The Wolfson
Geochemical Atlas of
England and Wales

Initiated and compiled by the
Applied Geochemistry Research Group
Imperial College of Science and Technology
London, England

Direction: John S. Webb
Sampling and Co-ordination: Iain Thornton  Analysis: Michael Thompson
Data Processing and Preliminary Map Production: R. J. Howarth and P. L. Lowenstein
Computer Programming and Final Map Production: R. J. Howarth

Assisted by
Sampling:
Field Supervisors — D. Hobson, L. Oldham, D. Recher and R. J. Wedling
P. Gordon, M. J. Hambrey, M. J. Hards, Miss A. Harvey, Miss P. Hastings, N. Holloway
Miss C. G. Hopkin, Miss M. M. Jensen, T. G. Kempton, C. J. H. King, Miss M. J. Lee, Miss S. Lemmon, K. Lernax
Miss R. Phillipson, H. W. Pitts, Miss S. L. Pritchard, N. W. Radford, C. M. Reeves, Miss J. L. Rogers, H. Roper
P. J. Strickland, J. Turpin, M. Whitely, Miss R. Whitaker, A. J. Wilson Clarke, D. Wooldridge

Analysis:
Research Assistant — Miss A. Steward
Spectrography: Team Leader — R. P. Campan
with Miss D. L. Allen, P. G. Guise, G. R. Shekhi, M. R. Stott
Other Methods: A. Doyle, M. R. Luers, A. M. Lock, S. Mitchell
Mrs. R. Nataraj, S. L. Sarkar, Mrs. V. R. Vine, R. D. Williams

Data Processing:
Team Leaders — Mrs. E. Ng Chiu-Hin, and Mrs. V. Emery
with Mrs. R. Menezes, Miss P. Patel, Miss L. Peters
Miss M. Robson, Mrs. F. Sherif

CLARENDON PRESS • OXFORD

1978
Foreword
by Professor Lord Zuckerman, O.M., K.C.B., F.R.S.

Quite apart from the contribution it makes to knowledge, there are at least three good reasons why this Atlas is to be welcomed. The first is that the ever increasing demand for raw materials in a world of rising expectation makes it essential that we know what is on our own doorstep. The exploitation of North Sea gas and oil has already become necessary in order to help slow down, and if possible reverse, the decline in our standard of living, and the day may well come when economic conditions require that we use more than we now do of other mineral resources in the small piece of the earth’s crust which we occupy. The second reason is that without a ready-to-hand geochemical atlas, those who plan our towns and roads, and those who farm the land or who grow trees, are to some extent working in the dark. The third is that people who are concerned to preserve the beauty and unique character of our landscape must know what it is that they are fighting to conserve. Whatever else, the Atlas which Professor Webb and his team have produced is a valuable tool in land-use planning.

Of course, it is not the only tool. It is the statutory responsibility of our national Institute of Geological Sciences, the successor body to the Geological Survey which was established in 1835, to carry out regional surveys of the country. The new Atlas complements the detailed geochemical surveys made by the Institute which, with mining industry and Geological Surveys overseas, have supported the work of Professor Webb in regional geochemical mapping from its start twenty years ago. Professor Webb’s first purpose was to provide a broad picture of the regional distribution of the elements in order to supplement conventional geological maps in area-selection for mineral exploration. The broadening of his aims was then encouraged by other national bodies, such as the Natural Environment Research and the Agricultural Research Councils. Professor Webb’s particular contribution has been the chemical analysis of stream sediments so as to obtain an idea of the constitution of the soils and rocks of upstream catchment areas, using computer techniques in the processing and interpretation of the data. The task was formidable, but it was matched by Professor Webb’s determination and leadership. The result is a work of real value.

I know I speak for all the Trustees of the Wolfson Foundation when I say that we were happy that we could provide the funds which were needed to launch the Atlas. We are proud, too, that the name of Wolfson is to be associated with what we trust is both a lasting achievement in itself, and a launching pad for further work in this field.

March, 1977
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Overlays in pocket at back of book
Solid Geology
Superficial Deposits
Compilation of this Atlas stems primarily from advances in the development of stream sediment sampling for mineral prospecting some twenty years ago. This approach, which has subsequently been employed with considerable success in mineral exploration for a variety of metals in many parts of the world, relies on the fact that the products of rock weathering and soil erosion tend to be funneled down the surface drainage system. As a result, the active sediment in the stream bed approximates to a composite sample of those materials derived from the catchment area upstream from the sample site. Consequently, in appropriate circumstances the patterns of mineral distribution in the rocks and/or soils may be reflected to a degree in corresponding variations in the composition of the stream sediment, although they may be subject to modification by secondary processes.

The conventional prospecting technique normally entails systematic sampling of the entire drainage system at all confluences and at regular predetermined distances upstream, followed by analysis for the ore metals and associated elements, with a view to detecting anomalous dispersion trains related to individual mineral deposits. Despite their relatively low cost per unit area, such surveys by the mining industry are necessarily limited to ground previously selected for its mineral potential or geological favourability, supported by regional geophysical information as appropriate.

In 1958, the Applied Geochemistry Research Group at Imperial College decided that the next logical step was to investigate rapid multi-element regional geochemical mapping as a tool to assist detection of potentially mineralized districts in which: to concentrate more detailed conventional reconnaissance aimed at locating individual deposits. Such primary surveys on the regional or national scale would therefore be strictly analogous and complementary to regional geological mapping. At that time (1958) it was believed that if suitable techniques could be developed, the compilation of multi-element regional geochemical maps would inevitably become an accepted national cartographic requirement, for which government Geological Survey establishments would be responsible.

Accordingly, with assistance from industry and the local GeologiCal Surveys we undertook a series of experimental surveys in Zambia and Sierra Leone. These included comparative studies of the relative merits of rock, soil and stream sediment sampling which demonstrated the latter to be the preferred medium for general mapping purposes, particularly in areas of heterogeneous geology and environmental conditions, and indicated the powerful role which computer and statistical methods could play in presentation and interpretation of the data. The results concluded conclusively that multi-element analysis of widely spaced stream sediment samples (at densities in the range of 1 sample per 2.5-190 km², depending on local conditions) could be used not only to delineate potentially mineralized districts, but also to provide fundamental geochemical information relevant to the regional geology as a whole. These studies (and those of other workers) also showed that, providing analysis was confined to the fine-grained fraction of active mineral sediment, the composition was relatively stable under a wide range of seasonal variations and topography.

The value of these maps in the context of environmental problems was also self-evident. Since 1963, our research was therefore extended to Ireland and the UK to investigate the applicability of regional geochemical mapping in fields such as agriculture, pollution and public health, in addition to geology and mineral exploration.

