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BRITISH GEOLOGICAL SURVEY

Applied geological mapping in the Wrexham area

computing techniques

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INTRODUCTION

Contract requirements

The Wrexham area applied geological mapping project (Contract No. PECD/7/1/290) was commissioned in 1988 by the Department of the Environment on behalf of the Welsh Office, and carried out by the British Geological Survey.

The objectives were to provide cover of modern geological maps for the Wrexham area and to present applied thematic information on geological conditions as they relate to planning and development. The main results of the study are given in Hains (1991).

The present report gives an account, as required in the contract schedule, of the techniques used for the production of the computer database and the preparation therefrom of applied maps. Conclusions are recorded on the suitability of the systems for application in further applied mapping studies.

BGS indicated in their response to the invitation to tender that computer techniques would be a significant aspect of the project. An earlier study of applied geological mapping in the Southampton area was a first detailed attempt by BGS and the Department of the Environment to develop procedures for computer production of maps for a variety of user requirements. Many problems were identified and solved during the Southampton study, but it was felt that another development stage was necessary before a standard method could be established for future work. Detailed descriptions of the methods developed for the Southampton study are given in reports on the database (Laxton, 1987) and mapping techniques (Loudon and Mennim, 1987), and are not repeated here.

It was agreed that the Wrexham project was a suitable candidate to take the work forward. Accordingly, the project included a significant element of computer input and manipulation to provide a store of data from which selected elements, from an individual borehole record to a detailed map, could be accessed. Applied geology maps were to be generated by computer from elements selected from the database.

The methods used for this project were an advance on those adopted for Southampton. They broke new ground and required significant development work. The methods were experimental but seen as leading to new standards for applied geology maps and a more accessible database.

Context of the study

Within the Wrexham project, the narrow objectives of the mapping methods were to accept and store digital representations of the geological maps, and to retrieve and display selected parts of the data as applied geological maps. Such maps, dealing with specific themes, can provide a clear presentation for a particular requirement. The conventional published geological map, on the other hand, can serve many purposes, but may require specialist interpretation.

In a broader framework, the work can be seen as providing tools for visualising a geological spatial model - concepts of what rock units are present in a particular area, where they are and how they are arranged, what they consist of, what properties they have, how they formed and changed through geological time. Maps may in due course be superseded by digital spatial models for storage and manipulation of cartographic information. However, there is no obvious alternative to conventional maps for field survey, nor for final presentation (at least at this stage of development of the technology). Screen based methods do not offer the large display size, high resolution and portability which the user requires. In time, however, the applied geological map may come to be seen as an ephemeral document which meets a defined short-term need, with the underlying digital spatial model the master source of up-to-date information (see Loudon, 1986).

The Wrexham project has made significant steps towards achieving the longer-term aims. The ability to hold a computer record of the present-day terrain and the three-dimensional data from rockhead contours and boreholes complements the digitised field maps with their record of the geology at surface. The required maps were obtained by selecting from the digital data using a relational database management system and a geographic information system, as described in the section on methods. The ability

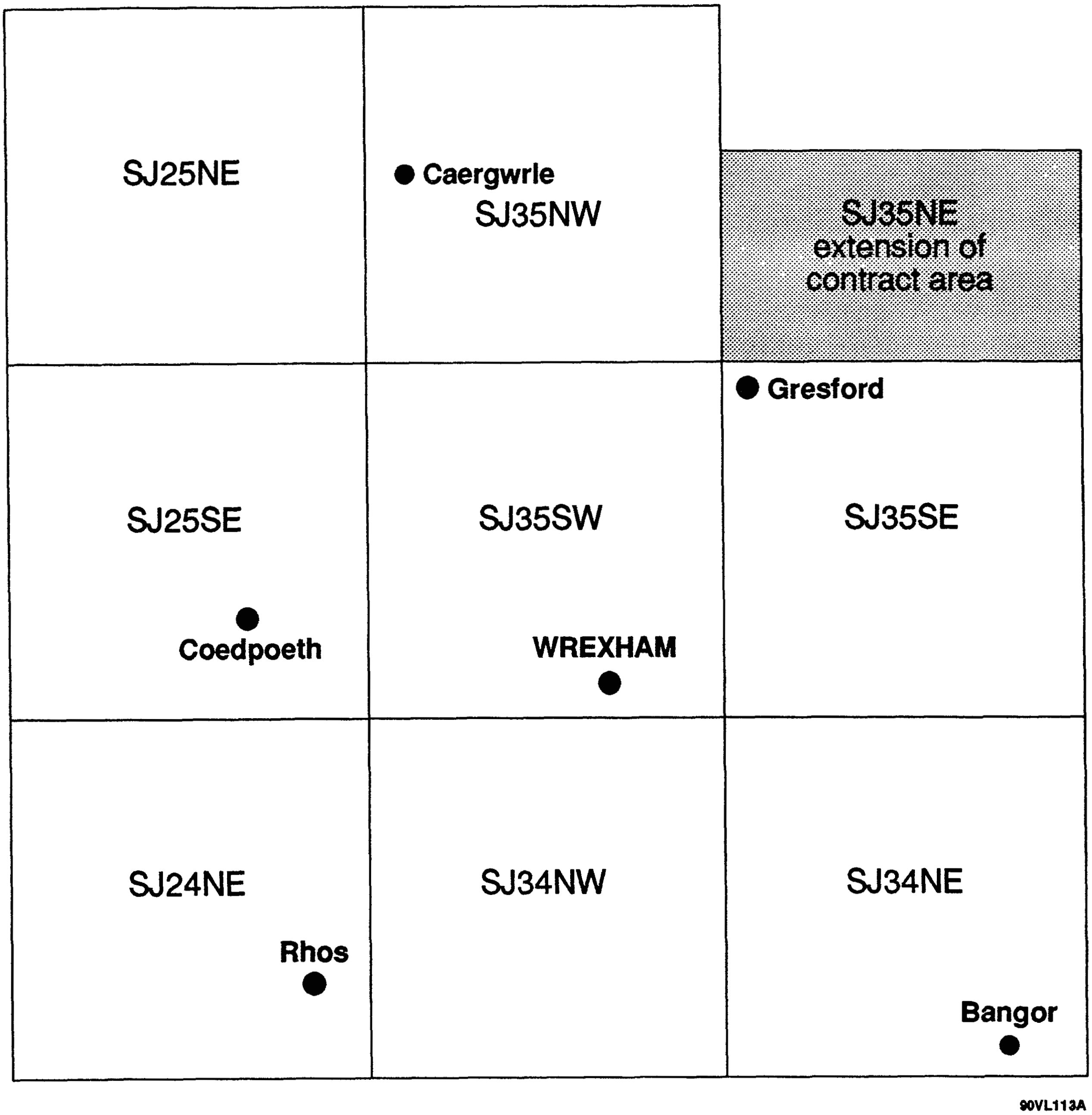


Figure 1. Contract area showing component 1:10 000 sheets

to print customised maps on demand, on a colour electrostatic plotter, has been demonstrated, as has the flexibility of generating colour separation plates from the same digital data for conventional printing where longer print runs are needed.

It has to be pointed out, however, that the techniques are still developing, and the methods used for Wrexham stretched the available technological capabilities. A significant complication was the necessity of operating with existing equipment and software obtained from many sources to meet general NERC requirements. A major task has thus been to develop methods of passing information between systems. The immediate emphasis was more on providing results for this project than on developing a robust production system for the future. However, a parallel project is now under way within BGS which aims to build on the Wrexham experience within a more general open-systems framework, helping to overcome artificial constraints on the movement of information.

Acknowledgments

The borehole and other point data were coded at Aberystwyth by J A Thorburn and entered at Keyworth by the Land and Marine Surveys (South) database group, in particular K A Holmes, J R A Giles and P M Lewis. The geological map data were digitised by A W Clifton and R W Armstrong of the Cartographic Development and Production Groups. At Edinburgh, K C Mennim and J L Laxton advised on the basis of their Southampton and related experience. K C Mennim supervised the cartographic bureau work in digitising, digital terrain models and assembly and production of the finished maps, and advised on electrostatic plotter map production. J L Laxton handled the geographic information systems work, with assistance from T Duffy of NERC Computer Services and B Gittings of Edinburgh University, and the applied geological map preparation.

The project leader, Dr B A Hains and his colleagues at Aberystwyth; the Nominated Officers, Dr R A B Bazley for BGS and Mr D B Courtier for the Welsh Office; and the project Steering Committee have provided advice and assistance with the computing applications throughout the project. Their valuable help is gratefully acknowledged.

NATURE AND AMOUNT OF DATA

The data to be input and assembled in the database fell into six categories

1) the scanned topographic base maps
2) scanned contours from the topographic map
3) linework from geological maps and mine plans
4) borehole data, mine shafts and adits
5) geotechnical (engineering geology) data
6) other point data such as location and type of quarries and kettle holes

Topographic base maps

The area covered by the contract included most of nine 1:10 000 geological sheets, and is shown in Fig. 1. Topographic bases at 1:25 000 scale were scanned at an external bureau (see section on Methods).

Scanned contours from the topographic map

The Ordnance Survey contours for the area were scanned in a similar way to the base maps, from an overlay showing only the contours, edited to remove labels and close gaps. The contours were processed to interpolate elevations at points 50m apart on a square grid. The interpolated values form a digital terrain model. This is more readily processed by computer than the original contours, for such purposes as calculation of drift thickness.

