MAPPING TECHNIQUES

BGS Research Report ICSO/87/3

WO/87/003

Natural Environment Research Council
BRITISH GEOLOGICAL SURVEY

MAPPING TECHNIQUES USING COMPUTER STORAGE AND PRESENTATION FOR APPLIED GEOLOGICAL MAPPING OF THE SOUTHAMPTON AREA

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Production of this report was supported by the Department of the Environment but the views expressed in it are not necessarily those of the Department

Bibliographical reference
LOUDON, T.V. and MENNIM, K.C. 1987
Mapping techniques using computer storage and presentation for applied geological mapping of the Southampton area
Research Report of the British Geological Survey No ICSO/87/3

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 EDINBURGH BRITISH GEOLOGICAL SURVEY 1987

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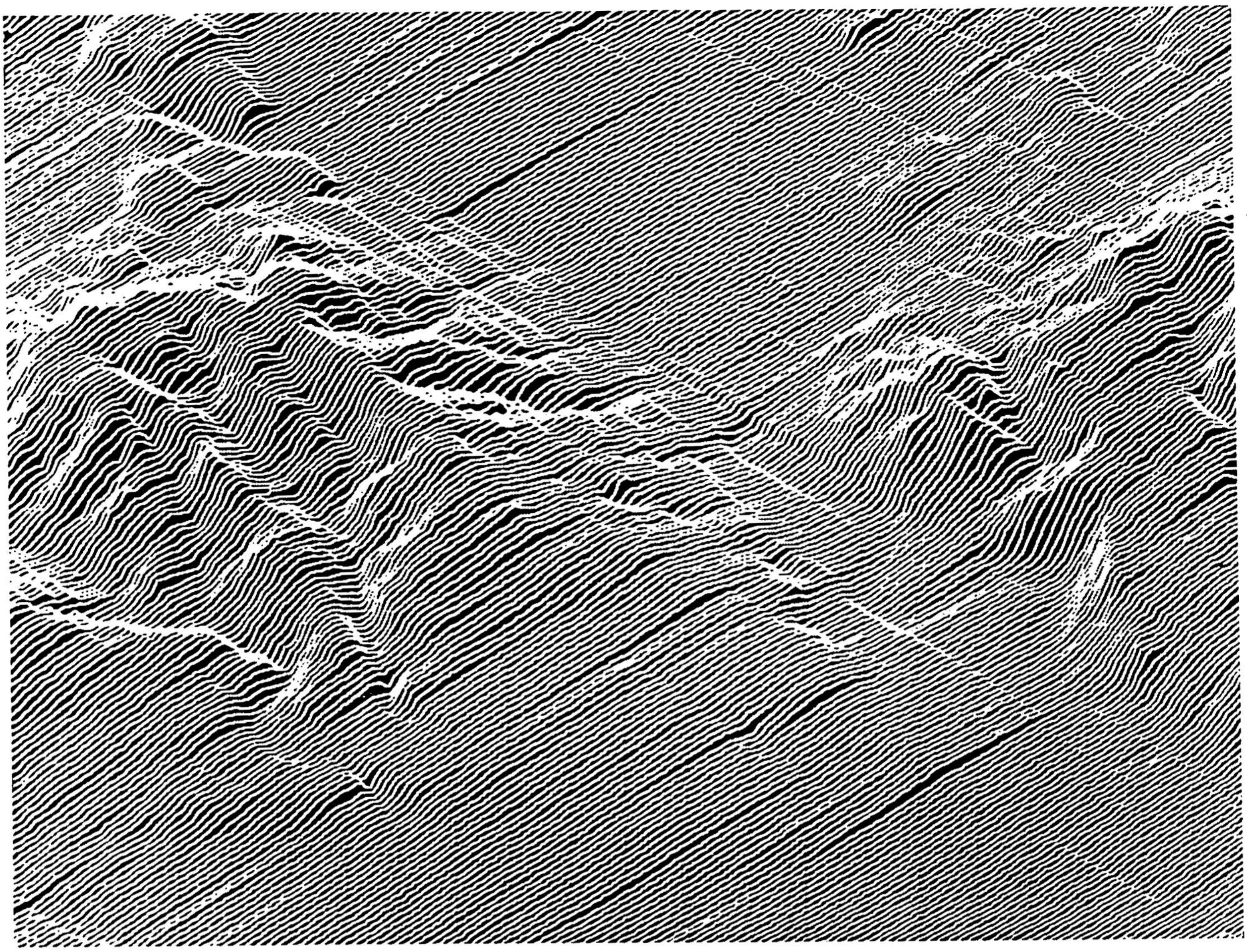

Frontispiece View from the south-southwest of a digital terrain model, showing the area around the city of Southampton.

Cover photograph

We see Southampton city centre from the air, looking northwards over the Royal Pier and Mayflower Park (where a boat show is taking place) in the foreground. The low-lying area in the left centre, occupied mainly by industrial buildings, is formed of reclaimed land over Estuarine Alluvium deposits. Most of the rest of the city is built on River Terrace Deposits overlying formations of the Bracklesham Group.

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APPENDICES

FIGURES

ACCOMPANYING DOCUMENTS

Two other BGS Research Reports are concerned with this project:

EDWARDS, R.A., SCRIVENER, R.C., and FORSTER, A. 1987
Applied geological mapping: Southampton area.
Research Report of the British Geological Survey, No ICSO/87/2.

Volume

1. Main report and appendix
2. Maps of solid geology
3. Maps of drift geology
4. Maps of drift thickness
5. Maps of rockhead contours
6. Maps of mineral resources
7. Maps of worked ground
8. Maps of availability of geotechnical test data
9. Maps of engineering geology, slope and aquifer distribution
10. Maps of made ground
11. Maps of borehole locations and Sites of Special Scientific Interest.

LAXTON, J.L. 1987
Computer databases of geological, borehole and geotechnical information for applied geological mapping of the Southampton area.
Research Report of the British Geological Survey, No ICSO/87/4.

EXECUTIVE SUMMARY

This study was commissioned by the Department of the Environment to develop and apply techniques of applied geological mapping for the purposes of land-use planning and development. It covers the area of the British Geological Survey (BGS) 1:50 000 geological map of Southampton. The study involved the computer manipulation of existing geological, geotechnical, hydrogeological and mineral resource data. The objectives were to develop the computer methodology, and to provide an archive of information, a set of applied geological maps, and descriptive reports in a form appropriate to all potential users.

The particular objective of this report is to describe the data presentation and map production techniques, in the light of the advantages and problems in computer storage and presentation of data. In order to give a broader perspective, the reasons for adopting particular methods and their relevance to longer term objectives in cartography are considered.

Two other accompanying reports were produced as part of the study. The principal results of the applied geological mapping of the Southampton area are given in Edwards and others (1987). The results include a set of maps prepared from the computer databases and a description of their significance, particularly in planning and land development. A second report (Laxton, 1987) describes the organisation of the databases and how they were used in the production of the applied geological maps of the area. The database contents are described in detail both for those who may wish to access the Southampton data directly and as a guide for those considering similar projects in the future. The geology of the area is described in the geological map (BGS sheet No 315, Southampton) and in a Sheet Memoir (Edwards and Freshney, 1987).

The conventional published geological map can serve many purposes, but may require specialist interpretation. In applied geology, it can be more helpful to have a clear presentation of specific aspects of the geology appropriate to a particular requirement. Several recent projects commissioned by the Department of the Environment have involved the preparation of computer databases, principally for borehole information, to assist the geologist in the preparation of working maps. It has recently become practicable also to hold lines and areas from the geological map in digital form, and this should lead to a more comprehensive computer system, appropriate for the preparation of applied geology maps.

Maps, together with other forms of pictorial representation, such as cross-sections and perspective views, are unsurpassed as a means of presenting geological information. They provide information about the geology at a location together with the context which may be essential to an understanding of its significance. The map is itself an information retrieval tool enabling the geologist by visual inspection to locate information by geographic coordinates, stratigraphic unit or topographic feature. Maps can be overlaid to bring together information on many topics, and for this reason the maps for this project have been prepared at the scale generally used by the planner, in this case, 1:25 000.

The data required for the production of the maps can be represented in the computer in several ways. Lines can be stored as the coordinates of a string of points spaced along the line - the so-called vector representation. More complex patterns, such as the topographic base map, can be represented as a raster, a set of digits in the computer memory indicating the presence, absence or colour of ink within each of a grid of small, square cells covering the map area. The form of a surface in three dimensions can also be represented as a grid (known as a Digital Terrain Model if it represents the land surface) in which an average elevation is stored for each cell. Borehole data and the results of geotechnical tests were stored as tables which could be cross-referenced with one another, and could be displayed on maps together with the cartographic information.

The vector data were entered on the computer (digitised) by following the lines with a cursor on a digitising table. The only data held in raster form in this project was the Digital Terrain Model and the contour data from which it was generated. The raster was prepared on an automatic raster scanning device using a bureau service. The tabular information was entered from a keyboard.