In summary, the specific objectives of our overall programme have been:
(a) investigation of the potential of widely-spaced stream sediment sampling coupled with comprehensive multi-element analysis as a rapid method of detecting broad-scale regional patterns in the distribution of the elements, wherein to concentrate more detailed surveys;
(b) development of methods for the automatic mapping of such data by computer;
(c) exploration of the role of primary reconnaissance of this type, not only in mineral exploration but in a variety of other fields, including agriculture, pollution and public health; and
(d) establishing criteria for the interpretation of the data in terms of the different users' interests.

The overriding consideration in the compilation of this Atlas was cost-effectiveness in obtaining useful maps in the fastest possible time and at minimum cost. This was achieved by a combination of rapid sampling and analytical techniques, followed by computer processing and plotting of the data. The total cost was in the order of £100,000. Although it is now seven years since the project was initiated in 1969, preliminary regional 1:652,000 line-printer maps were placed on open-file between 1972 and 1974. The delay in formal publication was largely due to problems experienced in data verification and reanalysis, and in solving the major problems of producing the software required prior to automatic production of coloured maps by computer. Merging of the regional data into one file, and preparation of smoothed 1:1,000,000 maps was accomplished in 1975, trials with the colour plotting techniques being completed in 1976.

Scotland was not included in this study because of the high extra costs involved in sampling relatively inaccessible areas. However, 1:250,000 sheets of Argyle, Caithness, Great Glen, Lewis, Little Minch, Shetland and Sutherland (and 1:50,000 sheets of Abingdon and Harlech) have now been covered by the Institute of Geological Sciences regional geochemical mapping programme.

Although the present investigation was undertaken primarily as part of our continuing research into the problems associated with large-scale multi-element, multi-purpose surveys and their interpretation, it is hoped that this Atlas, used in conjunction with geophysical, geophysical, pedological and other relevant sources of information, may have immediate practical and fundamental value in a variety of scientific and technological fields.

In general terms, however, it must be stressed that for whatever purpose that they may be used, regional geochemical maps of this type solve no problems beyond those of highlighting and otherwise assisting in the selection of areas wherein to concentrate more detailed (and therefore more costly) surveys to best effect. Furthermore, interpretation of the maps is not always straightforward and needs to take into account the many factors that can influence the composition of stream sediments. Discussion of these factors, and some examples of potential uses of the Atlas are given in later sections of this Introduction.

The final report of the project is due later to the many persons and organisations who have contributed to this project, but it is fitting that we should, at this point, state that compilation of this Atlas was only made possible by a grant of £65,000 from the Wolfson Foundation in 1969.

Technique

The optimum combination of sampling, analytical and data processing techniques can vary according to the specific purpose of the survey (e.g. mineral exploration for a particular type(s) of deposit) and local geological and environmental conditions. In these specific circumstances, it is normal practice to carry out a preliminary orientation study to establish optimum techniques for the particular problem and terrain to be surveyed. For multi-element, multi-purpose primary regional geochemical mapping, however, the chosen technique must of necessity be a compromise consistent with providing information useful to a diversity of interests under a wide range of local geological and environmental conditions. Detailed orientation studies to cover all these eventualities are impracticable and the chosen combination of sampling, analytical and data processing techniques used here were based on a synthesis of the experience gained over many years during the course of research and exploration surveys in several parts of the UK and elsewhere.

More detailed information concerning the techniques outlined below is available on request from the Applied Geochemistry Research Group (AGRG) of the Geology Department at Imperial College.

Sampling

Preliminary pilot studies in Ireland, England and Wales had shown that the tributary drainage systems and road or track networks were such that, though varying over the survey area, stream sediment
sampling at tributary-road intersections would give a mean sampling density of 1 sample per 2.5 km². Since the objective of these surveys was to detect broad-scale geochemical patterns (25 km² or more) and as the prime sampling cost lies in the time taken to reach the site, the programme for this Atlas was also based on sampling tributary-road intersections wherever the upstream catchment area did not exceed 25 km² (in practice, rarely in excess of 5–10 km²). Contouring of geochemical accessibility, notably parts of Dartmoor and Snowdonia, were sampled on foot. No samples were taken within conurbations and sampling was often severely restricted over ground underlain by massive calcareous rocks where there was little or no surface drainage system. The map on p. 19 indicates the sampling coverage upon which the geochemical maps are based. Sampling was completed over a 10-week period in 1969 by 28 two-person teams of undergraduate geology students operating from hired vans supervised regionally by four postgraduate geologists and coordinated by AGRG staff. A total of some 50,000 samples were collected at an overall cost of £22,600.

At each site, duplicate 100 g composite samples of the active stream-bed sediment were collected 10 m apart and at least 20 m upstream from the road; care being taken to avoid locally collapsed bank material and highly organic sediment. A sampling form, prepared for punching onto computer cards, required the recording of 26 items (grid reference, sample number, physical details of the stream and nature of its banks, the presence of Mn/Fe precipitation, possible contamination, etc.). Apart from the nature of the sample, sample location and number, subsequent analysis of these samples was based on some arbitrary, either because of subjective variation or non-essentiality. Such observations may be useful, however, in any subsequent follow-up stage.

The samples, collected in special wet-strength paper containers, were stored overnight at 60–80°C. One of each pair of duplicate samples was disaggregated (not ground) in a porcelain pestle-and-mortar and sieved to minus 80-mesh (c. 200 µm) for subsequent analysis, while the other was retained for reference purposes.

Sampling variability was examined in detail and was generally found to be within the analytical variability, with the exception of samples where the metal occurred as a discrete mineral, such as tin in cassiterite in south-west England. The relative merits of bulk sampling (1 kg composites) and fine-grinding were also examined. Taken in conjunction with the data processing methods employed and the major objective of delineating broad-scale patterns (as distinct from point-source data) the improved precisions to be obtained by bulk sampling, grinding, etc. were judged to be marginal in their effect on the type of maps comprising this Atlas and could not be justified in terms of the appreciable additional cost involved.

### Analysis

The majority of the elements examined were analysed spectroscopically. Four elements, As, Mo, Cd and Zn were determined by atomic absorption spectrophotometric (AAS) or colorimetric methods, since these elements are important for a number of practical applications and could not be adequately analysed spectrophotometrically. Other interesting elements such as Se, U, F and I, had to be omitted for financial reasons.

### Spectrographic technique

The samples were analysed on a direct-reading ARL 2900B Quantometer for Al, Ba, Co, Cr, Cu, Fe, Ga, Li, Mg, Mn, Ni, Pb, Sc, Si, Sr, Ti and V. Channels were also set up for As, Bi, Be, La, Zr and W, but the quality of the data (mostly below or near the detection limit) was such that it was decided that compilation of maps for these elements was not justified; the Mg map was also omitted on account of unacceptably low between-batch precision. Maps for Si and Ti were also omitted as they were found to give no additional useful information over the survey area sufficient to justify the extra cost of publication.

