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Regional geochemical mapping

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[Plates 1 and 2]

One of the prime requirements for effective study of environmental geochemistry in relation to health is the production of multi-element atlases showing the distribution of the elements on the regional scale. The choice of method for compiling such atlases can vary according to a number of geological, environmental and other factors. The overriding consideration, however, is to assist (in conjunction with other relevant sources of information) in defining, quickly and cheaply, potential problem areas wherein to concentrate more detailed studies to ensure maximum return from the funds and scientific manpower available.

Numerous sampling and analytical techniques have been employed. Each technique and approach has its own scope, limitation and problems of interpretation. Whatever method is chosen, the use of computer-based statistical data reduction, analysis and map compilation is mandatory.

Although it was apparent more than 20 years ago that geochemical atlases would eventually become a national cartographic requirement, regional geochemical mapping is still in the experimental stage. This trend is now evident in activity in a number of countries. The methods being employed, however, are so diverse that there is an urgent need for international collaboration aimed at securing data that are as mutually compatible as possible, having regard to the conditions, needs and resources of the individual countries involved.

1. Introduction

One of the prime requirements for effective study of environmental geochemistry in relation to health is the compilation of multi-element atlases showing the distribution of the elements on the regional scale. Recognition of this requirement is now evident from activity in a number of countries, but there are wide variations in approaches to the problem. This is not surprising when one considers both the early stage of development of the atlas concept, and diversity arising from variations in the magnitude, conditions, needs and resources of the countries involved.

As yet there is no generally accepted consensus regarding the techniques that might best be used to achieve common ground relevant to a problem that has a material bearing on the well-being of mankind as a whole. Within the scope of this paper it is not possible to cover any aspect in detail. Consequently, attention is directed to the broad issues of technique, presentation and interpretation of regional geochemical data. The treatment is to some extent controversial but it is hoped that this paper will stimulate the discussion and activity that are essential towards achieving the production of regional geochemical atlases. In the widest possible sense, such atlases are complementary and equivalent in their fundamental and practical value not only to conventional regional geological, pedological and geophysical maps but also to those maps currently being produced from satellite imagery.

2. STRATEGIES FOR REGIONAL GEOCHEMICAL MAPPING

In general terms, three main lines of attack have emerged, each based eventually on the analysis of one or more of a number of readily accessible sampling media, such as rock, soil, plant, water, and lake and stream sediment:

(*a*) extrapolation of the results of detailed studies in type localities considered to be representative of large areas;

(*b*) low-density multi-stage (hierarchical) sampling of large units considered to be relatively distinct;

(*c*) methodical wide-spaced sampling of the entire survey area.

Taking extrapolation first, the most obvious basis for selecting type localities is the geological map. Admittedly, there are well established variations in the trace element composition of such widely divergent rock types as basic and acid igneous and metamorphic rocks, sandstones, limestones and clays. Nevertheless, there are often significant differences in composition within a single geological unit, particularly in the stratigraphic (time dated) sedimentary formations which can vary in lithology from place to place. Even where the lithology is uniform, appreciable changes in trace element composition are not uncommon owing to variations in the source of the sedimentary material and/or to selective mobilization and redeposition of certain elements during the course of compaction and diagenesis. Similarly, there can be geochemical differences between igneous rocks of the same type and age and also within an individual intrusion or suite of metamorphic rocks. Further complicating factors arise when the bedrock is covered by superficial deposits of glacial, fluvial or aeolian origin and where interrelated variations in weathering, climate and biological activity can materially affect the trace element content of the near-surface material, which bears most closely on the soil–plant–animal régime. A similar type of extrapolation, based primarily on the national soil map, has been used to compile geochemical maps of New Zealand (Wells 1967).

In the U.S.S.R., Kovalsky and coworkers, faced with the enormous area of that country, have devised an interesting rationale for extrapolation based on the definition of biogeochemical zones characterized by (*a*) relatively uniform soil-forming processes, (*b*) climatic conditions and (*c*) comparable biogeochemical behaviour of the elements and the response of organisms to geochemical and physical factors of the environment (Kovalsky *et al.* 1970). While having undoubted value in environmental geochemistry, this approach does not provide multi-element geochemical atlases as such.

An entirely different approach has been investigated in the U.S.A., where the U.S. Geological Survey conducted a reconnaissance geochemical survey of Missouri State to develop and explore methods applicable to large regions (Tidball 1972; Miesch 1976; Erdman *et al.* 1976). The method was based essentially on random sampling of previously mapped broad geological, pedological, vegetational and hydrological units at very low densities ranging from one sample per 150 km^2 (agricultural soils) to one sample per 625 km^2 (uncultivated soils and vegetation). Statistical analyses of variance techniques were used to study and identify geochemical variations between each selected unit. For many of the 30–40 elements analysed in the different sampling media, the results indicated that the variability within units was comparable to or exceeded the variability between units, and that second-stage higher density sampling would be required to arrive at meaningful geochemical maps.

While we appreciate the daunting task of compiling useful geochemical maps of such large regions at a realistic cost, the results to date indicate that the extrapolation and multi-stage low-density sampling approaches can at best provide no more than a very broad initial guide to areas within which more detailed surveys might be required. Furthermore, quite extensive geochemical patterns of environmental significance could clearly remain undetected. These methods would therefore seem to be most applicable in those parts of the world where there are extensive relatively homogeneous geological, pedological and environmental units. They would not be applicable, however, in many countries such as the U.K., where the geology, soil type and other factors vary markedly on the small scale.

The third approach, methodical widespaced sampling of the entire survey region, is more attractive for a number of reasons, principally because (*a*) no prior knowledge or selection of specific geological or other geographical units is required (and in many areas the necessary information is either lacking or inadequate) and (*b*) the results provide the basis for compiling *multi-element*, *multi-purpose* geochemical atlases which can then be used as an *independent* source of information to assist in selecting areas for subsequent investigations of a variety of problems including those concerned with agriculture, land-use, public health and mineral resources. In addition, since the data are not influenced by subjective factors (other than those involved in the selection of sampling, analytical and processing techniques) the maps provide positive base-line information and can also highlight anomalies in metal distribution that might otherwise have remained unsuspected. Finally, quite apart from their practical value, such atlases have important fundamental significance in regional geology and, indeed, in any area of scientific research where knowledge of the geographical distribution of the elements is a relevant factor.

3. Sampling

Accepting the concept of methodical sampling, the main problem lies in the interrelation between choice of sampling medium, analytical procedure, data processing and map compilation. The overriding consideration is cost-effectiveness in the context of cost per unit area, the objectives of the survey, the funds available and the timescale: the influence of environmental and geological factors and the extent of the survey area on this choice is self-evident.

