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COMPUTER PROCEDURES FOR GENERALISATION OF GEOLOGICAL MAPS FROM 1:10 000 TO 1:50 000 SCALE

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COMPUTER PROCEDURES FOR GENERALISATION OF GEOLOGICAL MAPS FROM 1:10 000 TO 1:50 000 SCALE

(Based on report for DMPI project: Objective C, Tasks 3.2 and 3.3. December 1993)

T V Loudon and P A Humphries

SUMMARY

Generalisation is a process of reducing the volume of information while preserving its significance. It is required in order to maintain legibility on reducing the scale of a map. Many maps are digitised at 1:10 000 scale under the BGS Digital Map Production System, and computer methods are required to assist in generalising to 1:50 000 scale. The procedure is described in a data flow diagram.

Analysis of the rationale and procedures of geological mapping throws light on possible long-term changes to take advantage of new technology. Focussing on the decisions and procedures of generalisation clarifies the difficulties of developing an expert system. Neither approach leads to automation because the machine lacks the necessary background knowledge of geological processes and of human reasoning and visual perception.

An alternative is to develop interactive graphical procedures on the computer which support the geologist and cartographer in formulating and implementing decisions on generalisation. While this "amplified intelligence" approach relies totally on judgments made by the human expert, the computer assists with tedious operational tasks. It is a transitional approach, which should increase understanding of the complex decisions, and encourage acquisition of more fully structured knowledge, leading to further automation.

Present methods of manual generalisation cause the map to be less informative than it could be, and possibly misleading in unpredictable ways. The survey-scale map is itself a generalisation of the geologists' observations and interpretation. New technology offers unique opportunities for rationalising and improving map design and presentation.

Generalisation differs from statistical sampling in concentrating on presentation rather than on facilitating logical inference. Statistical sampling requires the underpinning of a formalised model. The digital geological spatial model (DGSM) can support more rigorous data collection than the map, and is therefore seen as the future key to a more reproducible, representative and testable representation of the real world geology.

The current emphasis, however, has to be on digitising existing geological maps, particularly at 1:10 000 and 1:50 000 scale. The two map series provide distinct but overlapping input to the DGSM, where they share the same structure and logical data model, but must be separately identified, to ensure that each is internally consistent. Where individual items have counterparts at both scales, the linkages should be identified, to encourage overall consistency.

A step by step approach to generalisation procedures within the DGSM is recommended, aiming to consolidate and build on current best practice and to incorporate new developments only after their value has been established by discussion and prototyping. Because many types of presentation can be generated from the DGSM, it is necessary to separate scientific generalisation, reflected within the DGSM, from cartographic generalisation, which should be deferred until the map is produced.

The systems currently supporting the DGSM are complex and expensive, and therefore restricted to expert users. They can generate a range of digital images which could be made more widely available, and could be handled with general purpose software. Techniques of digital data compression with information loss, which are currently an area of high investment and rapid progress world-wide, overlap with cartographic generalisation, and could be applied to such images for changing scale or display device.

1. BACKGROUND

1.1 The task and objectives

Within the BGS project for digital map production implementation (DMPI), objective C is an evaluation of digital methods for producing not only 1:50 000 scale geological maps, but also a database in which the digital elements of the map are described geologically.

As part of this objective, task 3 is concerned with the investigation and systems analysis of the generalisation process from the survey scale of 1:10 000 to the published scale of 1:50 000. Task 3.2 is concerned with deriving logical parameters and potential workflow for at least partly automatic reduction and generalisation of 1:10 000 scale map data for production of 1:50 000 hard copy maps. Task 3.3 is closely linked. This is to specify the user requirement, listing the desirable functions and limitations of the system, including the identification, but not provision, of necessary software. The two tasks are considered together as the subject of this report.

The background is set out in many of the project reports. Allen (1991) sets out the overall strategy. Loudon and others (1993) discuss the links between geological maps at the two scales. For convenience, their conclusions and recommendations are reproduced here as Annex 1. The conclusions still hold, and are the starting point for this report. Humphries (1993a) describes the present manual generalisation process, and Monro and Lowe (1992) discuss the user requirement for 1:50 000 digital mapping.

Generalisation of maps, on reducing the scale, is a complex, tedious and time-consuming task, requiring considerable intellectual effort by experienced geologists and cartographers. It is therefore important to capture the results and mobilise them in a computer environment. Large numbers of digital maps are now being prepared by BGS, and where 1:50 000 scale maps are prepared from digitised 1:10 000 maps, effort might be saved by automating the process of generalisation. The current objective is, therefore, to define computer methods for generalising more consistently, precisely, rapidly and efficiently.

The map information is captured as a digital geological spatial model (DGSM), see section 4, and held in a geographical information system (GIS) and relational database. The digital model is seen as the primary source from which both published maps and special-purpose thematic maps will be derived at various scales, and as a step towards three-dimensional modelling. The reasons for generalising models differ from those for maps, but like the map, the model must represent features at various levels of detail. It is also necessary to consider the cartographic generalisation and adjustment for preparing a map from the model.

Although much has been published on the automation of map generalisation (see the bibliography in Buttenfield and McMaster, 1991), the BGS requirement breaks new ground. Links between map and model do not appear to have been considered in the literature in any depth, and the need to relate the generalised theme (geology) to an independently generalised base map raises new issues. At the risk of stating the obvious, therefore, it is advisable to start from first principles: to consider why BGS produces maps at different scales; why the maps must be generalised; and how this is done.

Helpful and constructive discussion, advice and comments from numerous colleagues are gratefully acknowledged, in particular, the contributions of Dr P M Allen, E F P Nickless, D C Ovadia, I Jackson, D J Lowe, J L Laxton and K C Mennim. Their views, and those of BGS, do not necessarily correspond to those expressed here.

1.2 The need for different levels of detail

Representing information at various levels of abstraction is consistent with the way in which people view the world. The advantages of BGS producing maps at different scales, on base maps from the Ordnance Survey, include the following:

1. Customers can choose maps matching the extent of their area of interest, and the level of detail required.

2. Printing costs are reduced by publishing at the generalised 1:50 000 scale. At the survey scale, there would be little demand for each map as it covers only a small area.

3. Customers can obtain maps at an appropriate scale for overlaying their own maps.

4. Different applications relate to different scales. Allen (1991) pointed out that maps at 1:10 000 scale are required by external users such as planners, mineral extractive industry, construction industry and utilities, but are used internally either to answer an enquiry from an external source or for detailed scientific analysis. On the other hand, the scientific requirements of geophysical modellers, geochemists and hydrogeologists are best met at 1:50 000 and smaller scales.

5. Maps at different scales illustrate different aspects of the geology. Survey-scale maps place more emphasis on sources of information. The smaller-scale maps emphasise the influence of regional rather than local geological processes.

In the DGSM, it would be possible to hold the digital data only at survey scale, generalising at the time of map preparation. This would simplify updating, and would prevent different versions holding conflicting data (see section 6.1). Holding versions at several resolutions, however, also has advantages.

6. Input from different map scales can be accommodated in the model.

7. Data volumes are less for coarse resolution data, resulting in lower storage costs and faster access and display.

8. Storing the generalised versions ensures that they are unambiguously defined and reflect a considered, approved view of the geology.

1.3 Gains from generalisation

Generalisation is the process of reducing information volume while at the same time preserving the significant information to be portrayed. Advantages in generalising, particularly when the scale of a map is reduced, include the following.

Presentational aspects:

1. Preserving legibility. To remain within the constraints of the display device, such as pen widths and the limits of human visual acuity, line widths and map symbols at smaller scale are enlarged to occupy more space relative to the ground. A symbol 1mm across covers 10m at 1:10 000 scale, 50m at 1:50 000. On reducing the scale, there is a risk of information becoming congested and obscured, unless lines and symbols are redrawn, and if necessary omitted or repositioned.

2. Preserving appearance. Intricate crenulations on a thin line can merge to produce a thick line on miniaturisation. Smoothing the line avoids changing the visual impression. Natural features, such as coastlines or rock outcrops, differ in their appearance and geometrical characteristics at different scales. Generalisation may be needed to preserve the correct appearance.

Content aspects:

3. Maintaining spatial correlation. Because the base maps are generalised by the Ordnance Survey there may be a need to adjust the representation of the geology to maintain its correct spatial relationships with topographic features.

4. The essential character of large features and structures may be clearer after inappropriate spatial and descriptive details are removed.

Against this background of requirements for different levels of map detail and for generalisation, the possibilities of automating the process can be considered.