Although the map is an excellent means of presenting spatial information, it is less well suited to storage and retrieval. In order to prepare a specific map on demand, a computer database is required from which the selected items can be retrieved. A set of programs known as a database management system (DBMS) is required

to support data entry, checking, correction, rearrangement, up-dating and selective retrieval. The tables of data have the same structure as most existing geological data on the computer and were handled by the same proprietary DBMS (Oracle). The vector data were managed separately on a graphics work station. The lines were assigned to broad categories, such as solid and drift geology, at the time of digitising, and the lines required for specific maps were selected on the screen by pointing with a cursor. This was not entirely satisfactory, and a more complete description of the lines in an attribute table would be desirable in future projects. This would simplify the selective retrieval of cartographic items.

A wider range of map products is likely in future. Apart from the published geological map which has a large print run and wide circulation, it is likely that to an increasing extent applied geological maps will be available which have a small initial print run but can be copied on demand. For this project, such maps were prepared for 15 topics. From the cartographic databases, it will be possible to print maps on demand for specific purposes. In the longer run, the digital data may also be made available to the end-user for manipulation and display, perhaps together with information from other topic areas.

A range of plotting devices was available to display the information for this project. The graphics screen was used for editing and checking the maps. Pen plotters were used for plotting the geological line and point data. Raster plotters of appropriate size and resolution were not available in time, and the topographic base maps were handled by conventional photographic methods, and detailed ornament and text added by hand. With an electrostatic plotter now available, it may prove desirable to use a computer for these purposes in future.

In order to match the other 1:25 000 maps used by the planner, the geological line data were taken from the 1:10 000 scale maps which match the 1:25 000 topography exactly on reduction, unlike the 1:50 000 map which is generalised. Unfortunately, the geological 1:50 000 sheet boundary, on which the BGS mapping programme was based, contains parts of six Ordnance Survey 1:25 000 sheets. Although the total number of maps is therefore rather large, many users will require only those for a limited area. The Southampton area has recently been remapped geologically and some additional data were collected and collated for this project. The original material can be consulted in the BGS Exeter office and copies of the reports obtained from the BGS office in Keyworth.

The available technology has limitations, and much effort was expended in learning to use new techniques. It is important to develop a strategic view of applied geological mapping and the associated computer techniques at an early stage, for the techniques and the data should outlast the equipment and programs, and needless change is to be avoided. A number of practical difficulties arose which could be overcome in future with better equipment, more stable systems, more detailed description of the cartographic items, and more concise but directly relevant data. The development of consistent conventions is desirable, and the report lists the standards and conventions adopted in this project, although flexibility remains important at this early stage.

The benefits expected from the computer system include: efficiency; flexibility; clarity of presentation; ease of use; ease and speed of revision; cost-effectiveness; and improvements in the analysis, integration and communication of data, leading to a better understanding of its significance. To achieve this, a comprehensive computer system is desirable, handling the complete process from capture of the data to final printing of the map. Inevitably, at this early stage of development, not all the benefits were achieved, and compromises were necessary between the development of improved methods and the need to produce results using available tools.

It was concluded that computer methods are central to the development of a system with sufficient flexibility in retrieval and presentation to meet identified requirements for the preparation of applied geological maps for land-use planning and development, supported by an index and summary data to provide background for desk studies for site investigation. The combination of conventional and digital methods for map preparation is seen as an interim step, reflecting advances in the application of computer techniques, and pointing the way to future improvements. It is recommended that wider experience be gained by further studies of this kind, putting an emphasis on the evolution of a long-term strategy, using proprietary software where possible, and maintaining links with parallel work on Geographic Information Systems and spatial modelling in geology.

INTRODUCTION AND OBJECTIVES

This study was commissioned by the Department of the Environment to develop and apply techniques of applied geological mapping for the purposes of land use planning and development, and to examine the use of new technology in achieving this aim.

The programme of research had the following objectives.

(a) to develop a computerised database of geological and related information as a basis for safe, cost-effective planning for development and for exploitation and safeguarding of water resources;

(b) to develop methods of presentation of thematic maps and models from the data by interactive interrogation; and

(c) to present the data as maps and models accompanied by reports describing the techniques and the data.

The study area was defined by the boundaries of the British Geological Survey 1:50 000 Geological Sheet No 315 (Southampton) and comprises parts of OS 1:10 000 sheets SU20, SU21, SU22, SU30, SU31, SU32, SU40, SU41, SU42, SU50, SU51 and SU52.

The area of the study is one of extensive urban and industrial development and redevelopment. The South Hampshire Structure Plan indicates that this is a part of the county where further release of sand and gravel resources might occur. However there is an urgent need to avoid sterilisation of these resources by other development. The collation and presentation of data relating to the major industrial area around Fawley was seen as being particularly useful. Geological maps of the area at 1:10 000 scale have been completed recently and the appropriate Land Survey expertise was available.

The study involved the computer manipulation of existing geological, geotechnical, hydrogeological and mineral resource data to provide an archive of information, a set of thematic maps and descriptive reports in a form appropriate to all potential users.

The particular objective of this report is to describe the data presentation and map production techniques, in the light of the advantages and problems in computer storage and presentation of data. In order to give a broader perspective, the reasons for adopting particular methods and their relevance to longer term objectives in cartography and modelling are considered.

Two other accompanying reports were produced as part of the study. The principal results of the applied geological mapping of the Southampton area are given in Edwards and others (1987). The results include a set of maps prepared from the computer databases and a description of their significance, particularly in planning and land development. A second report (Laxton, 1987) describes the organisation of the databases and how they were used in the production of the applied geology maps of the area. The database contents are described in detail both for those who may wish to access the Southampton data directly, and as a guide to the structure and contents required for databases for applied geology map production for those considering similar projects in the future. The geology of the area is described in the geological map (BGS sheet No 315, Southampton) and in a Sheet Memoir (Edwards and Freshney, 1987).

The recent geological resurvey of the area, together with data collected from site investigation reports and boreholes, provided the basic information, much of it assembled specifically for this project. The Ordnance Survey collaborated in the preparation of a digital terrain model. The Soil Survey of England and Wales are now undertaking a related project within this area, also commissioned by the Department of the Environment, to examine soils and agricultural potential. The techniques are thus relevant in a wider context than applied geology. The ability to integrate spatial data from many sources is seen by Chorley (1987) as an important aspect of future Geographic Information Systems.

Digital methods are seen as being of crucial importance in the future production of applied geological maps. For example, the Department of the Environment, in their submission to the Butler Committee on Geological Surveying (ABRC, 1987) indicate the need to make available a variety of custom-made maps based on current information technology and developments in digital cartography. This is echoed in the Committee's report, in which it is envisaged that, in future, customers should be able to commission thematic maps and supporting data of particular areas and that the graphical and written information should be printed automatically from the computer database. Geological surveys overseas have identified similar objectives. In their long-range plan for a National Geological Mapping Program, for example, the United States Geological Survey consider that computer techniques will not only accelerate the map production process but in addition to the digitally generated geological map will produce a database to provide a wider range of information to users (USGS, 1987, page 23).

In the Southampton project there was a requirement on the one hand to prepare maps of value to the user and on the other hand to develop systems and ways of working to match the advance of information technology. The present report is concerned with the background methodology and its longer term development, together with the compromises that were necessary to generate useful products in the current state of the art. The long-term objective can be seen as the development of techniques for rapid and efficient presentation of geological information, relevant to specific requirements, such as planning or site investigation, in an appropriate form, more widely understood than the complex, multi-use geological map. This implies the use of the best available technology for efficient map production and management of the database.

The methods used in the project were based on work by many individuals, too numerous to acknowledge individually. The production of the computer-generated maps was largely the work of A. Clifton, K.C. Mennim, J.L. Laxton, and R.W. McGonigle. Dr T.J. Dhonau and the Edinburgh Drawing Office of BGS assisted in their final compilation. The nominated officers were R.J. Wood and subsequently P.J. Bide for the Department of the Environment, and W.G. Henderson and subsequently Dr T.V. Loudon for the Survey. The work was directed by R.C. Mabey for the Department and Dr B. Kelk for the Survey.

OVERVIEW OF THE MAPPING TECHNIQUES

The conventional published geological map sets out a view of the geology, which can serve many purposes, but may require specialist interpretation. Applied geological maps address a wider range of issues than basic geology, and should present clearly the specific aspects of the geology appropriate to a particular requirement - in the present study, land-use planning and development. The bulk of applied geological maps have in the past been produced by traditional drawing office techniques. Within the last few years, several applied geology projects commissioned by the Department have involved the production of a borehole database. This has supported map preparation, by allowing the geologist to select information and prepare plots of values or symbols as a working map, which he could then refine and pass to the drawing office.

The various components of typical applied geological maps are: point value data (for example, from boreholes); geological lines and areas; contoured surfaces; and the topographic base map on which the geological data is overlain.