As previously stated, for most practical purposes the sampling media include exposed or near-surface rock, soil, vegetation, water, and lake or stream sediment. Compilation of maps based on sampling and analysis of one or more of these materials on a more or less systematic basis is the essence of geochemical prospecting for mineral deposits. Here, the objective is to disclose patterns in the distribution of the elements that can be related to concealed mineral deposits. The sampling medium, sampling density and analytical technique are adjusted to achieve this in the most cost-effective manner. For environmental purposes, the only additional requirement is to increase the element coverage and to decide on the best sampling medium and sampling density deemed necessary to detect patterns of element distribution of a size commensurate with the economic, social or health objectives of the reconnaissance. When conditions (nature of the overburden, factors affecting metal dispersion, etc.) are essentially similar over the survey area, it is common practice to carry out a preliminary orientation study to determine optimum sampling and analytical technique. In broad-scale surveys of large regions, these conditions usually vary to such an extent that orientation studies can become impracticable and the chosen reconnaissance mapping system is necessarily a compromise based on a synthesis of previous experience and observation.

The problems of cost-effective, multi-element, multi-purpose geochemical mapping are extremely complex and must vary according to the environmental conditions and economic resources of any given nation. In this short paper the treatment is necessarily oversimplified, but the reader should keep in mind the interactions between sampling, analysis, data processing, map compilation and interpretation that may be needed to attain any given objective. In this instance, we are considering environmental geochemistry and health but, at the same time, a method which also produces useful information relating to mineral resources and fundamental science is clearly advantageous.

It is impossible to generalize in such a broad context, but taking the first option of choice of sampling medium:

Rock has the disadvantage that the sample is representative of only the small area in the vicinity of a sample site; compositional variations are dependent on the degree of weathering, and the more resistant rocks tend to be the most readily available; rock samples provide little or no information relating to man-made pollution and are costly to collect and prepare for analysis. Furthermore, they are of no use in areas covered by exotic overburden. The bedrock is, however, important in its effect on the composition of soils derived therefrom and of ground-water supplies extracted for consumption by humans and livestock.

Vegetation is discounted as a medium for compiling regional geochemical maps because of variations in chemical composition related to species, age and time of year; tedious sample preparation is also a factor. (Regional variations in vegetation related to trace element abundance in the soil have obvious environmental applications particularly when used in conjunction with airborne and satellite imagery. This important subject is not considered here, as the end product does not result in geochemical maps *per se*.)

Surface waters are not favoured primarily because there are diurnal and seasonal variations in composition and particulate matter related to rainfall; bulky samples need to be collected; composition is liable to change during storage; and the low levels of concentrations (often in the micrograms per litre range) pose analytical problems.

Soil is attractive in that it is easy to sample and analyse, reflects the composition of the parent material and is one of the closest links in the pathway of the elements into the crop–animal–man régime. The disadvantages of soil as a medium for regional geochemical mapping are similar to those for rocks because a soil sample is representative of only a small area and its characteristics can change markedly over short distances according to topography, drainage and a number of other factors affecting the soil formation process. High density soil sampling would be ideal but is economically impractical on the regional scale in many areas.

Active stream sediment represents the closest approximation to a composite sample of the products of weathering and erosion derived from the rocks and soils in the catchment area upstream from the sampling site. The sample is easy to collect, prepare and analyse, and the area which it is required to represent can be selected from either topographic or air photographic maps which are now available for most parts of the world. Unlike stream waters, the composition of the sediment is relatively stable and, although it consists mainly of clastic (mineral) material, there is usually some degree of relation between its composition and the soluble constituents of the associated stream water. Apart from their origin, stream sediments are subject to variations introduced by such factors as selective deposition during transport, precipitation of Mn and Fe oxides which can 'scavenge' certain elements (notably Co), and adsorption on organic matter. The impact of most of these variables can be minimized by analysis of the fine fraction (commonly 150–200 μm) and avoiding the collection of obvious organic-rich sediment and locally collapsed bank material. Ferromanganese precipitation has received considerable attention; it is mostly prevalent in those areas where soil formation promotes mobilization of these elements under reducing conditions and the elements are then precipitated when the local groundwater enters the oxidizing environment of the surface drainage. Experience indicates that the general significance of this problem has probably been exaggerated but, where it is suspected to have been important, methods are available for 'normalizing' the affected metal contents against the recorded concentration of Fe and Mn, particularly that fraction which is readily reducible. Another disturbing factor can arise in some areas of calcareous rocks where massive precipitation of $CaCO_3$ in the surface drainage system can seriously dilute the content of other metals; again this can be resolved, if necessary, by normalizing against the Ca content.

Two other media possess the advantage of stream sediment as natural composite samples. The *heavy mineral fraction* of stream sediment is one but is discounted for environmental purposes because it is mainly composed of resistant minerals, the constituents of which are virtually precluded from entering the food chain. *Lake sediment* is analogous to stream sediment in that it is a 'sink' for the products of weathering of the catchment area. In large areas of northern Canada, stream systems are poorly developed and the bottom sediment from the centres of the numerous lakes are being collected for mineral exploration at an average density of one sample per 13 km^2 (Cameron & Hornbrook 1976; Hornbrook & Garrett 1976). The scavenging influence of the organic-rich sediments, Fe and Mn oxides for U appears to be negligible. Other elements being studied include Co, Ni, Cu, Pb, Zn, Mo, As and Hg, but whether the data obtained from this material will be suited to environmental problems has yet to be ascertained.

It will be evident from the foregoing that, at this stage, tributary stream sediment is considered to be generally the best sampling medium for regional geochemical mapping. An adequate drainage system is obviously essential. Where this does not exist, the next choice would be soil sampling. A combination may well be required to obtain the desired coverage. Both media can give information on regional pollution but neither can be relied upon to pinpoint localized solid or liquid effluent which is usually discharged in the immediate vicinity of the source or into the main river systems and thereby constitutes a separate subject for *ad hoc* investigation.

Whatever the medium, sampling density is determined by the minimum size of the target area that can be justified on economic grounds, the timescale and resources available. In the U.K., where the mineralized districts are well known, the Institute of Geological Sciences is doing an admirable job by sampling all confluences of the tributary drainage required to locate individual mineral deposits, while at the same time analysing the samples for a range of elements of interest to environmentalists. The initial effort is being concentrated in geological areas with favourable mineral potential; extension of this programme to give complete national coverage will inevitably take several years to accomplish. In less well explored countries, a less rigorous lower density (and hence more rapid and lower cost per unit area) sampling programme may be more expedient in locating mineralized *districts* in which to concentrate more detailed surveys. The strategy at all times is to reduce progressively the target area stage by stage to locate the source, be it a mineral deposit, or the cause of an agricultural or pollution problem, as quickly and cheaply as possible.