Linework for geological maps and mine plans

The geological linework for all nine 1:10 000 geological sheets was digitised. This linework comprises solid and drift boundaries, faults and mineral veins. These sheets vary greatly in complexity from the intricate geology of the exposed coalfield around Brymbo [SJ 25 SE] and Rhosllanerchrugog [SJ 24 NE] to the simpler drift covered Upper Coal Measures and Trias of the eastern part of the contract area [SJ 35 SE and 34 NE]. The linework and marginal material (Figs. 2, 3 and 4) were plotted by computer to provide fair-drawn copies of the 1:10 000 maps.

Areas of underground coal workings were digitised from the British Coal mine plans. Most of these plans, some 70 in all, are held as copies

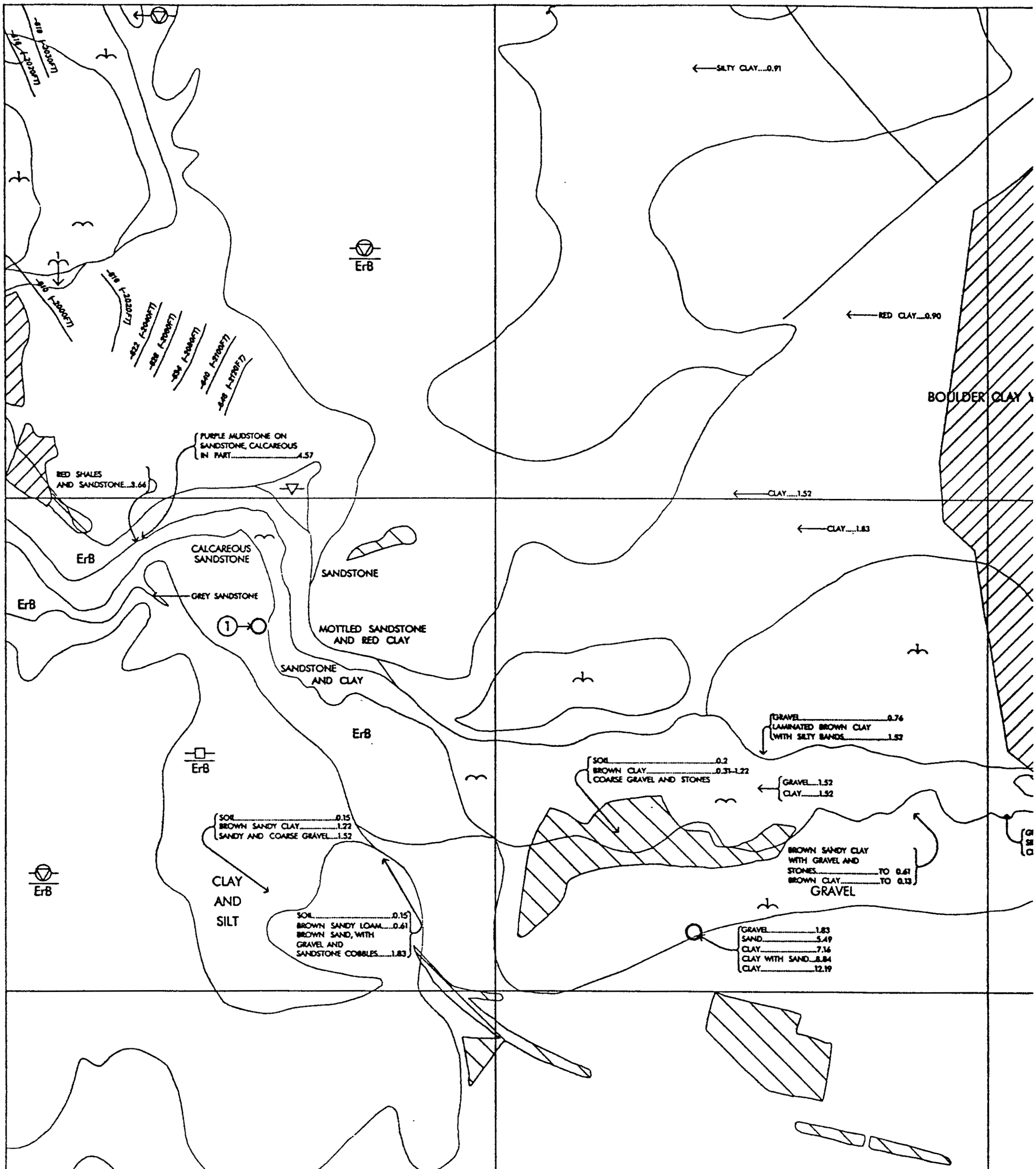
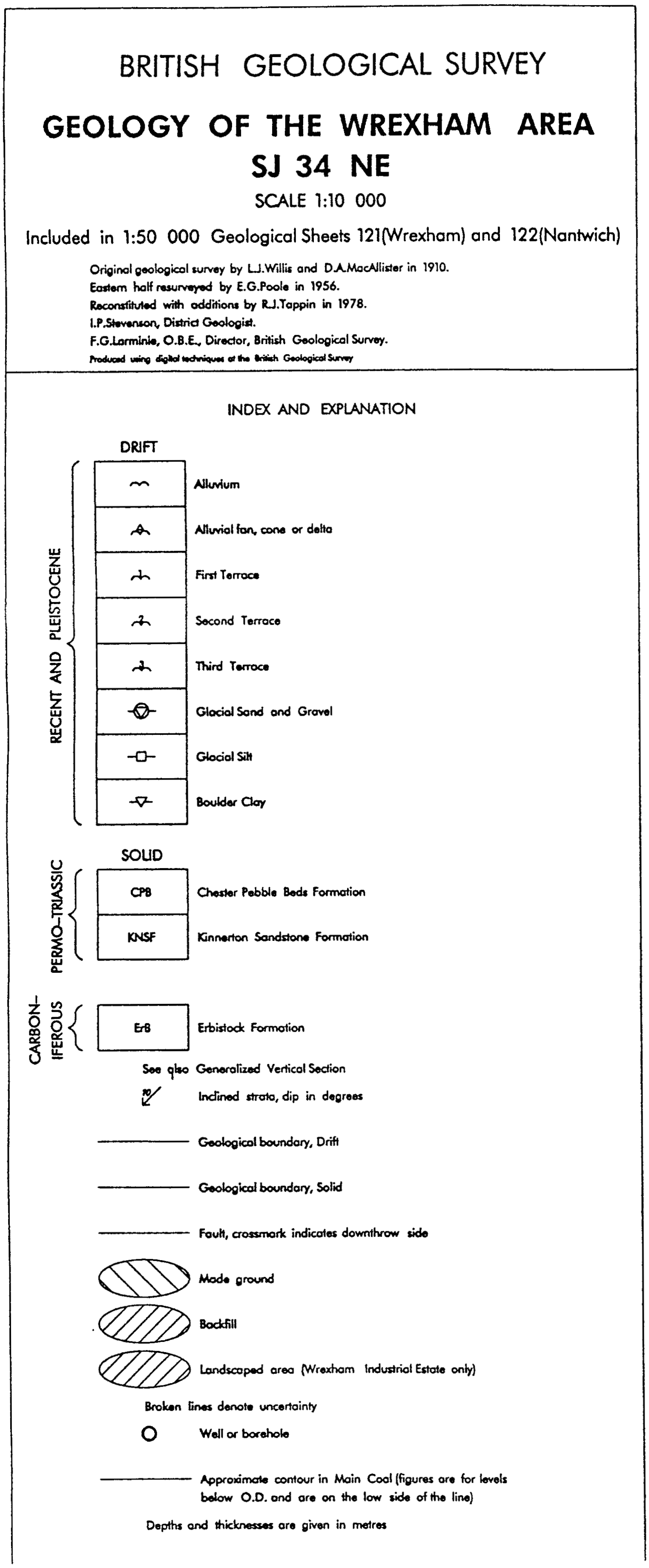


Figure 2. Example of digitised geological linework (1:10 000)