Computer plotting of points and values is well established. Recently, it has become practicable to digitise the lines and areas from the geological map, and select the required components for computer presentation. On the other hand, computer contouring still has important limitations, and computer plotting of the base map requires specialist equipment which was not available in time for this project.

Once in digital form, computer methods are available for storage and retrieval of the information, and editing and presentation of the results as a screen display or a plotted map. It is thus possible to use the computer in applied map production, but not all of the components are necessarily in digital form. Those that are, may be in different representations, reflecting different methods of digitisation. It may be necessary to bring together a number of plots with reproduction material from other sources to produce the final maps. For example, in the present project, computer plots of the geological information were combined photographically with base maps supplied by the Ordnance Survey. These aspects are described briefly in the next section of this report and in more detail in the Appendices.

The main advantages of the present computer methods are the flexibility of selection and presentation of the data. The main disadvantages are the unfamiliarity and inadequacies of systems at this early stage of their development. However, computer systems are developing rapidly and there is every indication that, as these problems are overcome, computer methods will provide the most economical and effective means of applied geological map production. A key question arising from the present study is the extent to which that point has now been reached.

THE NEED FOR MAPS

The emphasis in this report is on the production of maps. It could be argued that information technology will in future provide other methods for communicating spatial information. However, there is no indication that the geological map will be superseded as a means of presentation. The map, together with other pictorial representations such as cross-sections and perspective views, remains a powerful tool in presenting spatial information. Not only does it indicate the geology at a particular point, or the value of a variable at a point on a contour map, but the map also provides the context of the surrounding area, which is likely to be essential to an understanding of the geology. It shows the extent and outcrop pattern of a formation, and the sequence of adjacent rock types. Furthermore, the map provides this information in a form which the human eye and brain can readily absorb, visualise and interpret. The user can readily apply his background understanding of requirements and alternative solutions and his knowledge of the geological setting and processes to his study of the map. It is this background information which is not available and perhaps never will be fully available to the computer.

The map enables the geologist to retrieve information by visual inspection. Without computer assistance, he can readily locate information by grid co-ordinates, by reference to its position relative to geological features, by stratigraphic or other units colour-coded in the margin key, or by reference to topographic features. Colour is an effective device in discriminating, emphasising or identifying areas on the map. Shading can indicate shape and form.

Sequences of maps on different topics for the same area can help in understanding relationships. For example, the geologist might suspect from an outcrop pattern on a geological map that an anomaly shown on a gravity map indicated the presence of a hidden granite body and by reference to a topographic map and geochemical maps might conclude that the granite was responsible for geochemical anomalies downstream. The complexity of the underlying models suggests that such deductions are more likely to be made successfully by the geologist with the assistance of appropriate maps, than by the computer.

The planner may require applied geology maps to overlay on other thematic and cultural maps. For example, in selecting areas for future industrial development, he might wish to look at areas where no commercially workable sand and gravel deposits would be sterilised, where no mined coal seams near the surface could cause subsidence, where land slippage is unlikely, etc. To guide the planner's decisions, the map should depict clearly the relevant geological aspects while avoiding all irrelevant detail, and should be of an appropriate size, scale and accuracy to match his other mapped information. In order to generate such maps by computer, high quality graphic presentation equipment is essential.

TECHNIQUES AND PRODUCTS

There are several stages in the computer preparation of maps, including: *digitisation*, to make the data available for computer processing; *data management*, to handle input, checking, correction, editing, updating, storage, retrieval, collation and rearrangement of the data; *plotting*, to obtain the required output on paper or film; *map production*, in which the various components of the map are assembled in register with the base map to produce the final map; and *dissemination*, to make the required information available to the end user. Each of these stages is considered in turn, the technical details being given in the Appendices.

Digitisation

There are two principal methods of representing map data in digital form. One is to represent the lines on the map by the (x,y) coordinates of a string of points spaced along the line. On plotting, the points are joined by straight lines, or vectors, and the method is therefore known as *vector* representation. The other method is to represent the entire area of the map as a *raster*, or grid of small squares, known as picture elements or *pixels*. For each pixel, a digit is held to indicate whether or not a line passes through it. It is possible to convert from vector to raster representation or vice versa, by manipulation of the data in the computer. Details of both vector and raster methods are given in Appendix 1 on map production methods.

Most of the digitisation, that is, conversion of the map data to digital form, was carried out by placing the map on a digitising table and following the lines with a cursor which automatically records the coordinates of successive points (see Loudon and others, 1980). The resulting vector file can be stored and manipulated on the computer, as described later. In order to process the information, the geological significance of each segment of line must be known, for example, whether it represents a geological boundary, and if so which formations lie on either side. Each string of vectors, or line segments, can therefore be assigned an identifier, and the attributes of each line segment can be stored to make possible the extraction of specific lines for particular maps. In this project, the line segments were classified in categories which, in retrospect, were too broad for map preparation purposes, causing unnecessary work at a later stage.

A different technique was used to digitise the contour data for the land surface (see Appendix 3). The information is required in order to understand the three-dimensional implications of the geological map, and also to indicate possible areas of slope instability. The aim was to produce a *Digital Terrain Model* (DTM) which is a set of values of the elevation of the land surface at each square in a grid, in effect a coarse raster. In this form, computer processing of the elevation values is more readily achieved than in the form of the original contours. To generate the DTM, the contour lines were *raster scanned*, an automatic process which produces a raster representing the map by scanning it in a comparable way to the generation of the image in a video camera. In order to obtain the necessary resolution of 30 points per mm across the entire map, expensive specialist equipment is required, and the work was therefore passed to an external bureau. Having obtained the raster, the computer program identifies the areas between each pair of contour lines. With the help of some manual editing, contour values are inserted, and the program interpolates between contours to obtain the required grid values.

The other type of data needed to prepare maps for this project was the borehole information which was either used to plot symbols and values at the borehole locations, or to control the contouring of subsurface strata. The borehole data was recorded on coding forms and entered on the computer from a keyboard. Geotechnical data from the boreholes and elsewhere was entered as a separate dataset by the same method.

In future projects of this kind it is likely that raster scanning will play a more important role. Methods described in Appendix 1, which are now used for published maps, are likely, as costs fall, to become cost-effective (at a lower resolution) for applied geological maps. The topographic base maps, which were reproduced photographically in this project, could be more readily handled as a digital raster. Extensive libraries of maps are now being prepared in this way, for example, by English Heritage.

Data management

The map may be an excellent medium for presenting spatial information. It does not follow, however, that it is well suited to its other major role of recording and storing the information. Indeed, it can be argued (see, for example, Loudon, 1986) that there are major benefits in adopting digital methods for storing information on the complex sequence of interrelated surfaces and rock bodies and their evolution in geological time which is the concern of geological field survey. Not only is it impossible to record such information satisfactorily on a static two-dimensional document, but handling the variability of information density, the depiction of uncertainty and of multiple hypotheses, and the separation of observation and interpretation, all give problems on the conventional map. Computer generation of maps from the database, or more appropriately, from the digital spatial model (described in Appendix 5), may overcome these difficulties. The agreed interpretations can then be held and maintained in digital form, and maps can be generated as an ephemeral record for communicating results when required. This agrees well with the view that no single map can present a comprehensive picture of the geology, and that maps prepared in response to specific requirements can be more effective and easier to understand.

The ability to prepare a specific map on demand implies that there is a pool of information on the computer (the *database*) from which the required items can be drawn. Management of the data, that is, data entry, checking, correction, rearrangement, up-dating and selective retrieval, requires a set of computer programs known as a *database management system* (DBMS).

The data for the Southampton project falls into three main groups - the borehole, geotechnical and cartographic data. The borehole and geotechnical data can be structured naturally as a set of tables, each containing many horizontal rows (as laid out on a page), and several vertical columns which might have such headings as: borehole number, date drilled, easting, northing, ground elevation, total depth, etc. A second table might have each row corresponding to a borehole sample, with column headings: borehole number, sample number, depth, result of penetration test, etc. The occurrence of the borehole number in both tables allows cross-referencing between them, and is known as a *key field.*

This type of table is known in set theory as a relation, and the set of tables, cross-referenced by key fields, constitutes a *relational database.* Relational databases are in widespread use, and offer a flexible and appropriate view of much earth science data. Many relational database management systems are commercially available, including the one used in this project, known as Oracle. It is described in more detail in the accompanying database report (Laxton, 1987).

Unlike the borehole data, the lines and areas from the geological maps are less appropriately arranged in tabular form. For this project, the cartographic data were digitised, stored and manipulated on a graphics work station, comprising a microcomputer, a colour display screen, a digitising table and tape and disc storage. At the time of digitisation, lines were assigned to different categories, according to their geological significance (solid, drift, etc.). These categories were handled like map overlays, and displayed separately or together on the screen and as plots. Where required, a detailed selection of lines was made by pointing on a digitising table at lines to be deleted. Thus, maps can be prepared for a special purpose showing only that information which is directly relevant. The system is not ideal, and possible improvements are discussed in Appendix 2. For example, it may be desirable to hold detailed lists of map attributes as a table in the same relational structure as the borehole data, with links to the line data.

