDonald, 1972), these conditions may not have prevailed adjacent to all extrusive centres and as such breccias are not a ubiquitous feature. They are not developed, for example, adjacent to the 'central vent' of the Matlock Lava in the Masson Hill area (Walters & Ineson, 1981).

(Additional care must be taken in the interpretation of brecciated structures for 'pseudobreccias' can be produced by either the irregular iron-staining of a lava or the development of a fine net-like veining of a lava adjacent to mineral veins (see plate13; fig. B). In these instances their true origin may be determined by field relationships and transitional types within the aureole of a vein.)

Lava fronts

The slopes of the flanks of a scutulum-type activity are calculated assuming a gradual thinning of each lava flow. Although field and borehole core evidence indicates such thinning, at a number of localities lavas terminate abruptly and a flow front may explain this feature. Traill (1940) described the 144 Pump Station flow front at Millclose Mine as having pillow structures and a 'slaggy' appearance, features typical of subaqueous extrusion. Additional localities have been cited at Taddington (Cope, 1937) and near Middleton Limestone Mine (Smith *et al.*, 1967) as well as the Litton Mill flow front of the Miller's Dale Upper Lava exposed in the disused railway cutting above Litton Mill (SK 157729) and described in detail by Walkden (1977). He noted that the lava was palagonised, crudely stratified, finely brecciated in places and while not fresh, did not show features analogous with ancient weathering. As Walkden recorded (1977, p.358), the structure was similar to that of a flow front breccia formed as a result of lava entering water and shattering (Jones & Nelson, 1970). The chilling and brecciation was sufficient to halt the flow of lava and give rise to a steep flow front.

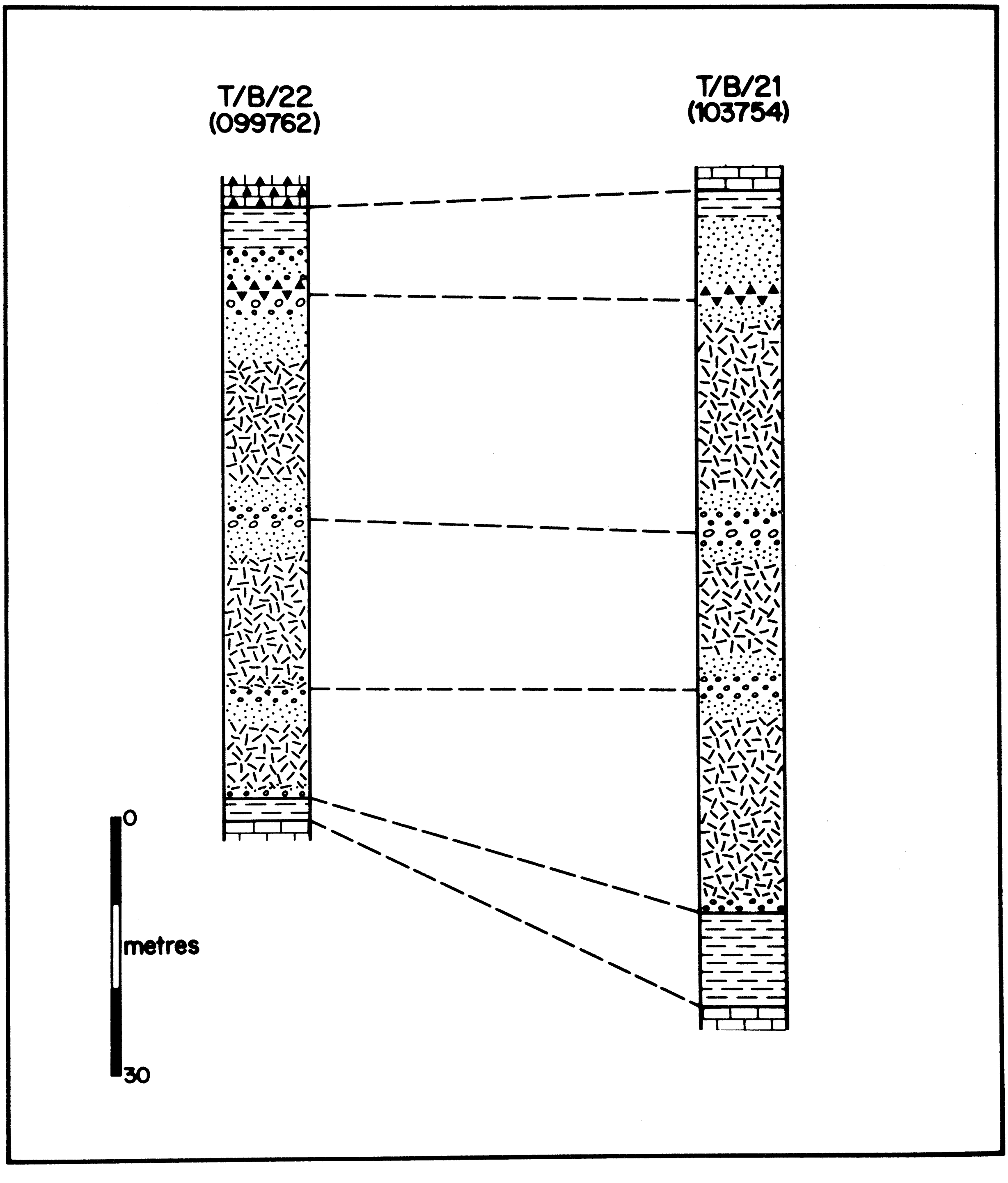
Pyroclastics

Each effusive phase contains a small but significant proportion of pyroclastic material. The lavas were either preceded and/or followed by explosive activity that resulted in extensive ash falls. As the ash deposits invariably cover a greater area than the lavas, they have enabled Walters and Ineson (1981) to suggest the correlation of lava horizons into adjacent areas. In this respect they used the Shothouse Spring, Ravensdale, Dove Holes, Pindale, Litton and Longstone Edge Tuffs which are the most extensive units.

The Dinantian stratigraphical sequence in the South Pennines is interspersed with numerous thin clay horizons which are commonly referred to as 'clay wayboards' (Walkden, 1972). They often represent emergent periods marked by palaeokarst surfaces bearing a cover of atmospheric dust-derived fossil soil (Walkden, 1972; 1974). Walkden (1972) and Somerville (1979) have demonstrated that they are typical K-bentonites derived from the degradation of volcanic ash.

Cones

The accumulation of ash around a vent forms an ash cone. The ash readily decomposes to a clay or to palagonite. If the ash cones are cemented together by the deposition of a secondary cement between the ash grains or by palagonisation, they are called tuff cones. Ash and tuff cones may resemble cinder cones, however, in the former the ejecta is thrown out at a lower angle and accumulates at greater distances from the vent than in cinder cones. They therefore have broader and lower profiles than cinder cones. MacDonald (1972) states that



Text-fig.4. Sketch sections of the Miller's Dale Lower Lava intersected in I.C.I. Boreholes T/B/21 and T/B/22 located near Tunstead, Buxton (for key see text-fig.3).

very broad steep-sided tuff cones are sometimes referred to as "tuff-rings". Although not formed at vents, littoral cones may resemble vent structures, however, they are formed by steam explosions where lava flows enter water. They are common along the shorelines of volcanic islands.

Tuff cones have been inferred or recognised at Ashover (Ramsbottom *et al.*, 1962; Kelman, 1980), Low Mine near Masson Hill (Arnold-Bemrose, 1907; Smith *et al.*, 1967), Prospect Quarry (SK 245574) near

Grangemill and in the Rowsley area (Walters & Ineson, 1981). In the northern area, the Pindale Tuff Cone has been described by Shirley and Horsfield (1940), Eden *et al*, (1964), Stevenson and Gaunt (1971) and Walters and Ineson (1981). Additional localities are located at Brook Bottom (Arnold-Bemrose, 1907; Walters & Ineson, 1981), Black Hillock Mine on Tideswell Moor (Walters, 1980), near to the Wardlow Mires No.1 Borehole (Stevenson & Gaunt, 1971) as well as beneath Longstone Edge (Walters & Ineson, 1981).

The cones contain devitrified lapilli-tuff and vitric tuff (shards). With an increase in the proportion of ash with respect to lapilli, graded tuff bedding becomes pronounced as shown in plate13; fig. C. Fragments of limestone (plate13; fig. D) derived from the vent walls are commonly associated with the coarser tuffs and an example was quoted by Shirley and Horsfield (1940) of a limestone block in excess of 1 m in diameter in the Pindale Tuff. Cinder fragments are bounded by fractured surfaces and often grade into pumice, while elongate vesicular lapilli, in possessing deformed vesicles, indicate they were fluid when ejected (see plate14;fig.A). Elliot in Ramsbottom *et al.* (1962) and Ixer (1975) reported that the lapilli were preserved in a green devitrified glass which was either relict palagonite or a clay chlorite mineral. With particular reference to the lapilli in the Pindale Tuff, euhedral pseudomorphed and partly pseudomorphed phenocrysts, in a devitrified matrix, represent plagioclase, olivine or augite. These pseudomorphs may occur as individual fragments in the tuff matrix and form a crystal-ash component. Another characteristic feature of the tuffs is the preponderance of devitrified shards indicative of a highly explosive eruption (see plate 14 ; fig. B).

Walker and Croasdale (1970) described tuffs from the subaerial Strombolain/Hawaiian eruptions and the shallow marine 'Sturtseyan type'. They indicated that achnelithic lapilli are typical of the subaerial eruptions while accretionary lapilli and large scale graded bedding characterise the shallow marine eruptions. The tuffs in the South Pennines show none of these features. The fragmentation is probably a result of phreatomagmatic activity which resulted from the interaction of the magma in the vent with the groundwater. The explosive nature of the ejecta is not in keeping with the quiet effusive activity associated with the main phase of shield construction.

A number of cone structures are characterised by the total absence or subordinate nature of lava. Typical examples are the Shothouse Spring/Grangemill Vents, Ravensdale Tuff, Litton Tuff and the Pindale Tuff (see text-figs. 1 and 2). These cones and their ejecta either occurred independently of a major extrusion episode or formed positive areas around which the lava flowed (Walters & Ineson, 1981).

The Grangemill Vents (Smith *et al.*, 1967) are spatially related to the Shothouse Spring Tuff. The tuff, at the horizon of the Matlock Lower Lava (text-fig. 2) in the Grangemill area, increases in thickness as the Matlock Lower Lava thins around the vents. The tuff may well have enveloped the lower ground around the cones formed by the vents.

The Litton Tuff is one of the largest cone structures in the area with a diameter of 6 km and a height in excess of 30 m. In profile it resembles a low angle basaltic tuff cone produced by high level phreatomagmatic activity. Stevenson and Gaunt (1971) noted that in the vicinity of the inferred vent (i.e. near Litton) a greater proportion of coarse ejecta, cinder and bombs occur. The extremities of the cone, intersected in the Wardlow Mires Borehole are repesented by a sequence of silty horizons deposited in shallow water.

The Pindale Tuff, outlined by exploratory drilling (Stevenson & Gaunt, 1971), indicates the presence of an elongate cone which may have attained a height of 30 m. The steep profile of the cone suggests that phreatomagmatic interaction was not as important as in, for example, the Litton Tuff Cone. Peripheral to the vent/s, coarse unsorted tuff pass into graded tuff, while to the north of the cone a flank eruption emitted the Cave Dale Lava. Cheshire and Bell (1977) reported that a tongue of the subaerial Cave Dale Lava entered shallow sea-water and formed a littoral cone at the site of the so-called Speedwell Vent in Castleton (SK 143 825).

Extrusion—Subaerial or Submarine

Since the lavas were first described by Geikie (1897) and Arnold-Bemrose (1894; 1907) statements or detailed arguments have proposed that they are either subaerial or submarine. Francis (1970) regarded the lavas as submarine flows while Ford (1977) said they were subaerial. Stevenson (in Chesire & Bell, 1977) stated that all the lavas were formed in a marine environment and were both preceded and followed by limestone deposition. The most detailed examination, discussion and conclusion was by Walkden (1977, p.357-8) who proposed a subaerial extrusion for the Miller's Dale Upper Lava at Litton Mills.

It is proposed that extrusive activity occurred on an emergent platform, and as such a variety of environments existed. Marginal to the platform, true pillow structures were noted and deep water facies are evident (Fearnsides & Templeman, 1932). Stevenson and Gaunt (1971) provided evidence of lavas banded with calcareous tuffs of submarine origin and implied that during the initial stages of extrusion, emergence could not be demonstrated. It was evident, however, in the upper parts of the thicker flows which may have built up above sea-level.

Walkden (1974 & 1977) has demonstrated that emergence of the platform was not always associated with extrusive activity. He noted that they are marked by potholed surfaces, crustiform textures and 'wayboard' clays. Lavas often overlie these erosional surfaces and an example was given by Traill (1940, p.204) from Millclose Mine. Likewise, the erosional surface beneath the Miller's Dale Upper Lava in Miller's Dale (Cope, 1937 and Walkden, 1977) relates to an extensive emergent period in the basal Brigantian. The Miller's Dale Lower Lava in Great Rocks Dale also overlies a strongly potholed surface infilled with 'wayboard' clay.

Further support that lavas were extruded on an emergent fully lithified carbonate platform is the absence of calcareous 'injection breccias' at the base of the individual flows. Injection breccias have been described by Strogen (1973) in Ireland, where the Carboniferous Lavas have been extruded into shallow littoral environments. The flow of lava onto an unlithified carbonate base creates steam generation and baking which results in the injection of the lime muds into the lava and the attendant brecciaion of the lava. In a section of the Cressbrook Dale Lava in the Eyam Borehole (text-fig.3) the base of the lava does not show any of the characteristic features typical of such palaeoenvironments. The presence of 'pipe-vesicles' characteristic of the flow of lava over a 'wet surface' has only been observed in the basal part of the Conksbury Bridge Lava at Conksbury Bridge.

Although extrusion may be coincidental with widespread emergence, on a local scale, the interplay between sedimentation, emergence and volcanicity was finely balanced. The transition from sedimentation to emergence is marked by tuffs with phreatomagmatic features, for example, at Low Mine (Walters & Ineson, 1981) and at Ashover (Ramsbottom *et al.*, 1962) the thin limestone intercalations demonstrate this interplay. Emergence in the central vent areas, with peripheral and periodic inundations of the lava, is illustrated by the Miller's Dale Lower Lava in the Wormhill/Great Rocks Dale area. Walters and Ineson (1981) proposed that the lava was extruded in this area, and although capable of being separated into distinct extrusive episodes (text-fig. 4), it does not contain limestone intercalations nor exhibit weathered 'boles'. Towards the periphery of the flow, limestones 3 to 4 m thick occur between the individual flows and have been located in the Litton Dale Borehole and in White Rake Opencast site (SK 146782).

The cessation of an extrusive episode, usually marked by pyroclastic activity, was followed by rapid subsidence, inundation and renewal of carbonate sedimentation. The overlying limestones exhibit thin transitional lithologies of tuffaceous limestone but only where the preceding pyroclastic activity is well developed. These horizons probably indicate a more gradual subsidence and inundation.

Conclusions

Structural, stratigraphic and palaeoenvironmental reconstructions indicate:—

1. The lavas are either composite lavas with two, three or more simple flow units or compound lavas. Multiple flows have not been recognised in the area.
2. Extrusion of lava occurred onto either a fully emergent lithified carbonate platform or an unconsolidated ash surface. In only one example, the Conksbury Bridge Lava, can extrusion have been onto an unconsolidated lime mud.
3. Volcanic breccias are recorded next to tuff cones and/or areas with the thickest lava flows. However, as they are not ubiquitous to these areas, they cannot be used to indicate the proximity of an extrusive centre.
4. Lava fronts may indicate a sub-aqueous or a sub-aerial environment or a flow entering water.
5. Tuffs and tuff cones may be related to lava outpourings or are independent of them. The fragmentation of the tuffs is due to phreatomagmatic activity.
6. The size and profile of the volcanic units compares with scutulum type activity, constructed from either a small number of individual effusive episodes or one proximal event of fluid magma. The emanative centre was a single or small number of vents.
7. Field evidence in support of these conclusions is the symmetrical outline of the lava and tuff deposits, the rarity of dykes and the correlation of known vent structures with areas of maximum 'lava' development.

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P. R. Ineson, Ph.D., C.Eng., MIMM, FGS
Department of Geology,
University of Sheffield,
Sheffield, S3 7HF

S. G. Walters, Ph.D., AMIMM, FGS
B.H.P. Exploration,
Currie Street,
Adelaide,
South Australia

Explanation of plates 13 and 14

Plate 13, Fig. A

Volcanic breccia, Cressbrook Dale Lava. Poorly sorted, angular clasts of partly chilled lava. Note absence of fine grained interstitial material. The dark matrix is silica and spherulitic chlorite intergrowths. Locality: Wardlow Mires No.1 Borehole (SK 18507553).