Figures 3. Marginal material for 1:10 000 sheet prepared by computer

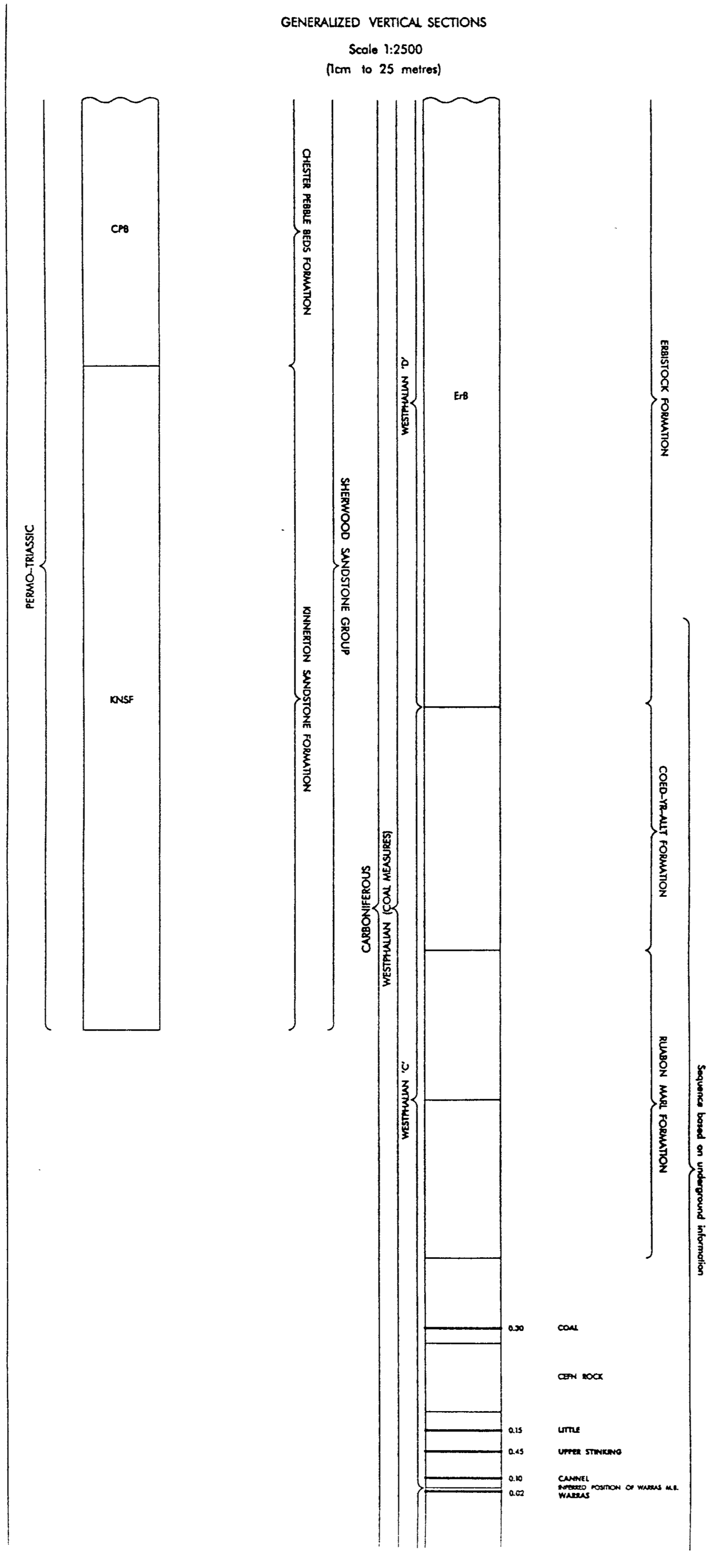


Figure 4. Marginal material for 1:10 000 sheet prepared by computer

on the 1:10 560 scale. Lines delimiting the extent of buried sand and gravel deposits were digitised from BGS Sand and Gravel Resources (IMAU) maps at 1:25 000 scale. Most of the linework for the 1:25 000 thematic maps was derived from these parts of the database.

Borehole data and mine shafts and adits

Data from 6 037 boreholes, mine shafts and adits were recorded. In the vast majority of cases, the only information for shafts and adits is their location. Data additional to those already held by BGS were collected from Clwyd County Council, Alyn and Deeside District Council, Wrexham Maelor Borough Council, the Welsh Development Authority, British Coal, the Welsh Water Authority and some private contractors and consultants. Lithological logs with an average of 7 lithological units were coded for 3153 boreholes (Figs. 6, 7, 8, 9). The method of validation of the borehole data is shown in Fig. 10.

Graphical logs of each borehole (Fig. 11) were produced to assist with coding the stratigraphy for each lithological unit. The stratigraphy is often unclear without comparison with other logs, and computer graphics enable this to be achieved more effectively than using written records. The stratigraphical classification of boreholes in the database is not yet complete.

Geotechnical data

Geotechnical (engineering geology) test data were almost entirely abstracted from site investigation reports. A few other borehole logs have associated test data. The data refer to up to 14 tests on nearly 5 000 individual samples or test points. Each test is related to the lithology of the sample tested and to its stratigraphical position.

Thematic maps were produced giving the broad engineering characteristics of both the solid and unconsolidated rocks, although some stratigraphic formations are poorly represented by test data. Graphical and tabulated summaries of data were also prepared and presented in the report of the engineering geology of the Wrexham area (Waine and Culshaw, 1991). However, the geotechnical values given in the tables are only a general guide and not a substitute for adequate site investigation.

The geotechnical database is maintained as a separate entity. However, all the boreholes for which test data are available are also held within the main borehole database, and each borehole has the same accession number in each data set.

Other point data

Several other categories of point data are included within the database and appear on various thematic maps. These categories include quarries and pits of various types and kettle holes. For quarries and pits, apart from their location the information includes whether the quarry or pit is active, disused or backfilled and the nature of the mineral extracted from it, such as sand and gravel, limestone, or clay.

METHODS

Approach and techniques

The system for production of applied geological maps (see Fig. 5) has quite a demanding specification, in which many components must be integrated as a robust system capable of handling a diversity of large datasets. The activity was undertaken within a computing environment which was determined in part by the stage of evolution of the technology, in part by investment decisions taken by NERC Computer Services and by BGS, and in part by the availability of external services. The existing computer facilities, which in total represent an investment of many millions of pounds, are described in Appendix 1.

Aspects of the computer-based applied geological mapping system are:

input of borehole, cartographic and other data

managing the data, in the sense of being able to edit, integrate, validate, store, update, selectively retrieve and reformat the data

communicating between the various devices and programs on which the work is undertaken

processing by calculation of mean values, contouring, etc.

assembling the data from various sources and presenting them in an appropriate manner, in particular as applied geological maps.

Data input

Borehole data

The original borehole records came from many sources, and are of widely varying quality, detail and data content. Within the database, an abstract from these data was assembled as a set of tables in which each row refers to one borehole, and each column refers to one attribute, such as ground elevation or total depth. A table contains comparable information for each item, which is clearly desirable, in order to ensure that like is compared with like during computer processing. The tables are known in mathematical terms as relations, and a database structured in this way is known as a relational database. The data were selected to be relevant to computer processing, and other information in the original records, which is specific to an individual borehole or which plays no part in the computer processing, can remain in the paper records, to which the computer file provides an index.

Borehole databases have been used for many projects in BGS over many years, and standard formats and specifications for data content have been adopted to simplify the use, access and integration of the data. Coding forms (Figs. 6 - 9) are used to control the transfer of data from the original records in order to ensure that the correct items are recorded in the correct manner. A keyboard operator subsequently enters the information from the forms on to the computer. The forms are also helpful when the data are being checked and validated, as the inevitable errors in data entry can be identified separately from the errors in transcription, and from those existing in the original records. Validation routines can then be run to help to ensure that the quality of the data does not deteriorate significantly on transfer to the computer.

The borehole information is stored and managed using the Oracle relational database management system (DBMS) on a VAX 8550 at BGS, Keyworth. The data can be accessed at the BGS Aberystwyth office and elsewhere through the Janet network. The borehole data is stored in two Oracle tables - one contains the BGS registration number, grid reference, total depth, depth to rockhead, driller, contractor, whether water struck, OD level of start point and overall reliability; the other contains downhole information including lithology, stratigraphy, depth, nature of boundaries (e.g. fault, unconformity) and a very brief description.

Geological lines

Lines representing geological boundaries, faults, etc., were also required for the production of the applied geological maps. They are represented by a sequence of coordinate pairs defining a string of points which recreate the line when joined in the correct order. Graphical data structured in this manner are said to be held in vector form, as the points are joined by straight lines or vectors. The strings of digital data representing different geological lines are likely to be of widely differing length. Therefore, this type of data cannot be readily held in the fixed-length relational structure described previously. On the other hand, the non-geometrical attributes of each line (such as fault, inferred) are appropriate for holding in a table. Line data for Wrexham were digitised using Intergraph cartographic