Mapping methods

The computer opens up possibilities for mapping which have not previously been practicable. For example, the perspective view of one or more surfaces, as illustrated in the Frontispiece, is an aid to visualisation which would be laborious to prepare without a computer. Since the cost of plotting a simple digitised map by computer can be little more than the cost of reproducing it from a film or paper copy, it is feasible to prepare series of special-purpose one-off maps based on data retrieval and presentation to meet a specific need. The maps may be discarded when the need has been met, and ephemeral, working maps are in fact frequently prepared by computer. In many cases, it may not even be necessary to print the maps, and inspection of a screen display may be adequate. The availability of *interactive graphics* (that is, the ability to make immediate changes in a graphic display by entering appropriate commands) means that many alternatives can be explored quickly and the best can be chosen without the expense and delay of preparing a paper copy. Positioning of symbols and text, and deletion and insertion of lines and areas, are efficiently handled in this way.

It does not seem practical to generate every map on a one-off basis in response to a specific demand. Instead, for Southampton, there is now available, firstly, the published 1:50 000 map which, though revised from time to time, is printed with a long print run and is widely distributed. All users of this map can be confident that they are seeing, and possibly citing, the same definitive information. Secondly, the applied geology maps of this project are available, but have a very short initial print run (25 copies). Additional copies can be quickly and cheaply prepared on an A0 copier, but to make this possible, colour has been avoided. In principle, revisions could be made to these maps when required, although, in fact, no decision has been taken to keep them up to date. Thirdly, it would be feasible, again in principle, to supply customers with maps to their own specification on demand. A final possibility is that digital data could be made available to the user for manipulation and display. The last two possibilities would require that the user is familiar not only with computer methods but also with the content of the digital database and has a knowledge of the local geology and the limitations of the data. At present, therefore, these two options are confined to users within BGS.

Equipment for digital map production is analogous to that used for digitisation. For high-quality reproduction material, a *raster plotter* can be used, in which a narrow laser beam scans across photographic film, flashing on to expose pixels selected by the pixel code held in the digital raster. Raster plotting is the reverse process to raster-scanning, and indeed the same device may be capable of both operations. For printing maps in colour, areas are filled with dots or lines to give an appropriate density for each area on each printing plate (see Mennim, 1986). At a much lower cost, but also at lower resolution, electrostatic plotters are now available to prepare large one-off colour maps. Display screens are also raster devices, although many accept vector data and rasterise it in an internal microprocessor. Ink-jet or thermal-transfer copiers can plot the contents of the screen in colour, but seldom at a size larger than A4.

Vector plotters are available from low-cost A4 desk-top units to large, high-accuracy, flatbed plotters. A pen or photohead is moved over paper or film along a gantry to give one direction of movement. Movement in the other direction is obtained by moving the paper from one drum to another on a drum plotter or by moving the gantry across the flatbed. A limited number of pens, of different colour or width, may be available. The vector plotter can plot line and point data efficiently, but filling areas with colour or ornament, and plotting dense detail, is more efficient in raster plotting. In the Southampton project, vector plotters were used for preparing the computer output.

Presentation of results

It is desirable that the applied geological maps should match the other maps used by the planner, and for this reason, most were prepared at the 1:25 000 scale. Geological maps were available at 1:50 000 and 1:10 000 scale. The published geological map at 1:50 000 gives a generalised view of the geology and topography. The geology was originally surveyed at 1:10 000 scale, and the 1:25 000 topographic map is a direct photographic reduction from 1:10 000. The geologists' field maps were therefore digitised, reduced and plotted in registration with the 1:25 000 topographic base map. The latter was screened photographically and combined with the computer-drawn lines and symbols.

The 1:50 000 geological map sheet boundaries do not correspond to any logical hierarchical subdivision of the country for digital mapping, and the area selected for this project is covered by parts of six Ordnance Survey 1:25 000 sheets. In order to obtain a reasonably clear, uncluttered presentation, 15 different topics were presented separately. In consequence, the total number of maps is rather large. However, many users of the maps will not in fact require the complete collection and may find that a restricted set of areas and topics is adequate for their purposes.

Access to results

The applied geological maps for the area are included in ten volumes of the accompanying report by Edwards and others (1987). Enquiries about purchase of the reports, or individual maps, should be directed to the National Geosciences Data Centre at BGS, Keyworth, Nottingham NG12 5GG. The original field maps and borehole records from which the database was extracted are held and may be consulted at the British Geological Survey, St Just, 30 Pennsylvania Road, Exeter EX4 6BX.

The computer data will be archived at the end of the project, and thereafter available internally for any subsequent work in the area. Technically, it would be possible to make the digital data available to external users by various means, including tape, disc, and on-line access. At present, however, there is no clear user demand, and it is desirable to gain experience in digital data dissemination with simpler index-level data initially.

For the user, the growing availability of digital data in BGS will provide an opportunity to obtain maps to meet specific requirements, as well as making it possible to publish a wider variety of maps emphasising different aspects of the same geological data and interpretation. Once the database and map production system are established, information technology can provide a means of ensuring that maps can be readily revised to reflect the most up-to-date information.

PRACTICAL DIFFICULTIES

In this section, attention is drawn to various shortcomings in the present system. This is not to throw doubts on the validity of the approach, but to discourage the repetition of mistakes and to point to requirements for future improvements.

Efficient data entry methods are important. Direct data entry of borehole information from the original documents to a microcomputer by temporary staff hired for the project was attempted initially, and was successful for index information. However, for detailed descriptions, completion of coding forms proved more satisfactory in trapping errors (they can be checked against either the original document or later, against the computer record). Keyboard entry was then performed accurately by a professional at 15 000 key depressions per hour, compared with the 1000-2000 key depressions and poor accuracy of an inexperienced operator.

As a new survey of the Southampton area is unlikely for several years, the computer data will probably not be kept up-to-date. Its value lies in its contribution to this and any future computer-based project in the area. Up to 20% of the borehole data which was recorded proved unnecessary for the project. A minimal dataset, rigorously validated to ensure that it corresponded closely with the paper records, would have led more quickly to useful results.

In order to use the cartographic data effectively in the production of applied geology maps, geological attributes of the data must be recorded. Efficient labelling of polygons and selection of lines on geological criteria could not be achieved on the rather small interactive graphics work station used for the project, but is desirable for future work.

The final products of the project were maps. There are good reasons to believe that graphic presentations are the best means of communicating results from such a project. There is much room for improvement in the presentation methods, and in providing clear and simple routes for passing information from one part of the computer system to another. The use of a lighthead or a raster plotter would have simplified the reproduction of the lines and symbols.

Irregular subdivision of the country by geological map-sheets causes difficulties at database and presentation levels. A regular subdivision into 100 km, 10 km and 1 km squares on the National Grid would provide a more consistent partitioning of data. The Southampton 1:50 000 geological map contains many part-sheets at 1:25 000 scale, as sheet boundaries on different scales do not coincide. This has greatly increased the number of maps prepared for this project.

The frequent changes to computer hardware and software throughout the project caused major delays while learning to use new tools. The changes included: from Mimer to Oracle database management system; from a Tektronix to an Intergraph graphics work station; from a DEC PDP-11/70 computer at Edinburgh to a DEC VAX 8600 at Keyworth, then to a VAX 8500 at Edinburgh; from an IBM-PC to a Burroughs data entry system. Inevitably, links between the Intergraph work station and a pen plotter, for example, were difficult to achieve and caused delays and diversion of effort. A more stable basis is now available for future work, although continued change is inevitable and desirable.

STANDARDS

A major, but unprofitable, task in the Southampton project was the building of bridges to connect different parts of the computer activities, for example, to pass data from the database management system to the interactive graphics system and thence to the plotter. This reflected the absence of clearly defined standards in these areas. In a rapidly developing field this is inevitable and although an integrated system design is desirable, it may not always be possible. The falling cost and ready availability of graphic work stations will increase the importance of standards, as a growing number of users attempt to access information by this route. The development and implementation of standards and ad hoc standards is in the hands of standard-setting organisations, such as BSI, and manufacturers. An individual user can have little influence in defining standards, but a more satisfactory system results if appropriate sets of conventions are used. The standards, conventions and some products used in the Southampton project are listed below, together with those that might be considered in similar future projects.

Operating systems:	Mainframe - VAX/VMS Workstation - VAX/VMS. Unix, OS2 are future possibilities.
Communications:	Joint Academic Network (Janet), Ethernet. OSI is a future possibility
Database:	Relational using SQL.
Cartographic data:	Held in proprietary Intergraph formats. Future standards uncertain.
File transfer:	Magnetic tape. ASCII files. Future possibilities - floppy discs, CD-ROMs. Cartographic files in SIF format. Future possibilities uncertain, but IGES, SIF and GKS metafiles are candidates.
Graphic presentation:	IGDS. Future possibility is GKS.

