CREATING CARTOGRAPHY FROM GEOLOGY

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Abstract

A geological spatial database has been created from the geological map using Geographical Information System (GIS) technology. The design and implementation of this database is described, including the creation of a logical model of the geological map, and the mapping of this into the physical model of the GIS.

The Digital Map Production System (DMPS) used to produce standard geological maps from the database is described. It is central to the concept of the DMPS that the cartographic symbology of maps produced is derived from the geological database. The graphic symbology used during capture is therefore quite separate from that appearing on output maps.

A principal objective of the system was the production of thematic maps. The different types of thematic map are described, along with the spatial and non-spatial queries used to generate these from the DMPS. Many thematic maps integrate additional geological data with that derived from the geological map. Command files have been written to embed geological reasoning into the thematic map production process, and to automatically generate consistent map marginalia

1 Introduction

Primary mapping by the British Geological Survey (BGS) is carried out at a scale of 1:10000. For the past 20 years the resulting information has been made available as a dyeline copy of the geologist's hand-drawn manuscript; the cartography of these is inevitably of variable quality. In addition such maps were soon out of date as new data became available, increasing the need for frequent revision of geological mapping in some areas.

As the map was seen as the primary means of both storing and disseminating geological information, there was a tendency to show all available information; this resulted in cluttered maps that were often difficult to read. One solution to this problem is to produce thematic maps depicting a specific aspect of the geology relevant to a particular application, thus creating simpler maps tailored to the requirements of end-users [1]. Such maps might be required at different scales and cover areas other than the 5km square tile of the standard map; they might also require the inclusion of information not usually shown on standard maps. Thematic maps may be produced rapidly on-demand and revised as new data becomes available, but using traditional cartographic techniques, they are expensive and time-consuming to produce and so are rarely updated.

It was recognised several years ago that these problems could be overcome by the use of digital techniques and a project to implement a digital geological map production system (DMPS) was set up [2] with the following objectives:

a) To establish a digital geological map database.

b) To facilitate the continuous revision of maps by updating the digital database.

c) To provide digital data to integrate with other data sets.

d) To produce better (more intelligible) maps.

e) To generate customised output.

f) To introduce consistent standards.

Although BGS had considerable experience in the use of digital cartography in the production of its maps it was decided at an early stage that the objectives of the project could only be met by the implementation of a geological, rather than a cartographic, database. A cartographic database could only contain information explicitly shown on the map, whereas much of the available geological information is either implicit on the map or not shown at all. For example a geological boundary may also be a fault which contains a mineral vein, usually only one of these features is symbolised on a map. Similarly an area coloured on the map to depict its lithostratigraphy will also have a lithology, not shown on the standard map, which may be required in the production of particular thematic maps.

When producing a thematic map, areas on the standard map may be combined together on the basis of some common geological characteristic, for example a simplified geological map might combine together all areas of Carboniferous rocks. Similarly a thematic map may need to draw on information in other geological databases, such as that of boreholes. The retrieval required from the borehole and the map databases may be both spatial and non-spatial (based on geological attributes), for example selecting all boreholes sited in areas mapped as sand and gravel that prove more than 5m of these deposits. The spatial component of the query requires the ability to build a topological link, in this example identifying those borehole points lying within specified areas. The geological component of the query requires the ability to interrogate both the map and borehole database in geological terms, selecting a particular deposit both shown on the map and proved in the boreholes. This requires the same means of classifying deposits to be used in both databases.

In order to create the geological map database it was decided to implement the DMPS using Geographic Information Systems (GIS) technology, and an overview of the design and implementation of the system to produce standard 1:10000 scale maps is given in [3]. In order to build on existing cartographic experience the Intergraph MGE/MGA™ [1] GIS was chosen. Distinct geological elements of the map, such as faults or mineral veins, were implemented as distinct GIS features each with an attached relational database table containing geological attribute information appropriate to that feature, such as the throw of a fault. This implementation allowed a geological spatial database to be created of the information derived from the explicit and implicit data contained within a geological map.

2 Implementation of the DMPS spatial database

2.1 The logical model

In order to translate the information from the geological map into a spatial database it was necessary first to construct a model identifying the logical relationships between the various elements on the map

[1]The use of a proprietary trademark in the text, indicated by ™, does not indicate endorsement or otherwise of the product by the British Geological Survey.

[4]. The model comprises an entity-relationship diagram, entity reports, and data item reports. The entities are the distinct logical elements of the model, such as 'Areal Landform' or 'Fold Axial Plane', and the principal logical relationships between these are shown on the entity-relationship diagram. The entities are composed of one or more data items, which are therefore the building blocks of the system.