Finally, on the subject of regional sampling, accessibility is a major factor. The prime costs at this point are the technical qualifications (and hence salary) of the sampling crews and the time taken in traversing between sample sites. Sampling technique and the level of supervision should therefore be adjusted to attain reliable sampling at minimum personnel cost. The objectives of the reconnaissance and sample density should be carefully considered as costs escalate dramatically if sampling has to be done on foot or by air transport.

4. Analysis

Analysis for regional geochemical mapping requires multi-element instrumentation, coupled where necessary with rapid atomic absorption spectrometric and/or colorimetric procedures, in order to achieve a wide analytical coverage at minimum cost per determination. The direct-reading arc emission spectrometer has been the central instrument to date, but is likely to be superseded in the near future by systems based on inductively coupled plasma excitation. Whatever the analytical system, it is highly desirable in the interests of efficiency that the multi-element output be linked automatically to a computer for subsequent storage, data processing and map production (see § 5).

The question of relative sampling, subsampling and analytical errors is critical (Miesch 1971; Nichols 1971). Clearly, all three must be compatible and, in this connection, numerous studies indicate that with modern instrumentation, variability due to field sampling and subsampling will often exceed that due to analysis (Howarth & Lowenstein 1971; Plant 1971; Bølviken & Sinding-Larsen 1973; Tourtelot & Miesch 1975; Plant *et al.* 1975; Cameron & Hornbrook 1976). Again, the correct optimum balance depends on local conditions, the objectives of the survey and finance. If the objectives and the promise of an economic return require precise values at individual sample locations (point-source data), then stringent efforts to reduce sampling, subsampling and analytical error can be justified. On the other hand, if the objective of the survey is to define broad areas for subsequent investigation in greater detail, then this can often best be achieved by accepting lower-cost sampling and analytical procedures accompanied by appropriate statistical techniques resulting in delineation of geochemical *patterns* of the desired size and contrast at an acceptable level of confidence.

In most surveys the samples have been analysed in numerical sequence. However, Miesch (1971) first drew attention to the value of randomization before analysis of samples passing through the sample preparation and analytical sequence in order to convert any systematic errors into random errors in terms of the patterns of the element concentrations when plotted on a map. Recent examples include those given by Plant *et al.* (1975). While we do not dispute the advantages of randomization, it is clearly not possible to randomize the entire set of samples involved in a long-term field programme extending over a number of years before analysis, since no maps would be produced before the end of the programme. Randomization should, therefore, be limited to as large a number of samples as deemed practicable in the interest of compiling maps of successive parts of the survey area for user applications as soon as possible.

Continuing data quality control is essential for the long runs of analyses typically encountered in regional geochemical programmes. Regular insertion of synthetic and/or natural standard samples similar in bulk composition to that of the survey samples, the use of internal standards (i.e. the addition of selected elements added to each sample in known concentrations), automatic correction for variation in bulk composition and background noise, and reanalysis of samples falling markedly outside the quality control limits selected, have long been employed. More recently, a variety of methods based on regular duplicate analysis of a random selection of the survey samples have been introduced (Garret 1969; Michie 1973; Plant *et al.* 1975; Thompson & Howarth 1976; Howarth & Thompson 1976). With multi-channel (element) spectrometers, the probability of any single element falling outside preset control limits in a batch may be quite high. In the interests of economy, reanalysis is therefore usually restricted to elements deemed to be the more important for the objectives of the survey. Clearly, the more stringent (and hence more costly) quality control procedures are necessary where reliable data are required for each sample site than where the data are subsequently processed for presentation as generalized spatial patterns in map form (see § 5). Ideal control strategies to suit differing requirements have still to be developed, the course of which will be greatly influenced by the recent dramatic decrease in the cost of minicomputers and microcomputers. These devices, when coupled to the analytical instrumentation, will not only speed up the time to assess the reliability of the analytical results but will also permit real-time adjustment of instrument calibration, corrections for drift, and other aspects of quality control.

Finally, on the subject of analysis, multi-element instrumentation and a throughput of, typically, 200 samples or more per day demand some form of automatic data acquisition and a computer-based management system for storage and retrieval. Results may be stored on paper tape, magnetic tape or cassettes, or on floppy disk, and management systems based on a large central computer have been developed, mostly by Government agencies, in a number of countries including Canada, France, the U.K. and the U.S.A. General accounts of several of the systems in use are given by Hutchison (1975).

5. Compilation and presentation of regional geochemical maps

Regional geochemical maps can be broadly classified into three types (table 1):

(*a*) 'point-source' maps indicating the element concentrations at each sample site;

(*b*) contoured or layer-tinted maps depicting spatial patterns in the distribution of the elements;

(*c*) multi-component maps showing the effects of simultaneous variations of several elements.

Hand-drawn maps are clearly inefficient except for relatively small areas involving a limited number of elements. Computer-based systems are imperative for cost-effective compilation of regional geochemical atlases in the broadest sense. Furthermore, since the data and sample–site coordinates will already be stored on tape, cassette or disk, computer mapping allows the flexibility of investigating several plotting options at little extra cost before choosing the best maps for final presentation; 'best' implies presenting the data in the form that provides the most readily discernible visual information required by the user. This flexibility is particularly important when the data are to be grouped into concentration classes for plotting as symbols, contours or layer-tinted units. Evans (1977) gives a very useful survey of methods for class selection.

Since it is almost impossible to discern patterns in maps showing numerical values, point-source maps usually consist of symbols of varying size and/or intensity or colour. A wide range

TABLE 1. EXAMPLES OF LOW-DENSITY REGIONAL GEOCHEMICAL MAPS†

region	area/km²	sample type‡	density km²/site	no. of elements	scale	map type§	aim‖	reference
Zambia	7.8×10^3	SS	2.6	9	1:0.20M	P	M	Webb *et al.* (1964)
Sierra Leone	2.6×10^3	SS	2.5	16	1:0.54M	C	M	Nichol *et al.* (1966)
Sierra Leone	3.9×10^4	SS	180	15	1:2.8M	P	M	Garrett & Nichol (1967)
Eire	1.7×10^3	SS	2.6	17	1:0.13M	P	M	Kieley & Fleming (1969)
Zambia	2.1×10^5	SS	188	16	1:8.5M	C	M	Armour-Brown & Nichol (1970)
Derbyshire, U.K.	2.5×10^3	SS	3.4	16	1:0.25M	P	M	Nichol *et al.* (1970)
Conterminous, U.S.A.	3.9×10^8	S	4.3×10^5	30	1:17M	P	M	Shacklette *et al.* (1971)
Ontario, Canada	3.6×10^4	L	12	11	1:0.25M	P	X	Hornbrook & Gleeson (1972)
Missouri, U.S.A.	1.8×10^5	S	157	32	1:4.5M	P	M	Tidball (1972)
N. Ireland	1.4×10^4	SS	2.8	22	1:0.63M	C, M	M	Webb *et al.* (1973)
Uganda	2.3×10^5	S, SS	70, 263	8	1:2.0M	C	X	Geol. Surv. Uganda (1973)
England and Wales	1.5×10^5	SS	2.8	24	1:2.0M	C, M	M	Webb (1975); Webb *et al.* (1978)
Shetland Is, U.K.	2.2×10^3	SS	1.8	20	1:0.25M	P, (M)	M	Plant & Rhind (1974) Inst. Geol. Sci. (1978)
Gt Plains, U.S.A.	3.4×10^5	S	2.6×10^3	26	1:4.8M	C	M	Tidball & Severson (1975)
Thailand	9.0×10^3	SS	1.5	14	1:0.12M	P	X	Garson *et al.* (1975)
Saskatchewan, Canada	1.6×10^5	L	11	12	1:0.25M	P	X	Cameron & Hornbrook (1976)
Saskatchewan, Canada	5.2×10^4	L	13	12	1:1.0M	C	X	Hornbrook & Garrett (1976)
British Columbia, Canada	1.6×10^3	L	32	12	1:0.50M	P	X	Hoffman & Fletcher (1976)
Winston-Salem, U.S.A.	1.8×10^4	SS	13	16	1:0.25M	P	X	Baucom *et al.* (1977)
Peru	2.5×10^4	SS	25	16	1:1.7M	C	X	Baldock (1977)

