DIGITAL SPATIAL MODELS AND GEOLOGICAL MAPS

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ABSTRACT

An increasingly diverse user requirement, and the growing importance of subsurface geology, create a need for greater flexibility in the presentation of geological map information. Computer methods are used in map production, and in databases to assemble raw information. To gain the full benefits of computer technology, however, it may be necessary to represent in digital form the geologist's spatial model - his ideas of the distribution, structure, composition, origin and evolution of a set of rock units. Some requirements of a digital spatial modelling system overlap with functions of Geographic Information Systems, Computer Aided Design systems and interactive graphics. Other requirements, such as palinspastic reconstruction and prediction of geophysical responses, are specifically geological. A spatial modelling project within the British Geological Survey has concentrated so far on self-contained prototype programs. In looking forward to production systems with their need to link to other subject areas, it may be desirable to limit new software to specifically geological aspects.

Published maps of the British Geological Survey (BGS) at 1:50 000 scale show in colour the areas underlain by each stratigraphic unit, with some indication of its lithological characteristics in the marginalia. The map base shows topography including contours, and the intersection of stratigraphic boundaries with the surface relief, supplemented by symbols showing orientation of strata, gives an indication of the geological structure. Subsurface information, available in increasing amounts from seismic surveys, mining, boreholes and wells, is considered in preparing the surface maps, but cross-sections and subsurface contour maps are needed to depict the subsurface more fully (see Whittaker, 1985). Geophysical information, such as aeromagnetic and gravity data, geochemical, hydrogeological and geotechnical information may also be shown on separate maps. The geological information which is thus assembled is required by a wide diversity of users, by no means all professional geologists, who are concerned with land use, planning, resource estimation, environmental impact, civil engineering, etc. Special purpose presentations, such as environmental geology maps, may be prepared for such purposes.

The introduction of computer methods means that many of the maps are prepared with computer assistance giving a digital record as a by-product (see Mennim, 1986). Extensive databases have also been constructed within BGS to hold raw data, such as borehole records, in digital form. Determining the future directions in the development of appropriate computer techniques requires consideration of the underlying nature of the information. The conventional geological map is in itself a powerful tool for information retrieval. Having selected a map of the appropriate area and scale, visual inspection quickly retrieves information on the basis of location from National Grid lines or topography, or on the basis of stratigraphy from the colour key in the margin. More important, the map shows not just data at a point location, but also the geological context of the surrounding area with further help from the marginal cross-section. The pattern of regional variation is all-important in understanding the geology. The practical importance of this aspect of the map suggests that in a computer-based system, a Geographic Information System (GIS) could usefully supplement the database.

Before turning to the inadequacies of this solution, a further reason for considering a GIS may be mentioned. Data integration to link say, surface and subsurface geology with geochemical and geophysical data must rely on visual comparison. Differences in sampling location, sampling scheme and spatial resolution as well as a lack of well-defined operational definitions and a non-homogeneous population make most statistical analyses invalid. A wide range of techniques for rapid display of single and multiple datasets as maps, cross-sections, block diagrams and perspective views is therefore required. Experience has shown the need for trial and error in these complex displays, and a powerful interactive graphics capability is therefore necessary.

Underlying the geological maps is the geologist's conceptual spatial model, that is, his opinions on the location, form and composition of the rock units and their origin and evolution. The map, as a static two-dimensional document, is a rather inadequate representation of the complexities of a sequence of interrelated three-dimensional bodies and their changes in geological time. If the model itself can be represented digitally, then the full detail of the conceptual model can be captured and communicated. Maps can be derived as projections of the model, not the model reconstructed from maps. Retrievals and GIS functions could be based on the digital model. The digital geological spatial model has many of the characteristics of a GIS, and one interesting possibility is that the requirement could be met by extensions to existing GIS software. Extensions would be required in several areas.

Polygon overlay, for example, is required to generate profile maps in which sequences of stratigraphic units are categorized and mapped, as well as simpler tasks like determining areas in which formation A is overlain by B. However, stratigraphic units are classified hierarchically and boundaries may be recorded at one hierarchical level and retrieved at another. This can be handled readily with numeric codes, where it is known that a boundary between units 6132 and 7234 is also the boundary between the 6xxx class and the 7xxx class. Such a code with the numbers arranged in stratigraphic order can also accommodate searches over a range in stratigraphic time. Simple 'less than' and 'greater than' comparison can retrieve all units between, say, 6132 and 7234. However, a hierarchical numeric code is inevitably an inhospitable array into which it is not possible to fit batches of new codes. The BGS Stratigraphic Code, therefore, has a four-letter mnemonic form. It is translated for storage and retrieval within the model into a concealed numeric form which is of purely local application. Experimentation within BGS has so far been with self-contained prototype systems, but a subroutine to generate polygon identifiers from a set of stratigraphic units could give access to existing GIS polygon overlay facilities.

