REGIONAL GEOCHEMICAL MAPS OF THE UNITED KINGDOM ENVIRONMENTAL AND ECONOMIC APPLICATIONS

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by

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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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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

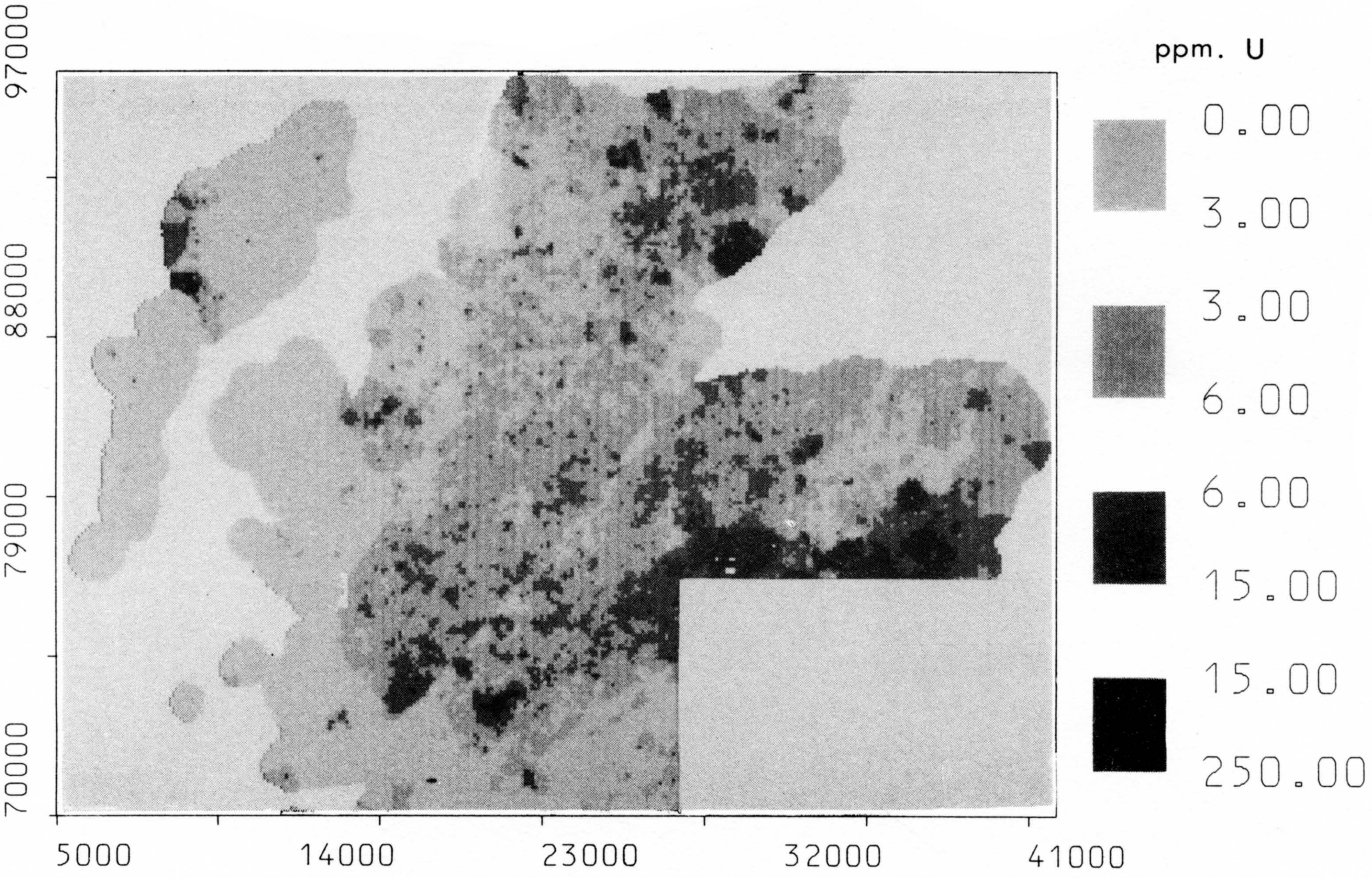
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Plate 11