† Surveys with densities greater than or equal to one site/km² are excluded as they are generally carried out solely for detailed mineral exploration purposes (see, for example, Cockburn 1977).

‡ Sample type: SS, stream sediments; L, lake sediments; S, soil.

§ Map type: P, point source; C, contoured, etc.; M, multi-component.

‖ Aim of survey: M, multi-purpose; X, mineral exploration.

of symbols have been employed but the most commonly used to date are graded circular symbols (Webb *et al.* 1964; Nichol *et al.* 1966; Hornbrook & Garrett 1976; Shacklette *et al.* 1974; Cockburn 1977). A scheme of proportional line symbols is being used by the Institute of Geological Sciences (Plant & Rhind 1974; Plant & Moore, this symposium). Point-source maps

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DESCRIPTION OF PLATE 1

Figures 1–4 are reproduced from Webb *et al.* (1978) with permission of the publishers, Oxford University Press.

FIGURE 1. Regional distribution of Zn (ppm = parts/10^6) in stream sediments from England and Wales. Unsmoothed map cell values based on 49464 data points. Classes based on 10, 20, 40, 60, 80, 90, 95, 99, and 99.9th percentiles. Sampling gaps, mainly due to lack of streams over carbonate rocks or to major conurbations, appear white.

FIGURE 2. Regional distribution of Zn after local moving average smoothing. Percentile classes as for figure 1.

FIGURES 1 AND 2. For

description see opposite.

FIGURES 3 AND 4. For desc

Combined element map for empirical **Copper** (red), empirical **Cobalt** (yellow), and empirical **Zinc** (blue) ; increasing colour contribution with increasing element concentration.

scription see opposite.

are necessarily limited to scales controlled by the area covered and the sample density. Consequently, unless the sampling density is very low, the largest practical scale is generally 1 : 250 000. Unless it is essential to have point-source information, patterns in the regional distribution of the elements are far easier to recognize visually from contoured or layer-tinted maps. This is particularly true of subtle variations which may nevertheless be significant.

Contoured maps based on fitting a polynomial 'trend' surface have been used experimentally (Nichol & Webb 1967; Nichol *et al.* 1969; Lepeltier 1977) but are not recommended as they are insensitive to relatively local geochemical variations of interest. A wide variety of computer contouring packages have been developed, mostly based on interpolation of the raw data on to a regular grid followed by contour 'threading' through the interpolated values (see Rhind 1975). Computational costs can be high for the more sophisticated systems, and maps produced by computer line-printer are being increasingly used as a low cost alternative for the rapid production of synoptic maps at scales ranging from 1 : 250 000 to 1 : 1 000 000 (Howarth 1971; Geological Survey of Uganda 1973; Webb 1975). Moving average smoothing is rapidly becoming the standard method of reducing noise from sampling and analysis and enhancing the clarity of regional geochemical patterns (Nichol *et al.* 1966; Armour-Brown & Nichol 1970; Webb *et al.* 1973; Hornbrook & Garrett 1976). By using line-by-line recursive scanning, smoothed maps of large data sets (10^6 items and more) may be processed rapidly with minimal computational overheads; by using an appropriate computer program, the data can be presented to a laser-graphic plotter (as used for satellite weather maps, for example) which can produce at very low cost master-films for printing maps in half-tone or colour (Webb *et al.* 1973; Webb *et al.* 1978).

The originals of the maps in figures 1–4, plates 1 and 2, have been produced by the laser plotter method. Figures 1 and 2 show the improvement in the clarity of the spatial patterns on smoothing with interpolation to fill in the smaller sampling gaps. Any correlation between the distribution patterns of the elements are enhanced using the same class boundaries (where possible) for each element, based on the concentration values corresponding to fixed percentages of the data. Empirical classes chosen by the user (figure 3) primarily for particular interpretation purposes (e.g. mineral exploration or agriculture, etc.) may make it more difficult to relate one element to another, mainly because of the visual problem when the maps for each element are based on different numbers of classes.

An outstanding problem is the development of methods for assessing the simultaneous interaction between the several elements composing a geochemical atlas. Visual integration is strictly limited and cannot possibly cope with more than two or three elements; even within this limitation only the most obvious interactions can be discerned in the geochemical patterns with any degree of reliability. Various statistical methods such as principal components and factor analysis have been used for this purpose (Nichol & Webb 1967; Garrett & Nichol 1969; Nichol *et al.* 1969; Armour-Brown & Nichol 1970; Nichol 1971; Miesch 1976; Erdman *et al.*

DESCRIPTION OF PLATE 2

FIGURE 3. Regional distribution of Zn with the use of 'best' set of empirical class intervals chosen by geochemists to emphasize major features. Local moving average smoothing has been applied.

FIGURE 4. Combined element map for empirical Cu (red component), Co (yellow component) and Zn (blue component). Colour mixing produces an increasing colour contribution with increasing element concentration. Areas with mutual deficiencies in all three elements appear as light grey tones.

1976). Cartographic methods using multi-arm 'wind-rose' symbols have also been investigated (Rhind *et al.* 1973; Plant & Rhind 1974; Leake & Smith 1975). Colour mixing, based on overprinting different colours varying in intensity according to element concentration, has also been examined (Lowenstein & Howarth 1972; Webb *et al.* 1973; Howarth & Lowenstein 1976; Webb *et al.* 1978; figure 4). While making progress, none of these approaches seems likely to achieve the final solution. The next step must be the development of real-time graphic-display c.r.t. systems that enable the user to 'converse' with the data held in the computer. This notion, incidentally, also holds the key to the optimum selection of class intervals for the presentation of single-element regional geochemical maps.