2. METHODS OF INVESTIGATION

The development of a computer system for generalising geological map data can be approached in at least three ways.

The first is an analytical approach, in which the rationale of geological mapping is examined and the functions of the map components and their relationships are analysed. Their significance can be considered and logical operations might perhaps be defined for generalising them. If this were possible, the operations could then be built into a rules-based system that could be automated.

A second approach is the "expert system" view, which attempts to tease out the structure of decisions made by geologists and cartographers during generalisation, considering the map content and its meaning only in so far as it affects these decisions. The decision tree could then be formalised and the result would be an expert system for map generalisation.

A third is the "amplified intelligence" approach, in which the geologist or cartographer makes the decisions concerning generalisation and implements them with computer assistance, selecting and controlling the computer processes through an interactive graphical interface. It is the approach which most obviously fits the requirement. It also paves the way for later adoption of an expert system if this should prove desirable.

The analytical and the expert system approaches must also be considered in some detail. They throw light on how an interactive system can best be structured, and how field survey methods could respond to the potential of new technology. The reasons for rejecting these approaches, as impracticable for the time being, must also be placed on the record.

2.1 The analytical approach

The analytical approach must attempt an explicit statement of the apparently self-evident issues of why maps are important in geological surveying, and what part they play in geological reasoning. The requirements for generalisation procedures can then be related to that statement.

2.1.1 Reasons for maps

The reasons for presenting geological information on maps (as opposed to, say reports or memoirs) include:

> locating or siting data items relative to one another, to the map coordinates, or to surveyed topographic features;
>
> visual detection of spatial relationships and significant geological pattern;
>
> visual detection of spatial correlation between patterns, and between datasets.

Examples may clarify what is meant by spatial relationships, patterns and correlation. Spatial relationships apply between the symbols, lines, areas and surfaces shown on the map, and also between the real-world features they represent. Thus a fault might be a *boundary between* areas of Carboniferous and Old Red Sandstone; a borehole site might *lie within* an area mapped as Carboniferous; a formation boundary might *converge with* the line of a river. A more complete list of spatial relationships includes: topological relations - within, coincident, contains, bounds, touches, overlaps, intersects; geometrical relationships - near, above, converges, oblique to, displaces, accentuates, in phase with, continuous with; together with synonyms, opposites and approximations.

Spatial pattern is familiar to geologists in, say, the geometry of sand bodies or minor folds. For example, the form of a sand body shown by an isopach map might show a bifurcating, sinuous pattern which suggested infilling of river valleys.

Spatial correlation of patterns in different datasets is investigated when, say, aeromagnetic and gravity anomalies are compared on map overlays. Spatial correlation between datasets is again a process of overlaying maps, to establish, say, which boreholes occur near construction sites.

2.1.2 Relevance to generalisation

The various reasons for mapping geology, which have just been described, have a bearing on the generalisation process, as in the following examples.

Boreholes are sited at the survey scale. Generalisation to match a smaller-scale topographic base may require adjustment of their position, inevitably making the locations less accurate. To obtain the most accurate locations the user must refer to the survey-scale map.

Some patterns visible at survey scale may have little significance for broad-brush studies. For example, wash-outs in a coal seam may not be relevant in explaining gravity anomalies, which would not be influenced by such small features. Generalisation may help to separate spatial patterns of different resolutions. The user should investigate spatial pattern at the map scale appropriate to the requirement.

There is similarity in the form of geological features over a range of sizes. For example, trickles of water down a mud bank may produce features resembling those of the Mississippi delta, and microscopic folds may have similar form to a gigantic nappe. The mathematics of this self-similarity is considered by numerous authors, many following Mandelbrot (1982).

There may be size limits to self-similarity, reflecting, for example, the spatial extent of different geological processes, or of a sedimentary or tectonic regime. Thus geological processes which created patterns displayed on the 1:10 000 map might be local depositional and erosional processes. On the 1:50 000 map, tectonic patterns related to the subsidence of a small sedimentary basin might begin to emerge. The processes and patterns reflected at various scales may be intrinsically different. A generalisation process, to filter out local effects and reveal the broader pattern more clearly, must be carefully designed to retain appropriate components of the pattern, reflecting the underlying geological controls.

Spatial correlation between mapped datasets has in the past been based on the use of Ordnance Survey base maps as locational standards to which other maps can be matched. This is one reason for presenting geological map information against a backdrop of a topographic base map. Geological lines and symbols are adjusted at derived scales to fit the generalised Ordnance Survey topography. While this will continue to apply to printed maps, it must change where the data are presented within a GIS, in which datasets are correlated by geographical reference rather than topography (see section 4).

An opinion from the topographic Survey of Israel (Peled and Adler, 1993) sounds a warning note: “The conventional mapping process involved generation of a photogrammetric manuscript, cartographic enhancement and colour separation, followed by offset printing. This conventional process is doomed not only because it is labour-intensive and dependent on skills rather than on technology, but also because of the demand for mapping information in digital form as part of the infrastructure of spatial analysis within Geographic Information Systems.” Although unusual in its forthright expression, the authors provide strong evidence for their view that “One can observe many similarities in the policy considerations of the national mapping agencies”. The topographic base map is not sacrosanct and will have a diminishing role as the yardstick for spatial correlation.

2.1.3 Maps and geological reasoning

Following on from the reasons for presenting information on maps, and their relevance to generalisation, a second issue in the analytical approach is the part which maps play in geological reasoning.

2.1.4 Sampling procedures

The geological map purports to represent some aspects of the real world which are relevant to the geoscientist. At any scale, the map is showing a selected subset of the information that could be extracted from the real world. In statistical terms, the population (all the relevant information that could have been obtained) has been sampled. The properties of the sample are dependent on the procedures by which it has been collected. According to Stuart (1962): "unless we are circumspect in our choice of sampling method there is no hope whatever of our being able to make scientific statements about the population from the knowledge we shall obtain from the sample."

Generalisation further reduces the amount of information from that shown on the survey scale map, and thus involves selecting a smaller sample (subsample) drawn from the original sample. The strategy for subsampling must be harmonised with the original sampling procedures, if valid conclusions are to be drawn.

If it cannot be stated clearly how the original sample was selected, and that sample is subsequently subsampled by an idiosyncratic and subjective process to produce the derived map, then it is likely that at best the map is less informative than it could be, and it could be misleading in unpredictable ways (see section 3.2).

There are reasons why rigorous sampling procedures have not been generally adopted in geological field survey. One is that the geologist is concerned with weighing evidence and drawing conclusions from a diversity of incompatible information sources, many of which are outside his control. Another is that the map has long been a dominant method of disseminating the geologist's findings. By concentrating on recording those features which can be shown on the final map, the geologist may have been able to make more productive use of his time, but in the process may have given undue weight to cartographic as opposed to scientific considerations. A third is that geological survey is partly an exploratory process, looking for features to reinforce or reject members of an evolving set of possibly unexpressed candidate hypotheses.

It also has to be said that a successful field sampling scheme must be complex. The population accessible to observation is a minute subset of the population of interest (the target population), and is not representative of it. Samples from several cross-cutting subpopulations may have to be collected simultaneously. For example, the structural geologist may be interested in average orientations of, say, bedding planes over a defined area, while also requiring a sample representing all possible orientations across folds to determine whether they are conical or cylindrical. This requires two distinct subsets collected according to different sampling schemes. In the first, every location, in the second, every orientation, should have an equal chance of being selected. Simple, rigid sampling methods could not cope with such needs, and an ill-considered sampling scheme is likely to be less successful than present methods.

2.1.5 The map as a generalisation of the geology

There are therefore important questions about the relationship of the geological map to the real world geology, and the way in which the map user is able to draw conclusions about the underlying population from the sample shown on any scale of map.

One possible answer is that geologists, before and during field survey, develop a conceptual model of the geology, based on their observations, measurements and background knowledge. The target population of which the map is a sample is then the evolving conceptual model. Even at survey scale, the map is a generalisation of this model, emphasising the aspects which the geologists believe to be particularly significant. Indeed, the greatest loss of detail due to generalisation and abstraction occurs when the geologist selects information in the field to depict on the survey scale map.

Faced with the impossibility of depicting the full complexity of his observations and interpretations (including three-dimensional characteristics, variable information density, ambiguity, gradational characteristics, uncertainty and overlap), the geologist records critical features which would assist another geologist to reconstruct the main aspects of the conceptual geological model by studying the map. With the aim of providing greater insight into the model, the geologist might exaggerate features, such as interdigitation along a formation boundary, which were unexpected or crucial to the interpretation.