Ideally the model would be of all geological entities in the real world, but the creation of such a model was considered impractical. Instead a model was created of those geological entities shown on a BGS standard map, which can be extended to include additional data sets. This is a sub-set of the potential model of the real geological world. It is quite distinct from a model of the geological map, in which the entities and relationships between them would be cartographic.

2.2 Mapping the logical to the physical model

The creation of the spatial database involved the mapping of the logical model into the physical software environment being used [5]. There are three basic modes of implementing entities: as relational database tables with no graphic component; as simple cartographic elements with no database linkage; and as full GIS features with a graphic component linked to an attribute table in the relational database.

The first group comprises in the main those geological objects which occur at a point, such as boreholes, samples, or structural measurements. Information about these objects has traditionally been held in relational database tables, although they could be implemented as point features in the GIS. However as many applications of these data are not map-based the extraction of the spatial information from the GIS for this type of processing was considered an unacceptable overhead. For this reason these data were retained in the relational database and an application written to generate graphic symbols from the data for map production. This method allows the geologist to select those instances of the point data that are to be included on the map, and this selection is stored for use at the time of map revision.

The second group of entities includes both those objects shown on the map which have no attributes, such as text notes, and those which have attributes but occur either very rarely or for which it is thought unlikely there will be a requirement to retrieve on the basis of their attributes. In these cases implementation as GIS features was not considered justified.

The mapped areas of geological units, and the main linear entities such as faults and fold axes, are implemented as GIS features. These objects constitute the principal components of the map and their implementation in this way allows for their interrogation both spatially and on the basis of their geological attributes, an essential requirement for the production of thematic maps from the database.

2.3 Geological layers

A standard geological map can show up to four discrete layers of deposits: the solid (pre-Quaternary) geology; the superficial, or drift, (post-Tertiary) geology; mass-movement deposits, such as landslips; and man-made deposits. Each of these has been implemented as a separate file in the GIS, but they can be combined together topologically to allow retrievals to be based on the interaction of the different layers. Topological files contain graphic elements and the spatial relationships within or between those elements, as well as maintaining the links to the attribute tables. The separation of the real geological layers into GIS layers has the advantage that the digital implementation closely reflects the real world. It is therefore subject to conventional geological reasoning and easier for geologists to understand.

Layer separation also ensures that a classification has to be given of each layer throughout the area of the map. On a traditional map lack of information is sometimes disguised cartographically, for example the type of superficial deposits beneath an area of man-made deposits may not be indicated and yet no clear statement made that this is unknown information. In the GIS such vagueness is not possible: where information is not known it has to be clearly stated as such.

3 Production of standard geological maps

3.1 Populating the database

The first step in creating the digital map database is for the geologist to produce a hand-drawn fair copy of the geological map which is given to a cartographer for digital capture. This original is clearly annotated so that the attributes attached to the graphic elements can be added to the database, such as whether a fault is normal or reverse.

The software allows linework to be entered directly into the GIS feature structure and attribution to be added interactively at the same time. In practice it has proved easier to carry out data entry as a two-stage process. A series of customised menus have been written which allow the cartographer to select a particular geological feature, such as a reverse fault. The software then automatically sets the digitisation parameters to a particular colour and cartographic level. At the end of this stage the map data has been entered in a purely cartographic format (the graphic data structure). A subsequent batch process then uses this structure to add the GIS feature linkages and attach the correct attribute tables. The graphic data structure distinguishes not only between GIS features, a fault from a fold axis for example, but also between instances of the same feature with different attribute values, such as a reverse or normal fault. This enables a batch process to populate many fields of the attribute database using the graphic data structure, thus saving a large amount of interactive data entry. Not all fields can be populated in this way, some attributes have too many possible values or occur too rarely to make their incorporation into the menu system and graphic data structure practical, but the amount of such interactive attribute data entry is kept to a minimum.

Area features are defined by a point centroid within the area boundary. The boundaries are digitised as a particular GIS line feature (Mapped Unit Boundaries) which have attributes distinct from the area they bound. For example part of the boundary of an area of sandstone may be an unconformity. A complete set of mapped unit boundaries is held for each geological layer, and where a mapped area is bounded by another type of line feature such as a fault, then the two line features are held coincidently, each attached to its own attribute table. The mapped unit boundaries are line-cleaned to ensure polygon closure, and the area centroid features are then generated automatically within the defined polygons - the linkage to the attribute table describing the area features is established during this process. Automatic centroid generation is preferable to interactive digitisation as it ensures no polygons are omitted. The attribute data for areas can either be entered interactively or, more usually, the graphic properties of the centroids are changed interactively and then this new graphic symbology used to add attribution in a batch process similar to that used for line features. This method is preferred as graphic editing is quicker than interactive attribution.