In summary, a wide range of cartographic methods are now available for computer-processing large sets of regional geochemical data rapidly and cheaply. Many of the more sophisticated techniques are readily available commercially. Colour printing is becoming an accepted output style for geochemical atlases because of its ability to convey more visual information at relatively little additional expense. The ideal forms of map presentation have still to be achieved, particularly those maps that show the interrelations within multi-element data and their geographical distribution.

6. Scope and applications of regional geochemical reconnaissance based on stream sediment sampling

It was evident 20 years ago that it was only a matter of time before regional geochemical maps, analogous to regional geological maps, would become an accepted national cartographic requirement (Webb 1958). An ongoing programme was therefore initiated at Imperial College to examine techniques for this purpose, first in Zambia and Sierra Leone and subsequently in the British Isles (for references, see table 1). It soon became apparent that stream sediment (conditions permitting) was the preferred sampling medium and that the scope for multi-element atlases of this type could be extended to embrace a wide range of environmental applications in addition to mineral exploration (Webb 1965; Webb *et al.* 1968). A parallel programme to explore this potential started in 1963. The results to date (some of which are included in the paper by Thornton & Webb in this symposium) have confirmed expectations of the value of the maps in relation to trace element disorders in agriculture, regional pollution studies, river and estuarine fisheries problems, water supplies, public health and land use.

Although considerable progress has been made, the present state of the art is embryonic. Techniques at all stages will undoubtedly improve, new fields of application remain to be explored and far more needs to be known concerning the geochemical and biological pathways of the elements before the full scope of regional geochemical data can be realized. In the interim, regional mapping with present-day techniques will certainly proceed: first because the problems of compiling atlases can only be identified by the collection of regional data and secondly because current methods, crude though they may be, are nevertheless capable of producing results of immediate practical value.

Quite apart from practical considerations, active stream sediment is Earth material on the move and as such it is an integral part of the geological cycle. Knowledge of its composition, particularly on the regional scale, can provide a unique body of scientific information of fundamental geological value (Webb 1970; Plant & Moore, this symposium).

Finally, it is to be stressed that the use of regional geochemical data is not always as straightforward as might appear, and fully effective interpretation of the data requires an interdisciplinary approach involving the geochemist as well as experts in the appropriate field of study, particularly where agriculture and human health are concerned.

7. General considerations

First, irrespective of how the basic data are compiled and presented, geochemical atlases solve no problems in themselves. Their prime function is to assist in delineating areas wherein to concentrate more detailed specialized investigations. The extent to which geochemical atlases are useful is dependent on the degree to which they can be interpreted for the widest possible range of practical and fundamental purposes. The very diversity of these requirements emphasizes the necessity for a truly multidisciplinary approach aimed at arriving at the best methods of acquiring and presenting regional geochemical information and also in the research to develop interpretational criteria to meet the differing interests of all the eventual users.

The responsibility for compiling national multi-element, multi-purpose geochemical atlases clearly lies with government. In many parts of the world, even a preliminary broad-scale coverage can take considerable time to accomplish. Geochemical surveys of very extensive areas have been and are being undertaken by national and international agencies and industry for mineral exploration. Many of these data and samples would be invaluable for environmental purposes. The acquisition of this material for deposit in national data and sample banks would be a major asset in the national interest.

With so many technical options and increasing activity of regional geochemical mapping at the national level, there is an urgent need, not only for multidisciplinary national groups but also for an international forum for the exchange of views aimed at securing the maximum degree of compatibility of techniques and data. A further problem is that of devising means of acquiring and presenting epidemiological information in such a way as to make full use of the geochemical maps in the context of human health and disease.