The sieved fraction of the stream sediment was ignited at 450°C for 3 hours. The sample (0.10 g) was mixed with 0.15 g of buffer using an acrylicite ball-paste in a polystyrene vial on a mechanical shaker. The composition of the buffer was 1 part (w/w) sodium fluoride and 1 part carbon powder with 0.0025 parts each of germanium dioxide and ammonium chloroplatinate, equivalent to 935 and 1730 ppm Ge and Pd in the buffer/sample mixture. The mixture was arced at 106 DC in air using an electrode separation of 10 cm and a burn-time of 90 sec with termination at 60 sec for Ge, Pt, Ti and Gd. The electrodes were 6 mm diameter graphite rods, the anode being cut flat and the cathode containing about 40 mg of the sample-buffer mixture hand-pressed into a conical cavity. The output from the spectrometer was converted directly into concentration values by an on-line Selatron analogue computer linked to an automatic typewriter and an IBM 545 card punch. Using a five-person team, the rate of analysis was 200 samples per day.

### Primary calibration

For the trace elements performed using mixtures containing varying levels of trace elements in a synthetic base, approximating in composition to intermediate igneous rock, prepared from specially purified material. The primary calibration was made on the major elements were made with commercially available standard rock standards. The calibration curves were stored in the analogue computer. Checks on the response of the instrument were made daily before sample analysis by means of repetitive analysis of two standards, one consisting of the pure base, and the other containing each trace element at a concentration of about 75% of the maximum of the useful range. Where necessary, the instrument response was adjusted to give the correct concentrations for these standards.

Possible interference effects were examined in detail. Spectral line overlap was tested by analysis of the rock-base standard containing high concentrations of one of each of the elements determined and some others that might cause interference; only Cr (line 2840 Å) and Ni (line 2949 Å) were found to interfere significantly (with Sn and Ga respectively). Corrections were made by appropriate equations applied during the preliminary stages of the subsequent computer processing. Variations in spectral background caused by changes in the concentrations of the major elements were examined by the analysis of a number of trace element-free mixtures of SiO₂, Al₂O₃, Fe₂O₃, MgO, CaO, Na₂O, and K₂O, ground together in various proportions, igniting some spectrographically as analysed for the samples. Any apparent levels in the trace elements were related to the major element composition by multiple regression techniques. Calcium was found to be the most important factor affecting several elements, including Co, Ni, Li and Sr. Again, appropriate corrections were made during the course of subsequent data processing. Arc effects related to variations in the major components were suppressed by the alkali metal buffer to the point where they were insignificant in the context of the present work.

### Realistic figures for the analytical precision of a single determination of each element are given in the Table. The reflect the total between-batch error incurred in sub-sampling, preparation and analysis based on the results obtained from eight stream sediment standards in over 330 batches of c. 200 samples. Gaussian error distributions were obtained for most elements, with the notable exception of Sn, for which the error distribution was skewed so that normal methods of reporting precision are misleading.

### Element precisions and detection limits

<table>
<thead>
<tr>
<th>Element (ppm)</th>
<th>Detection limit (µg/g)</th>
<th>Concentration range (ppm)</th>
<th>Precision of single determination (µg/g)</th>
<th>Precision of geochemical map (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al/3</td>
<td>1%</td>
<td>4.1–9.0</td>
<td>52</td>
<td>12</td>
</tr>
<tr>
<td>As</td>
<td>4</td>
<td>4–4.0</td>
<td>80</td>
<td>18</td>
</tr>
<tr>
<td>Ba</td>
<td>20</td>
<td>141–330</td>
<td>44</td>
<td>10</td>
</tr>
<tr>
<td>Ca</td>
<td>0.2%</td>
<td>0.03–6.5</td>
<td>99</td>
<td>10</td>
</tr>
<tr>
<td>Cd</td>
<td>0.5%</td>
<td>1–6</td>
<td>54</td>
<td>12</td>
</tr>
<tr>
<td>Co</td>
<td>2</td>
<td>6–77</td>
<td>54</td>
<td>12</td>
</tr>
<tr>
<td>Cr</td>
<td>5</td>
<td>7–820</td>
<td>54</td>
<td>12</td>
</tr>
<tr>
<td>Cu</td>
<td>3</td>
<td>6–580</td>
<td>56</td>
<td>13</td>
</tr>
<tr>
<td>Fe</td>
<td>0.5%</td>
<td>1.6–7.3%</td>
<td>48</td>
<td>11</td>
</tr>
<tr>
<td>Ga</td>
<td>2</td>
<td>4–19</td>
<td>50</td>
<td>12</td>
</tr>
<tr>
<td>K</td>
<td>0.05%</td>
<td>0.52–2.97</td>
<td>42</td>
<td>10</td>
</tr>
<tr>
<td>Li</td>
<td>5</td>
<td>21–221</td>
<td>62</td>
<td>12</td>
</tr>
<tr>
<td>Mn</td>
<td>21–3160</td>
<td></td>
<td>62</td>
<td>12</td>
</tr>
<tr>
<td>Mo</td>
<td>0.6%</td>
<td>3–15</td>
<td>62</td>
<td>14</td>
</tr>
<tr>
<td>Ni</td>
<td>3</td>
<td>7–949</td>
<td>69</td>
<td>14</td>
</tr>
<tr>
<td>Pb</td>
<td>7–520</td>
<td></td>
<td>69</td>
<td>14</td>
</tr>
<tr>
<td>Pt</td>
<td>5</td>
<td>5–17</td>
<td>70</td>
<td>16</td>
</tr>
<tr>
<td>Sn</td>
<td>7</td>
<td>22–1177</td>
<td>124(e)</td>
<td>33(e)</td>
</tr>
<tr>
<td>Sr</td>
<td>31–183</td>
<td></td>
<td>69</td>
<td>14</td>
</tr>
<tr>
<td>V</td>
<td>5</td>
<td>13–189</td>
<td>76</td>
<td>18</td>
</tr>
<tr>
<td>Zn</td>
<td>5</td>
<td>5–300</td>
<td>20</td>
<td>5</td>
</tr>
</tbody>
</table>

(a) Detection limit is quoted here with the lowest concentration at which one can be 95 per cent certain that the result is truly greater than zero.
(b) Concentration range for 50% of the data.
(c) Precision estimate which at which the result is true greater than zero.
(d) Precision estimates which at which the result is true greater than zero.
(e) Concentration range for 95% of the data.
(f) Precision estimate which at which the result is true greater than zero.
Work in progress suggests that several traditional practices in determination of analytical error lead to optimistically biased results, and the quotation of precision figures on a within-batch basis appears to be relatively common in the literature. While within-batch precision values may well be 20–30 per cent lower than the between-batch precisions, only the latter are quoted in the Table since it is these which govern the utility of the geochemical maps.

The standard deviation samples were carefully analysed for as many elements as possible by a variety of non-spectrographic techniques, mainly AAS, spectrophotometry and gravimetry. Agreement with the spectrographic results was close, except for Ba, where the spectrographic results were about 25% higher than those given by AAS. For Sc there was no method available for comparison at the low levels encountered.