Plate 13, Fig.B

Pseudobreccia developed in intrusive dolerite, Peak Forest. Note that fine, net-like, veining in proximity to a mineral vein has produced a texture resembling a breccia or pyroclastic rock. Locality: Near Blacklane Farm, Peak Forest (SK 102783).

Plate 13, Fig.C

Graded tuff with inclined bedding from the central cone associated with the extrusion of the Cressbrook Dale Lava. Locality: Exploration Borehole, Hucklow Edge.

Plate 13, Fig.D

Coarse poorly sorted analcite-tuff, with abundant inclusions of limestone fragments. Locality: as Plate 13; Fig. C.

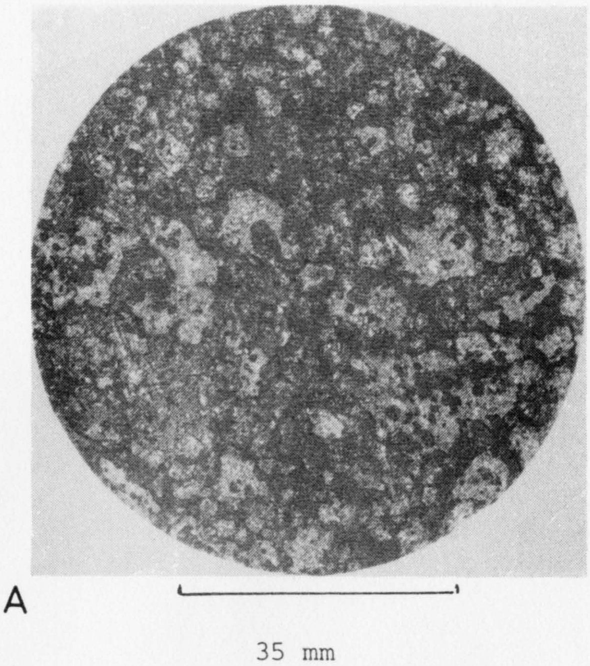
Plate 14, Fig.A

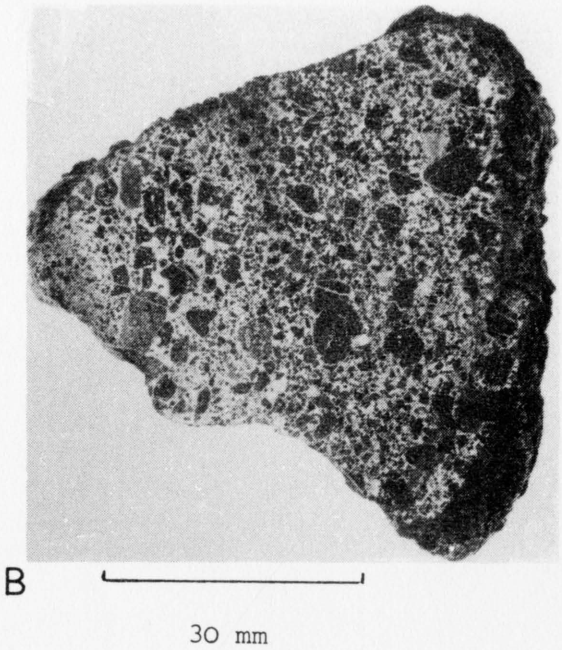
Photomicrograph of deformed vesicular lapilli from the coarse tuff of Plate 13; Fig.D. Large lapilli and abundant shards set in a calcitised matrix with analcite.

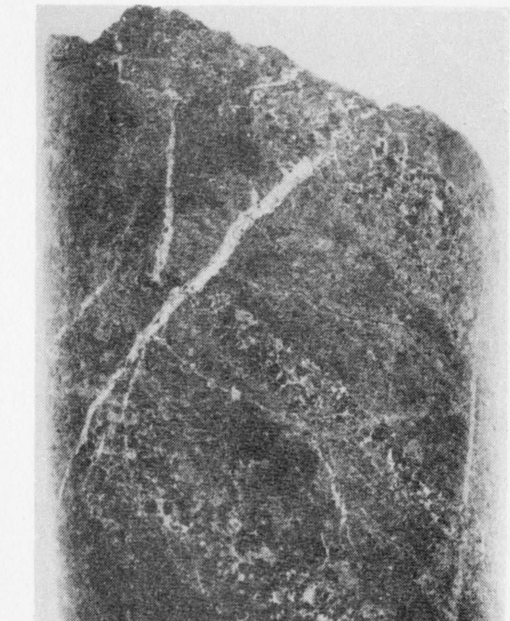
Plate 14, Fig.B.

Photomicrograph of highly fragmented and devitrified tuff. Devitrified shards now replaced by chlorite set in a matrix of recrystallised calcite and analcite. Locality: as Plate 13; Fig.C.

Plate 13







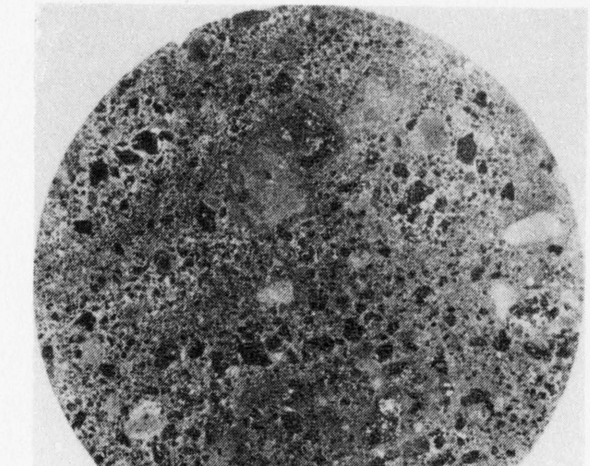
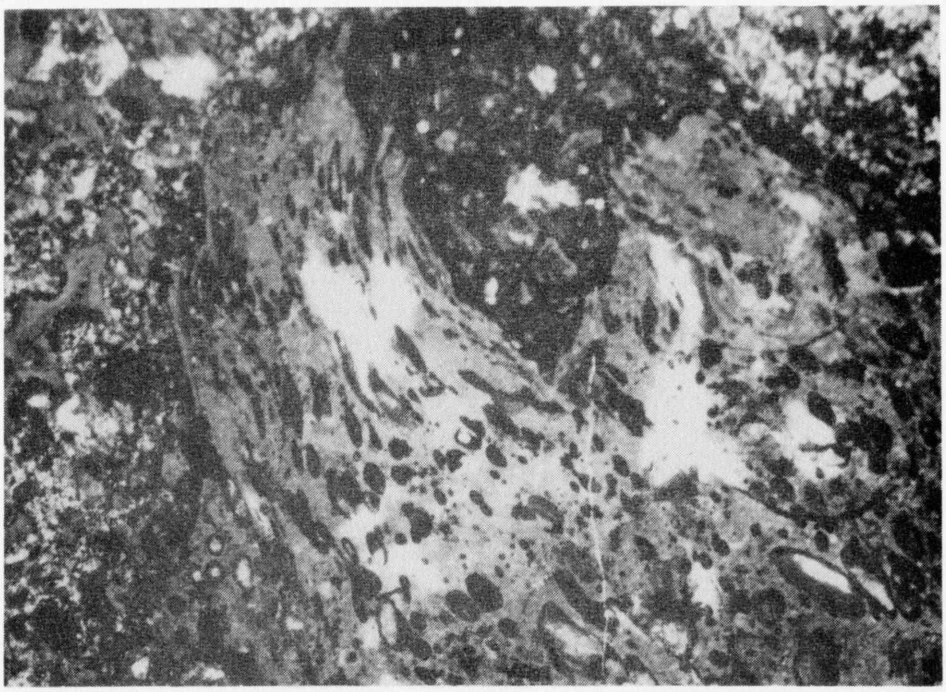


Plate 14



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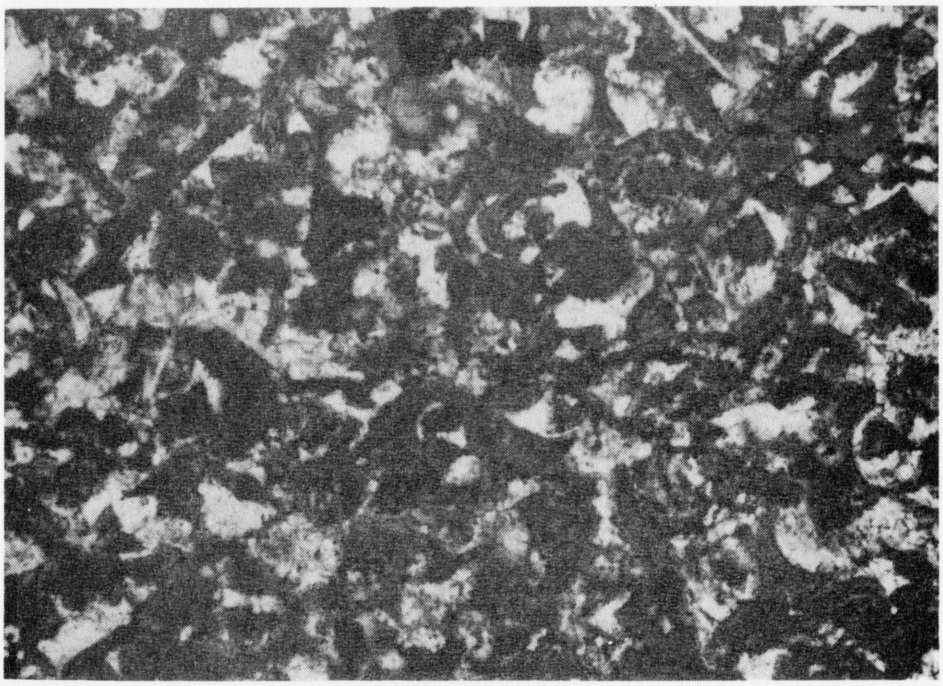


B

THE PETROGRAPHY AND GEOCHEMISTRY OF THE POTLUCK SILL, DERBYSHIRE, ENGLAND

by

P. R. Ineson and R. A. Ixer

Summary

The Potluck Sill is one of three sills that outcrop in northern Derbyshire. It is an ophitic olivine dolerite. Mineralogical determinations have shown the composition of olivine to range from $Fo_{72}-Fo_{63}$, plagioclase to range from $An_{65}-An_{45}$ and augite to range from $Mg_{44-40}\ Fe_{24-11}\ Ca_{45-34}$. Other major primary minerals include titanomagnetite and ilmenite. Minor amounts of analcime, natrolite, aluminous chromite, pyrite and chalcopyrite are present. Clays of the smectite group are the most important product of alteration of the ferromagnesian minerals. New geochemical data show there to be little variation in the 'unaltered' sill.

Introduction

A number of olivine dolerite sills are intruded into the Carboniferous Limestone of the South Pennines. These include the Bonsall and Ible Sills in the southern half of the South Pennines and the more numerous sills of the northern half that include the Potluck, Peak Forest, Mount Pleasant, Tideswell Dale and Waterswallows Sills (text-fig. 1).

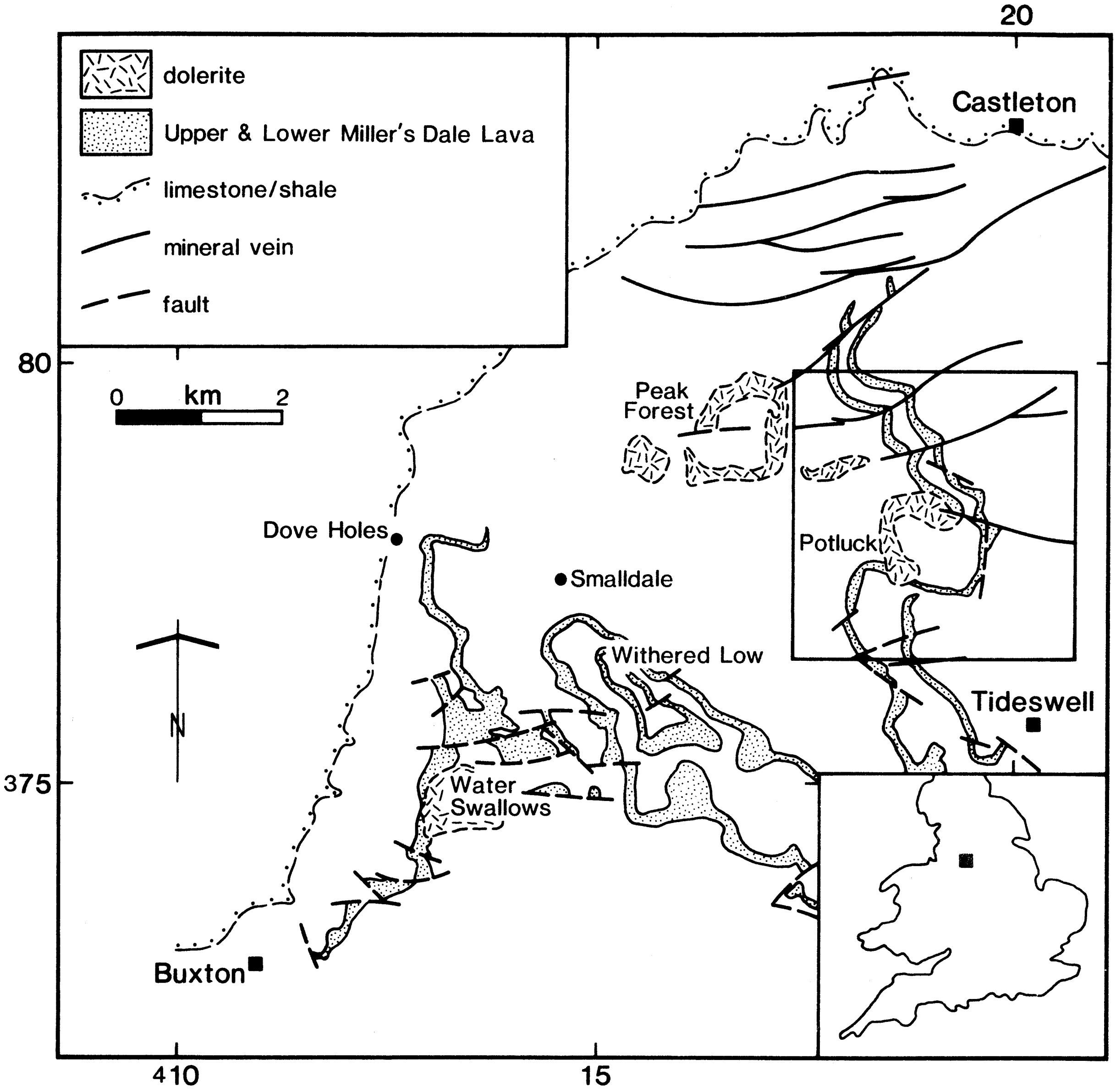
The Potluck Sill occupies part of Tideswell Moor (south of Castleton) (text-fig. 2) and is close to two other sills, i.e. the larger Peak Forest and the smaller Mount Pleasant Sill. Exposures of the sill are very poor, with the major surface occurrence being at Pittle Mere (SK 13647833). There are no clear contacts between the sill and the surrounding limestones and lavas. The main evidence of its extent is to be found in outcrop and mine dump debris as well as in auger material. Although the area of the sill, which is of the order of 0.5 km^2, can be estimated fairly easily there is some uncertainty about its thickness. Green *et al.* (1887) reported a minimum thickness of 600 ft (183m) of 'toadstone' at Black Hillock Shaft (SK 14107822) but Stevenson and Gaunt (1971) suggested that the shaft followed a feeder to the sill and hence was unrepresentative. Walters and Ineson (1980) indicated that where Tideslow Rake has intersected the sill, the dolerite is present to a depth of 146.3m.

Arnold-Bemrose (1894; 1907) identified the sill as an ophitic olivine dolerite and described in detail the alteration of the olivine (1894, p.613-20). More recently, Stevenson and Gaunt (1971) described the sill as being a coarse ophitic olivine dolerite comprising phenocrysts of altered forsterite-rich olivine and calcic plagioclase set in a groundmass of labradorite ($An_{63}\ Ab_{37}$) and augite with accessory orthopyroxene, ilmenite and magnetite. Walters and Ineson (1980) have described the hydrothermal alteration of the sill that has converted the dolerite to a 'white rock' similar to the White Whin of the North Pennines and consisting of kaolinite, calcite and albite.