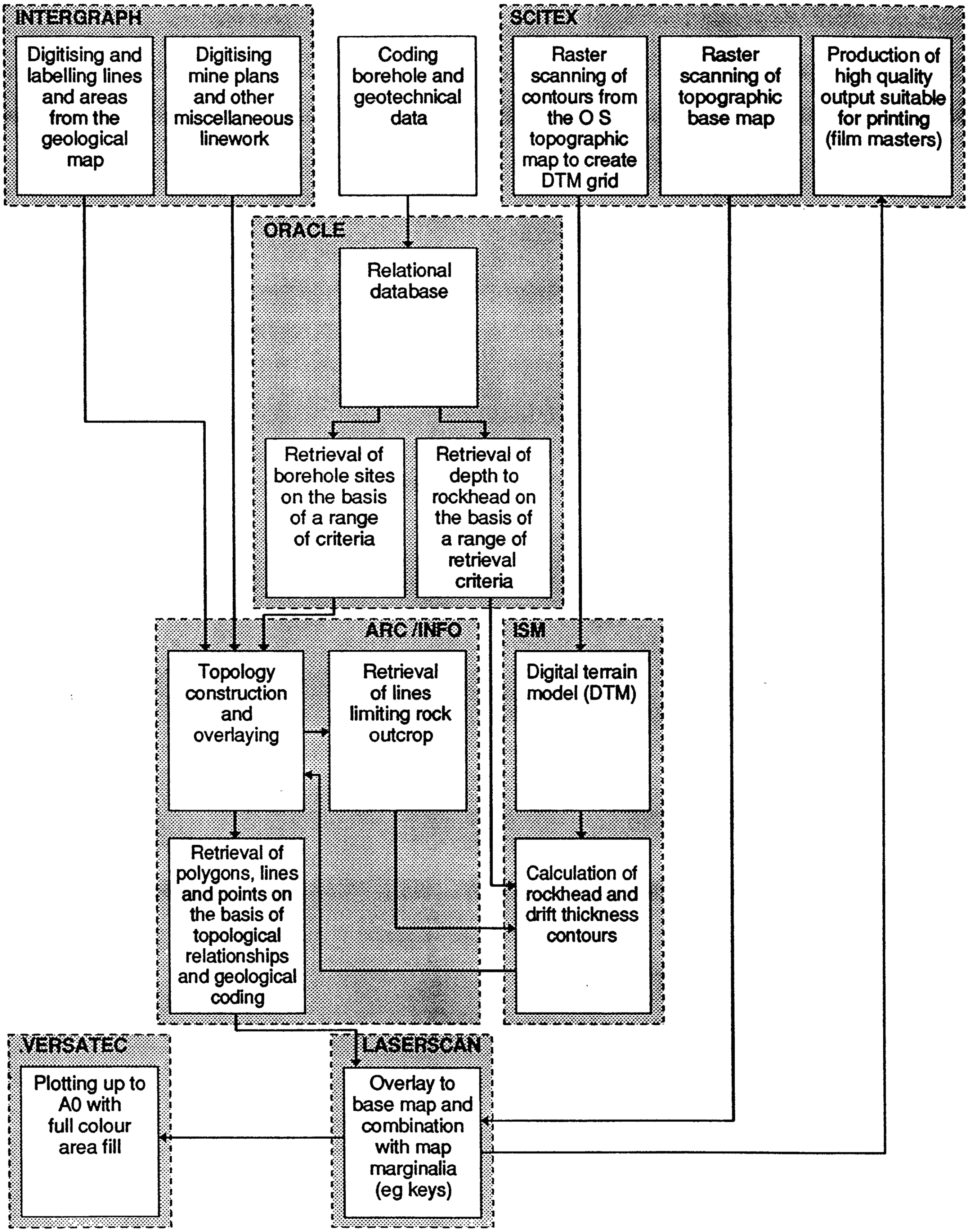


Figure 5. Data flow diagram for applied geology map production

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Borehole Reference Sheet A

REGISTRATION NUMBER: 1:10000 Quarter Sheet	Record Type	Number	Suffix		BOREHOLE NAME	COMMENTS	CONTENT
SJ35NW	BJ	1		A	LLAY MAIN COLLIERY NO. 1 SHAFT	NCB SHAFT NO. 32 AWAITING CLAS.	A
		2		A	W. DRFT		A
		3		A	388'S DRIFT		A
		4		A	LLAY BORING NO. 2		F
		5		A	LLAY HALL COLLIERY NO. 2 SHAFT	NCB SHAFT NO. 27 AWAITING CLAS.	A
		6		A	LLAY HALL BH		A
		7		A	HOPE COLLIERY NO. 2 SHAFT	NCB SHAFT NO. 3	F
		8		A	FFRWD COLLIERY NO. 3 PIT	NCB SHAFT NO. 25	F
		9		A	LLAY, CAE MAWR FARM BH + WELL		F
		10		A	PLAS MAEN HOME FARM BH	NO RECORD	A
		11		A	FFRWD COLLIERY PIT NO. 7	NCB SHAFT NO. 22	F
		12		A	FFRWD + PONT PLAS DROWSELL WRK	NO EXACT LOCATION PART SECT.	A
		13		A	LLAY MAIN COLL. U/E BH 6		F
				A			
				A			
				A			
				A			
				A			
				A			
				A			

Figure 6. Example of borehole coding sheet A

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Borehole Reference Sheet B

REGISTRATION NUMBER: 1:10000 Quarter Sheet	Record Type	Number	Suffix		NATIONAL GRID REFERENCE: Easting	Northing	Accuracy	Confirmed (+)	GEOLOGISTS INITIALS	Reliability	Start Point	ORDNANCE DATUM LEVEL (metres)	Accuracy	Inclination	Rockhead	Depth to Rockhead (metres)	Drilling Method	TOTAL DEPTH OF BORE (metres)	Water Struck	DATE OF DRILLING: Day	Month	Year	Confidentiality	Purpose	Fossil Specimens	Core Samples	CLIENT	DRILLER	PROJECT	CODER
SJ35NW	BJ	1		B	3279	5648	5			2	S			1	R		U					1916	N	C					Ø9AD	A
		2		B											U		U						N	C						
		3		B											U		U					1953	N	C			NCB			
		4		B	35Ø6	5652	5			2	S			1	R		U		WS			1911	N	C						
		5		B	3153	5516	5			2	S			1	R		U		U			1924	N	C						
		6		B	33Ø4	5577	5			2	S			1	R		U		U			19Ø8	N	C						
		7		B	3115	565Ø	5			2	S			1	U		U		U	P	RE	1914	N	C						
		8		B	3Ø56	55Ø8	5			2	S			1	R		U		U				N	C						
		9		B	34Ø	564	4			2	S			1	R		U		WS			1914	N	W						
		11		B	3Ø41	55Ø9	5			2	S			1	U		U		U	P	RE	1877	N	C						
		13		B	32561	56Ø33	6			3	U	-61Ø.21		1	U		U		U		5	1961	N	C			NCB			
				B																										
				B																										
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Figure 7. Example of borehole coding sheet B

BRITISH GEOLOGICAL SURVEY

Borehole Log Sheet J (for logs in imperial units)

REGISTRATION NUMBER 1:10000 Quarter Sheet	Record Type	Number	Suffix		DO NOT CODE	LITHOLOGY 1st Lith	Rel 1/2	2nd Lith	Rel 2/3	3rd Lith	Rel 3/4	4th Lith	Base of Bed	STRATIGRAPHY	Strat Rel	Depth Rel	Worked Beds	COMMENTS	DEPTH (Imperial) Yards	Feet	Inches
SJ35NW	BJ	4		J		SOIL														1	
				J		SAGR		MARL												29	6
				J		SAND		CLAY												79	
				J		SAGR														93	6
				J		BOCL														114	
				J		SAND		CLAY					RH							148	
				J		SDST														15Ø	
				J		MARL														158	
				J		SDST														2ØØ	
				J		MARL														22Ø	
				J		SDST														29Ø	
				J		MARL														375	
				J		SDST														38Ø	
				J		MARL		SDST												419	
				J		MARL														517	
				J		MDST														521	
				J		SDST														554	
				J		MDST												PLTY 567-582		589	
				J		COAL														589	6
				J		MDST												PLTY		6Ø9	

Figure 8. Example of borehole coding sheet J

BRITISH GEOLOGICAL SURVEY

Borehole Log Sheet M (for logs in metric units)

REGISTRATION NUMBER: 1:10000 Quarter Sheet	Record Type	Number	Suffix		DEPTH (metres)	LITHOLOGY: 1st Lith	Rel 1/2	2nd Lith	Rel 2/3	3rd Lith	Rel 3/4	4th Lith	Base of Bed	STRATIGRAPHY	Strat Rel	Depth Rel	Worked Beds	COMMENTS
SJ35NW	BJ	18		M	1.20	MGRD												
		18		M	5.25	GRAV		SAND										
		18		M	11.10	SAND												
		18		M	18.50	GRAV		SAND					TD					
		19		M	.30	SOIL												
				M	1.00	CLAY		SAND										
				M	3.00	GRAV												
				M	7.40	SAND												
				M	11.00	BOCL												
				M	21.25	GRAV												
				M	22.30	SAND												
				M	26.00	GRAV		SAND										
				M	27.50	SAND												
				M	31.40	GRAV												
				M	35.45	BOCL							TD					
		20		M	.20	SOIL												
		20		M	1.50	CLAY		SAND										
		20		M	4.50	GRAV		CLAY										
		20		M	17.00	GRAV												
		20		M	28.55	BOCL							RH					

Figure 9. Example of borehole coding sheet M

work-stations. The operator followed each line with a cursor on a digitising table which automatically recorded a sequence of points over which the cursor passed.

Geological lines may be boundaries defining areas (or polygons) with particular attributes, such as the area underlain by Upper Carboniferous. Again, area attributes can be held in a table, related to the so-called seed point for that area (a representative digitised point within the area to which it refers). The processes required to manage map data on the computer differ from those of a relational database management system. For instance, as well as the usual requirement for retrieval of items where the values of a particular attribute lie within a defined range, a requirement might be to retrieve all boreholes within the areas shown as Upper Carboniferous, or those lying within 500m of a fault, or those areas of made ground which overlie the outcrop of aquifers. Tasks such as these can be performed by a geographic information system (GIS). The ArcInfo GIS was used for this project, accessed at Edinburgh University from terminals in BGS.

Topographic base

In order to locate geological features and to understand the geometrical relationships of the strata, it is necessary to show the geology correctly positioned relative to a topographic base map. The geology is generally surveyed using the Ordnance Survey 1:10 000 scale map. Most applied geological maps are prepared at 1:25 000 scale, which may require some simplification of the geology, but the base map is a straightforward reduction of the 1:10 000 map. Some applied geological maps, and the majority of published geological maps, are prepared at 1:50 000 scale. As the Ordnance Survey 1:50 000 base is a generalisation of the larger scale maps, the representation of the geology must be adjusted to retain the correct relationship to the topographic features. In every case, there is a need to show the geology superimposed on the base map.

The topographic base map contains much complex detail, but there is no requirement to manipulate its elements individually. It is merely necessary to plot the map as a backdrop to the geology at the appropriate scale. Unlike the geology, therefore, which was digitised element by element in vector mode, the topography was scanned as a raster. The raster, a closely spaced grid of points, is created by scanning the map with a laser device which can classify each point on the map according to the amount of light reflected from it, and thus can record digitally whether the map is black or white at each point. The 1:25 000 scale base maps were raster-scanned on a Scitex scanner at an external cartographic bureau, on a grid of 30 points per mm.

Digital terrain model

The scanning equipment and associated software were also used for another purpose. This was to obtain a digital record of the Ordnance Survey contours of the area, and to prepare a digital terrain model (DTM) from them. The DTM is a square grid of numerical values representing the elevations of points, in this case 50m apart on the ground. Held in this way, the values are readily available for computer manipulation and display.