An attempt has been made to follow general BGS pratice in the content of the borehole data files (see Laxton, 1987). A consistent set of comprehensive data definitions is desirable even although each project may record data from only a limited subset. A general agreement on the contents of geological cartographic files is unlikely to emerge for some years. Although data transfer standards for digital cartography have been proposed (Haywood, 1986) they are only partly relevant for geology.

THE NEED FOR A LONGER TERM FRAMEWORK

The project had among its objectives the need to explore new methods in an area of fast-changing technology. Inevitably, widespread acceptance of new techniques in geology lags many years behind their development. Delays in investigating new applications of technology would therefore show short-term savings at the cost of long-term benefits. An attempt was made to strike a reasonable balance in this project between the need on the one hand to prepare documents of value to the user and the requirement on the other hand to develop systems and ways of working to match the advance of technology.

Some of the procedures were superseded even within the two-year life of the project. Indeed, none of the equipment and none of the programs used at the beginning of the project remained in use for the same purpose at the end. Other systems would have to be considered for a similar project starting now. The changes imposed a major overhead on the project. Despite upgrading in the devices and software, however, computer techniques for applied geological mapping should as far as possible follow a consistent overall plan of development. The techniques and the database last longer than the tools for their implementation. It is necessary therefore, to take a strategic view of longer term developments such as those described in Appendix 4.

It is desirable, also, to monitor practical difficulties , so that they can be avoided in future developments, and to develop and follow conventions which will minimise duplication of effort in future projects. These points were considered in previous sections.

BENEFITS OF COMPUTER METHODS

The benefits expected from computer systems include: efficiency; flexibility; clarity of presentation; ease of use; ease and speed of revision; cost-effectiveness; and improvements in the analysis, integration and communication of data, leading to a better understanding of its significance. Inevitably, at this early stage of development, not all the benefits are achieved.

The requirement to prepare applied geological maps for land-use planning and development is clearly identified (see Clayton and others, 1987). There is an associated need for detailed supporting data on site investigations, geotechnical and borehole data, particularly as background for desk studies preceding further site investigation. The raw data is of very variable quality, and could be misleading unless considered along with an interpretation by an experienced geologist. The main initial cost lies in assembling and interpreting the information and organising it for ready access. A computer database can save time and effort in this task (see Laxton, 1987).

Database management methods for borehole and sample data are well established and widely used. There are advantages in adopting a uniform approach and consistent standards of data recording and data content. The current BGS practice is satisfactory for internal purposes, but may need to be re-examined in terms of wider requirements (Clayton and others, 1987).

The preparation of working maps from the database to show the distribution of points, or for posting values or symbols, is also a well established technique. A map showing thousands of points can be plotted in minutes by computer, at a cost of a few pounds, whereas it could require some days of work to prepare manually. Provided appropriate facilities and a database are available, there is little doubt of the cost-effectiveness of the method.

To gain the full advantages of the computer, however, it is desirable to develop comprehensive computer systems which handle the complete process from capture of the data to final printing of the map. This would avoid the duplicated effort in, for example, digitising geological lines once for preparation of the published map, and again to match the lower degree of generalisation of the applied geology map. Having prepared working maps by computer, it would save the delays and costs of redrawing and combining them by conventional drawing office and photographic techniques. The Southampton project took some steps towards this objective.

A comprehensive system implies that the geological line data, contoured surfaces and the topographic base map should be available in digital form. The line data were digitised for the Southampton area using well established methods which are, however, expensive and prone to error. There is obvious future potential in linking this activity to the preparation of the published map, for which the lines were digitised separately, as described in Appendix 1. The method also needs further development in handling the line attribute data within a database, to ease the task of line selection for individual maps. These are areas of active investigation, and short-term working solutions are available, although these may not yet be cost-effective in isolation.

The digital terrain model prepared for this project (see Appendix 3) is an example of a surface held in digital form. Improved software for computer contouring of scattered borehole data is now available, but not in time to use it in this project. Editing of contours by a geologist is usually essential in order to take into account background geological knowledge. The results can be stored as a grid accessible to the database. This is by no means a routine procedure, at least outside the oil industry, and additional work is needed to establish appropriate conventions and procedures. When this is complete, there is every indication that computer drawing and manual editing will be a cost-effective method of preparing contours for many subsurface horizons.

Methods for raster scanning and plotting the topographic base map are described in Appendix 1. The cost may not at present be justified for a small individual project of this kind, and with procedural and copyright difficulties, digital datasets of maps have not so far been made widely available. Further progress depends partly on the availability of equipment for preparing the final product by raster plotting. Large colour electrostatic plotters have recently become available which may fill this role. Again, they were not available in time for this project.

In order to gain the maximum benefits from these techniques, access to a wide range of expensive equipment and software is essential, which probably could not be justified for applied geological mapping work alone. BGS now has access to a good range of such equipment, which has been purchased by NERC to meet general requirements. The main programs are purchased software representing many hundreds of man-years of effort. Installation and maintenance are major tasks, best spread across many applications. Expertise in the application of the technology is also needed, and can only be gained by experience in a number of such projects. The methods are, however, becoming more routine, and the costs are falling rapidly. Within the next few years they should be readily available to a wider user community. By that time, there appear to be good reasons for believing that large-scale methods of applied geological map production will necessarily be based on comprehensive computer systems.

CONCLUSIONS

1. There is an identified requirement to prepare applied geological maps for land-use planning and development. There is an associated need for detailed supporting data on site investigations, geotechnical and borehole data, particularly as background for desk studies preceding further site investigation. The raw data is of very variable quality, and could be misleading unless considered along with an interpretation by an experienced geologist.

2. Computer methods, because of their flexibility in selective retrieval and graphic presentation from large datasets, may be central to meeting this requirement.

3. A fully developed computer-based system for efficient data handling from digitisation to map production is desirable but was not available, and the procedures adopted for this project were a compromise between the need to extend knowledge of the methods and the need to obtain useful results.

4. The necessarily incomplete system used for the present project included the following components:

a) data entry - digitisation of lines from 1:10 000 geological maps, abstracting information on borehole and geotechnical data using coding forms and keyboard entry.

b) Digital Terrain Model - prepared by raster-scanning Ordnance Survey contours followed by use of special-purpose Scitex software.

c) data management - the Oracle relational database management system and SQL query language were used for the borehole and geotechnical data, the cartographic data was manipulated on an Intergraph graphics work station.

d) graphic presentation - plots were prepared through a standard GKS interface using pen plotters. Some additional material was added by conventional drawing office methods, and the base map was superimposed photographically.

The combination of conventional and digital methods was seen as an interim step in order to produce results before the system is complete. Improvements in the description of digital cartographic elements, in cartographic data management, and in digitisation and graphic presentation (including the topographic base map), are all required.

5. The project work was based on major computing systems (hardware and software)

purchased by NERC for general-purpose applications. Aspects which could be kept in mind in future studies include:

a) The programs, purchased from commercial suppliers, represent many hundreds of man-years of development effort.

b) Because of rapid developments in this field, programs and equipment have a relatively short life. Major changes during this two-year project absorbed much effort in learning to use new systems.

c) The high cost and rapid development of programs suggests that the purchase of commercially-available software is appropriate and the scope for in-house development is limited.

d) Despite falling costs, the expense of installation and maintenance is still a major overhead which is best spread across many applications.

6. The geological information has a much longer life than the equipment and the programs used to process it. There is therefore a need to work within a consistent long-term strategy, and to follow well-documented standards and conventions, which can help to ensure continuity of development and access to the geological information. Internal BGS conventions were used in this project, and may require to be extended in future to meet new requirements and external needs.

7. Although computer methods offer some immediate benefits, the major gains from an information system are long-term. Links between digital cartography, database management and computer graphics are essential to ensure that once data is captured in digital form it can be used to generate many end-products. Major developments, such as the integration of many sources of digital information in Geographic Information Systems (Chorley, 1987) and the development of digital spatial models to link geological data and interpretation (Loudon, 1986), should be seen as part of an overall strategy. Present systems should be capable of evolving towards longer-term objectives without extensive loss of previous work.

8. The present project can be seen as a step forward in the application of computer techniques to applied geological mapping, and points the way to further needed improvements. The development of comprehensive systems over the next few years, and their wider availability, is likely to lead to existing manual methods being largely superseded for this application. Further development work is urgently required.

RECOMMENDATIONS

1. Further development work is urgently required to extend the experience gained in this project into new areas, and to take advantage of the new equipment and software which is now available.

2. The development and implementation of a long-term strategy could help to ensure that data and methods can be progressively built on and extended, rather than starting from scratch in each new project. New projects should be seen as having important learning and experimental aspects.

3. For projects such as this one, the use of commercial software is recommended where it is available. The high development costs are set against many users, and widespread usage of software ensures greater reliability.