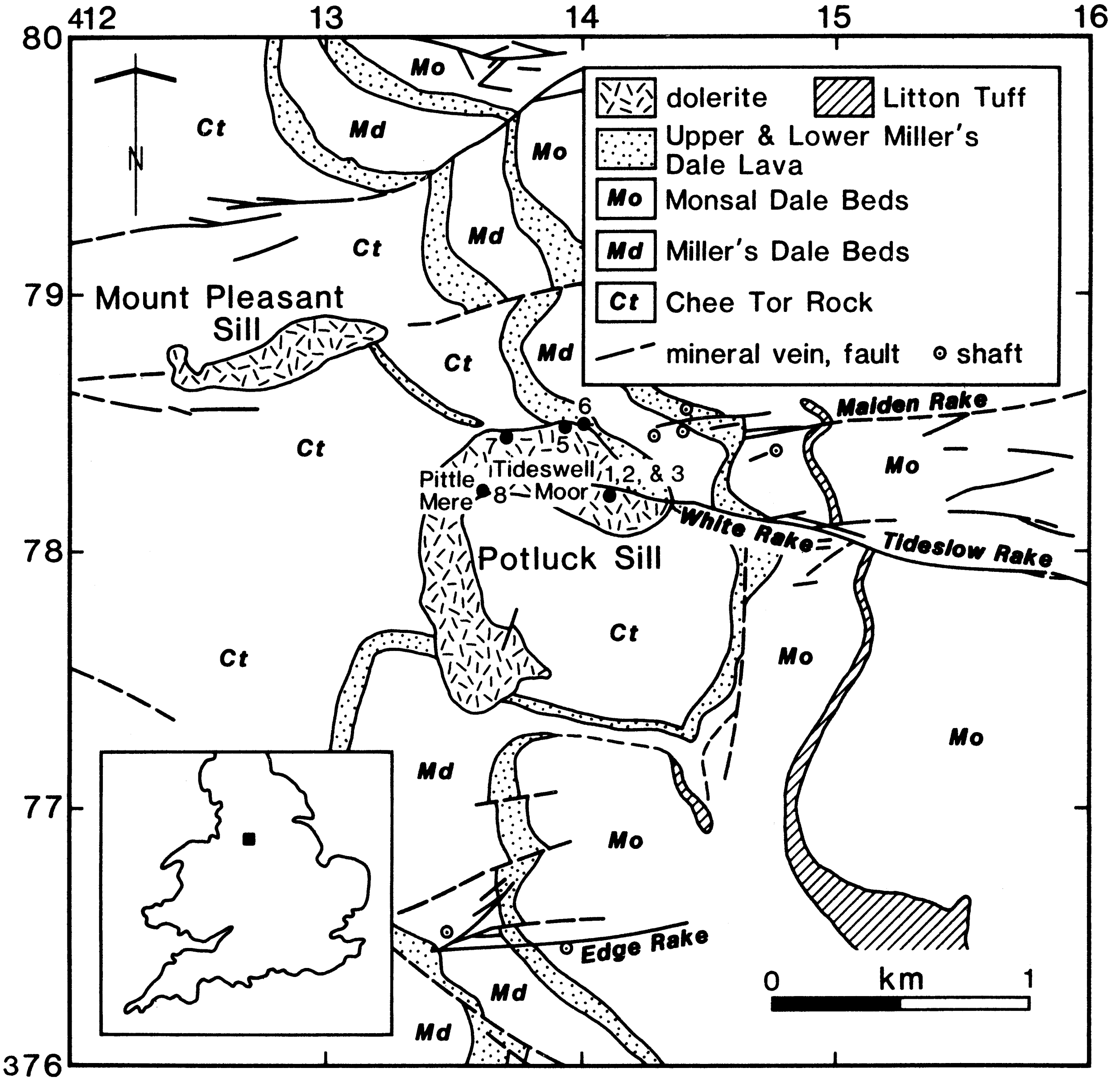
The present study of the Potluck Sill which incorporates mineralogical, petrographical and geochemical studies forms part of a more comprehensive study of the igneous activity of the South Pennines.

Techniques

Hand specimens of the Potluck Sill were collected to include all the various rock types. Most of the specimens were, however, from loose boulders. Multiple thin sections and one polished section of each specimen were prepared for petrographical studies using transmitted and reflected light. These techniques were supplemented by X-ray diffraction analysis which assisted in the identification of some of the secondary minerals.



Text-fig.1 Sketch map of the northern dolerite sills of Derbyshire.



Text-fig.2 Sketch map of the Potluck Sill

Electron probe microanalyses were made of some of the primary silicates and to positively identify the alteration products of the olivine. X-ray fluorescence analysis was used to analyse the material for both major and minor elements.

Petrography

In common with other Derbyshire sills, the Potluck Sill displays a number of different doleritic textures, which include the coarse ophitic dolerite described by Stevenson and Gaunt (1971) (plate15, fig. A); subophitic dolerites, and finer grained dolerites with an intergranular texture of clinopyroxene and plagioclase. Although no distinctive marginal facies of the sill is seen, a finer dolerite occurs at (SK 13777850) (Samples PL 71 & PL 72) close to the northern boundary of the intrusion. This dolerite has some petrological differences from the main dolerite. In hand specimen this dolerite is a dark blue-green fine grained rock with dark green phenocrysts of olivine or its pseudomorphs up to 3mm in length. No other phenocrysts are visible to the naked eye nor are amygdales seen. Weathering of the dolerite produces a 1-3mm thick brown limonitic crust.

The ophitic dolerite comprises olivine and rare plagioclase phenocrysts (1-3mm in length) set in a medium to coarse grained groundmass of unoriented plagioclase laths up to 1mm in length and ophitic plates of augite up to 3mm diameter. In the intergranular dolerite similar size olivine and plagioclase phenocrysts (1-3mm in length) are set in a groundmass of small plagioclase laths and subhedral augite crystals. Modal analysis for the dolerite types are given in table 1.

Table 1 Modal analyses of the Potluck Sill

	A	PL1	PL2	PL52	PL51	PL62	PL61	PL72	PL71	PL81	PL82
Olivine	1.1	4.08	0.00	3.1	1.9	2.4	6.6	0.8	1.3	1.9	3.0
Olivine Pseudomorphs	6.8	13.82	22.07	14.6	16.3	9.5	15.0	17.0	15.1	14.1	14.4
Augite	18.3	19.11	18.55	20.5	22.1	21.8	19.4	21.6	22.7	22.3	19.9
Plagioclase Laths	67.8	36.15	24.25	23.6	26.1	23.5	31.9	25.6	23.4	22.7	27.0
Altered Plagioclase Laths		1.64	2.19	3.0		2.0		4.1		1.7	
Plagioclase Groundmass		12.78	20.27	19.7	26.7	26.0	20.5	18.0	27.9	24.8	29.3
Altered Plagioclase Groundmass		7.12	4.85	7.0		6.5		7.2		4.0	
Opaques	1.5	3.35	5.00	3.6	4.0	7.0	3.4	2.1	3.2	3.9	3.5
Clay Matrix	4.5	1.89	2.19	1.8	2.3	1.1	3.0	1.7	4.4	2.4	2.1
Analcime	-	0.06	0.16	1.3	0.7	0.1	0.2	1.7	1.6	1.0	0.6
Thompsonite	-	-	-	0.9	-	0.1	-	-	0.2	-	0.2
Natrolite	-	-	-	1.0	-	0.1	-	-	0.3	0.7	0.1
Amphibole	-	-	-	-	-	-	0.1	-	0.1	-	-
Biotite	-	-	0.47	-	-	0.1	-	-	-	-	-
Calcite Veins	-	-	-	-	-	-	-	-	-	0.4	-
Limonite Veins	-	-	-	-	-	-	-	-	-	0.3	-
Counts		1640	1280	1150	1240	1200	1230	1200	1160	1140	1150

A — Stevenson and Gaunt (1971)

PL.1 & PL.2	SK 14107820	PL.71 & 72	SK 13777850
PL.51 & 52	SK 13937842	PL.81 & 82	SK 13657834
PL.61 & 62	SK 13947845		

Olivine occurs as euhedral to subhedral phenocrysts (up to 3mm in length) or as collections of smaller subhedral crystals (up to 2.5mm in diameter) associated with augite. These phenocrysts of olivine are often very altered. Finer grained olivine (up to 0.1mm in length) is totally pseudomorphed. Relict fresh phenocrystic olivine has a large 2V ($2V_\gamma \approx 90$) that suggests a composition close to the Mg end member forsterite (Stevenson & Gaunt, 1971) and similar in composition to the olivines from other Derbyshire Sills, notably Bonsall Sill (Smith *et al.*, 1967). Electron probe microanalyses, however, indicate that the relict fresh olivine has compositions that range from $Fo_{63}Fa_{37}$ to $Fo_{72}Fa_{28}$; but that mainly lie close to $Fo_{68}Fa_{32}$ (table 2).

Table 2 Electron microprobe data for Potluck pyroxenes and olivines

	1	2	3	4	5	6	7	8	9
	Pyroxenes				Olivines				
SiO_2	51.7	51.5	49.8	50.8	37.9	38.1	38.0	38.7	37.1
TiO_2	1.3	1.0	1.4	1.6	-	-	-	-	-
Al_2O_3	1.7	3.0	2.1	2.4	-	-	-	-	-
FeO	10.0	6.8	10.0	9.3	27.6	31.5	28.1	24.9	29.0
MnO	0.2	0.1	0.2	0.2	0.4	0.5	0.4	0.3	0.4
MgO	14.3	14.9	13.6	14.1	34.1	29.8	34.0	36.9	33.9
CaO	20.2	21.1	20.6	21.0	0.3	0.2	0.3	0.3	0.3
Na_2O	0.4	0.4	0.5	0.4	-	-	-	-	-
Cr_2O_3	-	0.6	-	0.1	-	-	-	-	-
NiO_2	-	-	-	-	0.2	0.1	0.1	0.2	0.2
Total	99.8	99.4	98.2	99.9	100.5	100.2	100.9	101.3	100.9
	Number of ions on the basis of 6 oxygen (pyroxenes)/4 oxygens (olivines)								
si	1.936	1.914	1.014	1.904	1.007	1.032	1.007	1.007	1.005
Ti	0.035	0.028	0.041	0.044	-	-	-	-	-
Al	0.076	0.130	0.098	0.107	-	-	-	-	-
Fe	0.313	0.212	0.320	0.291	0.614	0.715	0.623	0.541	0.638
Mg	0.797	0.825	0.775	0.787	1.353	1.202	1.346	1.428	1.333
Ca	0.812	0.838	0.844	0.845	0.008	0.007	0.008	0.007	0.007
Na	0.026	0.029	0.036	0.027	-	-	-	-	-
Mn	0.008	0.005	0.008	0.007	0.008	0.011	0.008	0.007	0.010
Cr	-	0.017	-	0.002	-	-	-	-	-
Ni	-	-	-	-	0.003	0.003	0.002	0.004	0.003
	Atomic Ratios								
Mg	42.0	44.0	40.0	41.0	69.0	63.0	68.0	72.0	68.0
Fe	24.0	11.0	16.0	15.0	31.0	37.0	32.0	28.0	32.0
Ca	34.0	45.0	44.0	44.0	-	-	-	-	-

Samples 1-4: Individual Ophitic Pyroxenes Samples 5-9: Individual Olivines in Relict Microphenocrysts
Potluck Sill coarse ophitic dolerite PL1 Black Hillock Mine (SK 141782)

Typically, olivine encloses 10–40μm rounded to euhedral crystals of a spinel that semiquantitative analyses show to be an aluminous chromite. The spinel shows zoning with a lighter reddish-brown margin of magnetite up to 10μm in width. The chromite is randomly distributed throughout the olivine crystals but often occurs as collections of five or six crystals. Even when the olivine is totally replaced the enclosed chromite remains unaltered.

Plagioclase feldspar is found as large phenocrysts, as unoriented lath-shaped crystals and as coarser groundmass plates. Knots of plagioclase phenocrysts, in total up to 1.5–2mm in length, consist of four or five equant crystals that characteristically display complex multiple twinning and some zoning. The cores of the phenocrysts show a fine grained myrmekitic intergrowth with augite that appears to have an ophitic relationship with the plagioclase. In addition the plagioclase carrys inclusions of ilmenite (20–60μm) and more abundant skeletal crystals of titanomagnetite (20–100μm in diameter) that themselves contain ilmenite lamellae. The phenocrysts show zoning and this is especially well seen in their inclusion-free 100–200μm wide margins. Although many phenocrysts have sharp edges some show strong resorbtion as do similar phenocrysts from the nearby Mount Pleasant Sill. However, much of the plagioclase occurs as unoriented lath-shaped (0.1–0.6mm in length) twinned but poorly zoned crystals. Although there is a compositional range from $An_{45}-An_{65}$ most laths have a composition of $An_{58}-An_{62}$ that is similar to the value of An_{63} given by Stevenson and Gaunt (1971). The most calcic labradorite ($An_{65}Ab_{35}$) occurs as lath-shaped inclusions within the plagioclase phenocrysts. Alteration of the labradorite laths is variable but typically the cores of the feldspar are replaced leaving fresh margins. A later feldspar occurs as coarser plates 0.2–0.8mm across, it is strongly zoned and is simply twinned and has lower refractive indices than the labradorite laths. It is often intensely altered to green clay minerals, analcime and zeolite minerals, with the alteration having been initiated along the feldspar cleavage.

Augite occurs as ophitic crystals up to 3mm across, as phenocrysts up to 1mm across or as microphenocrysts 0.25mm long that often surround olivine phenocrysts. In one section a 1mm diameter gas-bubble is infilled with euhedral augite crystals which have an equant habit in the centre surrounded by radiating prismatic pyroxenes. The augite is pale pink in colour, very faintly zoned, and weakly pleochroic. Electron probe microanalyses (table 2) show the ophitic pyroxene to be augite but with significant amounts of Na and Ti. The analyses are very similar to those given for the diopside-titanaugites from igneous rocks of the Duffield borehole (Harrison, 1977). Minor amounts of othopyroxene have been reported as an accessory mineral (Stevenson & Gaunt, 1971).

Trace amounts of a red-brown rhombic amphibole are associated with laths of ilmenite. The amphibole is possible a Ti-rich barkevikite or kaersutite. In addition zircon and biotite occur in minute amounts within the coarse plagioclase plates.

Ilmenite is the most common opaque mineral. It forms lobate laths that range in size from 60×5μm up to 1mm in length. The laths are intergrown with pyroxene and labradorite crystals, and often enclosed within a narrow rim of titanomagnetite 5 – 10μm in width. Lesser amounts of ilmenite occur as 40 – 100μm equant crystals, as small cores (10 – 20μm) to euhedral magnetite crystals (40 – 200μm) or as irregular patches up to 60μm in diameter of blebby ilmenite. The ilmenite is generally very fresh with only a little alteration to rutile along the edges of the laths or as 5 – 20μm patches.

Titanomagnetite like the ilmenite is intergrown with the pyroxene and feldspar. It forms euhedral octahedral crystals 10 – 100μm in size or larger subhedral crystals (0.2—0.5mm in diameter). Many crystals have a core of ilmenite or contain thin ilmenite lamellae (1 – 2μm in width) oriented along the (111) planes of the host titanomagnetite. Magnetite crystals from the unusual fine-grained facies of the dolerite (PL7) are distinctive in that they show distinct but gradual zoning, with a core of grey spinel (10 – 15μm in diameter) surrounded by magnetite 20μm in width and finally with small 5μm long ilmenite laths. These crystals occur intergrown with pyroxene and are not found in the olivine crystals. All specimens of the dolerite have a generation of magnetite that occurs as poorly crystalline aggregates (30 – 100μm in diameter) of individuals 2 – 5μm in size. These aggregates occur about ilmenite laths or are isolated in the groundmass. The individual magnetite grains are cemented by chalcopyrite and lesser amounts of bornite together with traces of pyrite. Typically the magnetite has totally oxidized to haematite. The main generation of magnetite is commonly oxidized to blue haematite (although the martite texture is absent) or less commonly to rutile as small 2 – 3μm patches or to sphene as 5 – 10μm wide rims.

Although the Potluck Sill is one of the least altered dolerites of the South Pennines it has undergone alteration with the growth of a number of new minerals including clays, zeolites and sulphides. Primary olivine is intensely altered and so too is plagioclase feldspar (most notably the platey groundmass feldspar) and titanomagnetite, whereas clinopyroxene and ilmenite are largely unaltered. (see plate15, figs. B & C and plate16, fig. A).

Arnold-Bemrose (1894) distinguished two types of alteration of the olivine phenocrysts which he called 'Potluck pseudomorphs' and 'Peak Forest types'. The former included red and green alteration products that were optically homogeneous and pleochroic and the latter green products that were homogenous, fibrous and often yellow-green in colour. He noted that both types were found in the same specimen and that the material was 'mica-like'. A detailed investigation of this material by Walters (1981), has shown it to be an Fe-rich nontronite (a variety of smectite-clay) and his results are given in table 3 together with other analyses of comparable material.

This smectite is itself replaced by calcite and/or silica in the more altered specimens of the sill. The carbonate has an iron stained rim that may reflect the original iron content of the previous smectite. In addition, small grains of chalcopyrite and pyrite (1 – 4μm) occur in the very centre of the altered fractures that typically cut across the olivine crystals, and very thin fibres ≤ 1μm wide of chalcopyrite lie in parallel with the clay minerals.