Other techniques. Zinc and Cd were determined by AAS after digestion with nitric acid. The resulting solution was diluted for the determination. When calcareous samples were encountered, an appropriate correction was made to the Cd result to compensate for the interference.

Molybdenum and As were both determined by well-established methods on solutions produced after fusion of the samples with potassium hydrogen sulphate. Molybdenum was determined by spectrophotometry after formation of the tellurite-dithiol complex and extraction into toluene. Arsenic was determined by the Gutzeit method. Using two-person teams, analytical productivity was 200 samples per day for Mo and As, and 300 samples per day for Zn and Cd.

Data quality control. A variety of control techniques were systematically employed to monitor the precision and accuracy of the data throughout the programme. The control systems were optimised to ensure re-analysis only of those samples where the results were biased to the extent of causing significant errors in the broad-scale features comprising the regional geochemical patterns.

Complete randomisation of the approximately 50,000 samples prior to analysis, although desirable in principle, was judged to be impracticable. The samples were therefore split into five geographical regions of c. 10,000 samples each, with which a degree of randomization was achieved during sampling since each team was issued with several blocks of sample numbers and there was frequent movement of their base camps from one part of the region to another. However, in these circumstances, control of variations between each analytical batch (c. 200 samples) was especially critical.

Within-batch variation. In the spectrographic analysis, samples showing obviously abnormal results were re-analysed immediately. Agreement and computer processed control data were available on the day after analysis. The information included results obtained by replicate (10–15) analysis throughout the batch of the two standards used for the daily calibration of the instrument. These were scanned for abnormal high means, variance and drift during the day. If any undesirable qualities were detected, a large number of the analytical channels (elements) were usually affected simultaneously, indicating instrument malfunction. If judged sufficiently serious, this led to batch rejection and re-analysis. Computer-produced control charts were also obtained for the levels of Ge and Pd (included in the spectrographic buffer) and the major element oxide sum for each sample in the batch. These charts were scanned for abnormally high variance, extreme variations, trends, periodicity and discontinuity. While some of these features could be the result of the nature of the samples, they were usually used as instrumental causes and could lead to re-analysis of part or all of the batch.

The within-batch variation for Zn, Cd, Mo and As was determined by duplicate analysis of every tenth sample; the second of each pair of duplicates being analysed together at the end of the batch to maximise the probable variation. In practice, the within-batch variation was rarely significant since the zero point and slope of the calibration curve were checked after every tenth sample.

Between-batch variation. Two methods were employed for the long-term control of between-batch variation of the spectrographic data throughout the programme.

The first method was based on the analysis of eight natural standard sediment standards within each batch. These were selected to represent sediment derived from streams draining the major igneous and sedimentary rock-types encountered in the survey. As far as possible, the normal range of trace element concentrations was covered. Standards consisting of 1 kg of sieved (~200 µm) material were repeatedly homogenised but otherwise treated exactly as the other samples. The element values for each standard were plotted on computer produced control charts up-dated at weekly intervals; the daily means for the calibration standards were also plotted for comparison with the behaviour of the natural standards. Since the number of control charts then would not exceed 150, a combined chart was also produced for each element showing the averaged normalised deviate for the ten standards. Any significant deviations on this chart could then be examined more closely on the charts for the individual standards. Any unacceptable batches were re-analysed.

As a further control, the map was compiled showing the locations of all samples analysed in each batch. Any patterns observed in the subsequent geochemical maps which coincided with batch sample clusters were regarded as suspect unless proved otherwise.

Between-batch control for Zn, Cd, Mo and As was controlled by replicate analysis of natural standards, and the re-analysis in a different batch of randomly selected samples representing about 2% of the total. The results were then compared to detect any between-batch bias.

Data processing and map compilation. The analytical corrections and quality control techniques were incorporated in a data management package with provisions for up-dating, adding, deleting or correcting the data on a continuing basis, with generation of quality control information and updated data files as output. The data for each of the five geographical regions of c. 10,000 samples was stored on magnetic tapes which were processed independently to produce preliminary working maps at 4 m:1 in (1:633,600). Finally, the entire set of 1,000,000 syncopic working maps for England and Wales was a whole. The scale of 1:2,000,000 was chosen for this Atlas as the maps would be a convenient size and would be compatible with The Atlas of Britain. The larger-scale maps, including those at 1:1,000,000 remain on open-file at Imperial College.

Line-printer mapping. Apart from the ability to cope with the volume of information, the criteria for the initial map display program were (a) maps should be as rapid and cheap to produce, owing to the necessity of experimenting with different class (concentration) levels; (b) some spatial smoothing should be introduced to reduce sampling and analytical 'noise' to bring out reliable regional patterns; (c) the maps should easily be produced at a variety of scales, and (d) their visual aspects should be such as to make recognition of the geochemical patterns as easy as possible.

The use of rapid line-printer mapping methods for geographical data display is well-established and, accordingly, a special package was developed for coping with up to 10,000 samples of regional geochemical data on the 4 m:1 and 10 m:1 line-printer perforator at the College Computer Centre. Up to 10 printed symbols of increasing visual density, representing increasing metal concentrations, were obtained by over-printing one or more characters. The size of the typewriter-like characters of the line-printer output (0.125 by 0.100 in.) implied that in many cases more than one symbol would fall on a single cell. In these cases, the values were averaged, using the geometric mean where appropriate, thereby introducing a first stage of smoothing. A further degree of smoothing aimed at defining broad-scale patterns with a reasonable degree of confidence was achieved by a spatial moving average technique. This was done using a 'window', normally of $3 \times 3$ cells, scanned across the mapped area cell by cell. The resulting average for each central cell has been shown to be stable to relatively large amounts of 'noise' and only a substantial improvement (accompanying a large increase in time and computer power) and analytical techniques would produce a significant enhancement of the broad-scale geochemical patterns sought. The cell positions quoted in the Table are extremely conservative estimates of the reliability of the overall trend, since the spatial correlation properties of the geochemical patterns will tend to lower considerably the estimation error. This arose not only due to the large areas of similar patterns in the percentile maps relative to the 'smoothing window size', but also by the strong spatial correlation between maps of different elements.

Provision was made for interpolation of values into blank cells (i.e., no samples) surrounded by at least four adjacent cells with sample values. This resulted in filling-in small 'holes' in the coverage, and preserving natural boundaries such as coastlines and lakes. Major non-sampled areas (conurbations and large areas with no surface drainage) thus appear blank in the smoothest maps. Comparison of the unmoothed with the smoothed zinc map (pocket and P.60) demonstrates the effectiveness of the technique.
For certain elements (Cd, Co, Li, Ni, Sc and Sn) which gave an appreciable proportion of map cells with 'zero' values (less than the smallest digit recorded) a special pre-processing procedure was necessary in order to overcome the effect of this on production of the smoothed, gap-filled map when using the geometric mean. However, a slight residual effect from this cause is apparent in some of the maps.