From this stage on all output cartography should be created from the geological map database. The retention of the graphic data structure would represent data duplication and allow some simple maps to be produced without recourse to the attribute database. However the graphic data structure and attribute database could become mismatched, particularly after a phase of map revision, which would result in conflicting maps being produced. For this reason once the graphic data structure has been used to create the GIS feature structure and populate the attribute data base it is resymbolised to a simplified structure that does not distinguish different attribute values.

The menu system also allows the cartographic entities and map marginalia to be digitised, these being held in separate files. Much of the information in the map key can be derived automatically from the contents of the geological database, and this method has the advantage of ensuring the key and map always match. This is a particularly important feature if producing maps of non-standard areas.

3.2 Cartography from the database

The primary purpose of the DMPS was not to produce standard geological maps; this could be done more cost-effectively using an ordinary digital cartographic system. However, it was nevertheless necessary to show that the system was capable of producing these maps. This is in part because the standard map is still a product much in demand, although as awareness grows of the range of map products that can be created from the map database there is likely to be a move to more customised products. Another reason to produce a standard map is that this acts as a check on the quality of the database. Although there are various checks at the time of data entry, such as by the use of dictionaries of permissable values, it is nevertheless possible to enter incorrect information into the database. This is difficult to check directly in the relational database tables. By producing a standard map, the cartographic symbology of which is a product of the values in the attribute tables, checking can be done visually which is much easier and more accurate.

There are four distinct editions of the standard map: solid priority, drift priority, solid and drift, and a monochrome version of the solid and drift edition. Different combinations of the solid geology and superficial deposits are produced according to the geological emphasis of each edition. For a number of these maps the extent of superficial deposits over solid geology is depicted as a buffer zone around the outer limit of the deposit. A workflow has been developed which generates different types of superficial buffer zone fully automatically from the map database.

It is central to the concept of the DMPS that the cartographic symbology shown on maps produced from the system is a product of the geological database. This is achieved using Intergraph Map Finisher™ software which uses the geological attributes to create a look-up feature table which specifies the output cartographic properties to be used to display particular graphic elements. For example the database could be used to identify the graphic elements depicting different types of fault, and each given a distinct output symbology. An important property of the Map Finisher™ feature table is its ability to give graphic elements a display priority which determines which feature is shown where features overlie one another. For example where a mineral vein coincides with a fault the feature table can be used to determine which is displayed and this can be varied between maps.

Different template feature tables have been developed to produce the different editions of the standard map. This is an important feature as, by producing all map editions from the same map database, not only is consistency between editions assured, but also a great deal of digitisation is saved. The power of the system is its flexibility - the template feature tables can be edited if required so that different symbology can be used for the same elements on different maps. Elements can be grouped in different ways on different maps or turned off altogether if not required. For example some maps might distinguish different types of fault and others might not. All of this is achieved without editing the map database. The system therefore allows a variety of cartographic products to be generated without further digitisation, while ensuring full geological integrity is maintained.

The feature table is able to reference more than one graphic file. In the production of standard maps up to eighteen different graphic files may be used, containing information derived from the various geological layers, superficial deposits buffer zones, cartographic entity symbols, and the marginalia. In addition a raster file of the 1:10000 scale Ordnance Survey topographic map is used as a backdrop to the geology.

The map key indicates which geological units appear on the map-face. It is therefore directly related to the attribute field which acts as the primary classification of the area features on the map (this is the attribute field which controls the colouring of areas on the map). An application program has been written which interrogates the map database for all distinct values of the area classification attribute for the superficial deposits and then draws key boxes of the correct colour for each. In addition a link between the attribute field and the corresponding dictionary table is established to generate the correct, and consistent, descriptive text for each mapped unit. Placement of the superficial deposit key boxes must follow a fixed order, which reflects the nature of the deposits. This has been coded into the application. Automatic key generation ensures that the map key and map always match, which greatly facilitates the production of maps of irregular areas.

The output maps are produced using a colour electrostatic plotter which gives a significant improvement in map quality over the black and white dyelines previously used. These can be generated on-demand as required by customers.

4 Thematic Map Production

4.1 Thematic Maps in BGS

Thematic maps (also known as environmental geology or applied geology maps) have been produced by the BGS for various parts of Britain. Geological data sets, even where held digitally, have been traditionally collated manually by geologists to produce mono-thematic maps (eg. mining information) and a number of derived multi-thematic maps which combine two or more themes (eg. engineering geology) [6]. The manually compiled themes may be digitised for map production, but the result is a cartographic product with no geological integrity.