A map was purchased from the Ordnance Survey containing only contour data. The numbers on the contour lines were deleted and all gaps in the contours were closed. After scanning on Scitex equipment at a cartographic bureau, some manual editing was done to indicate the values of the contour intervals to the computer, and a program automatically interpolated between them to produce the DTM. The terrain model is needed, for example, in preparing a drift thickness isopachyte map by computer, or displaying the geology on a perspective view showing the relief of the terrain. The digital contours may also be required for plotting along with the geology.

Data management

Aspects of data management have been mentioned in the previous section, including the use of a database management system (DBMS) for relational data and a geographic information system (GIS) for cartographic and spatially located data. The first step after input is always to check and validate the data to ensure that they contain few important errors, even if it is not practicable to eliminate them all. With borehole data, keying errors can be greatly reduced by entering the data a second time for verification, by the use of skilled staff, and by random sampling for quality control. The program which loads the data into the database carries out a number of checks which assist in detecting errors (see Fig. 10).

Graphical logs can be generated by computer for

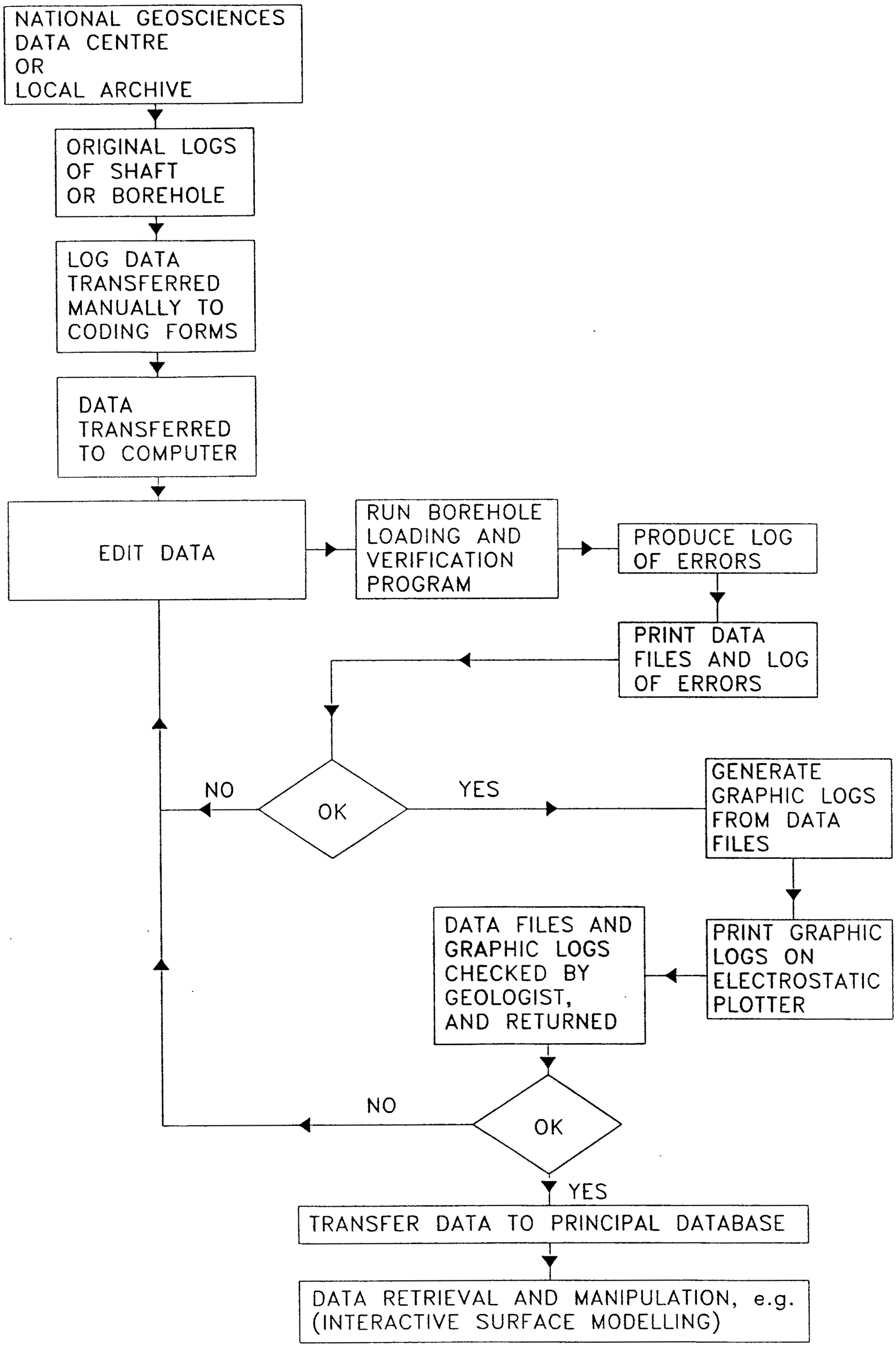
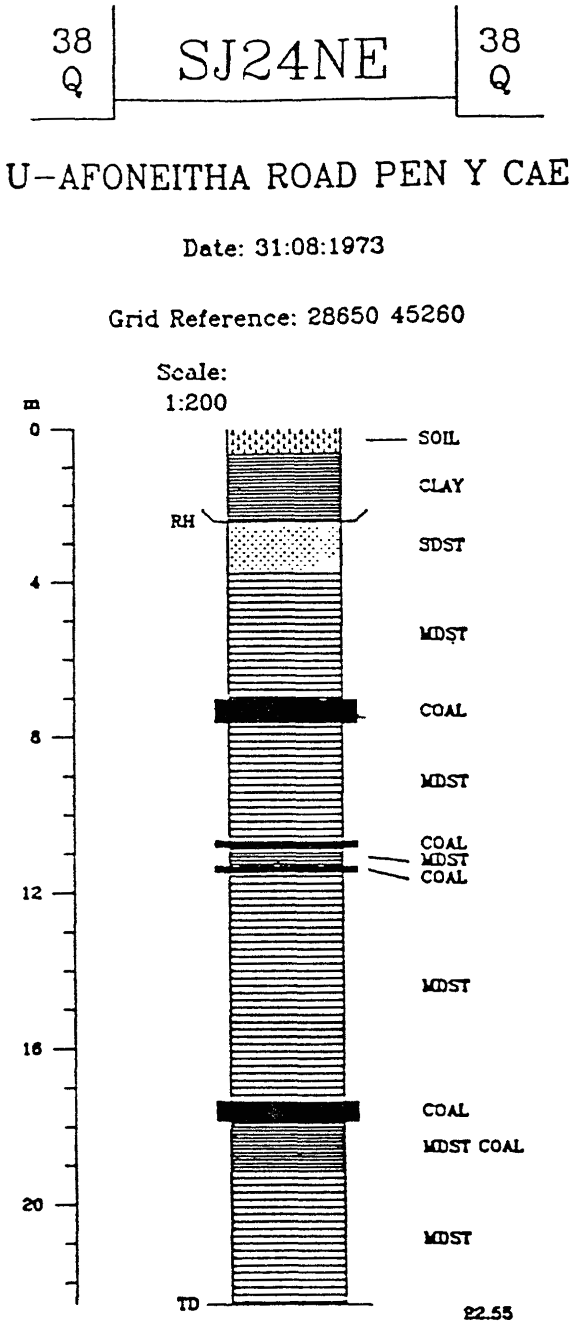


Figure 10. Validation procedure for coded borehole data



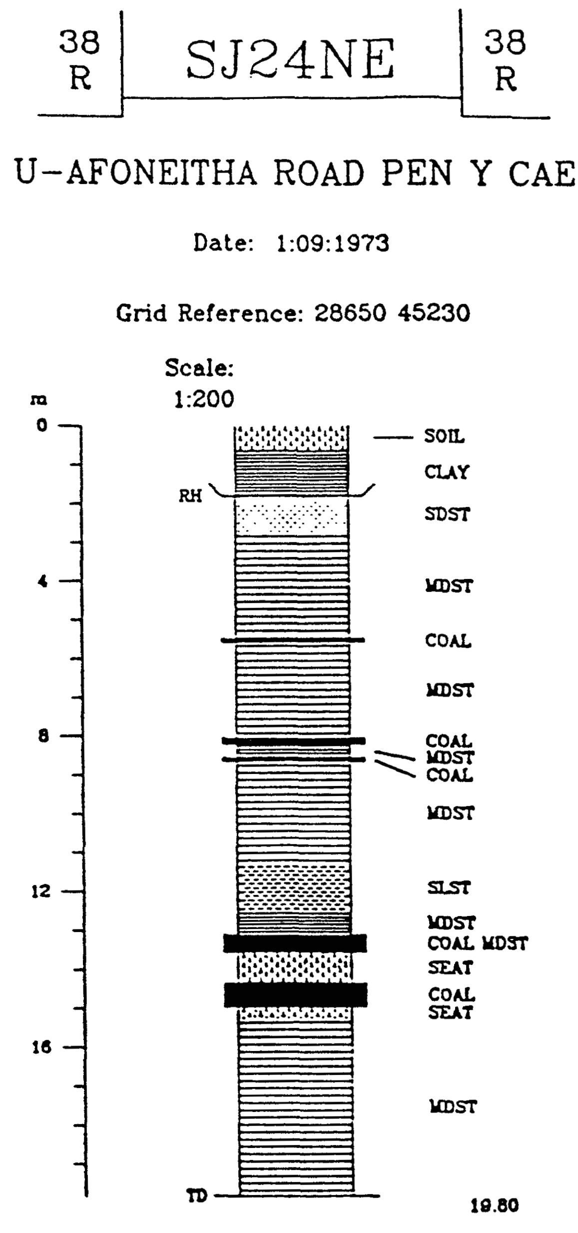


Figure 11. Examples of computer-derived graphic borehole logs

each borehole, for use by the geologist in assigning a stratigraphical classification (see Fig. 11). This stage also ensures that the geologist can look individually at each log to see whether there are unexpected aspects which might indicate an error in the keying, the coding, or in the original records. Several borehole records have been corrected or discarded as a result of this scrutiny.