2.1.6 Mapping rules

The geological map (as distinct from some geophysical, geochemical and resource assessment maps) cannot be seen as a statistically valid sample of the population. It is, however, a basis for conclusions about the underlying geology. There must therefore be rules which the map maker followed and the map user understands. Subsequent generalisation, in redrawing the survey-scale map with less detail for representation at other scales, must follow similar rules, emphasising aspects of the model which are thought to be significant at the scale of presentation. Study of the generalisation procedures may therefore throw light on the decision processes of the geologist mapping in the field and vice versa.

Unlike statistical sampling procedures, which establish reproducible and testable relationships between the population and the sample, the mapping rules are unrecorded, complex, and flexible, dependent on the underlying geology and its interpretation. There seems to be no prospect of capturing the knowledge base for computer-assisted generalisation. The geological map is an approved illustration of the considered interpretation of experienced geologists, but can be fully understood only through insight into the geologists' thought processes. The necessary background knowledge of geological processes and human reasoning and visual perception is not available to the computer.

Analysing the rationale of present procedures for abstraction and generalisation cannot therefore lead directly to an automated system. However, it does throw light on aspects of field survey and map preparation which could be modified to take advantage of modern information technology (see section 6.1).

2.2 The expert systems approach

Focussing on the decisions and procedures of generalisation, rather than analysing the meaning and purpose of the map, appears initially to offer a more promising route to automation. The expert system approach proceeds by systematically formalising cartographical folklore and rules of thumb, and organising them as a list of rules which form the rules base for an expert system. Numerous papers, many in the GIS literature, offer guidelines on expert systems for generalisation (see Buttenfield and McMaster, 1991), but there are few actual implementations and these are in narrowly defined areas.

The requirement is seen as arising from congestion, coalescence, conflict, complication, inconsistency or imperceptibility in aspects of the initial map. A generalisation point is said to have been reached when, for these reasons, reduction in the scale of the map causes the map capacity to decrease to the point where a change in the method of representation, by a process of generalisation, is necessary.

Many classifications of generalisation procedures have been proposed. A typical classification, illustrated in figure 1, is described by Mackaness (1991). Groups of symbols can be modified by changing the symbols, masking the symbols, or increasing the size differentiation between them. The overall amount of detail can be reduced by selecting, omitting and simplifying (reducing sinuosity). Information can be reorganised, but not necessarily eliminated, by combining or reclassifying, displacing and exaggerating.

A typical objective is to retain the essential character of some phenomena, while removing unnecessary detail. The characteristics of symbols, lines or areas which might contain essential information, and therefore should be preserved through the generalisation process, might include: occurrence (existence); location; spatial relationships (see 2.1.1); orientation; distances between objects; size; relative size; shape; amplitude; angularity; frequency; density; variation in density and relative density; pattern and extent of clustering. Preservation of some characteristics is likely to be at the expense of corrupting others. Trade-offs have therefore to be made, as illustrated by some of the examples which are described in section 3.1.

Robinson and Sale (1969, page 16) suggest that the cartographer's portrayal and the selection of the important and the subordination of the non-essential factors of the map data require that the map maker be well acquainted with the subject matter. Map generalization is largely intuitive on the basis that "this looks about right". The process is subjective, interactive, inconsistent, idiosyncratic, and requires insight into the meaning of the map. Individual decisions are not isolated. The components of generalisation are integrated through the holistic view of the map which human vision provides.

Within BGS also (see Humphries, 1993a), current procedures for map generalisation (see section 3) are highly subjective. There is a perceived requirement to reduce the amount of geological detail when information is transferred from larger to smaller scale maps. This is seen as necessary to produce a legible and informative end-product, conforming to the general characteristics and style of similar maps.

There are no specific BGS guidelines on how to achieve this objective, and those carrying out the task cannot offer a simple, comprehensive account of their decision processes. They appear to involve a complex sequence of cartographic and scientific judgments concerning individual components of the map, considered against a background of the map as a whole, and its relationship to the maps at survey scale and to the topographic base map.

An overall conclusion is that the present generalisation process does not lend itself to the expert systems approach. As with the analytical approach, the decisions require an understanding of the subject matter and human visual perception which the computer does not possess. The decisions are unstructured and poorly understood, and therefore cannot be codified as a set of rules.

2.4 The amplified intelligence approach

Fortunately, a third line of approach to the generalisation problem is available which may clarify theoretical issues without compromising longer term developments. It is strongly advocated by Weibel (1991). He accepts that judgments are best made by the human expert, and proposes that manipulation of the map contents should be controlled by an interactive computer process.

The geologist or cartographer (or both) express decisions by simple commands and monitor the consequences, interactively on the screen and by preparing one-off draft copies on paper. There is an analogy with a word processor where the human author writes the document, but with the assistance of the computer to carry out the mechanical operations of arranging and presenting the information according to the user's instructions. Loudon and others (1993, section 6) recommend this approach.

Weibel (1991) argues that the user's knowledge and intelligence can be amplified by a range of high-level tools for carrying out generalisation operations. He sees two main advantages in this approach. By building on current practice it leads rapidly to operational systems that may be used in productive work. Secondly, it is a transitional approach, which increases understanding of the complex decisions, and encourages acquisition of more fully structured knowledge about them, which may eventually lead to a full-scale expert system.

The system must provide clear and rapid visual feedback. It should assist decisions, for example by identifying lines and areas of undue complexity, and identifying overlaps and obscured objects. It should include tools to assist knowledge acquisition, such as procedures to log decisions and codify rules.

The decisions, and control of the system, should rely on human experts. Both geologists and cartographers are likely to contribute expertise, in their different areas. Both must therefore participate in map design decisions, although the computer should assist them with tedious operational tasks.

A major attraction for BGS is the gradual extension from existing practices, in which the geologist marks up changes on the map for implementation by Cartographic Services, towards a more fully automated system. However, some practical aspects of geological map generalisation and the requirements of the digital model must be taken into account. Both will now be considered.

3. ASPECTS OF GEOLOGICAL MAPS

3.1 Examples of map generalisation

The BGS procedures to generalise from 1:10 000 to 1:50 000 geological maps are described by Humphries (1993a) and Loudon and others (1993). A number of actual maps were examined for this report to see how the procedures work in practice. The examples are extracts from 1:50 000 maps, enlarged to approximately 1:10 000 scale and set alongside the corresponding 1:10 000 map from which they had been manually derived. Untypically complex maps were selected, because they show the problems more clearly.

The small enlarged areas of the map, without colour, are difficult to interpret geologically, but that is not the present purpose. The examples are not intended as a critique of current practice, but as an illustration of the mechanics of the process with a view to examining the feasibility of automation. They show how some problems of generalisation have been addressed. The loss of sharpness, accuracy and precision which is apparent in the examples is an inevitable result of the redrawing required for manual generalisation.

The first examples are taken from the Greenock Drift Sheet 30W. Symbols showing glacial striae in figure 2a are enlarged and some repositioning appears to have occurred in 2b. One symbol from the top right of 2a has been omitted, and a new symbol inserted at the top left of 2b. Some symbols have moved relative to topographic features. The overall pattern is shown, but it would appear that precise locations of actual occurrences are not important on the small-scale map.

Figures 2c and 2d show enlargement of drainage channel symbols. The width of the lines and the arrow heads and tails are enlarged, but the length, position and orientation are maintained, if only approximately. See, for example, the relative length of the arms of the symbol in the top right of the two maps.

Figures 2e and 2f show omission of a complete area of Drift, presumably because of its limited width, rather than its area. In figure 2g, the small circular area just right of centre, although possibly large enough to be legible at small scale, is linked to an adjacent area in 2h. The reason for the link going north rather than south is not obvious from the map. Figure 2i shows how three small areas, separate at large scale, are combined in 2j as a larger area of roughly the same dimensions on the ground. The boundary lines are smoothed.

An extreme example of complexity is provided by the Eastern Mull Sheet 44W, shown in figure 3. The dykes shown in black in the upper left half of figure 3a are generalised in 3b without any one to one correspondence of items between the scales. The average orientation, the lenticularity, and some of the variation in density are retained. The dimensions, shape and spacing of the dykes are greatly altered. Similar changes can be seen in figures 3c and 3d. In the lower right of figure 3a, the bands shown in white have been exaggerated in thickness in 3b, considerably increasing their proportional area.