Clay minerals, (the chlorite of Arnold-Bemrose (1894) and Stevenson and Gaunt (1971)) analcime and zeolite group minerals are found in the interstitial areas bounded by plagioclase laths and augite crystals. These minerals may represent a late stage residual product of the melt or the alteration of such products. Such a late stage occurrence of analcime and zeolites together with alkali feldspar and sodic pyroxene is common in the teschenites of the West Midlands for example the intrusion of Pouk Hill (Ixer, 1981), and from the Duffield Sill (Harrison, 1977). However the small amounts of analcime and zeolite (as shown by the modal analyses in table 1), the absence of accompanying alkali feldspars and pyroxenes, and the textural evidence showing that the secondary minerals replace the platey plagioclase feldspars, all suggest that these minerals are the products of alteration.

Although both X-ray diffraction of the whole rock samples and electron probe microanalysis of the olivine pseudomorphs both suggest that smectite clays are the most dominant group, both illite group clay and kaolinite are present. Walters and Ineson (1983b) suggest that this dominance of smectite is a characteristic of all the basalts and dolerites of the South Pennines except for a few unusual examples. The clays are light to dark green or yellow and fibrous to vermicular and characteristically form a thin rim (20μm wide) enclosing analcime or zeolites.

Table 3 Electron microprobe analysis of smectite in the Potluck Sill and comparable analyses

	1	2	3	4	5	6	7
SiO_2	42.8	45.7	43.05	39.11	46.83	43.98	45.12
TiO_2	-	-	-	0.18	0.64	0.16	0.23
Al_2O_3	4.1	4.0	6.40	3.29	8.92	10.15	5.13
Fe_2O_3	-	-	17.86	31.49	7.87	7.85	11.14
FeO	28.9*	28.3*	0.10	0.96	4.88	5.32	4.77
MgO	7.9	8.3	4.46	8.05	11.08	18.02	17.06
CaO	2.0	1.9	2.92	2.28	2.78	2.78	0.21
Na_2O	0.1	0.1	-	-	1.71	-	2.68
K_2O	-	-	-	-	1.93	-	0.85
H_2O^+	14.2**	11.7**	29.93	16.27	5.39	9.24	13.60
H_2O^-					6.81	6.24	
Total	100.0*	100.0**	104.72	101.63	98.84	103.74	100.79

1. and 2: Microprobe analyses, red pleochroic alterations of olivine—Potluck Sill (Walters, 1981). (PL.1. SK141782).

3. Fe-rich nontronite in altered basalt (Weaver & Pollard, 1973).

4. Average of five 'iddingsite' analyses (Ross & Shannon, 1925).

5. Mixed nontronite/saponite infilling vesicle in basalt (Scheidegger & Stakes, 1977).

6. Saponite in altered basalt (Weaver & Pollard, 1973).

7. Saponite in altered basalt (Seyfried *et al.*, 1978).

* Total iron as FeO

** Total H_2O calculated by subtraction of other oxides from 100%, may include small but significant values of TiO_2 and K_2O.

Analcime is anhedral to euhedral and often more abundant than the zeolites. It occurs as small rounded amygdales 100–200μm in diameter, as interstitial infilling, as thin veinlets or together with the other secondary minerals it replaces plagioclase. Some analcime looks altered and is cut by calcite veinlets. The presence of analcime in the intrusive rocks of the South Pennines has previously been noted by Tomkeieff (1928) from Calton Hill, and by Ixer (1972) from the Bonsall Sill. Its occurrence in the Potluck Sill together with the recognition of analcime-bearing amygdules (up to 1mm in diameter) from Peak Forest suggests it to be a widespread but minor component of the intrusive rocks. All optical identifications of analcime were confirmed by X-ray diffraction work (see plate16, figs. B & C).

Two types of zeolites occur, often together with analcime and enclosed within a thin rim of clay minerals. The earlier zeolite is clear, has a R.I. close to 1.540, first order birefringence and a radiating acicular habit. The properties are similar to those of thompsonite (but also of chalcedony). The second zeolite also has a radiating habit of more tabular crystals, and is natrolite. Zeolites are previously unrecorded from the South Pennine intrusive rocks and the present study could only recognise natrolite from the nearby Peak Forest Sill in addition to its presence in the Potluck Sill.

Very minor quantities of sulphides are present in the dolerites. The most abundant is chalcopyrite, with pyrite being locally common. Chalcopyrite occurs associated with the alteration of olivine, cementing the aggregates of late spongy magnetite or as small (2–40μm) subhedral to euhedral crystals that often rim ilmenite and magnetite. Chalcopyrite is found associated with bornite and idaite and is altered to rims of bornite, idaite or covelline and is oxidized to limonite. Bornite and idaite (2–3μm) are intergrown with the chalcopyrite that cements the magnetite, both occur as thin veinlets cementing fractured pyrite and both are altered to covelline.

Pyrite too is found in minor amounts except for the specimens PL71 & PL72 where it is the most abundant sulphide. Usually, pyrite forms small crystals up to 5µm in size within olivine pseudomorphs, or as 5–20µm in diameter cubes, it is enclosed in chalcopyrite. In PL71 however, larger 10–100µm diameter skeletal crystals are common and reach a maximum size of 350µm. These crystals enclose magnetite. The crystals are often fractured and are healed by bornite and idaite. Pyrite is extensively oxidized to limonite.

Weathering of the dolerites has had little effect. It has oxidized the sulphides to limonite and limonitically stained the silicate minerals.

Geochemistry

Very few geochemical data have been published on the olivine dolerite intrusive rocks of the South Pennines and this is in contrast to the more abundant data on the more alkaline intrusives of both the West Midlands and the East Midlands Coalfields.

Table 4 presents six new analyses of the Potluck Sill together with one of the highly altered bleached sill from Black Hillock Mine. Table 5 presents the CIPW norms for the six fresher specimens. These six analyses show there to be little significant variation in both major and minor element chemistry and this reflects the petrographical similarity of the specimens. There is however a slight difference between specimens PL 1 and 2 and specimens PL 5 and 8, in that the former two have slightly higher SiO_2, Al_2O_3 and K_2O contents and have quartz in their norms whereas the latter four have olivine.

More obvious trends can be seen when the bleached dolerite PL3 is compared to the fresher dolerites. The extreme alteration of the dolerite is seen to be accompanied by a substantial loss of total iron and MgO; significant loss of SiO_2, Al_2O_3 and Na_2O and by some reduction of TiO_2, MnO and P_2O_5. There is however, a dramatic increase in CaO and CO_2 and some increase in K_2O and total water. This change in major element chemistry reflects the change to the new minerology of the bleached sill which is calcite and quartz accompanied by kaolinite, smectite and albite. The trace elements show a general reduction and this is especially true for Ba, Sr, Co, Ni, Cu and Zn.

Only Cr shows a slight reduction and this is seen petrographically by the continued presence of chromite within calcite pseudomorphs after olivine.

Similar geochemical trends were reported from the hydrothermally altered Whin Sill (the Black Whin altering to White Whin) by Wager (1929) and Ineson (1968). In addition, the mineralogy of the North Pennines White Whin and the altered Potluck Sill are similar with carbonation and albitization being very important in both. However, the clay mineralogy is different, with illite-kaolinite occurring in the White Whin and kaolinite-smectite in Potluck. This variation may reflect the interstitial orthoclase in the unaltered Whin Sill (Dunham & Kay, 1965) as opposed to smectites at Potluck.

Conclusions

The present petrological study of the Potluck Sill, has confirmed that the sill is composed of olivine-dolerite. Detailed mineralogical studies of the primary silicates show the clinopyroxene to be augite that is less titaniferous ($TiO_2 < 1.6$ wt.%) than its optics might indicate. Similarly the relict olivine analyses show that the olivine is more fayalitic ($Fa_{28} - Fa_{37}$) than previous optical determinations have suggested (Stevenson & Gaunt 1971). The primary opaque mineralogy is a simple one of titanomagnetite, ilmenite and chromite, with haematite and copper and iron sulphides as common secondary minerals.

The later mineralogy is more complex and consists of clay minerals, zeolites and analcime, with average modal amounts of 2.9% clay ('chlorite') 1.0% analcime and 0.2–0.3% zeolites. The presence of analcime from Potluck Sill and nearby Peak Forest Sill and its known occurrence from Bonsall Sill and Calton Hill suggests that it may be a common accessory mineral for the olivine dolerites. The occurrence of natrolite has only been recorded from Potluck and Peak Forest Sills. The greater abundance of analcime than has previously been supposed suggests closer similarities to the more alkaline dolerites that surround Derbyshire. However, the occurrence of late stage alkaline pyroxene, amphibole and feldspars that are typical of the alkaline dolerites appears to be absent from Potluck Sill. The geochemistry shows that the 'fresh' olivine dolerites all have very similar major and minor element abundances, and no clear indication of any differentiation trends could be seen in the limited material available. With extreme alteration, the olivine dolerite is converted to a rock that approximates to an impure limestone that is similar to the alteration of the 'Black Whin' to 'White Whin' of the northern Pennines.

Table 4 Chemical analyses of the Potluck Sill

	PL 1	PL 2	PL 3	PL 5	PL 6	PL 7	PL 8
SiO_2	48.74	48.62	40.31	47.47	47.24	47.60	47.39
TiO_2	1.86	1.89	1.43	1.77	1.88	1.72	1.68
Al_2O_3	14.73	15.17	10.51	13.86	13.79	13.75	13.78
Fe_2O_3	4.21	4.17	0.71	4.04	2.80	3.86	3.80
FeO	6.58	5.32	0.32	7.55	8.59	7.66	7.82
MnO	0.17	0.12	0.10	0.18	0.17	0.17	0.18
MgO	8.09	6.65	0.52	9.42	9.98	9.30	9.57
CaO	8.94	9.68	22.96	8.24	8.55	8.05	8.52
Na_2O	2.67	3.00	0.78	2.94	2.52	2.80	2.80
K_2O	0.80	0.86	0.89	0.71	0.68	0.71	0.64
H_2O^+	2.43	2.30	3.26	3.29	3.10	3.20	3.40
H_2O^-	0.95	1.54	0.49	-	-	-	-
P_2O_5	0.30	0.30	0.21	0.25	0.26	0.24	0.23
CO_2	0.13	0.57	18.32	0.62	0.11	0.05	0.13
SO_3	0.04	0.04	0.28	-	-	-	-
Total	100.64	100.23	101.09	100.34	99.67	99.11	99.94
Ba	285	259	82	223	207	294	269
Co	88	81	32	-	-	-	-
Cr	303	379	293	353	366	349	348
Cu	80	86	15	85	84	77	98
Ni	219	275	50	224	245	231	240
Pb	17	7	6	6	10	9	10
Rb	17	15	9	23	16	17	20
Sr	358	402	100	409	310	290	342
V	175	196	155	206	197	204	196
Y	30	25	19	23	22	26	22
Zn	97	74	6	102	95	96	103
Zr	133	130	88	111	109	105	103

Samples: 1 Potluck Sill coarse ophitic dolerite
Black Hillock Mine—SK 141782 (Waters 1981)
2 Potluck Sill, ophitic dolerite from Black Hillock Mine. (Walters 1981)
3 Potluck Sill, altered dolerite (bleached white) with calcite, kaolinite and albite. Black Hillock Mine. (Walters 1981)

Samples: 5 SK 13937842
6 SK 13947845
7 SK 13777850
8 SK 13657834

Table 5 C.I.P.W. norms of the Potluck Sill.

		PL1	PL2	PL5	PL6	PL7	PL8
Q		0.87	1.11	-	-	-	-
Or		4.73	5.08	4.20	4.02	4.20	3.78
Ab		22.59	25.39	24.88	21.32	23.69	23.69
An		25.85	25.39	22.53	24.31	22.85	23.14
Di	(Wo	6.91	8.63	6.98	6.85	6.48	7.36
	(En	4.95	6.53	4.84	4.50	4.43	5.01
	(Fs	1.34	1.23	1.57	1.87	1.54	1.78
Hy	(En	15.20	10.04	10.05	11.08	13.05	10.24
	(Fs	4.11	1.89	3.26	4.61	4.53	3.63
Ol	(Fo	-	-	6.00	6.51	3.99	6.02
	(Fa	-	-	2.14	2.99	1.52	2.35
Mt		6.10	6.05	5.86	4.06	5.60	5.51
Il		3.53	3.59	3.36	3.57	3.27	3.19
Ap		0.70	0.70	0.58	0.60	0.56	0.54
Py		0.08	0.08	-	-	-	-
Total		96.96	95.71	96.25	96.29	95.71	96.24

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P. R. Ineson, Ph.D., C.Eng., MIMM, FGS
Department of Geology,
University of Sheffield.

R. A. Ixer, Ph.D.
Department of Geological Sciences,
University of Aston in Birmingham.

Explanation of plates 15 and 16

Plate 15, Fig. A.

Typical ophitic dolerite texture shown in the Potluck Sill. Smectite pseudomorphs after olivine (dark areas) occur in a coarse groundmass of un-orientated plagioclase and ophitic plates of augite up to 3mm in diameter. Plane polarised light. Black Hillock Mine Shaft (SK 14107822).

Plate 15, Fig. B.

Calcitised and albitised Potluck Sill dolerite with veining. The relict textures of the coarse ophitic dolerite (Plate No.15, fig. A) are preserved, dark areas represent coarse carbonate replacement of olivine phenocryst pseudomorphs. Pittle Meer (SK 13647833).

Plate 15, Fig. C.

A plagioclase phenocryst showing a core that contains abundant augite (dark grey) and iron-titanium oxides (black) and is surrounded by an inclusion free rim. Cross-polars. Spec. PL.81 (Table 1).

Plate 16, Fig. A.

Radiating prismatic augite crystals within fine grained dolerite that shows altered olivine microphenocrysts and an intergranular texture of plagioclase laths and augite. Cross-polars. Spec. PL.51 (Table 1).

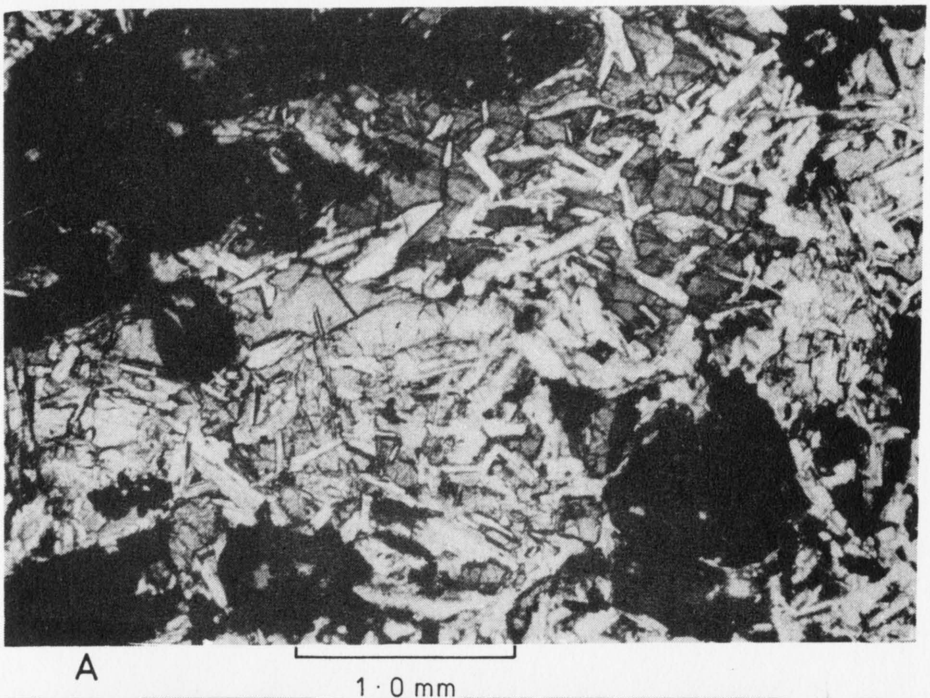
Plate 16, Fig. B.

Interstitial analcime (right, colourless) and fibrous zeolite (left grey) together with groundmass plagioclase (colourless with cleavage). Both the analcine and zeolite have a thin 'chlorite' rim. Plane polarised light. Spec. PL. 71. (Table 1).

Plate 16, Fig. C.

Subophitic dolerite containing an altered olivine pseudomorph (upper left) and rounded analcime (colourless centre). Plane polarised light. Spec. PL 51 (Table 1).