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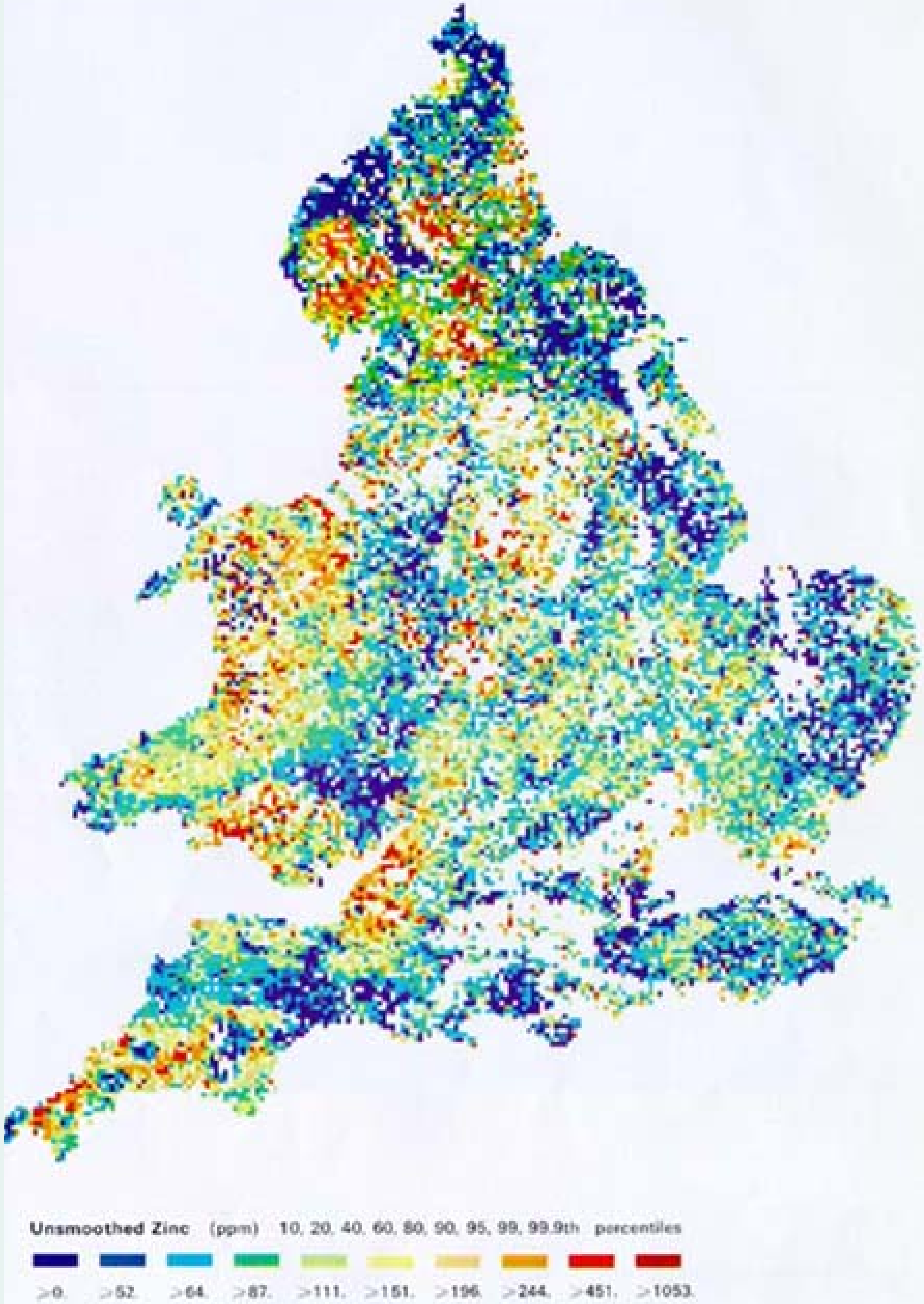
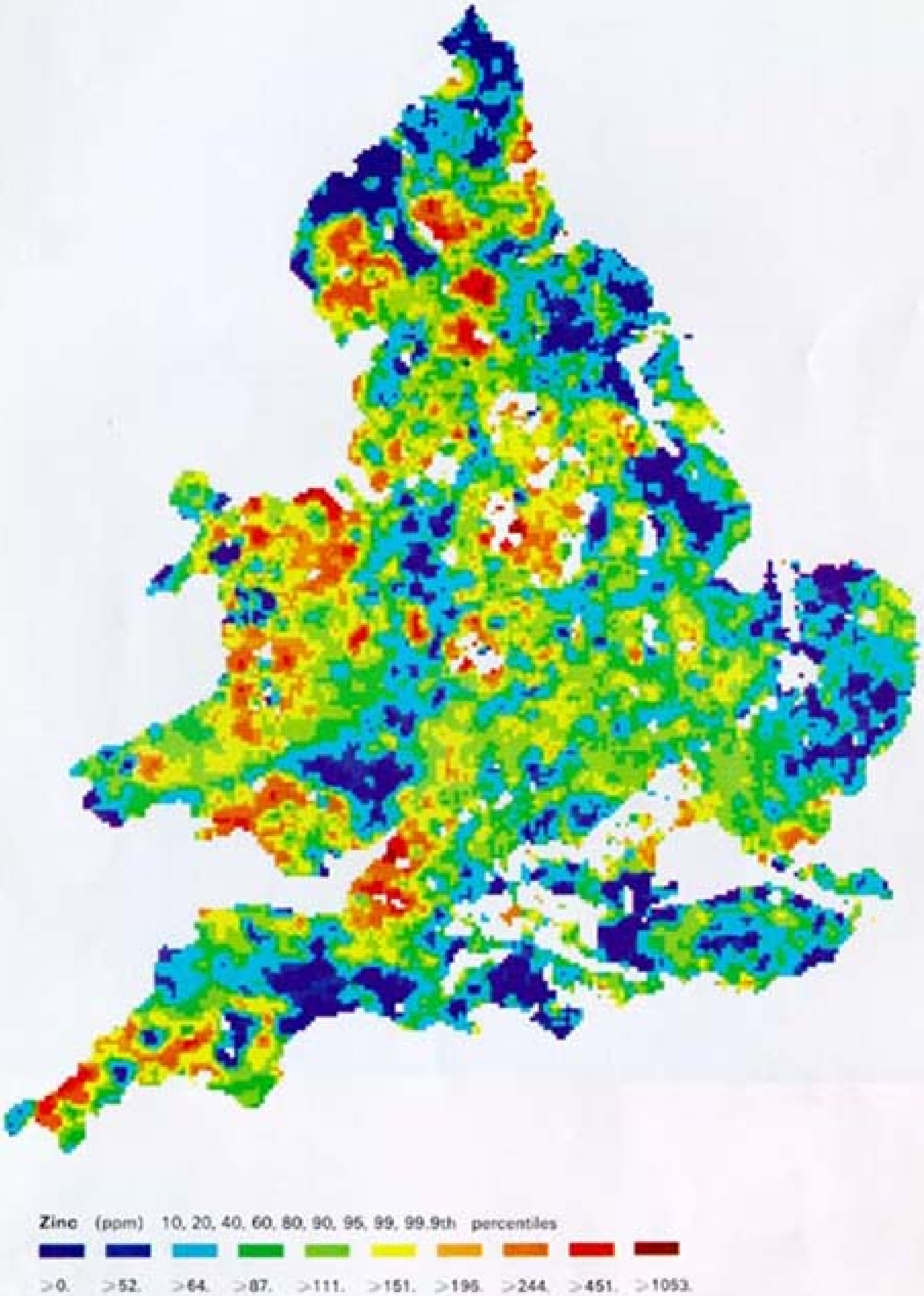
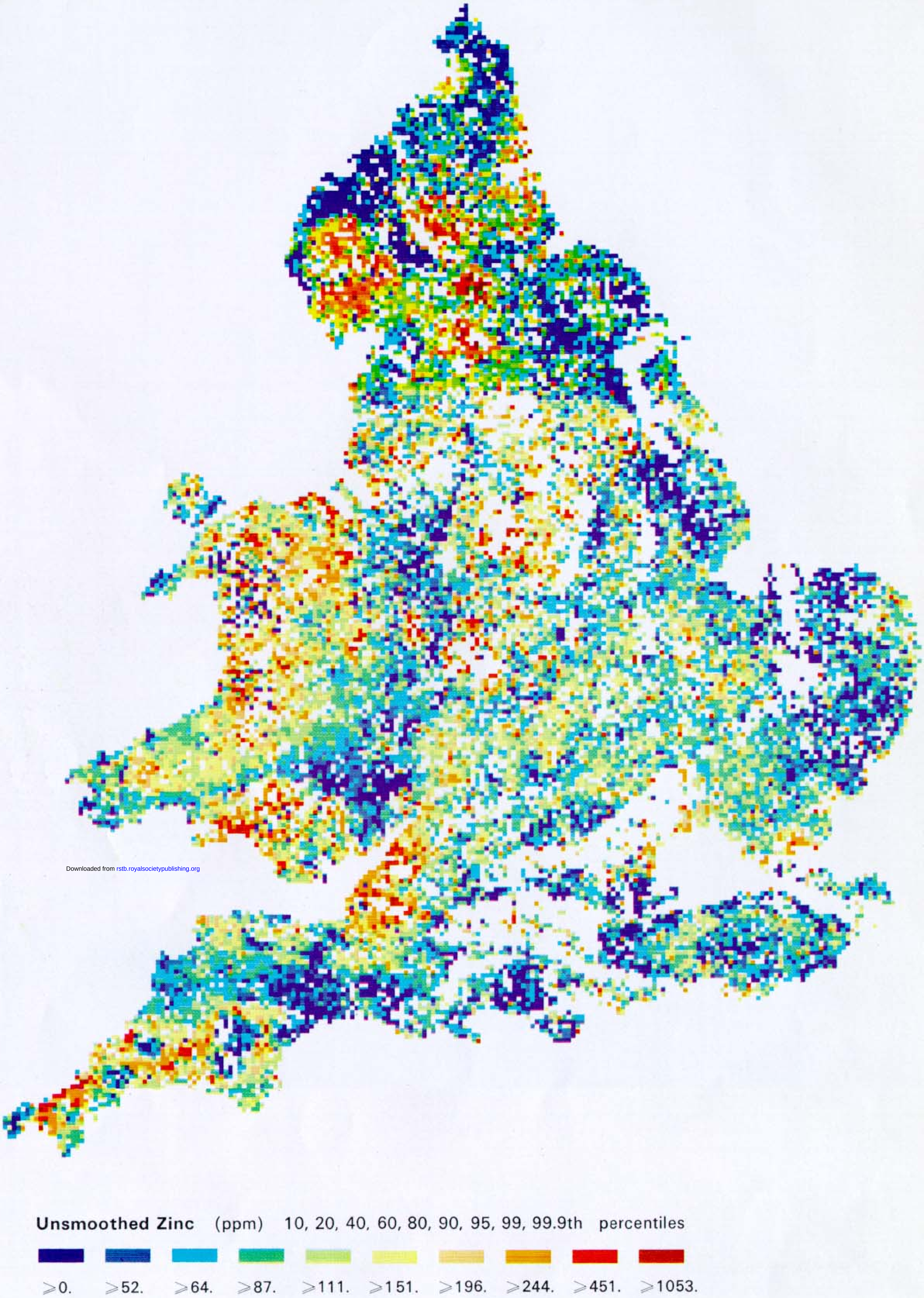