Figure 3f, also from the Mull sheet, shows how a dense swarm of dykes cutting the coastal exposures has been reduced in frequency for the smaller scale map, 3h and 3g. An attempt has been made to retain the variation in density, and average orientations are retained. Presumably not all dykes were mapped, and even at survey scale the thicknesses are exaggerated giving a false impression of their density. The dykes are shown only near their exposures, unlike formation boundaries which are shown whether observed or not. Elsewhere on this sheet, where dykes are less closely spaced, all mapped dykes are shown at both scales.

Figure 4b from Airdrie Sheet 31W, shows selection of three dykes from the eight shown in figure 4a. They have not been accurately repositioned relative to the topography, and some, but not all, lithological types and orientations are represented. Figures 4c and 4d show the removal of minor faults, selection of coal seams, and adjustment of the position of a coal seam in 4d to remove the effect of a minor fault. The actual strike of the coal seam is thus not quite parallel to the boundary shown on figure 4d. Presumably similar faults may exist which were too small to show even at survey scale.

Figure 4g shows selection of coal seams from 4e to give a clearer picture of the folding and faulting. The earlier one-inch map of the same area, shown in figure 4h, included a larger number of seams, at the cost of legibility. Their omission is not a great loss, as the existence and relative position of the other seams can be inferred from the generalised vertical section in the map margin. In figure 4j, the shape of the dolerite body in 4i has been smoothed, particularly at the southeast corner, although the redrawing unfortunately also affected the shape elsewhere.

Exaggeration of the coal seam in figure 4m meant that there was not enough room to place it between the dolerite body and the railway (see figure 4l). The geometry has been maintained at the cost of erroneously showing the seam intersecting the railway cutting. In the earlier one-inch map, shown as 4n, an alternative decision was taken, and the seam is shown terminating against the dolerite.

The Ambleside map, Sheet 30, and the Special Sheet SD19 at 1:25 000 scale, are the sources for figure 5. Figure 5b shows the introduction of a boundary line, on the left of the diagram, on the 1:50 000 map, which was not present at survey scale on 5a. Because of the gradational nature of the boundary, it was not thought appropriate to show a precise location at the larger scale (see Humphries, 1993a). Even at the small scale, the line represents a wide transition zone. Figure 5c shows symbols indicating the vergence of minor folds which for space reasons replace the separate syncline and anticline symbols shown at 1:10000 scale, but not illustrated here (Humphries, 1993a).

General conclusions that might be drawn from studying these and other examples are:

1. For many maps, generalisation of the geology from 1:10 000 to 1:50000 scale is not necessary (see Myers and Becken, 1993).

2. Selection, to reduce the number of, say, coal seams, dykes, or symbols, can improve the clarity and legibility of the smaller-scale map.

3. Exaggeration of some thin beds is required, leading to a need to displace some in closely-packed areas. Complex decisions may be needed about which spatial relationships should be preserved.

4. Small areas may be removed, aggregated or exaggerated, depending on their geological significance.

5. Adjustment and repositioning to match the generalised topography are not apparent in the examples.

6. Smoothing of lines is only occasionally desirable. Redrawing lines inevitably leads to a loss of quality, and in many cases, it appears that automatic miniaturisation would have produced a superior result.

7. One to one correspondence between items at the two scales is not always maintained. New boundaries and symbols may be introduced at the smaller scale.

8. Particularly in areas of complex geology, there is a trade-off among maintaining location, orientation, size, shape, density, frequency and variation in these characteristics. Maps at all scales are highly stylised, and it cannot be assumed that any of these characteristics is ever accurately represented.

9. Marginalia, particularly the generalised vertical section, are an intrinsic part of the map, vital to its interpretation. The information they contain should therefore be made available in the computer environment, linked to the map-face data to which they refer.

3.2 Characteristics of the geological map

Some data on the map, such as most formation boundaries, resemble scale drawings of surveyed features. Even at survey scale, however, the drawn line is a smoothed version of the real boundary, that is, the detail and variations of small extent are suppressed. As Mandelbrot (1982) points out, the length of a natural boundary increases without limit as the amount of detail is increased. Thus the length of the British coastline tends towards infinity as the outline of every headland and inlet, mud bank, boulder, grain, crystal, molecule, etc is included in the calculation. The smoothing process affects the location as well as every other geometrical characteristic of every part of every line.

More generally, each spatial record reflects the resolution (spatial extent) of its measurement. Thus, if each bedding orientation is measured over an area the size of a field notebook, individual values, and their statistical properties, will differ significantly from a similar set each measured over an area of a metre square. Logically, a strike and dip symbol on a 1:50 000 scale map might be expected to refer to an area 25 times as large as that on a 1:10 000 scale map. In fact, the symbols are normally a selected subset of the original measurements. The implicit smoothing and the spatial resolution of measurements are undefined and inconsistent.

On the survey scale map, the line of a formation boundary may be crenulate in an area of good exposure, but noticeably smoother where the boundary is concealed by superficial deposits. Presumably, the geologist is indicating that the boundary must exist in the concealed area, and although it may be as sinuous as elsewhere, the exact position of each bend is unknown.

The smoother line is marking a probable (in an informal, undefined sense) position of the boundary, and the smoothing is a form of generalisation varying within a single map to reflect locational uncertainty. Logically, the distinction might be maintained by applying additional smoothing to this area on change of scale, but instead the tendency is to carry through as much detail as is cartographically acceptable.

Algorithms are readily available to smooth lines by removing the short-wavelength variations. However, they distort geometrical aspects and shape characteristics, such as local orientation and angularity, which the geologist might wish to preserve or even emphasise. Different algorithms are appropriate for different circumstances, and in some cases, manual redrawing of the line may be necessary.

Many features of the geological map, as mentioned in sections 2.1 and 3.1, are highly stylised. The dyke swarms shown in figures 3f and 3g clearly do not depict the areal proportion of the outcrop occupied by dykes. The symbol representing each dyke has a width and form determined by cartographical considerations; a location and orientation based on field observation; and length determined by observation, interpretation and cartographic requirements. In these examples, the dykes are not extended far beyond the outcrop, whereas in figures 3a and 3b, the dykes extend much further, perhaps because of better exposure. Areas of other rock types, such as the coal seams of figure 4g, are likewise enlarged because of their geological significance, particularly where they would otherwise be too small to be legible.

The stylised lines and areas are partly symbolic, partly representational. On the other hand, some of the map information is portrayed by pure symbols. For example, borehole locations or glacial striae are depicted by symbols which indicate location, and possibly orientation, but are not scaled representations of the features. On changing the map scale, the relative size of the symbols is increased, and they may be replaced by new symbols, or the number of symbols may be reduced, perhaps in proportion to the original density, but more likely in response to lack of space on the map.

Some scaled representations may be replaced by symbols on generalisation. At large scale, for example, orientations of bedding planes and positions of fold axes may depict the structure adequately. At smaller scale, symbols to indicate the location and vergence of groups of minor folds may replace the detail (see figure 5c, and Humphries, 1993a). The two conventions may coexist in different parts of the same map. More confusingly, figure 3b shows a highly stylised symbolic representation of ring dykes, which in the absence of the detailed map (figure 3a) might be taken as a scaled representation. It is not clear to what extent the representation on the 1:10 000 map is also symbolic rather than scaled.

The user may not know the extent to which lines and areas on the map are scale drawings, stylised or symbolic representations, and lacks guidance about the spatial resolution of the observations and measurements. The user has the task of deciding to what extent a line is smooth because of the nature of the boundary, the map scale, the lack of exposure, or the risk of visual distraction. Although the customer may possibly regard a map uniformly packed with information as better value for money, the consequences are internal inconsistency and ambiguity.

Digital methods are introducing the greatest changes in map production of this century, and offer an opportunity to rationalise the process of generalisation and symbolisation to convey more exact information to the user in a more lucid and intelligible form. In the light of this, there could be value in a separate exercise to reconsider aspects of map design and presentation.

4. ASPECTS OF DIGITAL SPATIAL MODELS

4.1 Generalisation within the Digital Geological Spatial Model

4.1.1 The need to consider the DGSM

Automation is made more difficult by the problems of recording data and depicting the geological model on a static two-dimensional map. At every scale, the map provides a framework within which certain aspects, and only certain aspects, of the geology can be depicted in a particular way. A digital spatial model, such as that set out by POSC (1993, pages 1-215 to 1-232), provides a framework with other opportunities, different constraints and much greater flexibility. The digital geological spatial model (DGSM) is seen as the key to creating a more reproducible, representative and testable representation of real world geology (see Ovadia and Loudon, 1993). Maps can then be regarded as products generated from master data held in the DGSM.