Plate 15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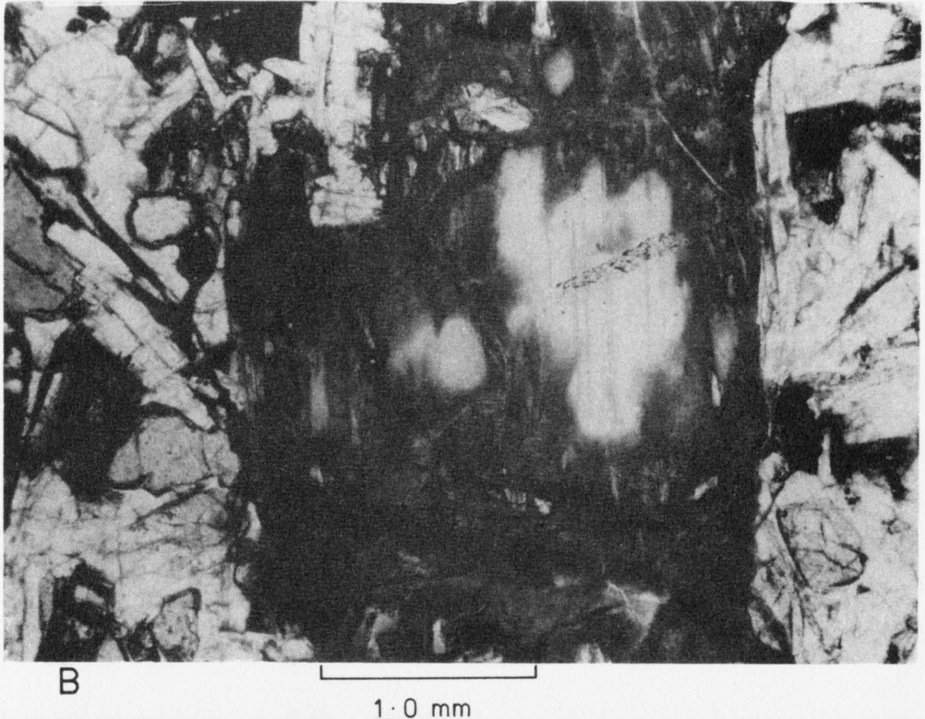
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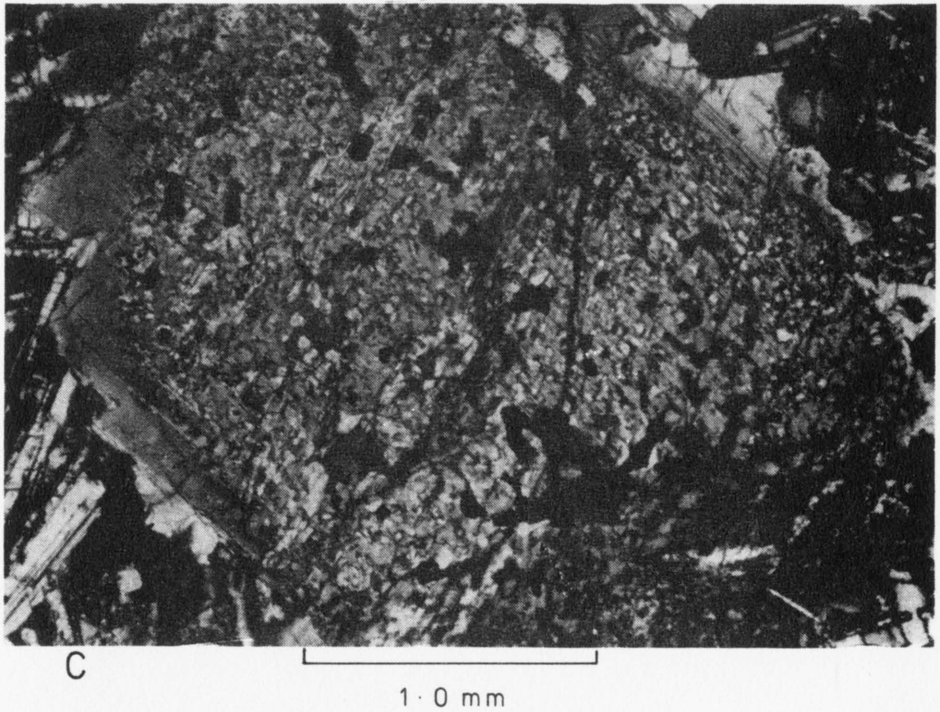
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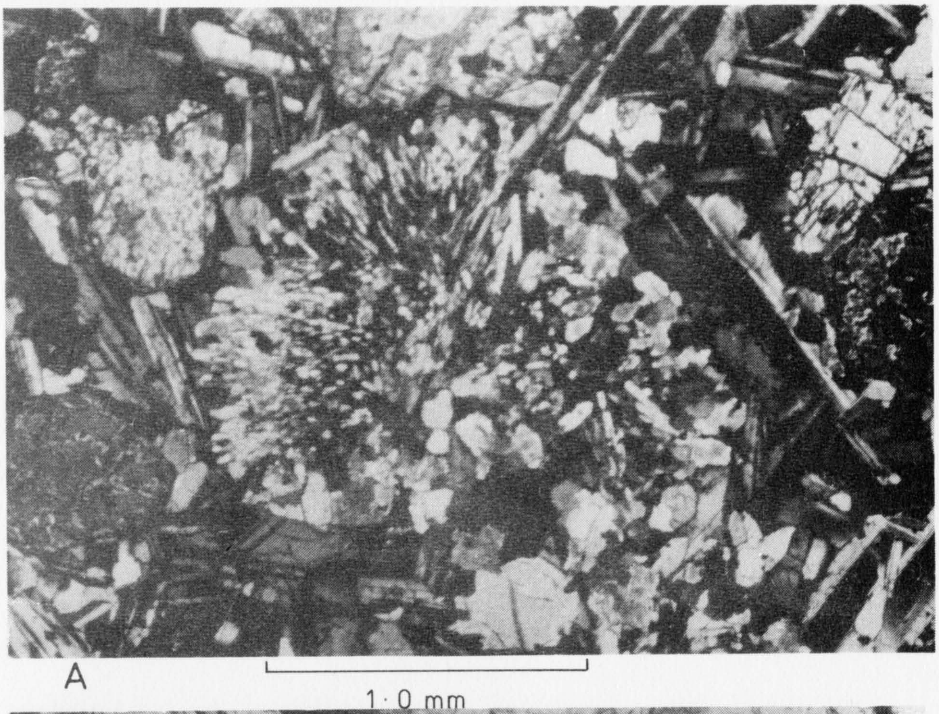
Plate 16



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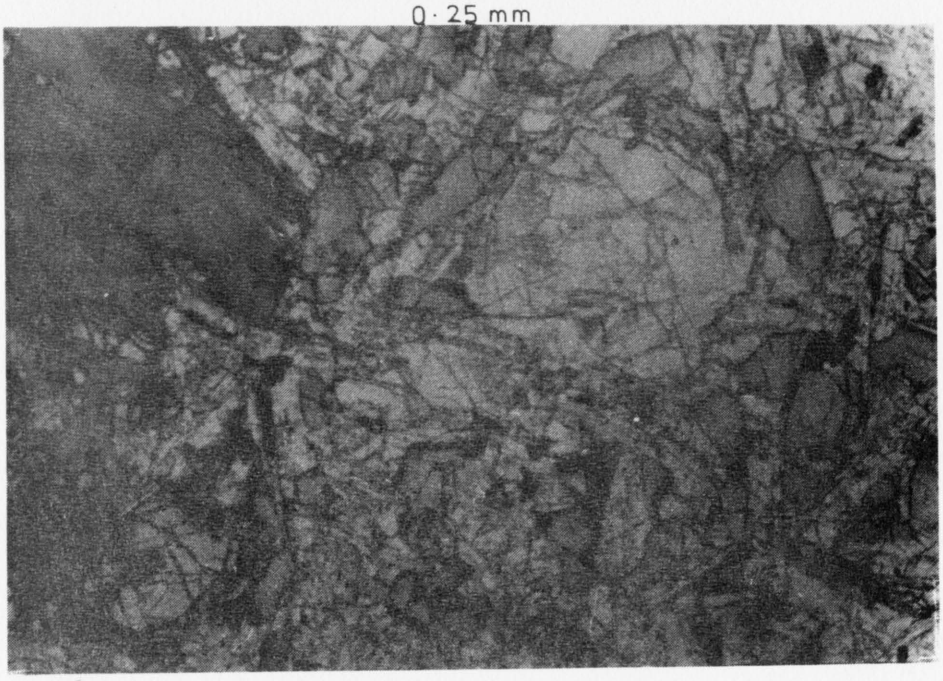

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THE PALYNOLOGY OF THE AALENIAN (MIDDLE JURASSIC) SEDIMENTS OF JACKDAW QUARRY, GLOUCESTERSHIRE, ENGLAND

by

J. B. Riding

Summary

The palynology of fifteen samples from the Naunton Clay, Harford Sands, Snowshill Clay and Tilestone of Jackdaw Quarry, Gloucestershire is outlined. Previous research is reviewed, concentrating particularly on the position of this sequence with respect to the standard ammonite zonation.

Palynological evidence for a minor marine transgression and subsequent regression in the Snowshill Clay is outlined and the biostratigraphic value of the dinoflagellate cysts *Nannoceratopsis ambonis* Drugg 1978 and *N. triceras* Drugg 1978 discussed. Selected taxa are illustrated and full species lists given.

Introduction

Jackdaw Quarry, Stanway Hill, Gloucestershire is an important exposure of rocks of the Aalenian Stage in the southern Midlands. It is the only continuous section described through the Naunton Clay, Harford Sands, Snowshill Clay and Tilestone. Samples from these units generally yielded well-preserved assemblages of palynomorphs.

Palynological techniques have proved invaluable in age-dating and correlation studies, particularly offshore. As a consequence of discoveries of hydrocarbons in the Mesozoic sediments of the north-west European continental shelf there has been a significant upsurge in Mesozoic palynology, yet few detailed records of Aalenian palynomorphs are available. The majority of publications on this topic are concerned with miospores, e.g. Couper (1958). A notable exception is Davey (in Penn *et al.*, 1980), who outlined the distribution of Aalenian and Bajocian microplankton from a borehole in Lyme Bay, Dorset.

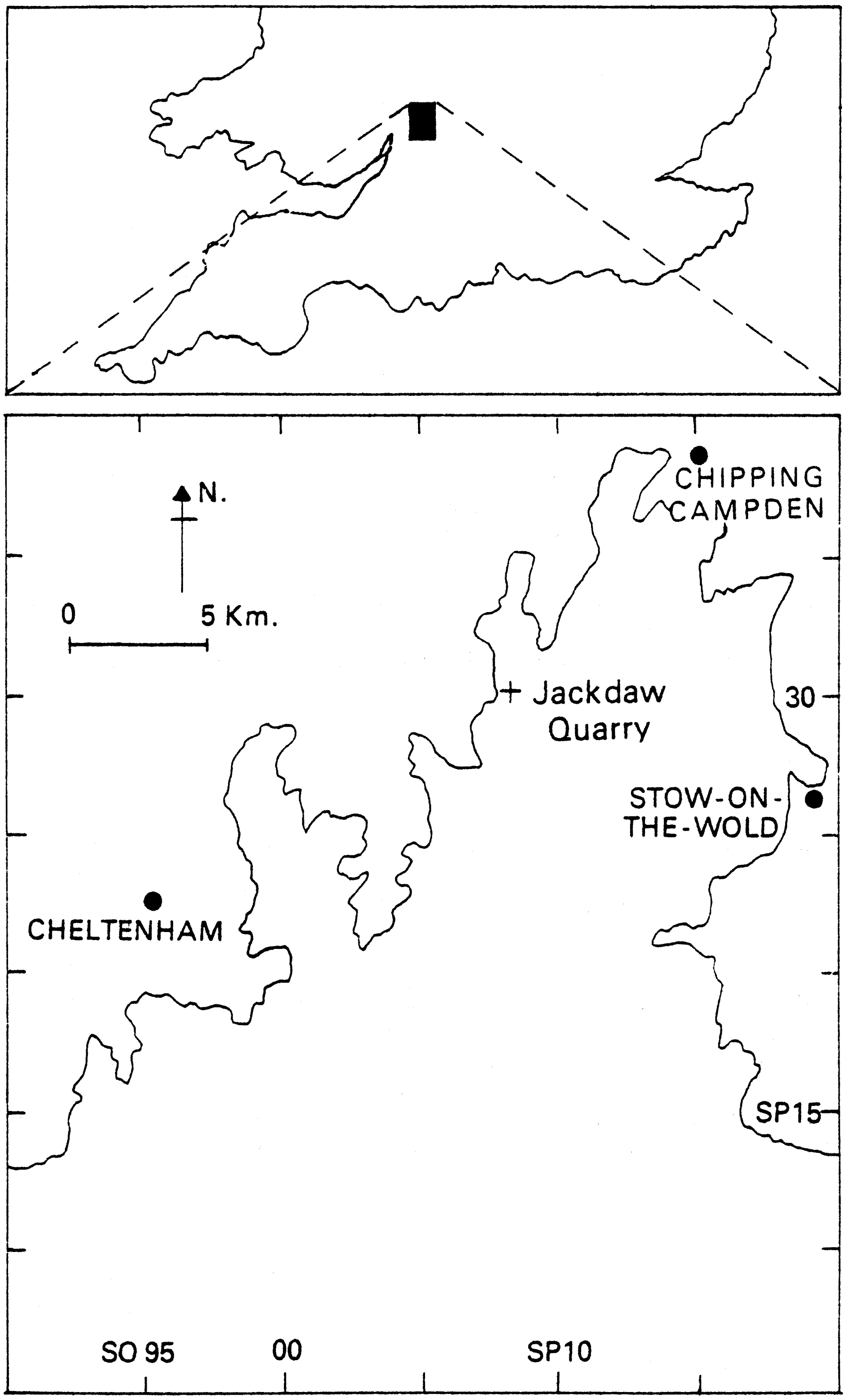
The Jackdaw Quarry; location and sample details

The location of Jackdaw Quarry (SP 078310) is shown in text-figure 1. The section present in the upper level of the quarry (above the Upper Freestone and below the Lower Trigonia Grit) is shown in text-figure 2. A full description of the quarry section was given by Parsons (1976), who recognised eighteen lithological units. The relative positions of the samples utilised are indicated in text-figure 2, which also shows the position of units three to fourteen of Parsons (*op. cit.*).

Geological background

The Naunton Clay, Harford Sands, Snowshill Clay and Tilestone (or Concava Beds of Arkell, 1933) are a series of thin sands, clays and limestones which show marked lateral variations in thickness and lithology. Together with the underlying (dominantly oolitic) limestone units, Scissum Beds, Yellow Guiting Stone, White Guiting Stone and Upper Freestone they make up the Lower Inferior Oolite in the north Cotswolds. The Naunton Clay—Tilestone sequence is confined to the north Cotswolds, occurring on the eastern limb of the Cleeve Hill Syncline between Cheltenham and Chipping Campden. The full extent of the original area of deposition is not clear because of folding and erosion.

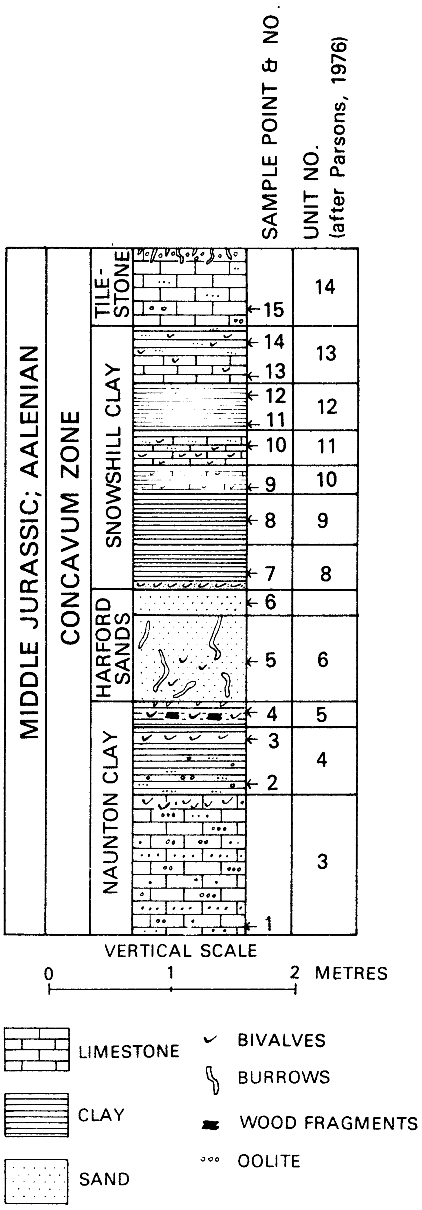
The lithologies exhibited by the Naunton Clay—Tilestone sequence are atypical of the Lower Inferior Oolite of the Cotswolds, which consists dominantly of pure oolitic limestones. According to Parsons (1976) the



Text-fig. 1 Location of Jackdaw Quarry. The solid line indicates the position of the Inferior Oolite scarp.

beds were deposited with an overlap from the north and were overstepped from the south by the Trigonia Grit (Middle Inferior Oolite).