4. Future developments can be expected to include links to broadly-based Geographic Information Systems and digital spatial models in geology. It is recommended that links be maintained with research activities in these areas.

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APPENDIX 1

MAP PRODUCTION METHODS

The published 1:50 000 map

The present-day user of geological information is better able to understand a map than a digital spatial model. Accurate communication between users depends on their all having access to the same sources of information. Therefore, the published map is likely to remain important for many years to come. A revised edition of the 1:50 000 geological map of Southampton was recently produced using computer methods, and although it was not part of this project, the production methods are relevant (see Mennim, 1986). Compared to a computer screen, the map is large, but carries detailed information, printed at high resolution and with the geology and the topography in exact register. Colours are uniform across the map, and as far as possible, identical to those used to denote the same rock units on adjacent maps. The user of the map can thus stand back from the map for an overview of the area, and can look more closely at individual parts, even with a lens if need be. The contrast with a computer screen will be referred to later.

The geological aspects of the map of Southampton consist largely of areas of colour, with some lines and symbols. To produce the map, the lines, including the boundaries of coloured areas, were drawn in the BGS Drawing Office on a stable film base. The film was then sent to an external bureau for raster scanning. In this process, the film is placed on a rotating drum. A narrow laser beam traverses the drum in a similar pattern to the electron beam traversing a television screen. For each successive point traversed by the laser beam a record is made of whether the film is black (1) or white (0). Colours, if necessary, can be recorded as numbers greater than 1. The image on film is thus converted to a pattern of digits stored electronically. The pattern is held as a raster, that is, as a grid of small squares, stored in sequence in successive rows from top to bottom of the image. Each of the small squares, known as picture elements, picture cells or pixels, is 1/30mm across in the case of the Southampton map. The image has thus been converted to a set of digits, some 500 million of them for a geological map.

The raster data produced by scanning is vectorized, that is, each line of the original drawing is traced individually through the raster and represented by a string of (x, y) coordinates of points spaced along the line. In the process, any irregularities of line thickness are corrected. The representation of the line for display (thickness, colour, style) can be selected at a late stage. The lines also define polygons - areas surrounded by lines - which on the 1:50 000 geological map are differentiated by colour. The polygons are detected by the software and the colour associated with each is input as a code. The draughtsman can assign the colour-code to each polygon by one of a number of methods, such as preparing an overlay for scanning with symbols identifying the colour code placed near the centre of each area.

The maps are produced by an offset-litho printing process which requires at least four plates to be prepared which determine the percentage density of black, cyan, magenta and yellow ink applied to each area of the map during printing. The percentage for each colour-code can be entered on the computer, which then has the information it requires to produce four (or more) new rasters, one for each printing plate, recording the density of colour for each area. From each raster a film master is prepared by raster plotting. Raster plotting reverses the raster scanning operation and can in fact use the same device in a different mode. The laser beam, now switched on or off for each pixel depending on the corresponding digit in the raster, creates a photographic image on film with the correct density for each area for that particular printing colour. The four film masters produced in this way can be passed to an appropriate cartographic printer for preparation of colour plates for printing.

The advantage of this technique compared to conventional methods is the saving of time and cost compared to the labour-intensive and error-prone task of cutting and peeling up to 20 intricate hold-out masks to produce the colour-separation components for plate making. The lines and symbols on the map are scanned by a similar method. The monochrome topographic base-map was scanned, digitally screened, and plotted on the black-plate master to ensure accurate registration with the geology.

This cost-effective method is now widely used in BGS for production of published maps. The relatively high cost of accurate scanning, processing and plotting is set against a long print run of some thousands of maps. As a by-product, digital tapes are available with a representation of the mapped geology at that scale, generally 1:50 000.

Digitisation at survey scale

The geological map is a two-dimensional representation of a three-dimensional model. Geological data are positioned relative to topographic features, such as streams and contours, depicted on the Ordnance Survey base map. The relationship of the geology to the topography is crucial for understanding the three-dimensional model. The geology is surveyed, not at the 1:50 000 scale, but at 1:10 000. Because of the cartographic generalization which has taken place between the 1:10 000 and 1:50 000 topographic maps, extensive editing of the geological lines is required to bring them to the correct relationship with the topographic features at 1:50 000 scale. As the editing requires an understanding of the geology and topography, it must be controlled by a trained draughtsman or geologist.

The 1:25 000 Ordnance Survey maps of Southampton, unlike the 1:50 000 maps, are a direct reduction of the 1:10 000 scale maps, and it was therefore appropriate to digitize the geology at the survey scale (1:10 000), rather than use the generalized 1:50 000 geology despite the latter being already available as a raster. The final maps must be available for copying on demand. Therefore, to keep copying costs reasonable, colour was not used, and with a very small print run, the overheads of the raster scanning and plotting methods described above could not be justified.

Lower-cost raster scanning methods are available, but the resolution would be inadequate to preserve detail or to give the precise registration needed with the topographic base. There are also relatively low-cost devices for plotting rasters. The most promising for this work is perhaps the colour electrostatic plotter which can print large-size colour documents rapidly. As with other raster devices, the speed of operation does not depend on the complexity of the image. Small internal distortions are likely, however, which would create unacceptable misregistrations with the topographic base map.

This could be circumvented by scanning the base map as well as the geology, and printing them together in one pass. Unfortunately, at 400 pixels per inch, the resolution may prove inadequate to record the full detail of the base map, particularly place names. The cost of redrawing the base map could not be justified for this project. For these reasons, an alternative method of digitizing was adopted, the so-called vector method. A digitizing table automatically records the position of a stylus when a button or foot-switch is pressed. The operator fixes the map on the table, and places the stylus over a point, pressing a button to record its position. A line is represented as a sequence of closely spaced points which on plotting are joined by straight lines or vectors. An area is defined by its boundary lines. The vector representation of a simple line image requires much less computer storage and processing than a raster representation, and is therefore well-suited to the linework of a geological map. BGS is experimenting with the use of vector methods in giving computer assistance to the geologist in preparing a fair-drawn copy of his field map. It can, however, be a laborious and error-prone technique for digitizing large amounts of existing material.

The vector method has advantages. The output can go directly to pen plotters or light-head plotters which are widely available in a range of sizes and resolutions and are adequate to produce maps of the size and quality required for this project. Such plotters cannot, however, adequately plot the topographic base which is in any case unlikely to be available in digital form. It is possible to plot the linework directly on the base map, but registration is difficult and the more flexible approach was adopted in this project of plotting the geological linework of the applied geology map on transparent film. Ornaments and symbols were added manually and the results combined with the base map photographically.

Compared with the methods used for the published 1:50 000 map, the vector methods for the applied geology maps are economical for short print runs, could accommodate regular updating and could be used for preparing one-off maps of specific topics. Computer editing of the lines to make small corrections or additions is straightforward. The preparation of maps on demand does, however, raise some new issues.

Maps on demand

The reason for printing the applied geology maps at 1:25 000 scale is to match them with maps of other topics used by planners at the same scale. Because they all relate to the same Ordnance Survey base map, they should also relate to one another. The currently available methods for preparing a one-off full size map for a specific geological topic at a reasonable cost are the use of a pen plotter, as in the Southampton project, or, for less precisely located data, the use of an electrostatic plotter. The pen plotter is particularly appropriate for line work, the electrostatic plotter for intricate detail and for filling areas. Both can plot in colour, although the colour range is limited. It would be possible to use these methods to print a map on demand with its own specific information content. The techniques require further development, however, and for the present project it was thought preferable to provide a limited number of map types for copying when required.

As a preliminary to producing a full-size map, or for preparing a page-size map, screen-based methods can be effective. The graphics screen of a computer work station is unlikely to have a resolution of much more than 1000 pixels in each direction, and is more likely to have the approximate resolution of a television screen, 640 pixels horizontally, 480 vertically. Up to 16 colours are usually available in a display, although many more are possible. The screen thus lacks the size and the detail of the conventional map. It does, however, offer one outstanding benefit. It is interactive, that is, the display can be made to change rapidly on instructions entered by the user. Thus a form of dialogue is possible between the user and the computer.

A benefit of interactive working is that a trial and error approach is possible. Different combinations of colours and line styles can be tried to find those that give the clearest representaton. Symbols can be moved to avoid obscuring the linework. Additions and amendments can be made and instantly checked. Different forms of presentation can be tried and the best selected for plotting on paper. Where the three-dimensional form of a sequence of rock units is to be depicted, interaction is particularly valuable in exploring many alternative lines of cross-section, determining the best position for perspective views, and overlaying combinations of maps of different rock units. In the same way as the viewer looks from one part of a map to another, and moves closer to examine points of interest, a computer can pan across a map held in its memory displaying different areas on the screen, and can zoom in to show small areas in detail or zoom out to show the entire map. A screen-based system may provide an adequate response to some user requirements without a paper copy being required.