The longer-term developments must be kept in mind, as otherwise needless constraints from older technology will be carried forward and impede future progress. Generalisation of models, as well as between scales of map, must therefore be considered.

4.1.2 Maps as source data

There is little doubt that geological surveying methods could, in principle, follow more rigorous statistical sampling schemes, thus meeting more fully the requirements of the DGSM as described in section 2.1 and 6.1. However, there are practical difficulties.

Field survey by BGS tends to be more concerned with bringing earlier studies up to date than with totally new investigations. Traditional geology has not tended to attract scientists with a strong mathematical leaning. Among many field geologists there is a conservative attitude to new methodology. Therefore, the detailed experimental development of surveying methods suited to new technology has not taken place, and consequently, radical changes to BGS field survey methods are not at present a practical proposition.

At this stage, priority must instead be placed on creating the digital model from the geological records currently available, which are mostly in map form. The key issue is whether the resulting DGSM will offer the data and the environment in which new scientific approaches, including more rigorous field data collection and generalisation, can flourish.

The DGSM, as described earlier, is currently little more than a digital representation of parts of the geological map. In the longer term, the DGSM may develop as a set of algorithms operating on datasets describing observations and measurements, statistical summaries of the spatial properties, and parameters controlling interpolation. Innumerable forms of visualisation and presentation will be feasible, with presentations akin to the current published geological map among the most important. For this last purpose, the existing data derived from geological maps can be seen as a preprocessed component of the DGSM, suitable for printing with little modification.

The existing map data also have another contribution to make to the model. Although not statistically representative of the real world, the map data, within margins of spatial error which can be estimated, provide a broadly accurate statement of the location of rock units and boundaries. Valid statistical information can thus be derived from the map data and marginalia, although it is accurate only at a coarser resolution than the map scale might seem to imply. Although a by-product of map making, the data will provide vital input of long-term value to the DGSM. Provided that the digital map data are regarded as part of an open-ended data store, therefore, they should actively encourage further DGSM development.

4.1.3 Scientific and cartographic generalisation

It is essential to separate the geoscientific aspects of generalisation within the DGSM from the purely cartographic aspects of generalisation, which may simply be ephemeral adjustments to fit a specific base map. For example, the classification of stratigraphical units as local or regional, and smoothing boundaries to remove the effects of local processes, could be regarded as geoscientific generalisation, and should be recorded in the DGSM.

Exaggeration of the thickness of coal seams for improved legibility, and adjustment of their position to avoid obscuring a nearby limestone band, or adjustment of a formation boundary to vee upstream accurately on a small-scale base map, are matters of cartographic generalisation, which must be invoked when maps are produced from the model. They should not be reflected back into the model, however, where the flexibility of presentation makes them unnecessary and undesirable.

This is entirely in keeping with the concepts that have been consistently followed throughout the digital map implementation programme.

4.1.4 Source data at different scales

The data models for BGS maps at the two scales under consideration are closely similar (Bain and Giles, 1992, Bain, 1992), and have been combined as a single logical data model covering all map scales (Bain, 1993).

It has been pointed out by Myers and Becken (1993) that cartographic generalisation of the geological data between the two scales is frequently unnecessary. The essential generalisation involves selective omission and aggregation of geological entities - changes which could be handled from a single database.

The concept of a single source of data, from which maps can be generated at many scales, is attractive because it overcomes the difficulty of managing several parallel databases which contain overlapping information, but are updated at different times.

For many years to come, however, it is likely that the data in the DGSM will come, not from field survey, but from digitisation of maps at various scales. Country-wide digital coverage will for some years be available only from small-scale maps. Coverage will proceed faster and be more complete at 1:50 000 scale than at 1:10 000. Because they come from different sources, there will inevitably be inconsistencies between the two scales, in terms of mismatches at sheet boundaries, different content and different line smoothing. If adjacent areas are to be consistent, the data must correspond to a single map series and scale.

In view of the need for different levels of detail within the model, the need to provide source data for conventional maps, and the need to accept different versions of data from maps at different scales, it is recommended that data should be identified within the DGSM as suitable for local, regional and national levels of detail. These broadly correspond to the information on 1:10 000, 1:50 000 and smaller-scale maps, as proposed by Lowe (see Lowe and Green, 1992).

In order to maintain links between data from maps at different scales, the smaller-scale map data will have to be tiled within the DGSM along the boundaries of the larger-scale sheets (see Laxton, 1994). Thus the digital record of a 1:50 000 sheet would be tiled on a 5km square grid to match 1:10 000 quarter sheets.

Lateral continuity between map sheets, or tiles in the model, requires edge matching to ensure that lines flow continuously across the tile boundaries. Smoothed lines do not coincide with their unsmoothed counterparts, and so must be edge-matched separately. Lines generalised for 1:50 000 scale from source data at 1:10 000 scale will need to be edge-matched to adjacent 1:50 000 sheets. The original versions of the 1:10 000 data should be edge-matched with the adjoining 1:10 000 sheets. Decisions about aggregation of stratigraphical units should be on a regional basis, so that they too conform on adjacent sheets.

4.1.5 Versions of items at different resolution

The question then arises of the extent to which versions of the data for different resolutions should correspond at the level of items such as individual line segments. There is a strong case for identifying item-level links where feasible (see Loudon and others, 1993). First, as Myers and Becken (1993) have emphasised, many items are identical on both scales of map. Second, as new information is obtained, and features are amended, it is necessary to consider the implications for revision at all resolutions. This is greatly simplified if linkages at item level exist. Third, consistency between the interpretations at all resolutions is highly desirable. Again, this is aided by item-level correspondence.

Items, particularly symbols, do not always have counterparts on maps at other scales. New symbols, and even new lines, may be introduced on generalisation, as described in section 3.1. The DGSM must therefore be able to handle items which are specific to a particular map scale. They must be clearly identified as such, for careful thought must be given to their treatment on revision and the complex implications for data at other resolutions.

4.1.6 Separating aspects of the geology

The need to respond to specific user requirements at every scale creates a need to categorise the information within the DGSM. The solution can be visualised as a set of layers or overlays which to some extent could be manipulated separately. Thus information on the spatial disposition of rock units on the ground might be separable from structural data, such as faults, folds and linear and planar orientations. Work on, say, deriving spatial statistics from the former would not then interfere with, say, differential geometry applications on the latter.

Lithological characteristics, data sources and geophysical measurements might in turn be regarded as distinct segments within the model and separate layers within the map, to be combined as and when required.

Layering would simplify the use of the data within a GIS or image analysis system. It provides flexibility in generalising different layers to varying extents depending on the requirement, as well as helping to ensure that each layer is internally consistent and complete.

4.2 Preparing maps from the DGSM

There are potential benefits from deferring cartographical decisions about a map until the time when it is actually produced. Constraining the DGSM by prejudging possible cartographic needs is unnecessary and leads to loss of potentially valuable geological information.

The geologist should be free to express his interpretations and observations as accurately as possible within the DGSM, which should then offer a single data source from which any type of map can be generated. This leaves for separate consideration the question of which maps can most beneficially be prepared from the model, and when and how this should be done.

4.2.1 Cartographic considerations

Some cartographic considerations are specific to the map type. For example, clutter is more likely to cause problems where solid and drift geology are shown on the same map. Because of its finer resolution, a conventional printed map can carry more detail than a map produced on an electrostatic plotter, or by a pen plotter.

The minimum legible width and length of lines, and size or width of areas and symbols, could be defined for each type of map. The computer system should then highlight lines or areas below this limit. This will help the cartographer or geologist to decide whether they should be omitted, exaggerated, or combined with similar areas nearby.

Aggregation, smoothing, selection and omission, placement of symbols and text, exaggeration and displacement, may then be required to obtain a legible map fitted to its topographic base. Quite complex cartographic decisions are required, which may have geological implications that have to be referred to the geologist. The system should assist by highlighting overlap and congested areas.

4.2.2 Standardising cartographic representation

It was argued in section 2.3 that the amplified intelligence approach should in time lead to greater formalisation of the decision-making process. It would therefore be helpful to relate each type of item in the DGSM to appropriate default cartographic representations, following agreed conventions concerning the form, style, ornament and colour of areas, lines and symbols, provided they can be overridden when necessary. This should encourage their consistent application, thereby producing more easily understood maps.

4.2.3 Exporting GIS data

The DGSM is a potential source of digital data for external users to import and combine with their own data in a GIS environment. Care is obviously needed to ensure that output from the DGSM is accurately registered with other spatial datasets when they are displayed together within a GIS. Grids or tic marks should be exported with the data as a registration check. The original source map, its base map and scale, and the extent of generalisation must be identified for the end-user.