FIGURES 1 AND 2. For description see opposite.



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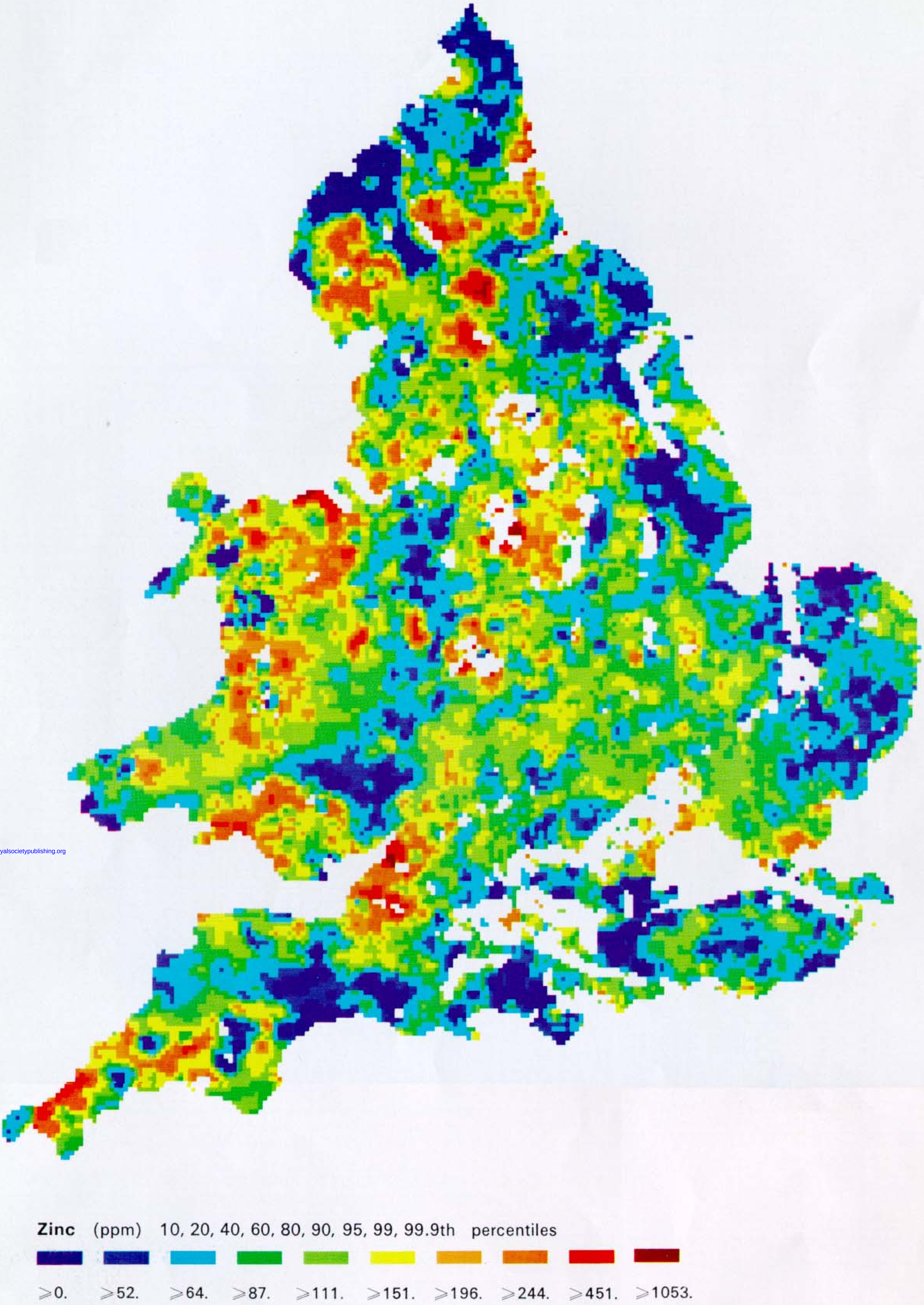