A screen display is effectively a raster, just as a television image is a raster. The input to the graphics display unit, of which the screen is a part, can be either vectors or a raster. The display unit contains rasterization software which converts from vector to raster form. A hard-copy unit can be attached to the display unit and can provide a copy on paper or film of the image on the screen. Many display units hold in their local memory a display of higher resolution than that shown on the screen (4000 pixels square or more). It is possible to pan and zoom within this larger image. It may also be possible to access the larger image for plotting on paper or film. Using such plotting techniques as ink-jet or thermal-transfer, attractive coloured images can be prepared. They are seldom larger than A4 page size and are of lower accuracy and resolution than a cartographic plotter.

In the Southampton project, screen-based interaction was used in checking and correcting the digitized lines and points, in selecting lines for display on the various maps, and in checking the geological linework before plotting. Future developments, discussed in Appendix 4, are likely to make increasing use of interactive computer graphics.

APPENDIX 2

DATA MANAGEMENT

The ability to prepare a specific map on demand implies that there is a pool of information on the computer (the database) from which the required items can be drawn. Management of the data, that is, data entry, checking, correction, rearrangement, up-dating and selective retrieval, requires a set of computer programs known as a database management system (DBMS).

The data for the Southampton project falls into three main groups - the borehole, geotechnical and cartographic data. The borehole and geotechnical data can be structured naturally as a set of tables, each containing many horizontal rows and several vertical columns which might have such headings as: borehole number, date drilled, easting, northing, ground elevation, total depth, etc. A second table might have each row corresponding to a borehole sample, with column headings: borehole number, sample number, depth, result of penetration test, etc. The occurrence of the borehole number in both tables allows cross-referencing between them, and is known as a key field.

This type of table is known in set theory as a relation, and the set of tables, cross-referenced by key fields, constitutes a relational database.

Relational databases are in widespread use, and offer a flexible and appropriate view of much earth science data. Many relational database management systems are commercially available, including the one used in this project, known as Oracle. It is described in more detail in the accompanying database report (Laxton, 1987).

Information from the set of linked tables in the Oracle database can be selected either through a simple menu system or by means of a query language known as SQL. A menu is a set of choices presented to the user on the screen, from which he selects the most appropriate option. In the light of the user's choice the computer either performs an operation or presents a new menu to enable the user to define his requirement more precisely. The advantage of the menu is that the user need not be familiar with the system - the computer provides the information needed to make a choice. The disadvantage is that the experienced user is presented with much unnecessary information and may be prevented from taking the most direct route to his goal. A menu system cannot deal with requirements that have not been foreseen and included in the menu.

The other means of selection is the query language SQL which is now widely adopted in relational DBMS, including Oracle. The user defines the criteria for selecting items for retrieval (for example, boreholes where there is a coal seam over 2m in thickness within 5m of the surface) and states which columns are to be retrieved and in which order the items are to be arranged. As illustrated in the database report, quite complex retrievals can be performed in this way. The disadvantage is that the user must know what data are available and how they are arranged across the various tables.

Information retrieved from the borehole database can be passed on to a display program and plotted as numbers, symbols or text on a map. However, this database contains only data about points and not the cartographic line and area information. It is necessary to link both kinds of data to meet future requirements.

Cartographic data, whether held in raster or vector form, do not fit naturally into the relational structure. Some workers in the field of cartographic databases have shown that it is feasible to manipulate such data within the framework of relational concepts (van Roessel, 1987), others suggest that cartographic data structures should be studied on their own terms (Kleiner and Brassel, 1986). No conclusive answers have yet been reached. It is clear, however, that selective retrieval of cartographic items requires a full description of the map data to be held in the computer.

The emphasis so far in digital cartography has been to describe the map data in terms, not of its geological significance, but of its graphic presentation on the map. Thus, in the case of the 1:50 000 Southampton map, information is held on the colour codes for each area, and the appropriate density of inks on the colour plates. On the 1:10 000 map, information is held on the line type (dotted, dashed, continuous) but not directly on its geological meaning (conformable, unconformable, faulted boundary).

In order to prepare applied geology maps on demand, geological descriptors must be attached to the lines on the map. A number of methods are available. On input, sets of lines can be assigned to different "layers", analogous to overlays on the map. In a particular display, layers can be switched off or on, just as a number of overlays might be selected for viewing together. Another method is to assign one or more feature codes to each line during or after digitization. The Ordnance Survey use such a method to distinguish between, say, fences, roads and rivers on their digital maps. Several feature codes or attributes may be required for one geological line, to indicate, for example, that it is the boundary between the Lower Carboniferous on the left and Upper Devonian on the right, that it represents a fault with a probable downthrow of 200m on the left, that its position is known to within 30m on the basis of outcrop and probably to within 5m on the basis of a topographic feature. Attribute data can readily be organised as a table in a relational database, but the line data, being of variable length, fits less naturally into this structure.

A third method is more appropriate to raster than to vector data. The geological map can be viewed as a set of areas or polygons, of which lines are a special case. The polygons can be identified in the raster, and the descriptors can be attached directly to them. Thus the polygons representing Lower Carboniferous and Upper Devonian strata would be identified directly, as would the long, thin polygon (line) representing the fault between them. At the time of field survey, the map may be thought of more naturally as a set of boundaries shown by lines. At the time of preparing a derived map, it may be more appropriate to consider it as a set of areas. The vector and raster approaches are not mutually exclusive, and in particular the transformation from vector to raster form is straightforward. Unfortunately, on the rather small computer system on which the Southampton 1:10 000 data were digitized, polygon attributes could not be handled satisfactorily. Instead, the lines were classified into a number of layers during digitization. This provided a coarse classification for selection for display. Where required, a detailed selection of lines was made by pointing on a digitizing table to the lines to be deleted.

APPENDIX 3

SURFACE MODELLING

In addition to representing geological boundaries, there is a requirement in applied geological mapping to represent the full three-dimensional form of some geological surfaces. The present-day land surface is one of these. Its intersection with older geological surfaces helps in understanding the form of the lower horizons and information on slopes has a bearing on the possibility of land slip. Unlike the older geological surfaces, the present-day surface has been surveyed in detail and a precise representation is available as the Ordnance Survey contour map. Contours are not the most effective representation for computer manipulation, however, and in collaboration with the Ordnance Survey, a digital terrain model (DTM) was prepared. The DTM is a grid of values - a coarse raster (see Appendix 1) - in which the average elevation of each cell in the grid is stored in the computer. Structuring the data in this way allows computer programs to perform grid operations, such as calculating the slopes between adjacent grid cells, calculating the line of intersection of surfaces, or the thickness of rock between two gridded surfaces. The grid is also a convenient structure for many forms of computer display.

The DTM was prepared by raster-scanning an overlay map containing contour lines only. As with the 1:50 000 map described earlier, polygons were generated by special-purpose software on the computer. The program for DTM production can, however, with some manual intervention, insert the correct contour levels for each polygon. The program requires information on the contour interval, and expects adjoining polygons to have adjacent contour values. On the basis of that information it interpolates an expected average elevation for each grid square, in this case 50m across. With minor manual editing, an adequate result was obtained.

Most geological surfaces, however, are known only from limited outcrop information and scattered points where they are penetrated by boreholes. The task of recreating the complete surface generally requires geological decisions which it may not be possible to implement in a computer program. For a number of reasons, the contour maps for this project were drawn by hand on the basis of value-posted maps drawn by computer. They were not a major part of the study and an appropriate contouring program was not available until nearly the end of the project. Geomorphological considerations play a part in contouring the near-surface horizons, and such controls are difficult to include in a computer program. In future studies, where somewhat deeper horizons are involved, automated contouring may well prove appropriate.

The possibility of generating and storing gridded data to represent a sequence of surfaces should be considered where the interaction of these surfaces is of interest. It is then possible to generate derived surfaces, such as the thickness of strata between two known horizons. This is particularly relevant for the production on demand of applied geology maps delineating areas on the basis of complex criteria, such as, the area underlain by coal seams totalling more than 2m thick within the top 10m of solid rock, and not overlain by more than 5m of drift. Such requirements cannot be met from map data by relational database management systems and may require specialized Geographic Information System software. They were not needed in the Southampton project.

The Digital Terrain Model was used in a number of ways. It was the basis of a slope map where calculations of slope between adjacent cells gave an indication of the slope over an area 50m across. A contour map of slope was prepared on this basis. Clearly, smaller areas of steeper slope may occur locally in narrow valleys or in excavations. Nevertheless, when considered in conjunction with the geological maps, the slope map gives a regional view of areas where slippage of land is more likely to occur. The other main use of the DTM was for visualisation of the form of the land surface by means of perspective views (see Frontispiece). Digitized lines can be shown in their correct position on the oblique view, thus showing graphically how geological features are related to the topography. The ability to show graphically the form of a landscape together with the underlying geology may be relevant, for example, in planning motorway routes, or in showing the effect of cut and fill or other changes to the contours of the landscape.