The next stage of validation involves the display of information for the area as a whole, for example in contour maps of geological horizons or thickness maps of particular intervals. Anomalous values are readily picked out by this procedure, particularly by contouring residuals - that is, the difference between recorded values and a smoothed surface. Experience in other projects indicates that close investigation of these anomalies is well worth while. In some cases, the reason is errors, possibly in the original records. In other cases, the anomalies have a geological explanation and are likely to be particularly significant in developing the geological interpretation. For obvious reasons, this stage cannot be reached until the data records are complete. Examination of sub-areas is not effective because of subsequent difficulties in edge-matching.

Validation of the cartographic data requires other techniques, provided by the GIS. Errors that frequently occur are, for example, duplicate digitisation of the same line, possibly in slightly different positions. The software can detect and display the areas enclosed by the duplicated line - "slivers" which can be removed by deleting the less correct line. If these erroneous areas remained, they could lead to false conclusions at a later stage. The converse error is that a gap may be left in the lines which bound an area. Software which is concerned, for example, with filling the area with colour, will continue to fill the colour through the gap into the adjoining polygon. These leaks are readily detected and plugged by correct use of validation procedures on the GIS. Other aspects of the cartographic work can be validated and corrected by normal cartographic procedures of overlaying and checking. The most powerful checking procedure is the use of the data by a geologist in the course of developing his interpretation. Geologists must notify all errors and ensure that they are corrected in the database and not just in the final maps.

Correction of errors is of course possible in a computer system, but it is desirable to ensure that the data are as correct as possible before they are input. Considerable time and effort has been wasted in the past by digitising maps which had not been finally checked, and subsequently having to undertake the expensive and time-consuming process of re-entry to account for changes made in the geological interpretation. Once the data are digitised, little time should elapse before the final products appear, and nothing is gained by submitting provisional versions. Updating is a different matter, and procedures should be reviewed in due course. So far in BGS, geological databases have been set up on a project basis without continual revision being attempted.

The Oracle DBMS makes it possible to construct complex queries involving cross-reference between various tables. Selection of data can be based on values which are calculated from several data items, such as total coal thickness. The SQL language, which has been adopted as a standard by many suppliers of database software, is used to express these queries. For routine and frequent enquiries a menu-aided retrieval system (MARS) has been developed in-house. The relational DBMS and SQL have limitations in handling sequences from boreholes or cartography. Other methods are described below, and additional work will be needed to extend the user interface and to provide links between systems that are easy to use.

Retrieval of cartographic data, and retrieval based on geographic areas, are best handled by a GIS, as described previously. The ArcInfo system is capable of handling large volumes of data, as was necessary in this application. It is not particularly easy to use, but complex operations can be performed. In the hands of an experienced user, it is a powerful tool for selecting data for an applied geological map. The GIS was accessed remotely at Edinburgh University for this project, but the LaserScan Horizon GIS and ArcInfo GIS have both been purchased by the NERC Computer Services and are now available for in-house use.

Communication

The Joint Academic Network (Janet) links the academic and research council computers in the UK, including those of BGS. The network was used in this project to prepare reports by collaboration between several centres; to pass data files from one point to another; to access data held remotely; and to use programs installed on remote computers. The network has made it possible to use computing resources at Keyworth and Edinburgh on this project, and to make use of Geographic Information System software installed at Edinburgh University while no comparable facilities were available within NERC. More comprehensive national networks will be available within the next few years, and could provide a means for making computer data, such as those for Wrexham, more widely available.

Surprisingly, communication between software environments (such as Oracle, ISM, Intergraph), even within a single computer, proved to be a more difficult problem than communication between computers. Exchange formats have been defined for transfer of data of various types, but are not used within all programs, and cartographic data in particular can be difficult to transfer. The most widely used transfer format which is sufficiently comprehensive for applied geological mapping is the Standard Interchange Format (SIF) defined by Intergraph. This is being used where appropriate, but additional code is necessary for passing data between many of the programs. The SIF format is less appropriate for raster data transfer, and the Intergraph Type 88 raster format was used for this purpose. International standards, such as Phigs, are emerging, but were not sufficiently comprehensive, clearly defined nor widely adopted to be appropriate for this project.

Processing

Data retrieved from the database and GIS can be processed and presented in a number of ways. Examples are the preparation of graphical logs mentioned above; the preparation of statistics for geotechnical data (see Waine and Culshaw, 1991); and computer contouring (see Results, below).

Map preparation

Until recently, the large plotters available to BGS drew lines by moving a pen or a lighthead over paper or film, which limits the amount of detail which can be displayed. Small-size (A4) ink-jet plotters can handle detail and can fill areas with colour or ornament, but cannot provide the resolution nor the size required for maps. Large-size high-resolution plotters have been used for some time through cartographic bureaux for published maps, but the cost of using them can be justified only by a long print run. Now, however, large Versatec colour electrostatic plotters are available in-house. The resolution of 400 dots per inch and width of 36 inches are appropriate for applied geological maps, and the cost makes print on demand practicable.

The electrostatic plotter is a raster device. That is, it does not plot by drawing lines as in the vector method, but by scanning the area in a similar manner to a television set or a computer screen. The picture as a whole is represented as a raster, or grid of cells, perhaps 12 000 by 12 000 in one map, each cell with the possibility of being left uncoloured, or printed with one or more of the four colours available in the four toner baths of the plotter. A large range of colours can be produced as half-tones. Unlike vector plotters, the plotting time is not dependent on the complexity of the picture. Vector representations of graphics, including the geological lines and areas mentioned above, can be passed to the electrostatic plotter, where they can be rasterised (converted to raster form) and areas filled with colour or ornament.

The raster representation of the topography was obtained by automatic scanning of the Ordnance Survey map on a stable base. It is normally advisable to scan at the resolution of the final plot, as there is some loss of quality every time the picture is adjusted to a new grid. However, in this case, the topographic base map was also required for high resolution printing and was therefore scanned at 30 dots per mm for Scitex plots, and subsampled at 400 dots per inch for the lower resolution of the Versatec electrostatic plotter.

Software has recently been obtained (from LaserScan) which can combine the geological information held in vector form with the topographic base data in raster form, and display them in a single Versatec plot.

The electrostatic plotter is ideal for printing a small number of copies of a map on demand. Where several tens of copies are needed, however, a lower cost and higher quality product can be obtained from the computer data by generating film masters (including colour separation films) on a specialist cartographic plotter. The films are used to prepare plates for conventional offset litho printing. As print runs of some hundreds were required, the final copies of the Wrexham maps were prepared in this way. The information, assembled within the LaserScan system, was passed to a Scitex system. Bureaux were used for plotting and printing.