BGS maintains an archive of databases of geological information (many in digital form) including geochemistry, geophysical data such as gravity surveys, hydrogeological data, and onshore and offshore borehole logs. These data are combined with information from the standard geological maps in the composition of thematic output. Although the existing digital databases may not all be directly compatible, digital integration of these data is considered a essential step in enhancing the usefulness and value of the individual data sets. Development of the DMPS provides a facility whereby many data sets can be combined, manipulated, and reclassified to produce thematic output according to criteria specified by customers. As the resulting digital product is connected to the underlying geological databases the individual map elements can be interrogated and their geological characteristics displayed. This meets two of the original objectives of the DMPS: the generation of customised output, and the integration of geological map data with other data sets.

4.2 Output types

By definition, customer-specified, on-demand output is difficult, if not impossible to define in advance. However, a list of the more obvious generic map types was anticipated and compiled, and procedures for generating these maps were established [7]. The categories identified as being the basis for most user-defined map output include:

a) single attributes,

b) combined attributes,

c) converging attributes,

d) irregular areas,

e) scale changes,

f) zoning.

Thematic maps are created in the Intergraph™ system through the interrogation of graphical elements and their associated attribute information in topological files. Queries are performed on the data held in a topological file to select those graphical features which have particular attributes or relationships to other features.

Spatial queries are boolean operations, such as overlay, intersection and exclusion. These are independent of any particular type of geological feature, for example the general intersection of points and polygons. Attribute queries enable specific geological features or groups of features to be identified, such as faults or areas of till.

In general thematic maps require a combination of spatial and non-spatial queries. For example to produce a map of areas of possible aquifer contamination from landfill: select all polygons of aquifer bearing rocks using their lithostratigraphical or lithological attributes; select all polygons of artificial deposits, which may contain contaminants, using attributes such as composition; perform a spatial query to select all areas of polygon overlay where both features occur (the convergence of the two attribute selections).

The database contains the mapped areas of each distinct unit shown on the standard geological map, but some products require a generalisation, or overview, of this information. A theme requirement may be to show the Coal Measures of a particular area, with no distinction between the individual formations within this group. The lithostratigraphic attribute of the individual mapped areas is queried to identify all those in the Coal Measures, and the resulting polygons combined and merged to produce a map of the group theme.

To produce output for irregular areas a border line is digitised and converted to a polygon feature that can be used in overlay operations. For example, the solid geology for Glasgow city was produced by performing an intersection operation on the 1:10000 scale geological data for the area with the polygon enclosing the administrative boundary of the city.

Although the map data input to the DMPS is surveyed at 1:10000 scale, output may be generated at a variety of scales. Initial map products at 1:25000, 1:50000 and 1:2500 scales demonstrated the flexibility of the DMPS data sets, dependent on the complexity of the data to be reduced.

Procedures similar to those used to create buffer zones for the solid and drift editions of the standard 1:10000 scale geological maps may also be used for generating zones around theme elements.

4.3 Incorporating additional data sets

Once the generation of thematic products from the geological map data of the DMPS had been established, integration of other data sets was investigated [6]. The thematic maps produced may be divided into the following categories:

a) inclusion of additional graphics,

b) using additional attribute information held in tables linked to the DMPS,

c) using data held in tables external to the DMPS,

d) incorporating data produced from digitally generated surface models,

e) incorporating data sets from other GIS.

Thematic maps generated using graphical information not held in the DMPS followed a digital cartographic route. The linework was digitised and polygons generated, without attaching geological attribution to produce the maps. It would be possible to incorporate this information in the DMPS structure if required through the creation of additional attribute tables.

New tables were created within the DMPS for additional attribute information, for example for man-made deposits. The existing polygon centroids were linked to the new attribute tables, and the graphical features could then be interrogated using both the DMPS attributes and the new thematic database information. In the case of man-made deposits an enhanced classification of the data was created. The basic BGS categories are made ground, worked ground, infill, and made & worked ground. The enhanced classification and additional tables allowed man-made features such as cuttings, quarries, and spoil heaps to be identified, and where the ground had been worked (eg. quarried) the extraction material was identified. The material used subsequently to fill the excavations, such as sand or ash, was also recorded.

A large number of digital data sets exist in BGS and these are compiled and maintained by different geological divisions. Combinations of these data may be particularly important, for example the identification of particular chemical elements combined with the location of man-made ground could provide important contamination information to local government and environmental organisations. Initially, point data were extracted from external databases and incorporated into the DMPS as graphical elements, however subsequently a method for linking the DMPS directly to other BGS databases was established.