APPENDIX 4

FUTURE TRENDS

Concepts of object-oriented topologically-related methods being advocated by some software suppliers may have a bearing on geological work and may require some explanation. At present, most graphics programs consider points and line segments as the basic entities with which they deal. The user, however, is more likely to think about his activities in terms of "objects" such as rock units or geological faults. The aim of object-oriented programming is to ensure that the objects are defined to the program in terms of their component parts, so that relationships can be maintained correctly when objects are manipulated by the program. The user can then express his programming requirements at a higher and more natural level.

Geometrical relationships refer to the position of spatial entities as defined in some coordinate system. To maintain the exact geometrical relationships from digitization to plotting requires high precision engineering and exact registration where several documents are involved. Maintaining the fit between geological lines and the topographic base map, for example, requires great care and expensive equipment.

Topological relationships, on the other hand, refers to aspects of spatial location which are not affected by "rubber sheet" deformations. If a map were drawn on a rubber balloon, for example, which was then distorted, distances and angles would change, but lines would still intersect at the same point, a point within a circle would remain within the circle, and the area to the left of a directed line would remain on its left. If such relationships as: above, below, near, within, intersects, converges with, coincides, bounds or overlaps can be expressed explicitly in the data and can be maintained throughout digitization, graphic manipulation and display, then less demand may be placed on geometrical precision with its consequent costs. The maintenance of these relationships on a map is likely to be more significant to the user than precise geometrical position. Such an approach would imply digitization of critical items from the topography along with the geology.

Once a map has been printed, minor geometrical distortions no longer cause difficulties for its use. Indeed, most users are satisfied with a folded map despite severe local distortion of the paper. If reference points and critical features are digitized from the topographic map and fitted to the geology as it is digitized, then it would be feasible to record topological relationships explicitly, such as: at point (x,y) a geological fault intersects a stream. A plotting device need not then maintain high geometrical precision to ensure that the items are shown in the correct relationship. Such an approach is not yet fully implemented on a commercially available system. The appropriate plotting device would probably be a raster display. The use of raster images has other potential implications for geological maps.

Raster images

Matching the geology to the topography has been an important consideration in the Southampton project, and would be even more important in an area of high relief. It is not clear, however, that the Ordnance Survey map will remain the most important base for geological mapping in the long term. Features shown on the map are not selected for their geological significance. For example, areas of outcropping rock are seldom shown. Developments in satellite imagery suggest that an alternative base may be available within the next few years. As shown in Figure 1, images currently available from the Thematic Mapper instruments on the Landsat satellite provide images which are photogrammetrically accurate. The Ipley Inclosure of the New Forest (within the Southampton area) has the same shape as that shown on the 1:25 000 maps. The image lacks the clear detail of the map, however, and the square pixels clearly visibly in Figure 1 are about 30m across on the ground.

Similar instruments (a Daedalus scanning system simulating SPOT channels) have been carried over the same area by aircraft to simulate higher-resolution satellite imagery during the 1984 NERC aircraft campaign. With 5m resolution, details of the Ipley Inclosure such as paths and even some trees, are clearly visible. Recent changes to the landscape, such as an excavated area, can be seen. An aircraft, unlike a satellite, is not a stable platform for the instruments, and as can be seen by comparison with the map, the image is greatly distorted. A more recent satellite, SPOT, can provide 10m resolution, and it is likely that future imagery will combine geodetic accuracy with high resolution. A hybrid image, perhaps combining names and contours digitized from a map with processed imagery from a satellite, could potentially offer a better base for geological mapping.

Imagery is collected and processed as a digital raster, and as related work in BGS has demonstrated, it can be readily linked to a raster-scanned geological map on an I^2S image analysis computer (Laxton, 1985). The imagery contains information collected from several different bands of the spectrum, which respond differently to aspects of the land surface. By computer manipulation, chosen aspects can be emphasised. In areas less affected than Southampton by the works of man, an indication of the geology can be obtained, even with the 30m resolution of the Thematic Mapper. Areas of peat cover, for example, have been identified in detail in upland areas. The raster shows scattered small areas of peat in a more natural representation than the precise, smooth, boundaries of the Geological Drift Map. Because a raster can show overlap, dispersion and uncertainty it may achieve greater realism than the earlier technology of pen and paper.

A final reason for believing that geological cartography may be affected by raster methods is that the amount of detail in an image can be reduced, and thus within limits a map can be generalised, by computer processing. There is therefore some hope of reducing the labour of rematching geology and topography on change of scale.

As mentioned previously, much of the data in applied geology maps lends itself to representation by rasters or grids, and the grid to grid operations provide a means of comparing, analysing and examining the interactions between different aspects of the map. For example, drift thickness can be compared with rockhead contours, or can be overlain by a map of, say, an intended motorway development. This suggests a convergence of database and cartographic techniques, leading to Geographic Information Systems and, in the case of geology, to Spatial Models.

APPENDIX 5

DATA INTEGRATION AND MODELS

There is little doubt that a database management system is a powerful tool for selective retrieval and manipulation of the data. To some extent also, the relational concept, linking datasets through key fields, provides the required flexibility in cross-referencing. A difficulty arises, however, with geological as with other spatially referenced data. The principal link between geological observations is their position in space. Spatial relationships are not the unambiguous links between say, an employee, his salary, sales commission and tax code which might occur in a commercial database. Spatial relationships include such concepts as: near, adjacent, above, within, contains, overlaps, intersects. They do not necessarily imply that two measurements at the same grid reference apply to the same object. Furthermore, different geological variables may well be sampled at different locations, and may have different spatial resolution and sampling schemes. Cross-referencing is not therefore concerned with individual items, but rather with a geological interpretation of the variables across the area as a whole.

A Geographical Information System (GIS) should in principle come nearer to meeting the geologist's requirements, in that it extends database management to include cartographic data, and provides functions such as determining overlap of polygons and interpolation of surfaces. The field of GIS is seen by the Chorley Committee (1987) as one of national concern. In concept it can provide the framework for integrating spatial data of many different kinds. At present, however, it seems that for geological applications, a relational DBMS, surface modelling, graphic display, and digital cartography are all required as part of the overall system, and are not fully integrated in an appropriate product. Until such time as adequate standards have been defined and widely accepted, some compromise is necessary with ad hoc links between parts of the system.

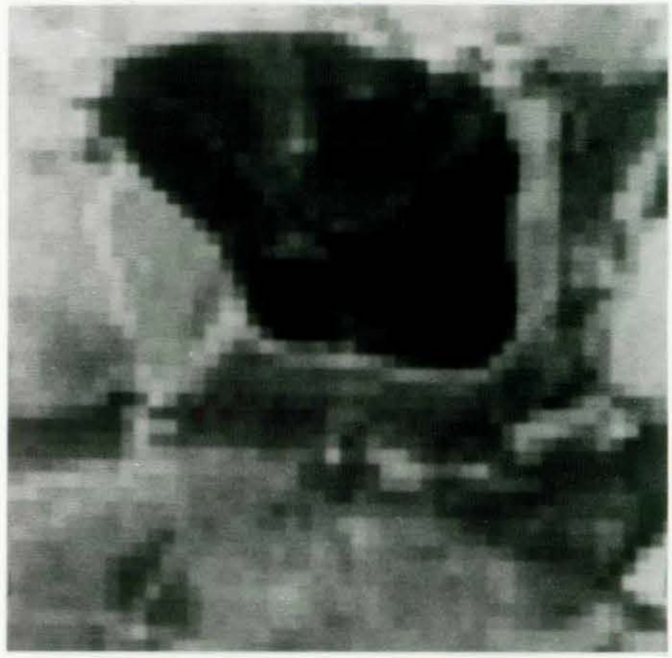
In the longer term, there are specific geological requirements which go beyond the functions of a GIS. The map or other display is a two-dimensional projection of a spatial model - the three-dimensional interpretation which geologists have developed of the rock units of an area, their form and disposition in space, their composition and their formation and evolution through geological time. As techniques are developed to represent more of this spatial model in digital form, the GIS may be seen by the geologist as a means of linking the output from a digital spatial model to other types of spatial data. Thus, on the one hand, the digital model enables the geologist to express his interpretation in full

Figure 1

(a) Satellite imagery of the Southampton area
In the lower left corner is an area of woodland known as the Ipley Inclosure. This smaller area is shown on
(b) the Ordnance Survey 1:25 000 map
(c) Thematic Mapper image at 30 metre resolution
(d) simulated satellite image at 5 metre resolution

(a)

(b)



(c)

(d)

detail, in a form accessible to the geological community as a whole, rather than being held only in the geologist's mind (illustrated by maps and sections). On the other hand, an authoritative interpretation is available for the preparation by computer of specific applied geology maps as required. The digital model can of course be updated when new data is received or new interpretations developed. These developments will require some further years of development before they are generally available, and existing experimental prototypes will require continued development to ensure that there is compatibility with the database and computer mapping system.