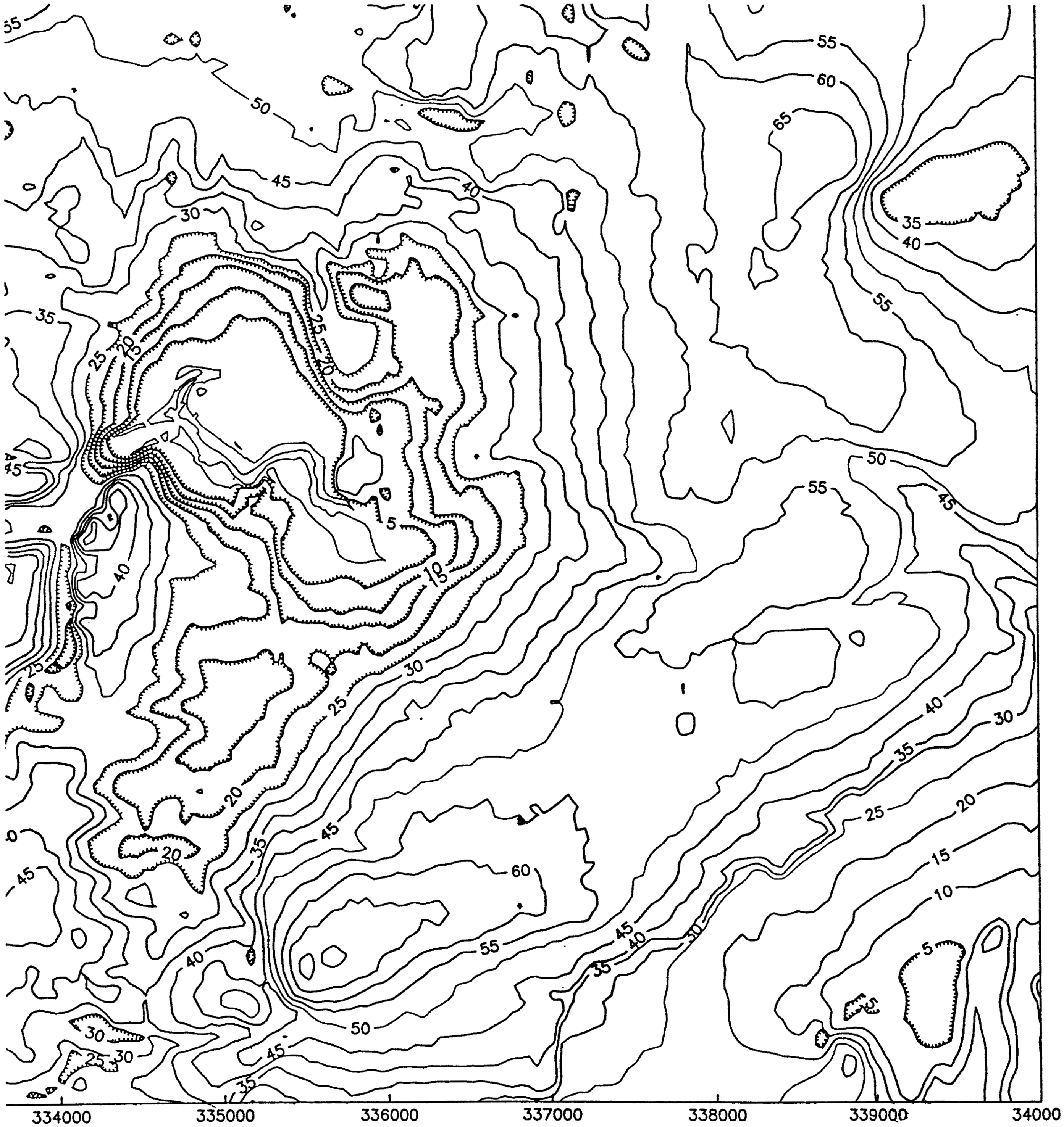


Figure 12. Computer-derived isopachytes of drift thickness

The flexibility of the overall system, in terms of the type of map that it can produce, is considerable. At this stage of technological development, however, the emphasis was not in making the system easier to use on a routine basis, but in getting the system to work at all. The technological development is very rapid, and given adequate resources, a simpler, cheaper and more robust system will be assembled.

RESULTS

An important result of the project is that the comprehensive database described above is now available on the computer for future use. A second important result is the advances made in the application of information technology to the production of applied geological maps. A third result is the production from the database of the following maps, which are included in Hains (1991).

Map 1. Solid Geology

The map contains three different types of geological information. Firstly there are the areas underlain by the stratigraphical units digitised from the 1:10 000 maps. Secondly lines representing coal seams, mineral veins and faults were retrieved for distinctive presentation, whether or not they form the boundaries of lithological units. Finally from the superficial deposits component of the geological map areas, former sites of opencast working were retrieved and overlain on the bedrock geology information. All of these operations were carried out within the GIS which contains topologically structured information on areas of bedrock and superficial deposits, along with a classification of line types such as coal seams.

Map 2. Drift geology

The map has two elements: areas of superficial deposits including man-made deposits, and points indicating the position of kettle holes. The former are held as a distinct coverage (a coverage is the digital equivalent of a map, map component or map overlay in the ArcInfo GIS) and reproduced with some simplification by grouping together similar units, such as all river terrace deposits. The latter are held, along with other point data such as the sites of quarries, as another distinct GIS coverage. Each point is labelled according to its type, for example kettle hole or limestone quarry, and in the case of quarries its status, for example active or backfilled. Points of any particular type, such as kettle holes, can therefore be retrieved for distinctive display.

Map 3. Rockhead elevation

The rockhead contours were produced using the Interactive Surface Modelling (ISM) computer gridding and contouring package. The inputs required are the depths to rockhead proved in boreholes, the areas of bedrock outcrop, and the digital terrain model.

The areas of bedrock outcrop can be retrieved in the GIS and overlain on the digital terrain model held in ISM to provide heights of rockhead where rockhead is at surface. These heights are then combined with the height of rockhead proved in boreholes, which is retrieved from the Oracle database, and together they are interpolated by ISM to produce a grid of rockhead values for the project area. Various refinements were carried out, including the incorporation of boreholes not proving bedrock but which provide a maximum height of rockhead, so as to produce a final rockhead grid. This was then contoured in ISM and plotted along with the sites of boreholes retrieved from Oracle, and the lines indicating the areas of bedrock outcrop.

Map 4. Drift thickness

This map (see Fig. 12) is a derivative of the rockhead contours. The difference in height between the rockhead contours and the digital terrain model gives the thickness of superficial deposits (drift). This difference can easily be calculated in ISM by the subtraction of the rockhead contour grid from the DTM grid, and the resulting new grid contoured and plotted along with the lines indicating areas of bedrock outcrop. These latter also represent the lines of zero drift thickness.

Map 5. Mining activities; coal/metalliferous

There are five elements included on this map. Shafts and adits are held in the Oracle borehole database but coded distinctively from boreholes. These were retrieved and plotted. Secondly areas of made ground and backfill related to mining were retrieved from the superficial deposits coverage in the GIS. The third element comprises lines indicating the outcrop of mineral veins. These are coded as such in the GIS coverage of bedrock geology and can therefore be retrieved for distinctive plotting. The fourth element comprises areas of underground working in one or more coal seams. The extent of working in each of 22 coal seams was digitised and held as a separate GIS coverage. The GIS was then used to overlay these one on another to identify areas underlain by one seam as opposed to more than one seam. The two resulting categories were plotted distinctively. The final element is the 30m drift isopach derived from the ISM drift thickness map and plotted to depict areas with more than 30m of drift cover. The relevant lines were transferred from ISM to the GIS where they are held as a separate coverage.

Map 6. Bedrock resources, except coal or metalliferous

The categories of bedrock resource are a subset of the lithological classes shown on map 1, and are derived in the same way by grouping stratigraphic units using the GIS. However these are only shown where there is less than 10m of drift cover and the lines delimiting these areas are derived from the drift thickness map (map 4) calculated by ISM. The relevant lines were transferred from ISM to the GIS where they were held as a separate coverage. This coverage was then overlain on the coverage of bedrock resource classes which were only plotted where they lay outside areas of greater than 10m drift thickness. The final element of the map was the sites of quarries and pits, distinguished by both type of material extracted and the status of the working. As described above this information is held in a distinct GIS coverage from where it can be retrieved for distinctive plotting.

Map 7. Sand and gravel resources

The map contains data from four sources. Areas of man-made ground and surface exposures of sand and gravel are derived from the coverage of superficial deposits simply by selection of the relevant categories within the GIS. The map also shows areas where sand and gravel occurs beneath overburden and the lines defining these areas were derived from the published maps of sand and gravel resources. This information was held as a separate coverage in the GIS and combined with the selected elements from the superficial deposits coverage to produce the final map. The third element on the map are the locations of sand and gravel pits, plotted with distinctive symbols according to their status. This information was drawn from the point data coverage held in the GIS as described above. The final element comprises sites of boreholes proving sand and gravel with an overburden ratio of less than 3:1, and boreholes put down for the BGS sand and gravel survey of the area. This information is held in Oracle from where the necessary retrievals can be made.

Map 8. Engineering geology - solid

Map 9. Engineering geology - drift

These maps are derived simply by selecting and grouping units from the bedrock and superficial coverages respectively, on the basis of their engineering geological properties.

Map 10. Physical constraints to development

The map contains data from four sources. Areas of soft ground, quarry and other infill, made ground, landscaped ground, and landslip are all derived from the drift geology map. Some categories involve grouping the mapped geological units in the GIS as described above. Two data sources - the solid geology coverage and the 30m drift isopachs - are required to derive the areas where mine working may have taken place within 30m of the surface. The drift isopachs are overlain on areas of Bettisfield Formation and areas where the formation is buried by less than 30m of drift were derived by the GIS. Finally, the sites of adits and shafts were retrieved from the borehole database and plotted as for map 5.