Three changes in the software were necessary prior to processing the combined data for the final colour plotting: (a) the rectangular shape of the line-printer characters induced a slight directional distortion which was removed by progressively smoothing the baseline function; (b) the color was unnecessary to use recursive line-by-line smoothing as the total number of cells involved (c. $35,500$) exceeded the capacity of the computer core store; (c) smoothing was performed on the basis of actual concentration values rather than map-cell grey-level values.

Lasergraphic plotting. While use of rapid line-printer plotting is a convenient method for producing preliminary working maps, they suffer from the disadvantage that patterns in the middle to low concentration ranges are relatively difficult to discern. This problem has been largely overcome by the production of maps from original maps in which the photographic density of each cell is a measure of the metal concentration level. The presentation has been further improved in comparison with the grey monochrome maps comprising our experimental Atlas for Northern Ireland, by overprinting in two or three colours.

Production of the continuous tone images upon which the accompanying maps are based was made possible using a Dresser LGP7203 lasergraphic plotter system (at Seiscom Ltd., U.K.). The plotter was initially used extensively for geophysical data processing and the development of its monochrome mapping capability in 1971. In essence, it employs a helium-neon laser, the light from which is modulated by computer-generated plotting instructions as it scans across a stripe of dimensionably stable photographic film (analogous to a television line-scan system). Our software generates a master tape on the CDC computer system containing plotting instructions for the grey-level information for each map, automatically stacking the maps to make full use of the 40-in. film width. This tape is then converted to line-scan plotting instructions on an IBM 370 computer, which generates a new tape to be read by a mini-computer controlling the plotter. (We are currently developing a programme to generate LGP plotter tapes on the CDC system.)

Multi-colour representation of the chosen concentration (class) intervals used in this Atlas was achieved using a method of pre-processing the monochrome LGP plotter tape, developed by Seiscom Ltd. in 1975–76, to generate separate images corresponding to each colour combination (magenta, blue and yellow) required for the final printing in register.

Alternatively, three single-element monochrome map images may be combined in a similar way to produce maps showing the simultaneous variation of all three elements by subtractive colour mixing. Special reflectance of the laser beam reduces the spot size slightly at lower intensities and accounts for the faint white line at the margin of the lightest red and blue tones in the two-colour maps. However, this does not occur with the three-colour maps, owing to the different combination of intensity levels present.

Given the appropriate software, map production by lasergraphic plotting is extremely rapid and relatively inexpensive.

Selection of concentration (class) intervals. Two maps were prepared for each element, based on empirical concentration intervals and the other on statistically determined intervals.

Selection of the class intervals for the empirical maps was based on the prior experience of the different user requirements and the frequency distribution of the values encountered. The final intervals and the two-colour presentation were chosen with a view to emphasizing the high metal areas (of interest in mineral exploration, agricultural toxicity, pollution and public health, for example) and the low metal areas (of particular interest to agricultural and dietary deficiencies). For each individual element, up to six line-printer maps using different class intervals were prepared from which the one giving the maximum information from these points of view was selected for incorporation in the Atlas.

A visual representation of the patterns inherent in the data is obtained by selecting class boundaries on a percentile basis (i.e., a known proportion of the data having concentrations less than the lower boundary of each class). This method appears to give more information concerning subtle patterns in the intermediate concentration ranges. Previously, equal decile intervals were used for the Atlas for Northern Ireland but, as the main practical interest is generally focussed on the relatively low and very high values, a mixed system has been used here with class boundaries at the 10, 20, 40, 60, 80, 90, 95, 99 and 99.9th percentiles. While emphasizing the top and bottom tails of the frequency distribution, this system also provides for reasonable definition of patterns in the intermediate concentration ranges which could be of particular interest in relation to fundamental aspects of the regional geochemical or geological distributions as a whole. In order to obtain the best definition of these intermediate patterns, three-colour printing has been used for the presentation of the mixed-percentile maps. Percentile maps for Cd and Sn could not usually be produced because of the high proportion of values falling below the detection limit. The percentile selection technique ensures that the maps have the same number of classes chosen on an exactly comparable basis. The empirically selected maps can differ considerably in appearance and the number of 'best' human-selected classes of interest differ, quite apart from the fact that the basis of their choice may also differ. Inspection of the maps in this Atlas will show that spatial correlation between element patterns is more obvious in many cases in the percentile-based maps.

Notes on interpretation and geological significance of the Atlas

No attempt is made here to make a full interpretation of the Atlas, either as regards the geology or the technological applications outlined in the following section. The objectives are to note some of the geological correlations underlying the general validity of the techniques and to indicate the factors that need to be accounted for when using the Atlas for the variety of different user interests.

The main factors influencing the geochemical patterns are the bedrock geology and nature of the overburden, contamination and environmental conditions.

Bedrock geology and overburden

In drift-free areas covered by residual soil or where the superficial overburden is glacial till of local origin the patterns are generally related to the underlying bedrock (p. 17 and overlay), although in local till-covered terrain there may be some smearing (usually less than 10 km) in the direction of ice movement. Where the superficial cover is exotic, either glacial or alluvial, the patterns reflect the composition of the cover rather than the underlying bedrock. The map on p. 18 (and the overlay) show the distribution of glacial and other superficial deposits, but the available maps do not always differentiate between locally derived glacial deposits and those of exotic origin; this fact must therefore be taken into account when interpreting the maps in this Atlas, as well as when using the Atlas for the variety of different user interests.

The stream sediment is essentially a composite sample of material derived from the upstream catchment area, it will be appreciated that small-scale variations within the catchment will tend to be averaged out in the composition of the sample. The patterns will therefore only reflect broad-scale or highly anomalous compositional variations in the bedrock and/or overburden.

Amongst the outstanding patterns associated with igneous rocks are those related to the granites of south-west England. Although associated with the same batholith, the granites are characterized by differing degrees by high K, Ga, Li, Al, low Ba and, as might be expected, by low Co, Cr, Mn, V and Ni; the highest Li patterns coincide with the Bodmin (entered on grid reference SX2075) and St Austell (SX0555) granites; K is relatively high over the Bodmin and Dartmoor (SX6575) intrusions, and Ga attains its greatest concentration over the St Austell and Lands End (SW4030) granites. A number of elements are enhanced in the vicinity of the granites, notably As, Co, Cr, Fe, Ni and Sc. These could be related, in part at least, to the basic 'greystone' that occur in the surrounding rocks. The ultrabasic complex of the Lizard in Cornwall (SW7515) is clearly evident in the high patterns for Cr, Co, Fe, Mn, Ni, V and Sc, coupled with low Li, K and Cs. The Ordovician volcanic series in the Lake District in northern England (NY3930) are well expressed by high

* Grid Reference as shown on p. 6.
patterns for As, Cd, Co, Fe, Mn, Sc, V and Zn. As a final example of correlation with igneous activity, the complex of lavas, tuffs and granites in the Arrochar Hills (NT3002) are characterised by high Ba and K, with moderate Al, Ga, Sr and V.