4.3 Models at other resolutions

There are requirements to integrate data from different scales within the DGSM. For example, subsurface formation depths, derived, say, from borehole or geophysical data, must be related to surface geology known in greater detail from field mapping. An application of this kind is described by Cameron and others (1989).

Geological features and properties may be measured over any spatial extent. Therefore, the DGSM must be capable of accepting, reconciling and combining data at any spatial resolution. It must also support comparisons and interaction with other spatial models of, say, gravity anomalies or geochemical analyses of stream sediment samples.

Generalisation of the DGSM data may be needed before comparing them with other data of coarser resolution. Otherwise, like is not being compared with like, and spatial correlation may be obscured by irrelevant detail.

The full complexity of the DGSM is required only at the survey scale and a simplified, generalised version is more appropriate for many applications. The reasons for this, and the future options, require some background consideration of the wider context.

5. THE WIDER CONTEXT

5.1 Information technology developments

Map generalisation can be seen as a special case of data compression and decompression techniques (codecs). Data compression refers to a reduction in data volume, and decompression to the restoration of more complete information from the compressed form. A simple example is run-length encoding, where, instead of transmitting a sequence of, say, 23 blank spaces, one blank is transmitted preceded by the message that it is to be repeated 23 times. The original data may be compressed for more compact storage or transmission, and recreated for manipulation or display.

5.1.1 Data compression

The data compression techniques applied to raster images can be quite complex, and may require considerable processing power at the point of compression. After transmission, similar processing power is required for decompression. There is thus a trade-off between the savings in storage and transmission and the cost of additional processing. The availability of special-purpose codec chips greatly reduces the cost, and makes it possible to incorporate the processing capacity within a fax machine, telephone or video recorder.

A lossy codec is a technique in which some information is deliberately lost, thus allowing much greater compression. An extreme example is the representation by BBC Scotland of the outline of the country using only three straight lines, a significant reduction on the full representation, which, as mentioned in section 3.2, is immeasurably large.

The motivation for work on digital data compression arises from the need to handle very large volumes of data with finite storage and transmission capacity. Examples are: operating faster facsimile transmission, video telephones and videoconferencing over existing telephone lines; providing high-definition wide-screen television within the limited bandwidth of existing broadcasting channels; downloading by cable of computer games and films to home video recorders; storage and transmission of images for flight simulators or virtual reality systems; storage and processing of complex images from remote sensing and film animation.

From this perspective, it can be seen that digital map generalisation is a special case of an activity in which neither the geological nor the cartographical community is a serious player. The question is therefore, not whether we can contribute to this work, but whether we can take advantage of work being done elsewhere.

Codecs are an active area of research, where innovation is so rapid that it is unlikely that even currently agreed ISO standards will be relevant for more than a few years. Most existing standards refer to simple, established techniques which involve no loss of information. For generalisation of geological maps and models, newer methods, and some techniques which are still at a research stage, have more to offer, such as the following examples.

One method involves the digital equivalent of the hologram, where the amount of detail in the reconstituted image depends on the proportion of the compressed dataset which is decompressed. Another “fractal” method (see Anson, 1993) takes advantage of the self-similarity mentioned in section 2.1 to store patterns recurring at different sizes and positions to recreate the image.

Another technique is object-orientated, breaking down the images into separate objects which obey their own rules. Thus animation of dinosaurs in the film *Jurassic Park* (to take a geological example) treats each as a separate object within the class of, say, velociraptors, and the landscape and its elements as objects belonging to another class. By defining the rules of behaviour for each class of object, a relatively compact representation of an animation sequence can be conceived. For a brief, non-technical account of codecs see Anon (1994).

The more advanced techniques are those with the more obvious relevance to geology. The ability to detect pattern, to build an image from known patterns, to suppress detail, to analyse separately objects related to specific geological processes, must be relevant to geological survey. Future technology offers the promise of being able to analyse, emphasise and correlate spatial patterns and generalise them separately or together to any level of detail, rapidly and even interactively.

Some work on three-dimensional generalisation has been reported and some studies of methods of generalising surfaces, such as the multiresolution database described by Ware and Jones (1992), have geoscience applications in mind. The main thrust of data compression work has been concerned, however, with text, images and sequences of images. These developments have a bearing on how BGS should position its work on generalisation to take advantage of likely future developments in information technology.

5.1.2 The relevance to geological generalisation

The current DGSM is supported by relational database management systems and geographical information systems (GIS). The systems are expensive and complex, and access is consequently restricted to expert users. Datasets are therefore required which can be more widely shared and processed with simpler software.

On the one hand, the current DGSM must be extended within the framework of detailed analysis and data modelling to improve its ability to handle data from a range of sources, and generate detailed conventional maps.

On the other hand, simplified datasets could be extracted for general access. An initial phase of generalisation can greatly reduce the complexity of the data structure. Thus the numerous attributes of spatial elements at survey scale might be simplified to only one or two. Three-dimensional aspects of the surface mapping, and precise matching of the geology to topographic features, are less significant when the scale is reduced. Indeed, many requirements for the generalised data could be adequately met by an image. For example, the mapped surface geology can be related to subsurface geology by draping a two-dimensional representation over a digital elevation model of the land surface.

In the longer run, advancing technology should extend full access to the detailed DGSM. Meantime, limited generalisation for smaller scales, for different devices, and for special-purpose maps might be more efficiently handled from simplified images than from the full DGSM.

Generalisation of the image reduces its spatial resolution and colour discrimination. Adjacent pixels (picture elements or cells) with a similar colour code would thus be aggregated before those of very different colour codes. The computer system mimics the eye which, with increasing distance, can no longer distinguish small areas of similar colour.

This offers a mechanism for distinguishing, when an image is created, between those components which must remain distinct or must be preserved through a wide range of resolutions, and those which are purely local and can be amalgamated for a regional view. This approach is particularly powerful if the data are segmented as separate images dealing with different aspects of the geology, as described in section 4.1.6.

Image analysis systems can adjust the colour spectrum to reflect the differing emphases of the various requirements. During display, the colours are mapped to the screen through a colour map table, which can be readily edited to combine or aggregate specified colours. In this way, generalisation criteria could be built into images, although this implies some reconsideration of aspects of map design (see also the end of section 3.2). The images would be the basis for further informal generalisation to match one-off requirements.

5.2 The BGS geoscience information system

The "information system" is a broad concept, including data and interpretation, and embracing manual and paper-based systems, registries and libraries, and the personal knowledge of staff as well as systems based on information technology. The system is the organised set of procedures by which information is gathered, analysed, interpreted, recorded, stored and disposed of, and made useful and available.

The computerised part of the system is more limited in scope, but equally general in concept. It can be visualised as a number of layers, of which the topmost are concerned with indexing and providing access paths to the information. The central layers are syntheses providing an integrated view of UK geoscience, conceptually dominated by the DGSM. The lower layers hold supporting and independent datasets.

The data architecture and detailed data models provide some coherence to the overall structure, but many datasets were collected within projects which had their own specific and undocumented investigational design, data collection methods and operational definitions, which make full sharing of the data impossible. The computer data are handled within a number of incompatible software environments, which present additional barriers to sharing data, and software integration platforms are only now emerging as a realistic future prospect (see POSC, 1993).

It is nevertheless vital that the DGSM should develop as an integral part of the computer information system. Available information at any level of generalisation should be identifiable within the index layers. Cross-references from the DGSM to detailed data sources must be possible. and simplified shared images should be readily accessible. Generalisation should be seen as an integral part of the process of geoscientific interpretation as well as map making, and the procedures should be firmly integrated in the BGS information system as a whole.

6. IMPLEMENTATION

6.1 An ideal and a feasible system

6.1.1 An ideal system

Earlier sections provide a basis for describing an ideal system, as well as the reasons why it cannot realistically be implemented. Taking the ideal as a starting point gives a basis for designing the inevitable compromises and identifying future directions.

1. The ideal system would be based on a single coherent DGSM, accepting data from many sources with data capture techniques designed to match the model requirements. The model would be capable of holding information related to all aspects of the geology, providing a reproducible, representative, testable, shareable and communicable representation of geology in the real world. The model would be internally consistent, approved and quality assured.

2. Generalisation would be seen as a continuous process of increasing the level of abstraction and reducing the volume of information. It begins with the real world geology and the field geologists' observations and conjectures about it. The volume of information is greatly reduced when the geologist chooses the parts of his mental picture which he wishes to record. The information is further reduced by generalisation to levels of lesser detail, such as maps at smaller scales. It involves combination and correlation with data gathered separately at other spatial resolutions. It concludes with the stimuli and impressions which the end user receives from inspection of the maps, diagrams or other displays. Generalisation procedures would ideally reflect a uniform strategy regardless of the scale of representation.