The need to extend GIS facilities arises also in capturing the geologist's interpretation. Conventional geological maps contain a large element of interpretation, and indeed much of their value to the user lies in their offerring a considered and authoritative assessment of the available evidence. Computer interpretation is clearly inappropriate, as the computer lacks the geologist's background knowledge of regional characteristics and their variation, of geological processes and their effects. However, it is possible to enable the geologist to express digitally at least some of the hypotheses that he develops about an area. By capturing his interpretation in the three-dimensional model rather than the two-dimensional map, a higher degree of consistency with all data sources, and thus greater accuracy, can be expected.

Geological interpretation is involved in interpolating complete surfaces from scattered data points. Contouring and gridding programs are widely available, some surprisingly expensive, some with the algorithims concealed for proprietary reasons, but none apparently suitable for expressing a geological interpretation. Interpolation must be local, for geological processes change abruptly from one area to another. It must be possible to force a simple pattern of lines of curvature and fold axes on the surface, so that the strain bears a recognisable relationship to the stress field. It must be possible to relate the form of successive members of a sequence of surfaces in a manner consistent with their depositional and strength characteristics. There should be a possibility of controlling the shape characteristics of a surface (steep-sided reefs, rounded sand bars, asymmetrical dunes). Fault patterns must be geometrically valid, consistent with adjacent areas, strength characteristics and stress fields. The secondary surfaces, such as faults and fold axial planes, generated by the structural deformation of the stratigraphic surfaces, intersect the rock units and have their own rules governing their geometry.

In this area, Computer Aided Design (CAD) Systems have more to offer than GIS. The piecewise parametric bicubic surfaces used in CAD (see Peters, 1974; Foley and van Dam, 1982) seem appropriate for representing structural surfaces, with their non-parametric equivalents more suitable for gently folded stratigraphic surfaces. The intersections of structural and stratigraphic surfaces are lines which can be regarded as patch boundaries shared by both surfaces, and meeting the constraints of both. This method of interpolation uses slope and twist values at each node, raising the possibility of adjusting these by geometrical transformation to match fold patterns and shape tensors while retaining the fit to measured elevations. In the CAD environment, calculation of thicknesses, areas, volumes, etc. is usually possible with reference to a sequence of surfaces. As matter is seldom created or destroyed during geological processes, and voids seldom exist at depth, such calculations can be the basis for a material budget during erosion, deposition and deformation - another test that geological hypotheses are internally consistent. As some suppliers in the CAD field have diversified into GIS and digital cartography, existing systems might be found to meet such requirements. However, there are further requirements for the geological model which make the off-the-shelf solution somewhat elusive.

Another requirement of the geologist is to be able to turn back the geological clock, to prepare palinspastic reconstructions of earlier episodes in the geology of an area. For example, a study in the Inner Moray Firth basin (Barr, 1984) has attempted a restoration of strata to positions they occupied in Jurassic and Cretaceous times by removing the effects of subsequent faulting. The quantitative estimates of amount and direction of extension obtained by these techniques lead to a better knowledge of the present-day disposition of these strata and assist in understanding the regional structural evolution.

Much geological data, from seismic surveys, mines, wells, boreholes and outcrops, provide direct evidence on the surface and subsurface geology relevant to the spatial model. Other data, such as geochemical analyses of stream sediments or gravity or magnetic data, do not provide direct information which uniquely determines the geometry of the strata. Instead, the initial view of the model may be based on other information, and the expected values of, say, gravity, determined from that model. If the expected and observed values are not consistent, an iterative modification of the model is required. Requirements of these kinds are unlikely to be met by general-purpose CAD or GIS software, and at the very least modular extensions to existing products will be required.

Geology is not an isolated world, and no discipline can expect to find self-contained solutions to technological problems. It is to be hoped that in time the civil engineer may call up geological models while working with cut-and-fill software for motorway design, or that the geologist can relate his field observations to digital elements in topographic maps. In general, there appears to be a slow change of emphasis from the map as the final authorative document to an expression of three-dimensional concepts in a digital model, from which maps are derived as projections of the model for a particular purpose at a particular time. If the map is eventually seen as a more ephemeral document, there must be a need to make the digital model widely accessible. There are obvious, but nevertheless troublesome, implications for ease of use, cost, portability and compatibility with display devices. If the gestation periods for GIS and CAD are any guide, the digital spatial model in geology has moved a short distance along a long road, and must take full advantage of all related work.

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