The stream sediment patterns associated with the sedimentary formations, from the oldest to the most recent, are largely dependent on the lithology (argillaceous, arenaceous or calcareous) of the drainage. The patterns, however, not only reflect variations in the lithology of the principal formations constituting the stratigraphic succession but also variations—where they exist—in the composition of similar lithological types within or between the formations shown on the geological map. Examples include: (a) the pattern related to the Lower Palaeozoic (Cambrian-Silurian) rocks, comprising massive shales and greywackes with occasional suites of volcanic rocks, which are characterized by high Al, Co, Ga, Fe, Mn and Ni; Sc and Li are also moderately increased over these formations in Wales and the Ordovician in the Lake District; (b) the Old Red Sandstone in south-east Wales and parts of the Devonian in south-west England show relative enrichment in Cr; the Devonian and parts of the Carboniferous are also enhanced in Li in the south-west; (c) the Coal Measures in south Wales, the Pennines (SK5450 to SE2040) and Durham (NZ1015 to NU0020) are accompanied by high Cu, Co, Fe, Mn and Sc, with moderate Ni and Zn; (d) the Triassic formations generally show higher Ba, Sr and K—this is particularly evident for Ba and Sr in the Bristol district (ST6073); (e) moderate Cu, Fe and As patterns occur over the Jurassic sediments, as being related to ironstone facies, particularly in Northamptonshire (SP8960 to SK5250); the Chalk shows strongly in Cr, Cu and Sr and generally low in other elements, as would be expected; (g) monobdenum and in places Cd and As are commonly related to marine black shale horizons ranging in age from Lower Palaeozoic to Mesozoic; the most intense patterns occur over the Lias south of Bristol; (h) the basin-stratigraphy of these sediments in the extreme south-east England is strikingly evident in the ovoid patterns for Al, Ba, As, Co, Ga, Fe and Mn accompanied by moderate Ni, K, V and Zn; while some of these patterns may be enhanced by secondary environmental effects, others are undoubtedly related to the geochemistry of the various sedimentary horizons comprising this structure.

While it is clear that many of the geochemical patterns reflect features that might be expected from the known geology, it is even more important that they also provide evidence concerning the geographical distribution of elements that would not be susceopt to such geological factors and, if present, to the survey. These patterns relate not only to lithological variations but also to geochemical variations within the igneous rocks and sedimentary formations of the survey area. (The same conclusion is also true for the Pre-cambrian metamorphic terrain as shown on our Geochemical Atlas for Northern Ireland and generally low in other elements, as would be expected; (g) monobdenum and in places Cd and As are commonly related to marine black shale horizons ranging in age from Lower Palaeozoic to Mesozoic; the most intense patterns occur over the Lias south of Bristol; (h) the basin-stratigraphy of these sediments in the extreme south-east England is strikingly evident in the ovoid patterns for Al, Ba, As, Co, Ga, Fe and Mn accompanied by moderate Ni, K, V and Zn; while some of these patterns may be enhanced by secondary environmental effects, others are undoubtedly related to the geochemistry of the various sedimentary horizons comprising this structure.

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Environmental conditions

Considerable attention has been given to the possibility of "spurious" patterns related to natural environmental conditions. Of these, the potentially most important problems lie in areas of moorland, peaty acid soils where Mn, Fe and other metals may be leached during weathering and soil formation and re-precipitated in the oxidizing stream environment or adjoining bank soils. In these circumstances, co-precipitation of elements such as Co, Zn and As, could give rise to enhanced background levels and thus misleading stream sediment patterns. Although this tendency has been noted in a number of such areas, in no case have the resultant patterns been sufficiently enhanced as to pose a major problem of interpretation, except in the agricultural context (see later). The problem could be more significant, of course, in areas of extensive moorland areas over the Lower Palaeozoic rocks in North and Central Wales and in the Lake District, however, the manganese patterns—possibly enhanced by secondary processes—could well be reflecting the manganiferous horizons known to occur in these formations.

There are many other environmental factors that can influence the concentration of the elements in the stream sediments, such as extremes of pH, biological activity, accumulations of organic matter and precipitation of calcium carbonate in some streams draining calcareous rocks. These could however be important in detailed follow-up studies but have not yet been shown to have any marked effect on the broad-scale patterns shown in the accompanying maps.

Technical applications

In addition to the fundamental geological applications indicated above, multi-element geochemical patterns of this type have a number of valuable potential uses in a variety of technological and environmental fields including: (a) area selection for mineral exploration; (b) delineating suspect areas of clinical, sub-clinical and latent fracture elements disorders in crops and livestock; and (c) environmental studies, including land-use and public health with particular reference to trace element pollution surveys, the assessment of water quality for potable supplies, the metal content of foodstuffs and in medical geography.

In whatever context the Atlas may be employed, it is essential to appreciate that the data present broad-scale geochemical patterns and that the first phase in pin-pointing precise areas of interest should rely on more detailed conventional stream sediment sampling to all the tributary drainage within the patterns shown on the maps. At all stages, full use should be made of available geological, geophysical, pedological and other relevant sources of information, as well as taking into account the various factors mentioned above which influence the composition of the stream sediments (see previous section).

Mineral exploration

England and Wales have a mining industry going back to Phoenician and Roman times. It is not surprising therefore that the broad-scale patterns for the base metals should have outlined all the old mining districts where the patterns have to a greater or lesser degree been enhanced by local mining and smelting activity. Such patterns are evident in south-west England (high Sn, Cu, As, Pb and Zn) and the lead-zinc districts of the Mendip Hills (Pb, Zn, Ba and Sr; ST5052). The major centres of lead-zinc deposits in Wales, including Hafren-Miners (SJ2970), Llithfaen-Miners (SH4820) and Plynlimon (SN8080) and in West Shropshire (SJ3500) are characterized by high Pb and Zn with high Cd and Ba in some cases, and the copper mineralization at Parys Mountain, Anglesey (SH4588) is also shown by the strong pattern for Cu in this area. Other examples are the base metal districts of the Pennines in Central and Northern England (NY9040, NZ3000, SE0065 and SK2063), which are clearly demarcated by strong patterns for Pb, Zn, Ba and Cd, and the Lake District in north-west England (NY3515) by high Cu, Pb and Zn. The cupriferous sandstone formation in Cheshire (SJ1585) shows high Cu and As, with no reference has already been made to some of the other mineral occurrence formed by high Fe and V accompanied in places by As and Sc.