The environment of deposition of the quarry sequence has been interpreted, on the basis of sedimentological and palaeontological evidence (Parsons, *op. cit.*), as a shallow-water, marginally marine coastal plain. The occurrence of deep-burrowing bivalves and intense bioturbation (Mudge, 1978) suggest that the Harford Sands represent intertidal conditions. The presence of plant impressions and rare, thin, impersisent lignite layers in the Naunton Clay suggests that the area of deposition was close to a richly-vegetated shoreline.



Text-fig. 2 The Naunton Clay-Tilestone sequence at Jackdaw Quarry. Units 3-14 of Parsons (1976) and the positions of the samples are indicated.

Development of the lithostratigraphical nomenclature

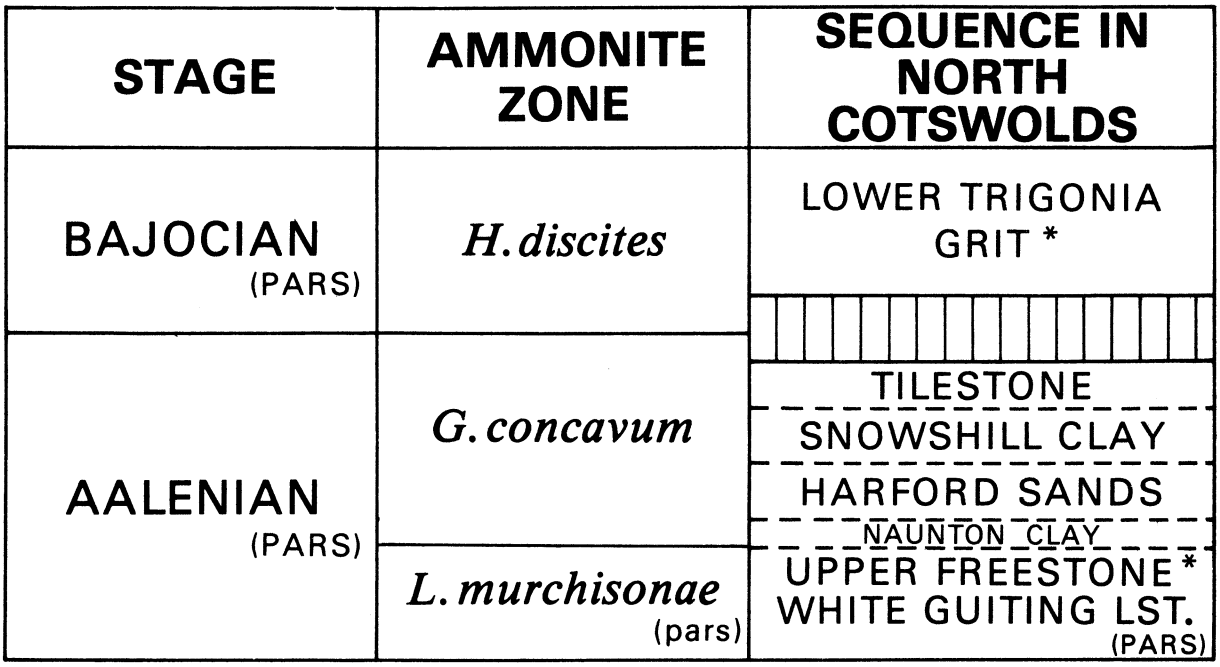
The Naunton Clay was named by Richardson (1929) and the Harford Sands, Snowshill Clay and Tilestone by Buckman (in 1888, 1897 and 1901 respectively). Cave and Penn (1972) suggested that the Naunton Clay—Tilestone sequence should be included in the Middle Inferior Oolite, but Parsons (1976) rejected this proposal. Cave and Penn's interpretations suggest that the Upper Freestone/Naunton Clay junction is unconformable. Parsons (*op. cit.*) pointed out that at Jackdaw Quarry this junction is gradational and demonstrated that the Tilestone/Lower Trigonia Grit boundary is unconformable. Hence Parsons (*op. cit.*) retains the Naunton Clay—Tilestone sequence in the Lower Inferior Oolite.

Mudge (1978) stated that, in his view the Naunton Clay—Tilestone sequence is partly equivalent to the underlying Upper Freestone and overlying Lower Trigonia Grit. He proposed that the entire sequence should be called the Harford Sands Member (of his Lower Inferior Oolite Formation), the type section being Harford Railway Cutting [SP 134218]. However, Cope *et al.* (1980) rejected this proposal because it would have altered a long-established stratigraphical nomenclature, thereby contravening the recommendations of Holland *et al.* (1978).

Ammonite biostratigraphy

There is no direct evidence that the *Graphoceras concavum* Zone is represented in the north Cotswolds. Buckman (1910) recorded a specimen of '*Graphoceras*' sp. from the 'Snowshill Clay' of Stanway Hill, but Parsons (1976) demonstrated that it came from the Lower Trigonia Grit.

Parsons (*op. cit.*) identified an ammonite from the Tilestone of the Harford railway cutting (housed in the Oxford University Museum) as *Graphoceras* cf. *apertum* (Buckman), a form found in both the *G. concavum* and *Hyperlioceras discites* zones.



Text-fig. 3 Adapted from Cope *et al.* 1980, this diagram shows the position of the Naunton Clay-Tilestone sequence with respect to the standard ammonite zonation.

Asterisks indicate positive ammonite evidence for the unit's age (vertical ruling indicates non-sequence).

Ammonite data has proved that the Lower Trigonia Grit is of *H. discites* Zone age (Parsons, *op. cit.*) and that the Upper Freestone lies within the *Ludwigia murchisonae* Zone (Mudge, 1978), (see text-figure 3).

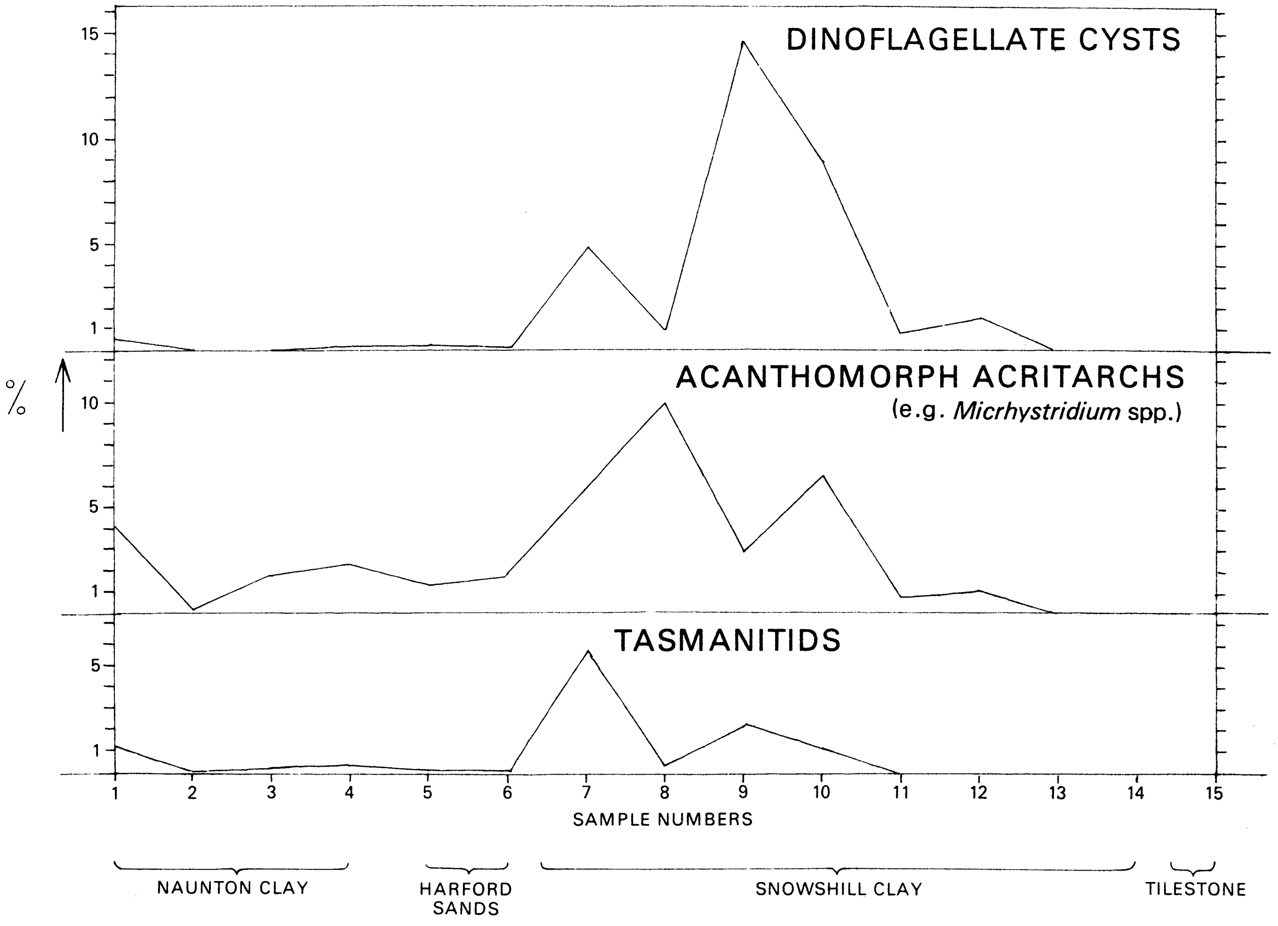
Text-figure 3, adapted from Cope *et al.* (1980) summarises the ammonite evidence, which suggests that much of the Naunton Clay—Tilestone sequence is of *G. concavum* Zone age.

Preparation and the nature of the palynomorph assemblages

Standard preparation techniques were used to extract the palynomorphs. The samples from the Naunton Clay, Harford Sands, Snowshill Clay and Tilestone generally yielded abundant, well-preserved palynomorphs. The underlying White Guiting Stone and Upper Freestone were sampled, but proved barren of palynomorphs. Limestone samples, particularly from outcrop, often yield very poor palynomorph assemblages due to oxidation of organic matter during deposition, diagenesis and weathering.

All of the residues recovered were dominated by terrestrially-derived material, i.e. spores, pollen and woody tissue. Marine palynomorphs (dinoflagellate cysts, acritarchs and tasmanitids) were consistently present but numerically subordinate to terrestrial elements.

Palynology has been used with great effect in palaeoecology. The relative proportions of terrestrially-derived and indigenous marine palynomorphs have proved a reliable guide to relative distance from shoreline or the degree of marine influence. Text-figure 4 shows the relative proportions of dinoflagellate cysts, acanthomorph acritarchs (spiny spheres of presumed algal origin) and tasmanitids (the remains of presumed green algae) in the samples studied from the Naunton Clay—Tilestone sequence. A clear increase in marine influence upwards through the sequence is shown by text-figure 4, the lower portion of the Snowshill Clay having many more indigenous marine palynomorphs than the rest of the succession.



Text-fig. 4 The abundance of the three major groups of marine palynomorphs within the interval considered expressed as a percentage of the total assemblage (miospores and microplankton).

All of the samples can be considered to indicate marginal marine conditions, although it appears a minor marine transgression occurred during early Snowshill Clay times. It is evident from text-figure 4 that the three marine palynomorph groups 'peak' at different times; the tasmanitids are the first group to reach their acme and the first to decline, followed by acanthomorph acritarchs and then by dinoflagellate cysts. This pattern suggests that the different groups reacted sequentially to the minor marine transgression postulated for the lower Snowshill Clay.

Wall (1965) when discussing the palaeoecology of the British Lower Jurassic found that acanthomorph acritarchs e.g. *Micrhystridium* Deflandre 1937 preferred a partly enclosed, inshore environment whereas polygonomorph (polygonal, spiny forms) and netromorph acritarchs (elongate/fusiform spiny bodies) seem to characterise offshore, open-marine palaeoenvironments. He postulated that acritarch assemblages dominated by a single species represent inshore conditions, while diverse assemblages indicate open-sea situations. He also suggested that long-spined acanthomorph acritarchs preferred quiet, low-energy conditions and that forms with short spines characterised high-energy, turbulent environments. The Naunton Clay, Harford Sands and Snowshill Clay all yield good assemblages of the acanthomorph acritarch genus *Micrhystridium* (see text-figure 4). The relatively long-spined species *Micrhystridium fragile* Deflandre 1947 consistently dominates these assemblages and hence a placid, inshore marine environment is inferred.

The only dinoflagellate cyst genera encountered were *Nannoceratopsis* Deflandre 1938 (four species recorded, in fairly large numbers, particularly in the Snowshill Clay) and very rarely, *Sentusidinium* Sarjeant & Stover 1978 (one form recorded, very rarely). Due to its presence in marginal marine (and even estuarine sediments) *Nannoceratopsis* is considered to have been euryhaline. In situations where species of *Nannoceratopsis* dominate the dinoflagellate cyst assemblages, marginal conditions are suggested.

The evidence from the acritarchs and dinoflagellate cysts agrees with the quiet, low-energy nearshore environment postulated by Parsons (1976) and Mudge (1978). Tasmanitids, the presumed cysts of unicellular green algae belonging to the Prasinophyceae typify subsaline marine conditions. They appear to characterise brackish water or shallow water (often restricted) marine environments, where the salinity has been reduced due to freshwater runoff.

Miospores overwhelmingly dominate the assemblages, consituting, on average, 85% of the palynomorph assemblages. Gymnospermous pollen accounts for 75% of the miospores and pteridophyte spores for the remainder. The relative abundance and diversity of pteridophyte spores (17 genera, 29 species) indicate the proximity of a land area with an abundant and varied pteridophyte flora. Species of the gymnospermous pollen genus *Spheripollenites* Couper 1958 are by far the commonest components in the samples studied, often reaching 30% of the total palynomorph assemblage.

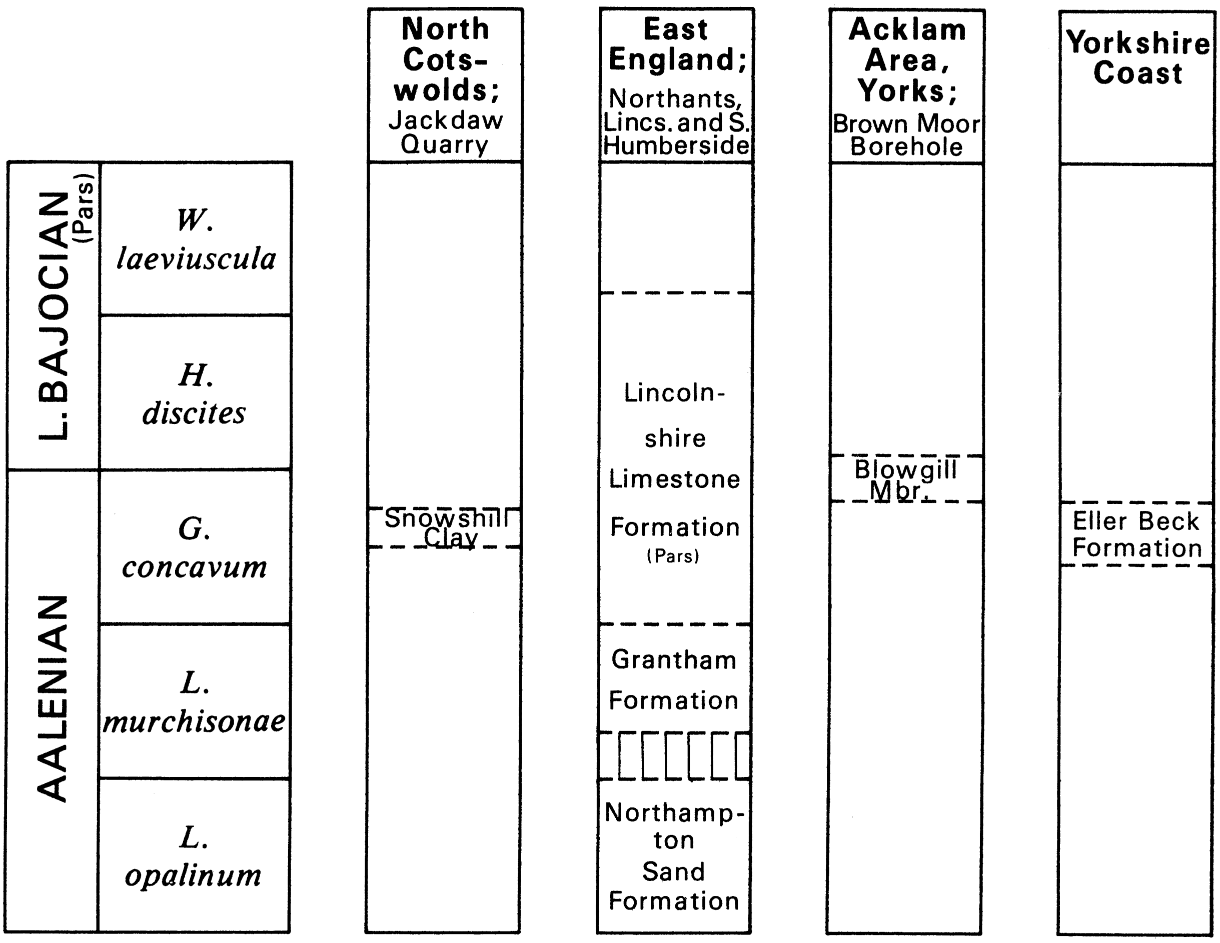
Stratigraphic Palynology

The miospore taxa present are relatively long-ranging forms and it is not surprising that there are no significant changes in the floras throughout the section. The miospore assemblages accord well with other European Aalenian/Bajocian records (Couper, 1958; Tralau, 1968; Guy, 1971). The acritarchs and tasmanitids are also relatively long-ranging and appear to be of little use stratigraphically.