Two routes for incorporating surface models were tested. The first used models generated with the Dynamic Graphics™ Interactive Surface Modeller™ software held on a VAX™; the second used an Intergraph™ software package (Microstation Terrain Modeller™) which could be directly linked to the GIS. Surface models generated from Ordnance Survey (OS) grid data and borehole rockhead data were used as a base to drape the solid and superficial deposits geology, enhancing visualization of the relationship between the geology and topography. Contours of depth to glacial deposits were generated from the borehole database and incorporated as additional graphical information. Within the Intergraph™ system 2D elements from the geological map could be converted smoothly to 3D (and vice versa) and draped over an OS digital terrain model (DTM), while maintaining their geological attribution.

Users and potential users of geological information work with a number of GIS. Data transfers between the Intergraph™ based DMPS and some of the other GIS in common use were investigated to attempt to meet anticipated customer requirements of data compatibility between systems. Conversions of data between the DMPS and (PC based) MapInfo™ and ArcInfo™ systems have proved that data exchange is possible and that hardware and software differences are becoming less significant.

4.4 The use of command files to generate standardised output

Thematic products can be generated either through interactive methods, accessing the software's tiered structure of menus and forms, or by using command files to activate and operate these processes. Development of command files for thematic map production had two aims. First to provide a standard method for frequently repeated procedures, for example for the production of irregularly shaped maps of the solid geology, superficial, man-made, and mass-movement deposits for one or more 1:10000 scale sheet areas. An advantage of using command files is accelerated processing time, whereby the user bypasses a number of interactive processes by directly 'commanding' the GIS to carry out certain operations.

Second, use of these macros allow those with little GIS and/or Intergraph™ expertise to use the DMPS to generate output: geologists can interactively interrogate the data as part of their scientific investigations. The transfer of skills to non-GIS specialists for manipulating the data sets held in the DMPS is a fundamental objective in the transfer of technology from IT specialists to the scientists who fully understand the data and wish to benefit from the functionality of a GIS. The need for this transfer of skills is particularly important when extension from 2D geological data in GIS to 3D interpretation of that data is contemplated [8].

The command files are structured so that the geological integrity of the data held in the DMPS is maintained when the system is interrogated by non-geologist users. Embedded geological reasoning within the files ensures that queries are made according to geoscientific criteria. This has a threefold benefit; the system responses make sense to geologists; non-geologist users are constrained to geologically coherent queries; and a degree of quality assurance is provided for the output data.

As part of the investigation of methods for thematic map production and the format of thematic output, a design for marginalia layout and key contents was devised. A standardised template was developed for thematic output that gives a basic layout but is flexible enough to allow a variety of customer specified products. In tandem with the development of command files (macros) for thematic map production, a command file was written to output marginalia in a format that complies with the standard template. This macro produces a number of boxes for the marginal information, such as a key and title, and allows users to place these where appropriate.

5 Conclusions

The DMPS is able to hold more data than is shown on a conventional paper geological map, and allows that data to be interrogated against a wide range of spatial and attribute queries. It represents the transformation of the geological map into a geological spatial database.

The DMPS can produce standard geological maps of a higher cartographic quality than was possible using traditional methods. Because all editions of the standard map are produced from the same geological database consistency is ensured; in addition the amount of digitisation required is reduced. It is also possible to alter the cartographic specification of a particular map with ease, with no need for new data entry or editing.

Digital production has quality control benefits for 1:10000 scale standard map production. For example producing mosaics of solid, superficial deposit, artificial deposit, and mass-movement maps for areas covering a number of 1:10000 scale sheet areas clearly illustrates where edge match errors occur. The production of thematic maps for all major attribute features across standard map boundaries is therefore a way of identifying original geological and subsequent data entry errors.

GIS technology has provided the ability to generate thematic output of varying scale, shape, and content according to customer-specified criteria. The provision of geological data at a scale which matches that of a customer's data sets improves the applicability of that data. Additionally, offering information that crosses sheet boundaries using customer-defined areas, for example city limits, is a great improvement on the conventionally produced map. The ability to select and combine different elements from the DMPS and establish connections to other databases provides a method for rapid and innovative map design.

The command files devised for thematic map production provide a user (geologist) -friendly interface to the system. They enable the interrogation and manipulation of data sets held in the GIS by geologists and other non-GIS specialists.

Acknowledgement

This paper is published with the permission of the Director of the British Geological Survey (NERC).

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