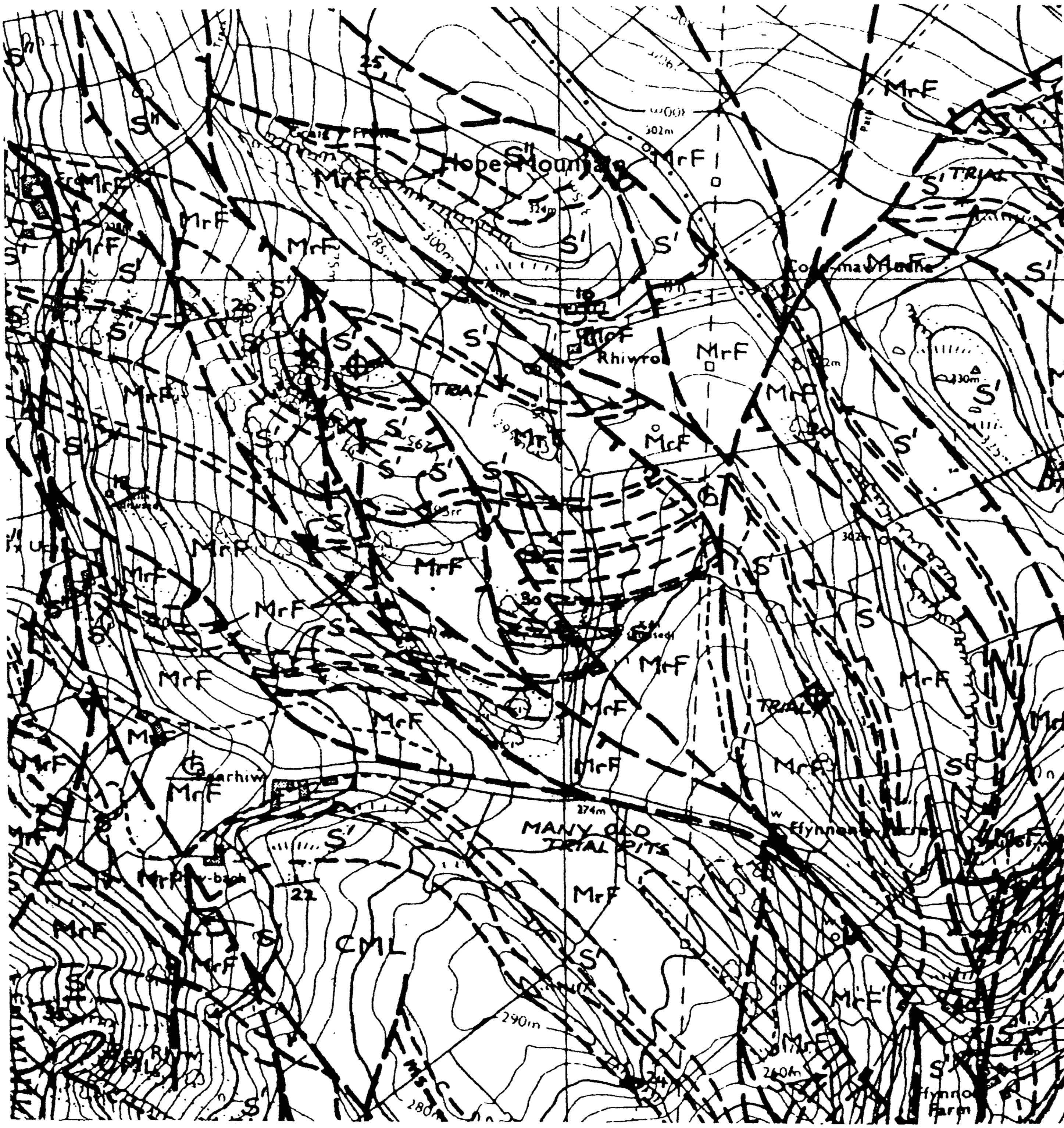


Figure 13. Complex area of geologist's hand-drawn map

CONCLUSIONS

1. The project has shown how maps digitised at survey scale can be combined with digital terrain models and borehole and other subsurface data, including computer-contoured surfaces.

2. A geographic information system and relational database management system have been used to retrieve information selectively and generate a wide range of applied geological maps.

3. The maps have been registered to a raster-scanned topographic base and can be printed in colour on demand using a colour electrostatic plotter. For longer print runs, film masters can be generated to prepare plates for conventional printing in colour or monochrome.

4. The results are a major step beyond earlier work in the Southampton area, and bring a new perspective to computer applications in geological survey. They have a crucial bearing, for example, on proposals for a computer-based production line for 1:10 000 geological maps. The work suggests that the integrated view represented by the geological map (and thence the digital spatial model) should have a central position within a computer-based information system. This may lead to a more considered evaluation of priorities in digitisation of the supporting data, such as borehole data, which are inevitably partial and incomplete.

5. Information has been gathered on costs, which are not presented here, but must have a bearing on future decisions. It is interesting, for instance, that the digitisation of borehole data for Wrexham was a significantly larger cost element than the digitisation of the map data.

6. The staff effort for computer activities in this project was estimated in advance with reasonable accuracy. However, it was not sufficiently appreciated that some of the operations must be fully completed before the next step could be undertaken. In particular, final validation of the dataset as an entirety by production of contour and other maps has proved by recent experience to be time-consuming. The maps cannot be prepared satisfactorily until all the data are available. They must then be scrutinised carefully by the geologist, and it is entirely possible that sufficient errors are found to require the production of new maps and a second validation cycle. Inevitably, with other duties including possible field work, a rapid response from the geologist may not be possible. In general, enough time must be provided in a project of this kind to assemble the data and validate them before the interpretation and map preparation phase. In addition, where the techniques are based on new technology, unforeseen delays are always a possibility.

7. Some of the map material presented for digitisation was unclear or ambiguous in areas of complex geology (see Fig. 13). Where the digital model is seen as the master record, there is no difficulty in accepting detailed maps at a larger scale where they can clarify the interpretation. There may also be a need to develop methods of recording alternative hypotheses or uncertainty on the computer. Where uncertainty has been concealed by unreadable cartography, however, this cannot be correctly digitised. There is a need to reconsider field mapping practice to take full advantage of the computer's ability to record the distinction between observation and interpretation, accept records at different scales and to link details of text, such as field notes, and graphics, such as field maps.

8. Many tools are needed in producing acceptable maps, and many major software systems and computers at many locations were used to prepare the Wrexham maps. For this to be possible, an open systems approach seems desirable, and work on this has already started within BGS. Ease of use and ease of access will be essential features of a production system. The emphasis in the Wrexham project was in getting the tools to work, not in developing a production system.

9. The longer term issues of cartographic data management, including updating and storage, must be addressed. For example, the laborious and hit-and-miss procedures for ensuring that the same corrections to the cartographic data were made on the digitising system, the GIS and on the paper records would be totally unacceptable on a production system.

RECOMMENDATIONS

Many technical problems have been overcome within this project, opening the way to more detailed consideration of future developments of digital cartography in geology. Planning a production system will entail consideration of many topics, and may be best carried forward by a combination of, on the one hand, strategic planning, and on the other follow-up projects similar to the Wrexham and Southampton applied geological mapping studies. Issues which require urgent consideration include the following:

1. A clearer analysis of objectives and procedures should be made to guide future planning, extending from field survey work to eventual usage of the map products.

2. The value and relevance of data must be carefully analysed. More data (particularly about boreholes) were recorded for Wrexham than were used. Some data may be misleading, and the sheer volume of data caused inefficient working.

3. The costs of alternative manual and computer methods should be carefully assessed to give a rational basis for setting priorities and charging for products.

4. Consideration must be given to procedures for the longer-term storage and use of expensive digital data.

5. Clear plans for a prototype production line for production of geological maps of all kinds from a digital database should be drawn up. This should clarify the time sequence of events and the procedures for correcting, validating, authorising and controlling quality at each stage. The master copy of the data must be clearly identified and procedures must be established for ensuring that other copies do not diverge from it. Such a prototype system could be tested in future projects.

6. Projects such as this one must be tightly managed. Delays in obtaining data and changes to the map specifications as the study progresses may be inevitable, but the knock-on effects on timing and costs must be controlled.

7. A more integrated computer environment, with a better user interface and better links between the software components, including database management systems and geographic information systems, must be developed before these methods can be implemented on a larger scale.

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APPENDIX 1

Computing facilities in BGS

The computing environment

The computer-based part of the BGS Information System runs on equipment and general-purpose programs which are selected, purchased and maintained by NERC Computer Services. The cost of developing major programs is so high that generally they cannot be written economically in-house. Instead, copies of software must be purchased which are not specifically targetted to BGS needs. The inevitable consequence at this stage in the evolution of computer methods is that the user may have to learn to use a different system for each phase of his work. Formats may not match between programs, causing difficulty in passing information from one stage of processing to the next. The present computing environment is determined by past investments by BGS, NERC, computer companies and software houses. Although the environment is certainly imperfect, it represents a very large investment, and is the only realistic basis for further progress.

The user interface

Each major software product has its own user interface, developed specifically for that product. Many are quite complex, as is necessary for advanced applications. Some tailoring is successfully done in-house, to make the programs easier to use, particularly for routine applications. The user interface is an active area of research world-wide, and there is a move towards greater standardisation. A menu-aided retrieval system (MARS) has been developed in-house.

Existing facilities

Hardware

Mainframe computers at Keyworth (DEC VAX 8550 and 8600) and Edinburgh (VAX 6410) are linked by the Joint Academic Network (Janet). Local area networks (LANs) have been installed at both sites. In addition, Prime computers are used by the Hydrocarbons Group at Edinburgh, and an IBM 4381 at Wallingford by the Hydrogeologists and for the Library map catalogue. Administrative data are held on a IBM computer at Swindon. Work stations include Vaxstation, Intergraph and Apollo equipment. Tektronix graphics terminals, IBM personal computers (PCs), other microcomputers, laser printers and numerous terminals are in use. Specialist equipment for image analysis (I2S), digitising tables, pen plotters, ink-jet plotters, and large colour electrostatic plotters (Versatec) are available at the two main BGS sites. External bureaux are used for specific purposes, such as cartographic work on Scitex equipment.

Software

Software in regular use includes Oracle for database management, Lex for document processing, Uniras software and GKS for graphic presentation, Unimap and ISM for computer contouring, AutoCad for graphic editing, Intergraph Microstation for cartographic input and editing, I2S for image analysis, SAS for statistical analysis, JACS for administrative information, and Laser-Scan and Arc-Info on pVAX workstations for GIS work and Scitex software (externally) for cartographic purposes. A wide variety of other software is in use on PCs, including Lex and WordPerfect for word processing and dBase for data handling. Specialist software is also written and maintained in-house, particularly for geophysical applications.

Data

Many large datasets are held under Oracle at Keyworth and Edinburgh, and some smaller files under dBase and other PC data management systems. The largest data collections in BGS are those of the Global Seismology and Geomagnetism Research Groups, and these are handled with software developed in-house. Text and cartographic data generally are held as sequential files, but increasing amounts of map data are being held within a GIS. Some use is still made of the Status data management system at Wallingford for managing text data, and the Cartonet system is used for a pilot study in map indexing. External bibliographic databases are accessed using Dialog.