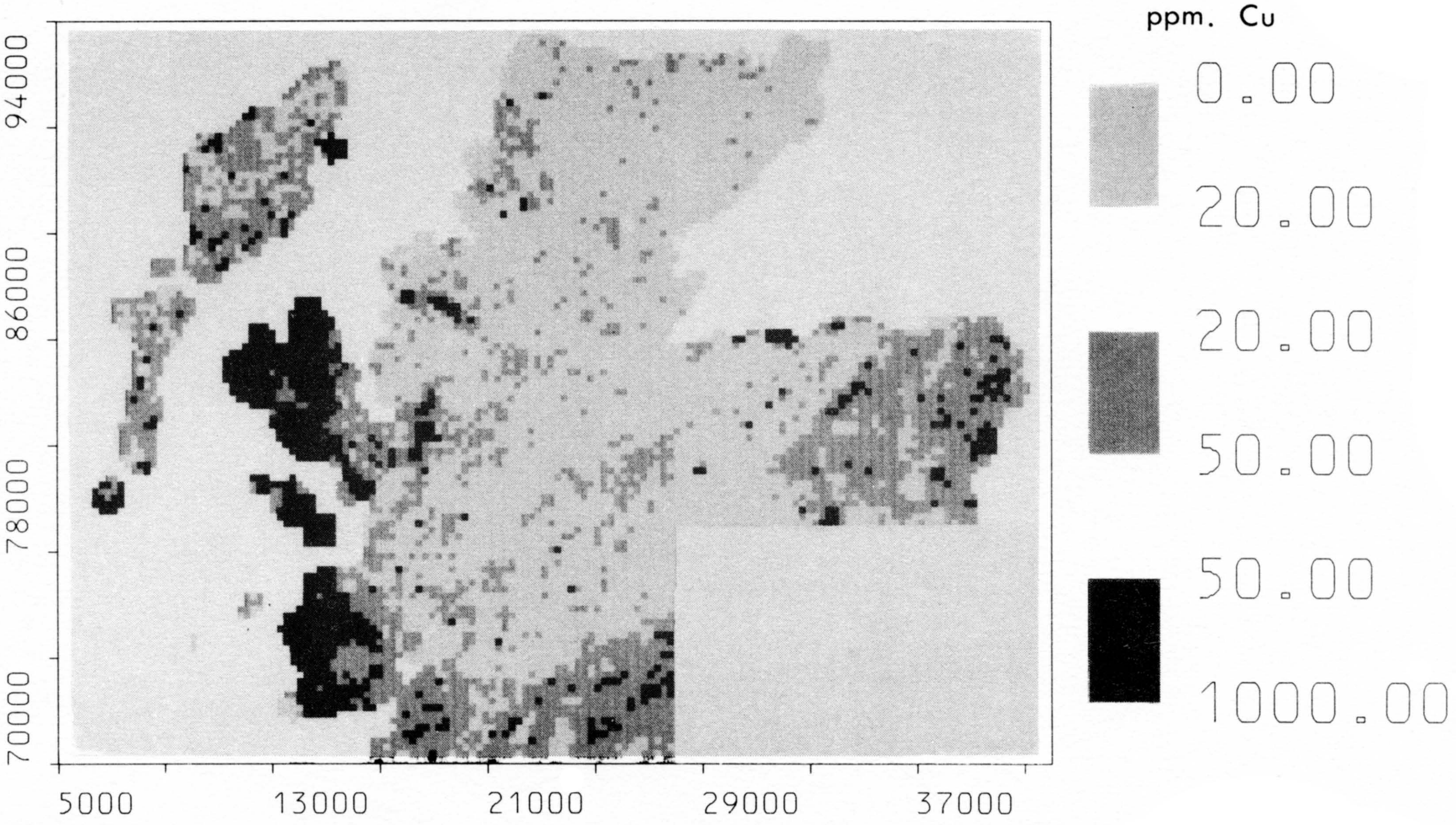
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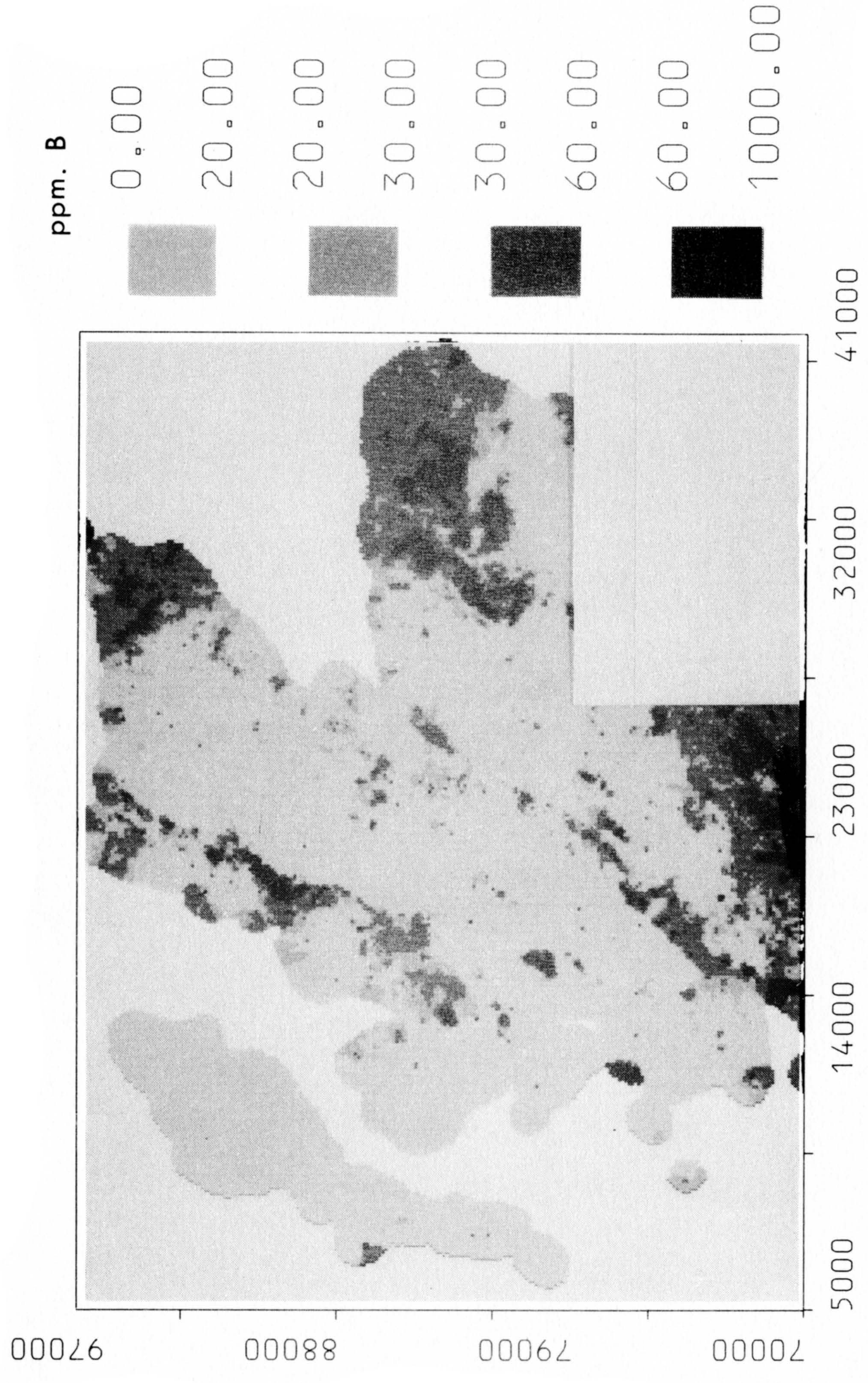
Plate 12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