In contrast, dinoflagellate cysts are used extensively for age-determination and correlation in the Jurassic. The ranges of *Nannoceratopsis gracilis* and *N. spiculata* are well estabished (Thusu, 1978; Sarjeant, 1979), both species occurring from the late Pliensbachian to the Bathonian. *Nannoceratopsis ambonis* Drugg 1978 however, appears to be more restricted stratigraphically, being confined to the Snowshill Clay (samples 7-10 of text-figure 2) in the Jackdaw Quarry sequence. The author has recorded *N. ambonis* from the Northampton Sand Formation, Grantham Formation and from the Lincolnshire Limestone Formation, all in eastern England, and from the Blowgill Member (Cloughton Formation) of Brown Moor Borehole in North Yorkshire (Gaunt *et al.*, 1980). It is also present in the Eller Beck Formation of North Yorkshire (R. Woollam, pers. comm.). These occurrences are summarised in text-figure 5. In terms of abundance *N. ambonis* is commonest in the *Graphoceras concavum* ammonite Zone, and appears to be confined to the Aalenian and early Bajocian. The type material is from the German Aalenian (Drugg, 1978). *N. ambonis* was figured by Fenton and Fisher (1978, as *Nannoceratopsis* sp. 1) who gave a breakdown of its stratigraphic distribution in north-western Europe (data which accord with the information in text-figure 5), and reported the species from the Aalenian of Greenland and Arctic Canada.

Also of value biostratigraphically is *Nannoceratopsis triceras* Drugg 1972 which in the Jackdaw Quarry section was found rarely in sample 10 (Snowshill Clay, Unit 11, see text-figure 2). The author has however, recorded this species from the *Dactylioceras tenuicostatum* Zone (early Toarcian) to the *Hyperlioceras discites*/*Witchellia laeviuscula* zones (Bajocian) of eastern England. The observation by Drugg (*op. cit.*) that this form is very rare throughout this interval, yet consistently present is concurred with here. It is reported from the Late Pliensbachian of north-western Europe as Dinoflagellate sp. 1 by Morbey and Dunay (1978) and as "*Parananoceratopsis triadis*" (informal name) by Morbey (1978). Wille and Gocht (1979) describe *Nannoceratopsis tricornuta*, which is a junior synonym of *N. triceras* from the Lower Toarcian (Lias epsilon) of south-western Germany. The holotype is described from the German Aalenian,(*Leioceras opalinum* Zone), Drugg (*op. cit.*, pl. 6, figs. 10 & 11), who also figured two specimens from the Callovian (*Peltoceras athleta* Zone), but in view of the large stratigraphical gap between the Pliensbachian/Bajocian interval and the Callovian these specimens were probably reworked. To summarise, *Nannoceratopsis triceras* ranges from the Pliensbachian to lowermost Bajocian in north-western Europe.

Sentusidinium sp. was found very rarely in the Harford Sands only (sample 5 Unit 6, see text-figure 2). The large and varied plexus of forms referable to *Sentusidinium* Sarjeant and Stover 1978 includes biostratiographically useful species. However, comparable forms to *Sentisidinium* sp. have been observed throughout the Jurassic, so it does not appear to be of great biostratigraphical value.



Text-fig. 5 The rock units yielding *Nannoceratopsis ambonis* in England (partly adapted from Cope *et al.* 1980).

Species Lists

Miospores

Spores

Acanthotriletes cf. *midwayensis* Pocock 1970	
Auritulinasporites intrastriatus Nilsson 1958	
Auritulinasporites scanicus Nilsson 1958	
Calamospora mesozoica Couper 1958	(Pl.17, fig. 7)
Concavissimisporites verrucosus Delcourt & Sprumont 1955 amended Delcourt *et al.* 1963	(Pl.17, fig. 4)
Coronatispora valdensis (Couper 1958) Dettmann 1963	
Cyathidites australis Couper 1953	(Pl.17, fig. 1)
Cyathidites concavus (Bolkhovitina 1953) Dettman 1963	
Cyathidites minor Couper 1953	(Pl.17, fig. 3)
Cyathidites punctatus (Delcourt & Sprumont 1955) Delcourt *et al.* 1963	
Dictyophyllidites crassexinus (Nilsson 1958) Tralau 1968	(Pl.17, fig. 6)
Dictyophyllidites harrissii Couper 1958	(Pl.17, fig. 2)
Duplexisporites problematicus (Couper 1958) Playford & Dettmann 1963	
Foveotriletes subtriangularis Brenner 1963	
Gleicheniidites senonicus Ross 1949	
Ischyosporites variegatus (Couper 1958) Schulz 1967	
Leptolepidites bossus (Couper 1958) Schulz 1967	
Leptolepidites major Couper 1958	
Leptolepidites rotundus Tralau 1968	
Lycopodiacidites cerniidites (Ross 1949) Brenner 1963	(Pl.17, fig. 5)

Lycopodiumsporites austroclavatidites (Cookson 1953) Potonié 1956
Lycopodiumsporites clavatoides Couper 1958
Lycopodiumsporites semimuris (Danzé-Corsin & Laveine 1963) Resier & Williams 1969
Obtusisporis cf. *canadensis* Pocock 1970
Obtusisporis convexus Pocock 1970
Obtusisporis juncta (Kara-Murza 1956) Pocock 1970
Osmundacidites wellmanii Couper 1958
Todisporites major Couper 1958
Todisporites minor Couper 1958

Pollen

Alisporites thomasii (Couper 1958) Pocock 1962
Araucariacites australis Cookson 1947
Callialasporites dampieri (Balme 1957) Sukh Dev 1961
Callialasporites microvelatus Schulz 1966
Callialasporites minus (Tralau 1968) Guy 1971
Callialasporites trilobatus (Balme 1957) Sukh Dev 1961
Callialasporites turbatus (Balme 1957) Schultz 1967 (Pl.17, fig. 10)
Cerebropollenites mesozoicus (Couper 1958) Nilsson 1958 (Pl.17, fig. 11)
Classopollis classoides (Pflug 1953) Pocock & Jansonius 1961
Cycadopites carpentieri (Delcourt & Sprumont 1955) Singh 1964 (Pl.17, fig. 12)
Cycadopites minimus (Cookson 1947) Pocock 1970
Cycadopites nitidus (Balme 1957) Pocock 1970
Perinopollenites elatoides Couper 1958 (Pl.17, fig. 8)
Podocarpidites ellipticus Cookson 1947
Podocarpidites multesimus (Bolkhovitina 1956) Pocock 1962
Spheripollenites psilatus Couper 1958
Spheripollenites scabratus Couper 1958 (Pl.17, fig. 9)
Vitreisporites pallidus (Reissinger 1950) Nilsson 1950

Microplankton

Dinoflagellate cysts

Nannoceratopsis ambonis Drugg 1978 (Pl.18, figs. 4 & 5)
Nannoceratopsis gracilis Alberti 1961 (Pl.18, fig. 1)
Nannoceratopsis spiculata Stover 1966 (Pl.18, fig. 2)
Nannoceratopsis triceras Drugg 1978 (Pl.18, fig. 3)
Sentusidinium sp. (Pl.18, fig. 6)

Acritarchs

Micrhystridium fragile Deflandre 1947 (Pl.18, fig. 9)
Micrhystridium lymensis Wall 1965 var. *gliscum* Wall 1965 (Pl.18, fig. 11)
Micrhystridium rarispinum Sarjeant 1960
Micrhystridium recurvatum Valensi 1953 (Pl.18, fig. 10)
Micrhystridium stellatum Deflandre 1942 (Pl.18, fig. 12)
Veryhachium sp.
Caddasphaera halosa (Filatoff 1975) Fenton, Neves & Piel 1980 (Pl.18, fig. 8)
Leiosphaeridia sp.

Miscellaneous

Prasinophyceae; *Tasmanites newtoni* Wall 1965 (Pl.18, fig. 7)

Sarcodina; Foraminiferal test-linings.

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J. B. Riding,
Institute of Geological Sciences,
Ring Road Halton,
Leeds, LS15 8TQ.

Explanation of Plates 17 and 18

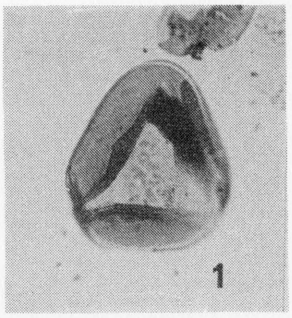
Plate 17

Miospores and pollen from Jackdaw Quarry
(for detailed explanation see text).

Plate 18

Microplankton from Jackdaw Quarry
(for detailed explanation see text).

Plate 17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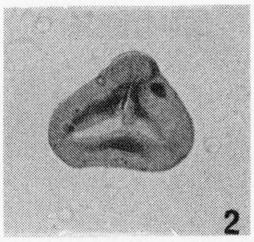
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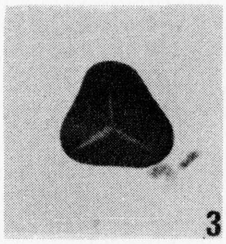
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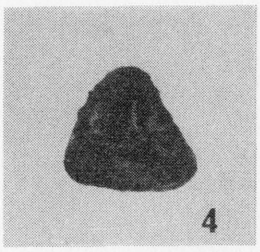
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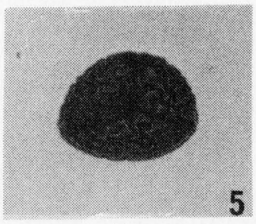
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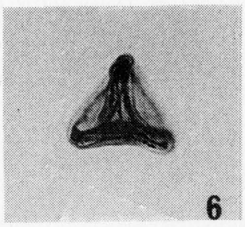
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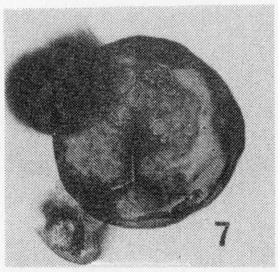
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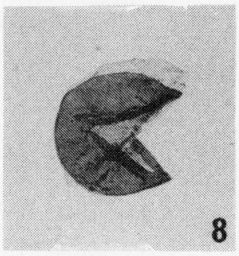
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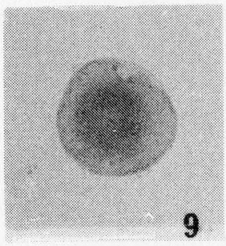
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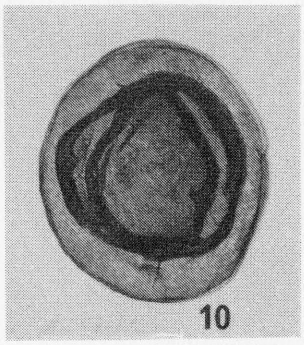
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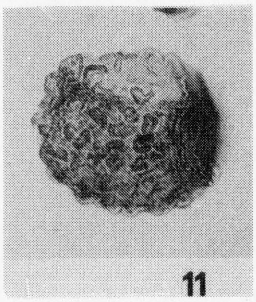
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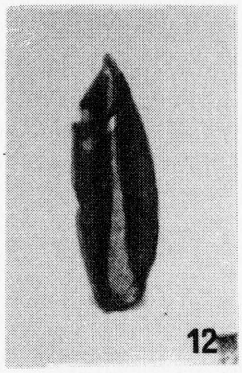
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Plate 18


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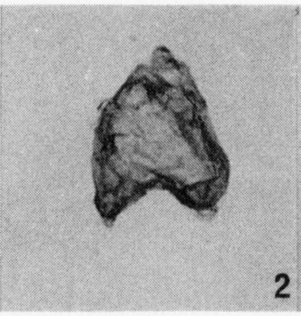
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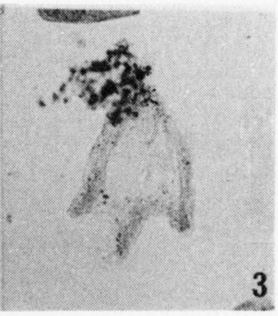
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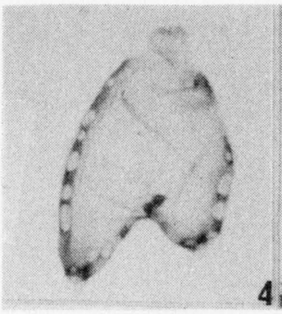
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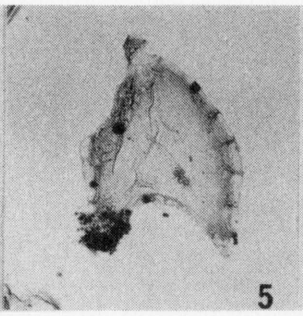
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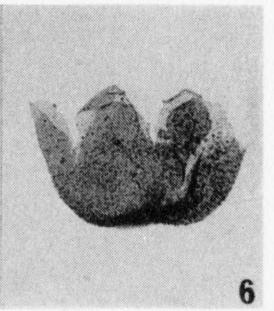
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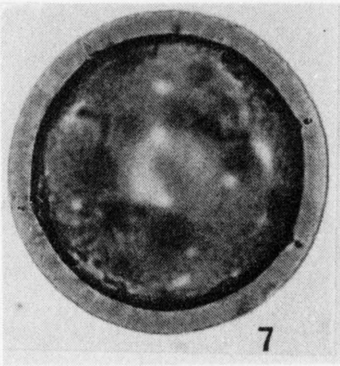
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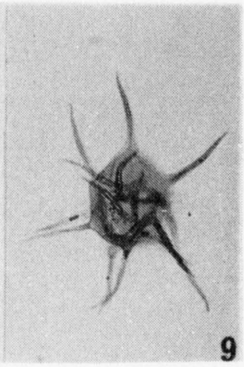
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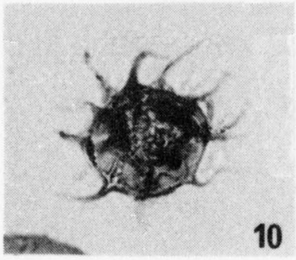
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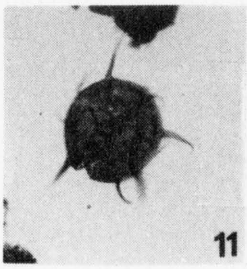
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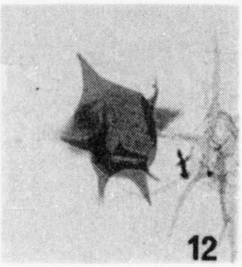
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REVIEWS

CROUCHER, R. and WOOLLEY, A. R. *Fossils, minerals and rocks. Collection and preservation.* Cambridge University Press and British Museum (Natural History), London. 1982. 60 pp. illustrated, index. £3.25, hardback.

For any one species of fossil or mineral, there must be a limited number of very good specimens showing all or most of the important characteristics. Those that are found must be adequately conserved and curated. This little book is directed mainly at the amateur geologist and purports to tell them exactly how to go about this task. It might also provide a few useful tips for the professional geologist likewise, or for anyone fortunate enough to come across valuable specimens. Rock samples are more easily acquired but even so, specimens from rare or temporary outcrops should be adequately curated. Special techniques are described especially for vertebrate fossils.

The authors infer that their readers will have some geological knowledge. At least they will know rock, mineral and fossil specimens when they see them. Any specimens that they are likely to take home can be considered of value. The need for conservation of localities and safety procedures is explained in the first few pages. Thereafter, it appears that every locality must look after itself, as shown by the number and variety of recommended tools (figs. 2 and 3) that can be used and which are described. The authors appear to draw the line on explosives but very large hammers, pick-axes and shovels are standard equipment for any aspiring specimen hunter and locality destroyer. There must be a conflict of conscience here between conservation and collecting. Having solved that problem the book then deals adequately with methods of recording data, labelling and preservation of the specimens.

The book describes modern techniques for extracting specimens from rock matrix and for the preparation of artificial casts. There is a formidable list of chemicals and stores needed by the modern collector. Fortunately, a list of suppliers is given (correct at the time the book was printed) although whether or not the small quantities usually required by amateur geologists are available is not mentioned. Many of the chemicals listed are toxic in one form or another but the book does go into the safety aspect of their use in great detail.