3. The value and justification for the entire activity lies in the end result, namely the communication of information enabling the end user to make better decisions. The model would ideally provide information for display at any scale and level of detail, fully integrated with other aspects of the information system, and would be able to generate images for any type of representation automatically.

An analogy is the ability to describe an image in PostScript (see Adobe Systems, 1985), which can then be displayed at a wide range of sizes on many devices. This is because the device driver has the ability to adjust the image, for example by thickening lines or redrawing the text, improving the legibility by matching the representation to the defined constraints of the device. Cartographic conventions and generalisation procedures would be defined to ensure that the final presentation gave a consistent, clear, accurate, balanced and unambiguous view of the selected aspects of the geological model.

4. The various stages of computer processing would be controlled by the best qualified expert: the initial stages of data capture and scientific generalisation by the field and regional geologists; cartographic generalisation by the cartographer; data management by the curator; and decisions on special-purpose map content, generalisation and display by the user.

6.1.2 Practical constraints

The reality is that practical constraints prevent the ideal system being attainable at present. The constraints can be listed with numbers corresponding to those in the previous section.

1. The available input to the DGSM is from several overlapping, incompatible and conflicting sources, principally maps at survey and derived scales. The data have already been collected,

using subjective procedures and methods devised for an earlier information technology, primarily directed at the production of a limited number of comprehensive map series (see Loudon and others, 1993). Other potential sources of input from deep geology and geophysics are not directly compatible and so far have not been tapped by the DGSM. Quality control procedures focus on approval of maps.

2. The generalisation procedures are subjective, and any automated system must rely on detailed decisions by human experts (see section 2).

3. The existing facilities for producing and generalising images are designed for use by skilled cartographers trained in computer techniques. The digital cartography systems do not interoperate with the remainder of the BGS information system. Production systems combining ease of use and flexibility of presentation are not yet available. Cartographic conventions and generalisation procedures covering a wide range of geological map types have not yet been rationalised and codified.

4. Existing information technology can provide flexible systems for many of the functions required by the DGSM. At present, however, they are complex, expensive and require skilled and experienced operators. They are not suited to casual use, and few geologists have adequate technical skills to operate the current systems. It is therefore generally necessary for the end user to work through an intermediary.

6.1.3 Compromises

Because of the constraints, compromises are required to ensure immediate progress, both in moving towards the ideal system and in mobilising the information for easy access.

The following steps summarise appropriate compromises which were recommended earlier:

1. Data should be captured from 1:10 000 maps where this is cost-effective, or otherwise from 1:50 000 scale. Items should be labelled to indicate their source and their relevance at local, regional and national levels of detail. Data should edge-match and be laterally consistent at each level of detail (4.1.4, 4.1.5).

2. Matching versions of items at local and regional levels should be held where both are needed. For example, generalisation of 1:10 000 data to match surrounding 1:50 000 sheets will be necessary, and the generalised versions corresponding to the original items should be stored for later reuse (4.1.4).

3. The cost and complexity of the digital map production system mean that the DGSM is not yet suited to general access. Instead, simplified images at local, national and regional levels of detail may be extracted as shareable components of the BGS information system (5.1.2). It is vital that the DGSM should develop as an integral part of the computer information system (5.2, 6.2).

4. It is appropriate to extend the DGSM for three-dimensional modelling and to support test beds for new field survey techniques. Developing technology will almost certainly make wider access feasible in due course, and this should be a medium-term objective (5.1.2).

5. Computer-based generalisation should follow the “amplified intelligence” approach, in which the human expert makes decisions which the computer implements. One aim is to rationalise and codify the decisions for future development
(2.3).

6.2 The system specification

Programmers customising the generalisation facilities could work most efficiently to a clear and precise specification. The possibilities of defining the system, describing the procedures, and formalising the specification are therefore explored.

The data flow diagram of Annex 2 [available only in the paper copy of this report] describes a proposed system for computer-based generalisation within the Digital Map Production System. Similar diagrams in Humphries (1993a) describe the current manual generalisation procedures. The conventions are explained in Humphries and Bain (1993).

It is clear from the data flow that the geologist would benefit from access to the full facilities of the BGS information system during model generalisation and map preparation. For example, computer access to borehole locations and descriptions, to data dictionaries, stratigraphical and lithological codes, and even to geophysical, geochemical and geotechnical datasets, might be helpful. Conversely, the DGSM at all scales is of wide relevance to other geoscience studies.

6.2.1 The geological decisions

The geologist makes decisions on generalising maps after examining the originals together with a miniaturised copy. Examples of decisions that could be reflected in the DGSM will now be considered, within the framework of the reasons for mapping geology listed in section 2.1.

The first reason given in 2.1 was locating or siting data items relative to one another, to the map coordinates, or to surveyed topographic features. The precise location of, say boreholes or observed glacial striae or strike and dip measurements, is most accurately recorded at survey scale, and should not be generalised. The geologist must, however, consider which of the occurrences best reflect the distribution on a regional scale. They should be flagged accordingly. The role of these items has changed at the smaller scale. There is no longer a requirement to determine the precise location of individual occurrences, but rather to display their spatial pattern and relationships.

Visual detection of spatial relationships and significant geological pattern was seen as the second reason for presenting information on maps. In the course of generalisation, it is appropriate to separate pattern and relationships which have regional significance from those of purely local significance. The pattern of selected boreholes may indicate which areas have been examined for underground water supplies, or the areas of best data control for subsurface geology. Glacial striae symbols might be selected to illustrate the regional pattern of ice movement.

Stratigraphical considerations will determine which rock units are of regional and which are of purely local extent and thus might be aggregated with others, perhaps retaining boundaries of local units as form lines. Structural considerations would determine which orientation measurements, folds and faults should be retained to show major folds and the regional faulting pattern. The items of regional significance should be flagged in the model.

Smoothing of lines may remove local effects to reveal the regional pattern more clearly. The smoothing algorithm (which is liable to remove all short wavelength components) must be chosen with care to ensure that regional properties are retained. For example, the erosional nature of a boundary might be indicated by undulations, which were small but nevertheless significant in the regional interpretation. Where a line is smoothed, both the original and the smoothed version should be retained in the model.

Spatial relationships can be significant, and it may be necessary to retain the relationships on generalisation. The fact that a borehole penetrates a fault, that a formation boundary vees upstream, or that a dolerite sill converges with a coal seam may be of geological interest over a range of map scales. Such relationships are implied but not explicitly stated on the map, and line smoothing or selection could break the relationship.

There is a case for identifying important spatial relationships (such as those listed in section 2.1.1) explicitly in the DGSM. Where the link is to an external entity, such as the river into which the formation vees, the relevant portion of the river could also be digitised and included in the DGSM. The identification of spatial relationships is best undertaken during field survey.

The background considerations which have been reviewed in this section provide a possible framework for defining the functions to be implemented within the computer system.

6.2.2 Formalising the procedures

The geologist or cartographer is faced with balancing a complex set of alternatives when making decisions about generalisation procedures. A decision which may improve one aspect of the presentation is likely to be at the expense of some other aspect, and the trade off between the two is complicated by knock-on effects.

The most favourable balance is a matter for human judgment, in the light of knowledge of the uses of the map or model and of the underlying geology. In order to implement a system on the computer, however, the functions which the computer will perform must be formalised, and presented in a way that the user can readily understand.

The specification is best developed by cartographers familiar with the system, working in conjunction with geologists and software experts. Various scenarios can be rapidly explored on paper, matching possible requirements against software capabilities.

An illustrative scenario of a possible sequence of operations follows [Table 1], within the framework suggested by the discussion of the previous section. The decisions made by the user are listed on the left, the expected computer response on the right. When agreement has been reached on paper, the possibilities can be explored further by prototyping aspects of the requirement.

For simple functions at least, the system should be easy for the geologist or cartographer to use. The user should be able to make decisions and see their consequences without delay on the screen. Hard-copy edit plots will also be required to see the overall effect of a large number of changes. The activities just described would be carried out on a copy of part of the approved DGSM. The changes might then be submitted for approval, and subsequently replace the earlier data as the new approved version.

During development, prototype systems could be investigated efficiently by geologists working with experts in the existing software, who could demonstrate the capabilities of the existing software and jointly evaluate potential benefits before significant investment is made in customisation.