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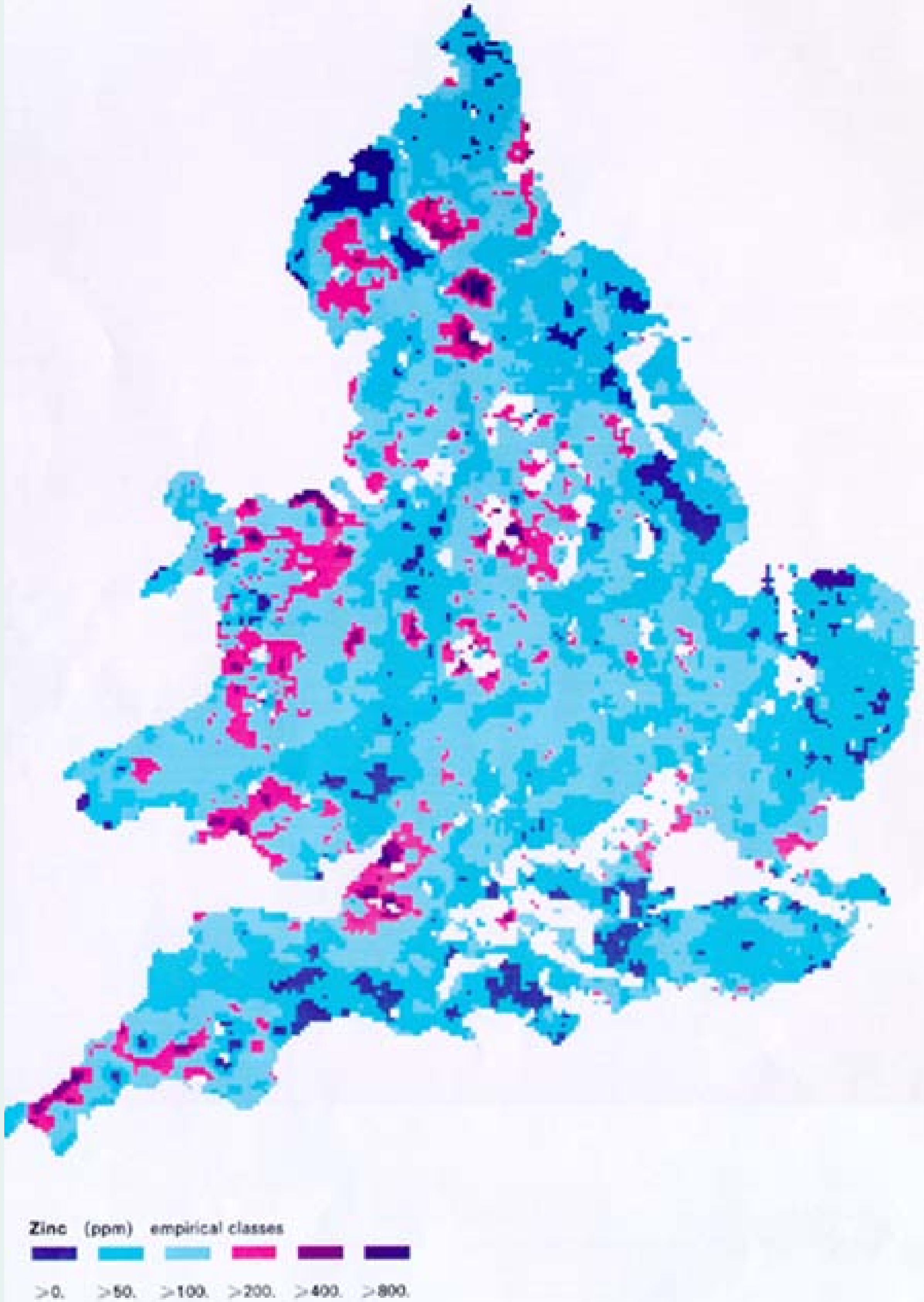
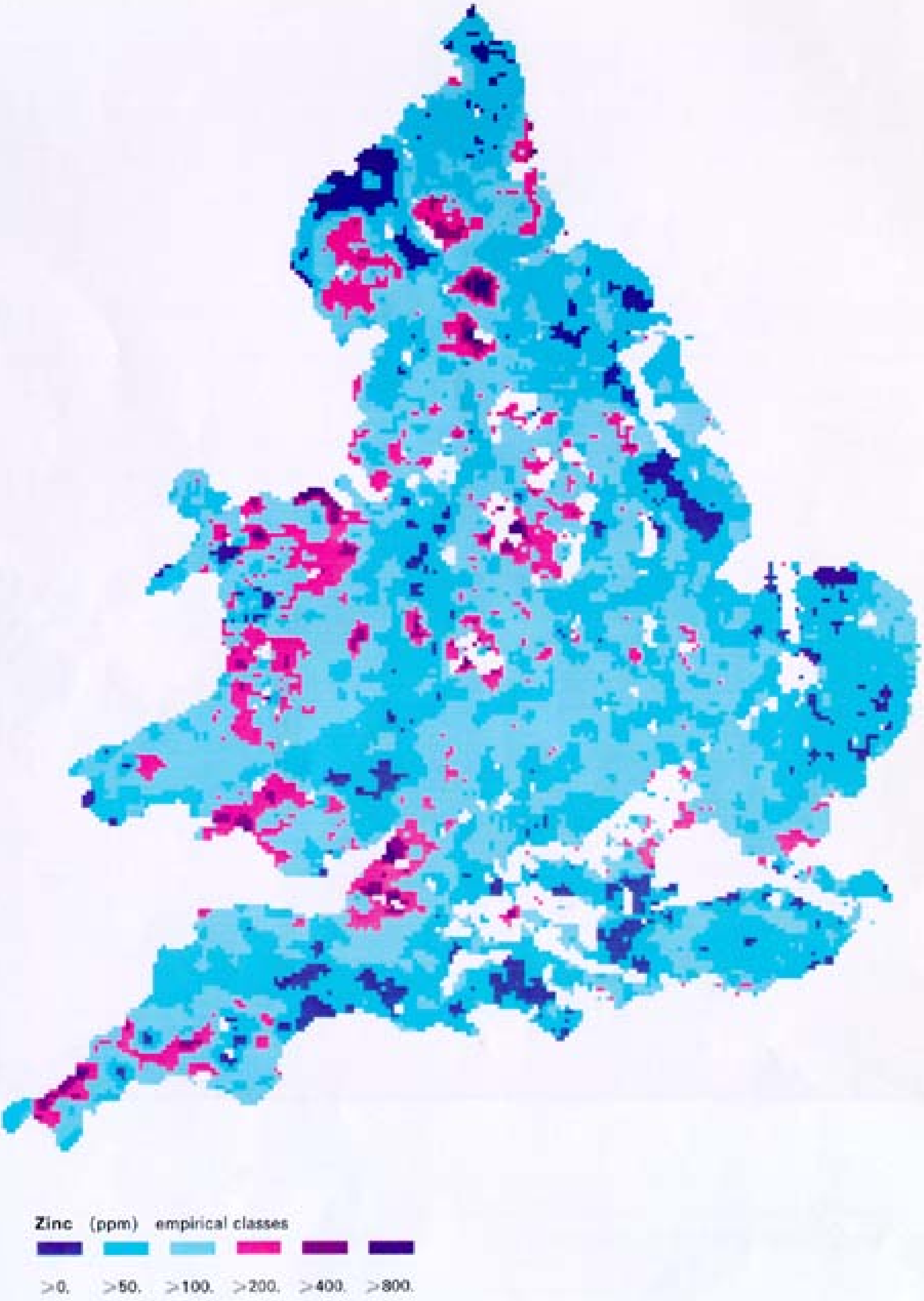


Combined element map for empirical **Copper** (red), empirical **Cobalt** (yellow), and empirical **Zinc** (blue); increasing colour contribution with increasing element concentration.

FIGURES 3 AND 4. For description see opposite.



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