Having used the chemicals, there is then the question of their disposal. There is more to disposal than just washing in the sink. The book gives clear instructions for safely removing spent and possibly re-activated chemicals. Has the time come when it is really not safe to use anything but the simplest techniques in the home? The more sophisticated methods should only be used in specially prepared laboratories and under supervision. There is scope here for Adult Education Institutes and Geological Societies and Geology Departments to combine to give a service to the enthusiastic amateur geologist to prevent horrific accidents. Members of the East Midlands Geological Society will know that in cooperation with the Nottingham University Department of Adult Education a start has been made along these lines for E.M.G.S. members.

Don't expect this book to tell you exactly where you can find good specimens. It is a question of having found them, what is then to be done with them. I think the authors hope that once the specimens are no longer required by the finder they will have been adequately curated and preserved to be of value to others in museums. Now this point is not very well explained in the book. Members of geology departments and museums have all had experience of being led down the garden path to the shed, which now holds the once valuable collection of JOE BLOGGS, deceased many years before and whose widow has at last got round to disposing of the collection. We find all the labels and packaging have been eaten by rats and mice. Rain and damp has played havoc with the preservation of the specimens themselves which appear to be preserved only as amorphous powders, at the best covered in dust and grime. It is clear that the really good specimens should be donated almost immediately to the county or local museum. Other specimens should be offered to teaching establishments—Universities, Colleges of Higher Education and to schools long before the collector has got fed up with looking after them.

The book clearly deals adequately with the middle ground and should be read by all aspiring collectors. Perhaps a chapter on the disposal of collections could be written for a revised edition.

F. M. Taylor,
Dept. of Geology,
University of Nottingham,
Nottingham NG7 2RD.

LOF, P. *Elsevier's mineral and rock table*. Elsevier, Amsterdam. 1982. Wallchart. Dfl. 40.00 to Dfl. 12.00 (dependent on quantity).

Lof's attempt towards producing a comprehensive wall chart as an aid in the identification of minerals and rocks is admirable. The large chart, measuring 0.71 × 1.35 m, is amply illustrated and contains a wealth of data in summary form. Importantly, there is also a list of the source references used in the compilation and the cross-referencing is well accomplished.

Any potential purchaser who has not had the benefit either of seeing a copy or of reading Elsevier's publicity brochure should be advised that the sections on mineral identification, which take up more than two-thirds of the chart, are not concerned with the properties of hand specimens but with microscopic methods of identification. The title does not make this clear.

The section on ore minerals contains excellent reflected-light photomicrographs and the minerals are arranged, as claimed, in a logical and easy-to-follow format. Lof has followed a similar method for the rock-forming minerals (the largest section) subdividing those which are anisotropic on the basis of combinations of colour, birefringence and the presence or absence of two cleavages at 56° or 88°. Whilst this is a perfectly valid treatment which some may prefer, there is the inevitable consequence that the more traditional method of treating the silicate minerals by class (inosilicates, tektosilicates etc.) is not followed. Inevitably, therefore, data for any given class or sub-class (e.g. pyroxenes, amphiboles) are spread among several columns. A further criticism, this time of detail, is that the summary data given for each mineral is more complete in some instances than in others. For instance, for a student who might be looking at a thin section of a blueschist, it is very useful to find the information that glaucophane and lawsonite occur in high-pressure metamorphic rocks, and that jadeite is a common associate. By contrast, there is often no information given about the paragenesis of a given mineral: for example, we only find out that cordierite occurs with anthophyllite under the latter. Also, we learn that humites occur in metamorphosed calcareous rocks, but nothing is said about wollastonite and, similarly, whilst kyanite is described as occurring in pelitic schists, nothing is said about sillimanite or staurolite. Other criticisms of this section would be that there is a lack of information concerning distinguishing features, always helpful when there is the chance of mis-identification, and that there is no indication of which minerals are commonly major constituents of rocks and which are accessories, or very rare.

The section on rocks comprises a number of diagrams and tables to illustrate descriptive terms and classifications. The treatment is as comprehensive as could be expected. All of the common igneous, metamorphic and sedimentary lithologies are covered as, indeed, are some rarer groups such as phosphorites and charnockites.

At a price of Dfl. 40.00 for a single copy, the chart is not by any means cheap. However, there are generous discounts for bulk orders (e.g. 50 copies: Dfl. 690) and, despite the criticism of details concerning the section on rock-forming minerals, it is a chart which will be a most useful, and aesthetically pleasing, aid in teaching laboratories. For office use, one should first carefully check the available wall space! It is rather doubtful that the chart will always "save you the trouble of consulting numerous different references" as Elsevier's brochure states, but it will certainly be a most valuable source of summary data for the more advanced student of mineralogy and petrology.

D. Field,
Dept. of Geology,
University of Nottingham,
Nottingham NG7 2RD.

SECRETARY'S REPORT FOR 1980

The seventeenth year of the Society maintained a steady membership of around 500, although each year some were lost through resignation and a few from their membership lapsing, the new members tended to make up the loss. The varied programme of meetings and excursions during the year had their enthusiastic following and as usual we were fortunate in obtaining speakers and leaders who made each occasion so worthwhile.

There were thirteen meetings in all, eight indoor and five field excursions, consisting of four day trips and one week-end.

The Annual General Meeting on 1st March was attended by 54 members, and ran very smoothly with no problems. It was followed by a Collectors' Meeting and the ever popular 'Bring and Buy' stall, which on this occasion made a handsome profit of £38.50. Our thanks to Mr. J. H. Sykes for donating this to the Society, and for his hard work in running the stall and in preparation of the specimens. Members' exhibits were set up in the Swinnerton Laboratory and made those who had not contributed feel a little guilty at the effort put in to make such a fine display.

The names and titles of exhibits are as follows:

Earth Sciences on Stamps	P. I. Manning
Some Precious Stones — or just Quartz	N. Leiter
Mineral Collection	Mrs. D. M. Morrow
Middle Triassic Bonebed. Vertebrate Fauna from Germany	J. H. Sykes
The Outer Hebrides	Mrs. M. Beaumont and Miss E. Ramsell
Pseudomorphs	Mr. & Mrs. T. F. Bridges
Fossils from the Lower Cretaceous, Lincs	D. Penney
Pebbles from Beaches	J. Cantrill
Random Gleanings	G. S. Robson
The Mercian Geologist Vol. 1-6, Vol. 7 No. 1-3	Dr. F. M. Taylor
Computer Addressograph	Dr. F. M. Taylor
Orthid Brachiopods	C. Champion
Ovum Problematica (Ezra)	Natural History Museum Wollaton Hall
Manufacture of thin sections for the Department of Geology	J. Travis

The Joint Meeting with the Matlock Field Club was held on Saturday 15th March at a changed venue, the Department of Geology, University of Nottingham. Previously the meeting had always taken place in January but in the hope of encountering more clement weather, it had been decided to try a March date. The audience of about 40, largely Society members, listened to Dr. R. G. Thurrell talk on Minerals and the Countryside, a subject very relevent to the Trent Valley and Derbyshire.

The April meeting took place on the 12th and had a close relationship with the previous talk. Mr. J. A. M. Barnett spoke on the Geology of the North East Leicestershire Prospect or better known as the Belvoir Coalfield. The 70 members attending gave Mr. Barnett a hard time with their searching questions. He had also mounted an exhibition of 19th century mining in the Swinnerton Laboratory.

The first excursion of 1980 to the Wrekin area of Shropshire on 18th May was led by Dr. P. H. Bridges. He had most kindly stepped in at short notice and gave the 40 members attending a most interesting day's geology examining rocks of the late Precambrian and early Palaeozoic. He had, as on a previous occasion, prepared polished specimens and photographs of the rocks in thin section, which were much appreciated.

The 15th June saw 50 members joined by several Leicestershire Literary and Philosophical Society members accompany Dr. T. D. Ford along the disused railway from Monsal Head to Millers Dale, an excursion which had been undertaken in October 1972, and enjoyed as much by those attending on that previous occasion as by the new members.

Another repeat excursion occurred on 13th July to Charnwood. Again one of our members gallantly stepped in at short notice owing to the ill-health of the original leader. Mr. Moffatt not only talked of the geology of this classic area, but also its history, flora and fauna.

On 14th September 34 members on the coach with various cars following made a traverse of the East Midlands Coalfield in North Derbyshire. Mr. J. H. Rippon, a member of the Society, led the group from Cutthorpe, Chesterfield, using Cresswell Crags Visitors' Centre as a lunch stop, to Whitwell Works Quarry, and finally, to a National Coal Board borehole. The drilling operation being completed, the party picked over, and came away with, some interesting pieces of core.

The 1980 week-end excursion was spent in the Lake District from 3-5th October and was led by Dr. G. C. Brown. Three Guest Houses were used for the 30 people attending, Stonegarth, Glendale and Foye House in Keswick. An introductory talk was given by the leader on Friday evening at Stonegarth. Saturday was spent on the Eycott Hill lavas, Mungrisedale (Skiddaw Slates) and examining their relationship to the Carrock Fell Gabbros and Skiddaw Granite, along the River Caldew, finishing at Threlkeld granite quarry. On Sunday the party met at the south end of Bassenthwaite Lake for the outcrop of Barf Slates; thence to the dolerite-slates contact at Friars Crag; lunch and stream exposures at Grange Village; Borrowdale Volcanics at Grange Fell and finally to the Ennerdale granophyre outcrop. A successful week-end even though the President was locked out of the Guest House on one night, and the leader on both. The Proprietor seemed to imply that 'all decent men be abed by 11 pm!'.

The Winter session started with an indoor meeting held on a Thursday evening 16th October. The Lecture Hall in the Department of Geology was completely filled, standing room only for latecomers, to hear Dr. T. D. Ford lecture on the Geology of the Grand Canyon, which he liberally illustrated with slides. A nostalgic reminder for all those members having visited the area 2 months previously.

On 8th November Dr. A. M. Evans talked of Fluid Inclusions and their use in Mineral Exploration, attended by about 40 members of the Society. He described his work which he hoped eventually would lead to an indication of workable quantities of minerals, such as copper, in granite masses.

The last meeting in 1980 on 29th November was preceded by an Extra-Ordinary General Meeting. The Treasurer proposed that, to take advantage of a considerably lower Auditor's fee, the Auditors appointed at the Annual General Meeting in March should be changed from that of Stephenson, Nutally & Co, to Edward Parsons. The meeting of about 40 members agreed unanimously. The lecture on the Geology of North East Ireland then followed and Mr. H. E. Wilson, a previous District Geologist of the area, gave members a fascinating look at the region.

The first meeting of 1981 took place on 17th January when Professor W. S. Pitcher talked of Andean Geology on Horseback. He described his encounters with the people of the area and tried to convey the vastness of this mountain desert.

The Foundation Lecture was given this year by Dr. Julia Hubbard on 7th February, who spoke on Enigmatic Coral Reefs, describing her work in many parts of the world, to a full Lecture Hall. Owing to my indisposition, the President's husband, Mr. Morrow, most kindly provided transport on this occasion.

So Dr. Hubbard's excellent lecture brought to an end the series of indoor and field meetings for 1980. Our thanks to the leaders: Dr. P. H. Bridges of the Division of Geology, Derby Lonsdale College of H. E., Dr. T. D. Ford of the Department of Geology, University of Leicester, Mr. W. S. Moffatt at Loughborough, Mr. J. H. Rippon of the National Coal Board and Dr. G. C. Brown of the Open University. Also to the speakers: Dr. R. G. Thurrell of the Institute of Geological Sciences, Keyworth, Nottingham, Mr. J. A. M. Barnett of the National Coal Board, Dr. T. D. Ford, Dr. A. M. Evans of the Department of Geology, University of Leicester, Mr. H. E. Wilson of the Institute of Geological Sciences, Keyworth, Professor W. S. Pitcher of the Department of Geology, University of Liverpool and Dr. Julia Hubbard, University of London, King's College. They readily gave their time to provide members with an informative and interesting programme for the year.

The circular was sent out every month except August when there were no meetings and for the first time appeared in colour as a quantity of paper had been available for purchase at a much reduced cost. It had publicised other Societies' activities and courses being held in different parts of the country, as well as being used by several members to advertise 'things geological'. As the postage continues to rise, the Society is increasingly appreciative of those who hand deliver for this valuable service, both for circulars and of course, the Journal. Both the Editor and Secretary will always be pleased to hear of anyone able to help in this way.

Council had 6 meetings during the year, discussing the programme and trying to ensure that interesting lectures and excursions were arranged that would cater for all tastes. We hope we get it right, but we are always open to suggestions and prepared to try something new if the support is there. All the affairs of the Society are discussed at these meetings and any items for the agenda should be sent to the Secretary at least 3 weeks before the next Council Meeting, which is always notified in the circular.

The membership of the Society showed a slight increase compared with 1979 and was as follows:

Honorary	Ordinary	Joint	Junior	Institutional	Total
2	262	120	4	119	507

The Mercian Geologist had been published twice, Vol. 7, No. 4 in April, and Vol. 8, No. 1 in November. It cannot be too strongly emphasised that the help given by those collating, enveloping and distributing, is of great value in the production of the Journal. Without these willing members, it would cost nearly twice as much and every Journal is checked individually.

The Society Exhibit which travels around the East Midlands publicising our existance, toured the Branch Libraries in Nottinghamshire and we are grateful to the Library Services for their very great help in transporting the Exhibit between the locations.

The University of Nottingham and Professor P. E. Baker continue to allow the Society the use of the Department of Geology for our activities and functions, with these facilities at out disposal, we are able to maintain a high standard. We cannot too often express our sincere thanks both to the University and Professor Baker and I am sure they realise how grateful we are.

Finally, my own gratitude to all Members of Council and members of the Society, some coming to my rescue at very short notice, others willing to be persuaded to speak or be leaders, they all help to make the work of Secretary a little easier and certainly a most enjoyable task.

W. M. Wright

LETTERS TO THE EDITOR

Dear Sir,

I have read with interest the article in vol. 9 no. 1 by G. Miller on, "H. H. (Arnold-) Bemrose, 1857–1939." Mr. Miller and readers may be interested to know that although several manuscripts, notably his paper on, "Boulders in the Derbyshire drift" have been lost, almost all his six-inch and twenty-five inch field slips have survived. They are housed in the map collection in the Dept. of Geology at Nottingham University.

Yours faithfully,

R. J. Firman

THE MERCIAN GEOLOGIST

Journal of the East Midlands Geological Society

The journal first appeared in December 1964 and since that time 33 parts, comprising 9 volumes have been issued; the last, Vol. 9 No. 1 in Jan., 1983. The Mercian Geologist publishes articles especially on the geology of the Midlands of England, but other articles have been published which are of current interest to geology generally. Contents include original papers, review articles, biographies, bibliographies, excursion reports, book reviews and the Secretary's report on Society activities.

For Contributors:

Authors intending to submit manuscripts of papers for publication in the Mercian Geologist are asked to follow the format of papers included in a recent number of the journal, and if possible to provide two copies. As the journal is read by Members with a wide spectrum of geological interest and ability, authors are asked to ensure adequate introductions for their papers, particularly, if the subject has not been reviewed in the journal over the last few years. The paper should be complete in itself without the need of the reader to refer to specialist journals not easily available to the average Member of this Society. It follows that the length of the paper may be greater than that published by some other journals but authors are asked to be as lucid and concise as possible and to avoid repetition.

Text-figs. normally occupy a full page of the journal, but part diagrams can be fitted into the typed page. Double page diagrams have been published with a single fold but each printed page has to be folded by hand. The standard reduction by our present printing process is approximately × 0.75. Thus the optimum size for the original diagram, including space for caption, index and explanation if required on the diagram, should be 285×190 mm (285×380 mm with a single fold). Greater reduction is possible but care must be taken with the original to ensure that at the final reduced size (230×155 mm; or 230×310 mm) the smallest letters are no smaller than 1 mm and that there is a similar minimum spacing between letters and lines. Bar scales (metric) should be provided as the exact reduction cannot be guaranteed.

Half-tone plates are reproduced at the original size, and should not exceed 230×155 mm. The quality of the published photograph depends initially on the quality of the original and it follows that the photographs submitted should be exactly as the author would wish them to appear in the journal—good contrast, in focus, adequate magnification and without distortion.

If there are any points of difficulty, please do not hesitate to contact the editor during the production of the manuscript. The editor's sole concern is to produce excellent quality papers to be enjoyed by all readers. Please send completed manuscripts to the editor.

For Readers:

All parts of the journal are available for purchase and a detailed contents list will be sent on request. Current numbers of the journal are usually obtained by subscription: [32 parts issued in 18 years].

Year 1983

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Institutional Members	£6.00		

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Complete volumes, 4 parts; £13.00 (£12.00 Institutions; Other Members £10.00).

Librarians in overseas libraries and geological institutions may take part in an exchange scheme organised by the Science Library of the University of Nottingham. About 200 institutions throughout the world receive the Mercian Geologist by sending in exchange, original geological periodicals.

Address: Editorial matters, manuscripts, exchanges, orders for back numbers

The Editor, Mercian Geologist, Department of Geology,
The University, Nottingham, NG7 2RD, England.

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