These obvious patterns related to known mining districts may assist in delineating areas for closer density conventional reconnaissance, as well as indicating more subtle patterns shown by the base metals in areas where the known geology and regional geophysical
information are potentially favourable for mineralization. This could be particularly relevant in relation to types of deposit that were not actively prospected in the past, such as the low-grade copper deposit at Coed-y-Bryan (SH7525) and uranium (now being sought by the Institute of Geological Sciences using geochemical mapping techniques) and in the more intensive search for industrial minerals. The regional geochemical data taken in conjunction with geological and geophysical information could also assist in exploration for ‘blind’ deposits in the vicinity of the known mineral districts.

During the course of our pattern-checking programme, relatively little follow-up has been done on mineral exploration aspects of the Atlas since this was thought to be more properly within the province of the mining industry and the Institute of Geological Sciences. Some attention has been given, however, to certain features bearing on interpretation, notably the tin and arsenic patterns in southwest England, which are more extensive beyond the limits of the known mineralization. Extension of the patterns has in part been related to working during the Pliocene marine transgression, and anomalies due to this cause can generally be distinguished by the absence or supporting arsenic and/or copper values. The widespread arsenic patterns were found to be in part due to smelting and acid drainage in a region of high mineralogical rich in the soil and bedrock, especially around the Dartmoor and Bodmin granite intrusions. Minor lead–zinc patterns were followed up in South Wales and the possible use of stream sediment data in conjunction with other geological information was investigated as a means of locating base metal targets subject to possible multi-element interactions and inter-relationships, the effects on the health of animals and plants and the importance of these factors to the agricultural industry. The value of combined element maps in this respect is illustrated by that for Cu, Co and Zn (pp. 63 and 69) which clearly highlights those areas where all three elements are present in low concentrations.

In concluding this section, it is necessary to stress that the problem of interpreting stream sediment data in terms of the metal content of the soil can be complex. While most of the agriculturally important area of England and Wales correlation between the wide patterns of trace element maps in stream sediments and the local soils has been shown to be good, there are some notable exceptions. For instance, in poorly-drained organic moorland conditions or where upland soils are podzolized, certain trace elements, such as Mn and Co, may be leached from the surface horizons and either accumulated deeper in the soil profile or re-precipitated in neighbouring down-slope soils or in the stream-bed. In these circumstances patterns of Mn and associated elements portrayed in the stream sediment maps do not reflect the composition of soils in the catchment. These areas are clearly defined where soil maps are available and the advantages of combining knowledge of soil type with the stream sediment data are manifest.

Pollution

High concentrations of some metals in the environment may endanger the health of animals and man, the suitability of foodstuffs and water supplies for human consumption. Such metals as Cd and Pb may be present as pollutants from industry or originate from the weathering products of natural metal-rich bedrocks. In order to evaluate man’s contribution of such metals as contaminants, it is important to establish natural variations in metal distribution related to the geochemical composition of rock and soil.

The reconnaissance maps provide a useful catalogue of base-line information and at the same time highlight specific areas contaminated by past metalliferous mining and smelting and by present-day industry and urbanisation. For instance, the map for Cd shows cadmium-rich areas in south-west and central England and Wales contaminated by the mining and smelting of sulphide ores, where in some instances the mining activities commenced as long ago as Roman times; the same map highlights at least two areas of recent industrial pollution (ST5277, SS9582) and several areas underlain by cadmium-rich marine black shales (e.g. SK1755).

In the context of pollution the maps have three major applications:

(a) Land-use and farming: The survey has indicated extensive areas in which soils are contaminated with one or more of the elements As, Cd, Cu, Pb and Zn (see for example the combined metal maps, derived from mining and other industrial activities), Not all soils within the anomalous patterns are polluted and the geochemical maps do no more than draw attention to those areas where detailed soil examination is important. Even when contaminated soils are confirmed, the metal may not be readily available to the crop or pasture; the form and uptake
of the metal then requires study, and if dealing with foodstuffs, the edible part of the plant or animal should be examined. In Derbyshire, for instance, the survey delineates land contaminated by past mining and smelting and reflects some agricultural soils containing more than 1 per cent Pb; uptake by pasture is however relatively low with plant values of under 100 ppm and 300 ppm Pb in summer and winter grass respectively. On the other hand, blood values reflect to a degree the high lead status of the area, perhaps due to ingestion of lead-rich soil by the grazing animal.

The maps show apparent 'haloes' for Cd, Cu, Pb and Zn around several industrial towns and cities; to date these patterns have not seemed to reflect any large-scale soil contamination.

(b) Water supplies: Trace elements in river water may at times exceed the recommended guidelines for the quality of potable waters suggested by the World Health Organisation; for instance, international and European standards for drinking water recommend limits of 0.6 mg/l. Cu, 0.01 mg/l As and 0.1 mg/l Pb.42 In the future, EEC requirements are likely to be more stringent.

Preliminary investigations into the applications of geochemical reconnaissance maps to water quality assessment have been encouraging. As a follow-up to the maps published in this Atlas, studies in four metal contaminated and un-contaminated river systems in south-west England have shown that high concentrations of Cu, Pb and Zn are more likely to occur in the water of stream and rivers with higher rather than normal contents in the sediment.45

Therefore, the relationship between metal contents of drainage and water is variable and subject to factors such as rainfall, run-off, water hardness and local environmental conditions, the maps would seem to be useful in assisting in the siting of stations for water monitoring, in that the sediment usually provides a more stable index of the metal status of the drainage than the water itself, which is subject to large-scale diurnal and seasonal variations in metal content. The multi-element stream sediment data also provide a list of suspect elements for inclusion in monitoring programmes. Research in this field is continuing with the aim of improving interpretative criteria.

(c) Estuarine Fisheries: Elevated levels of metals in British coastal waters are limited to estuarine sites and inshore waters and are found to be due in part to drainage from industrial and mineralized areas.46,47,48 Geochemical studies in an area of North Wales (SH7555) highlighted by the maps for Pb and Zn showed up to 1 per cent of both metals in the sediment of mineralized tributary drainage of the River Conway with up to 3000 μg/l Zn in the waters. Waters drawn from the estuary for use in an oyster hatchery showed marked fluctuation in zinc content ranging from 1 to 470 μg/l Zn, related to tidal cycle and time of year.49 Toxicity tests showed oysters (Crassostrea gigas) placed in a contaminated estuary in south-west England rapidly accumulated Cu, with the content of whole-tissue dry matter rising from 250 to 6000 ppm Cu over 6 months.50 The relationship between metals in waters, particulate material and sediments in the input drainage and the estuary are however extremely complex and while general relationships have been established, more work is necessary to define the form and bio-availability of metals in relation to their source before the geochemical maps can fully be utilised in this context.

Medicine and public health
The relationship between trace elements in the natural environment and human disease is controversial and causal relationships are limited to those between fluorine in water and dental caries, iodine and goitre and (in Russia) molybdenum and endemic goit. Neither F nor I are included in the Atlas and Mo levels in the UK are far below those determined in the Mo mining areas of USSR. In studies on cardiovascular disease in Britain, high levels of Pb were found in human bones in soft compared with hard water towns,51 though this is more likely to be due to plumbo-solvency than to direct relationships with geochemical factors. Cancer of the stomach in parts of North Wales has been correlated to the Cu: Zn ratio in garden soils,52 though this has not been confirmed elsewhere. Similarly, above normal amounts of Cu, Pb and Zn in garden soils have been reported in localities with abnormally high prevalence of multiple sclerosis, and high Pb and Zn associated with above normal mortality rate for cancer of the stomach, though whether there is any causal relationship is not known.53,54

Local mortality and morbidity statistics are on the whole poor and it is difficult to obtain reliable information for comparison with the geochemical maps. Similarly, base-line data on the trace element content of human tissues is extremely limited and regional studies in the UK lacking. The Atlas maps do provide, however, a unique source of information to assist in the selection of sampling locations for such surveys and in building up a base-line data bank for epidemiological studies.55 As previously indicated, they also focus attention on key areas for detailed surveys on soils, foodstuffs and water supplies, that may form an integral part in future studies on geochimistry and health.

The map for Pb has already been used to select areas to study the relationship between soil Pb and childhood Pb burdens. Garden soils in villages near old mines and smelters in Derbyshire ranged from 1000 ppm to over 2 per cent Pb, compared with 200 to 1000 ppm Pb in neighbouring areas. Lead levels in blood and hair of 2–3 year old children were significantly higher in the high Pb villages than in the controls.56 It is envisaged that more studies on the health aspects of these maps will develop in the near future as interest in this subject increases in the UK.

Concluding remarks
The maps comprising this Atlas are regarded as experimental prototypes compiled as a result of a research programme into the concept and problems of compiling rapid, low-cost, multi-element, multi-purpose maps commenced in Africa nearly twenty years ago. Many of the patterns in the Atlas remain to be checked in the field and much research remains to be done to devise appropriate interpretational criteria suited to the variety of user interests. Whatever the purpose—be it mineral exploration, environmental studies or any branch of fundamental research where the distribution of the elements is a relevant factor—regional geochemical maps of this type have no problems beyond those of assisting in the selection of areas wherein to concentrate more detailed surveys to best effect. It must be stressed that interpretation is not necessarily straightforward and can only be undertaken in conjunction with knowledge of the geology, pedological and geophysical information (as appropriate) and other factors that can influence the composition of the stream sediment.

We hope that this Atlas will have immediate practical value and lead to the development of future generations of more definitive surveys. In this connection, the Geological Division of the Institute of Geological Sciences is currently engaged on the compilation of a geological map based on stream sediment sampling of tributary confluences in Scotland which it is hoped will eventually be extended to cover the whole country, leading to maps giving point-source information at 1 : 50,000 and 1 : 250,000 scale.

With these prospects will provide users of information in the UK it is even more important that they show the work required to compile multi-element, multi-purpose national geochemical atlases in those countries where the geology, mineral potential and environmental base-lines are less well established. The fact that geochemical atlases are an essential complement to the geological map should be obvious and the multi-purpose potential is such that we hope this concept will eventually lead to international cooperation with a view to compiling compatible data for the benefit of the world community as a whole.

Acknowledgements. As stated earlier, compilation of the Atlas was due entirely to a substantial grant from the Wolfson Foundation. The Foundation have also generously agreed that any royalties to Imperial College resulting from this publication shall be used by the Applied Geochemistry Research Group for further research aimed at improving the interpretation and usefulness of the Atlas.

We are also indebted to the Natural Environment Research Council for financial assistance which contributed towards solving the complex problems of compiling the computer software involved, and to the Agricultural Research Council, the Ministry of Agriculture, Fisheries and Food and the White Fish Authority for assistance in selecting the utilisation of their results in their respective fields.

In addition to those members of the Applied Geochemistry Research Group named on the title page who helped in the sampling, analysis and data processing, we extend our gratitude to those of the Computer Centre at Imperial College for their assistance and advice with regard to the computer problems, particularly Mr. G. W. Nordanholt, Mr. J. Benbow, Mr. J. Greenaway, Mr. S. Budd, Mrs U.
Dove and Mr D. E. Evans. We are also grateful to Mr P. S. Ferrer of Selcos Ltd. for his cooperation and advice on laserographic plotting and providing the interface required for the production of the colour-separated master-prints for the Atlas.

We are also grateful to our colleagues Dr D. R. Boyle, Professor J. P. Sutterley, Professor Janet Watson, and Dr S. H. L. Molyne and Dr Jane Plant of the Geochemistry Division of the Institute of Geological Sciences, for their valuable comments and suggestions concerning the contents of this introduction.

The simplified maps showing the topography, the solid and superficial geology are based on those prepared by the Ordnance Survey and the Institute of Geological Sciences.

References

Sample Distribution
Distribution of the 49,484 sample points.
Calcium (percent) 10, 20, 40, 60, 80, 90, 95, 99, 99.9th percentiles
Copper (ppm) empirical classes

- ≤0
- ≤7
- ≤15
- ≤30
- ≥60
- ≥120
Lead (ppm) 10, 20, 40, 60, 80, 90, 95, 99, 99.9th percentiles

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Lithium (ppm) empirical classes

≥0.  ≤12.  ≥25.  ≤50.  ≥100.  ≥200.  ≥400.
Manganese (ppm) 10, 20, 40, 60, 80, 90, 95, 99, 99.9th percentiles

0.0 0.226 0.267 0.410 0.555 0.674 0.911 2.219 5.690 9.491

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Molybdenum (ppm) empirical classes

-0.5

-1.0

-1.5

-2.0

-2.5

-3.0

-3.5

-4.0

-4.5

-5.0
Potassium (percent) 10, 20, 40, 60, 80, 90, 95, 99, 99.9th percentiles
Strontium (ppm) 10, 20, 40, 60, 80, 90, 95, 99, 99.9 th percentiles

- 0
- 22
- 29
- 38
- 51
- 79
- 106
- 143
- 286
- 477
Vanadium (ppm) 10, 20, 40, 60, 80, 90, 95, 99, 99.9th percentiles

- < 0
- > 13
- > 20
- > 33
- > 48
- > 66
- > 81
- > 94
- > 115
- > 154
Combined element map for empirical Lead (red), empirical Copper (yellow), and empirical Zinc (blue); increasing colour contribution with increasing element concentration.
Combined element map for empirical Copper (red), empirical Cobalt (yellow), and empirical Zinc (blue), increasing colour contribution with increasing element concentration.
Combined element map for empirical Molybdenum (red), increasing colour contribution with increasing element concentration; and percentile Copper (blue), increasing colour contribution with decreasing element concentration.
Combined element map for empirical Cadmium (red), percentile Zinc (yellow), and percentile Lead (blue), increasing colour contribution with increasing element concentration.