A step by step approach is recommended, aiming to consolidate and build on the best current practice and to incorporate new developments after they have been explored by discussion and prototyping. Attempts at this stage to provide a rigorous specification for this loosely defined, creative and evolving activity are unlikely to be helpful.

A full functional specification and integration with the wider system for digital map production will be essential, following successful prototyping.

7. CONCLUSIONS AND RECOMMENDATIONS

The conclusions of the earlier report reproduced in Annex 1 are confirmed. Implementation should follow the guidelines listed in section 6.1.3 and 6.2.2 and repeated below. Collaborative effort involving geologists, cartographers and software experts will be needed, requiring the allocation of appropriate resources.

1. Data should be captured from 1:10 000 maps where this is cost-effective, or otherwise from 1:50 000 scale. Items should be labelled to indicate their source and their relevance at local, regional and national levels of detail. Data should edge-match and be laterally consistent at each level of detail (4.1.4, 4.1.5).

2. Matching versions of items at local and regional levels should be held where both are needed. For example, generalisation of 1:10 000 data to match surrounding 1:50 000 sheets will be necessary, and the generalised versions corresponding to the original items should be stored for later reuse (4.1.4).

3. The cost and complexity of the digital map production system mean that the DGSM is not yet suited to general access. Instead, simplified images at local, national and regional levels of detail may be extracted as shareable components of the BGS information system (5.1.2). It is vital that the DGSM should develop as an integral part of the computer information system (5.2, 6.2).

4. It is appropriate to extend the DGSM for three-dimensional modelling and to support test beds for new field survey techniques. Developing technology will almost certainly make wider access feasible in due course, and this should be a medium-term objective (5.1.2).

5. Computer-based generalisation should follow the “amplified intelligence” approach, in

which the human expert makes decisions which the computer implements. One aim is to rationalise and codify the decisions for future development (2.3).

6. A step by step approach is recommended, aiming to consolidate and build on the best current practice and to incorporate new developments after they have been explored by discussion and prototyping. Attempts at this stage to provide a rigorous specification for this loosely defined, creative and evolving activity are unlikely to be helpful.

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Annex 1: Extract from BGS Technical Report W0/93/3 1993

Links between map database systems from different scales by T V Loudon, D J Lowe, K A Bain, K Becken, K A Holmes, J L Laxton, K C Mennim and R C Parnaby.

7 - CONCLUSIONS AND RECOMMENDATIONS

1. Context

la. Data related to the geological map should be added to, and maintained within, a self-contained segment of the BGS geological database, conforming to the overall data architecture, metadata and standards. Delays to map production because of this, however, would not be acceptable.

lb. The contents of the geological database must be maintained by geologists, preferably working in multidisciplinary teams. Their local and background knowledge is essential for maintaining consistency in the database and GIS for map production.

1c. The technology to support the full DMPI strategy is not available now. It can be expected to be available well within the currency of the data, and short-term expedients are possible in the meantime.

1d. The digital data, as well as the maps derived from them, should be seen as a marketable product.

2. Generalisatlon and data capture

2a. The data should be maintained at local, regional and national levels of generalisation, all held within a single database. The database is primarily for scientific purposes. No separate cartographic database should be developed, and maps at all publication scales should be derived from the scientific database. Maps should be available from the database to meet customer specifications, not just for a few fixed scales, tied to specific topographic base maps.

2b. Items, such as line segments, which exist at more than one level of detail, should share the same attributes and end points, so that both can be amended to reflect changes. Where one segment at a derived level includes many segments at survey scale, the many to one relationship should be exact and should be recorded in the database.

2c. Data for many scientific purposes, and for use in a GIS, should not be adjusted to match a specific base map. The required cartographic adjustments can be made at the time of map production, but only if they are really required. They should not be reflected back to the scientific database.

2d. Every effort should be made to automate the process of smoothing geological lines, areas and surfaces.

2e. Consideration should be given to storing some points, lines and areas in three dimensions, to preserve the geometry recorded at survey scale.

2f. As far as it is economically feasible, data should be captured at survey scale. Even where no 1:10 000 map is to be produced digitally, the elements to be included at 1:50 000 should preferably be digitised from the 1:10 000 map, generalised, and included in the database at both levels of detail.

3. Areas where additional work is needed

3a. Quality assurance procedures must be developed for the database.

3b. The current data model must be extended to take account of geometrical and GIS aspects, and to provide the framework for cross-relating data held at various levels of generalisation.

3c. Additional work is needed on the digital representation of the stratigraphical table, on which depends procedures for selecting and combining map units, and for maintaining consistency between maps of different areas.

3d. Version control must be implemented in the database, before continuous revision can be attempted.

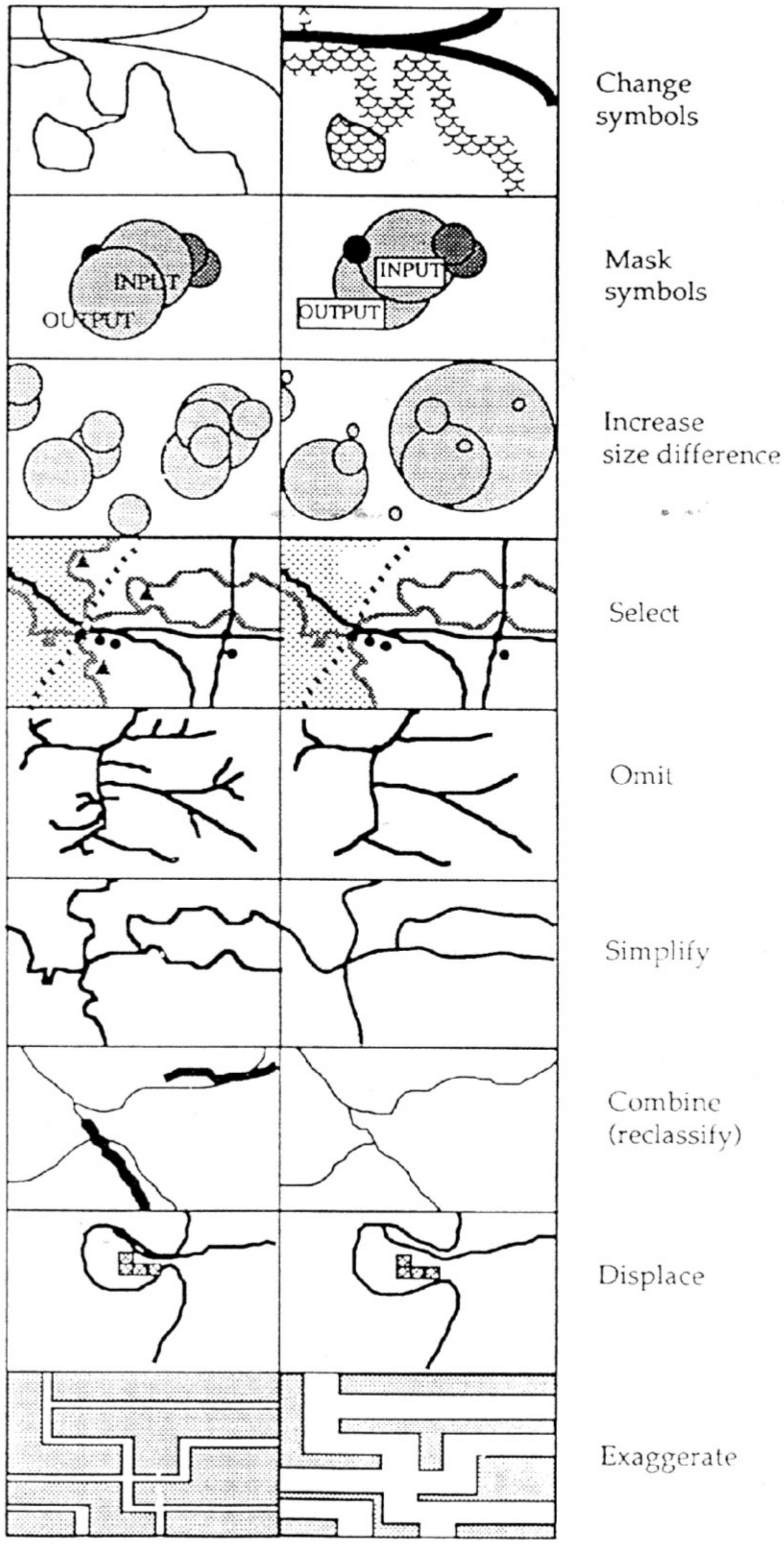
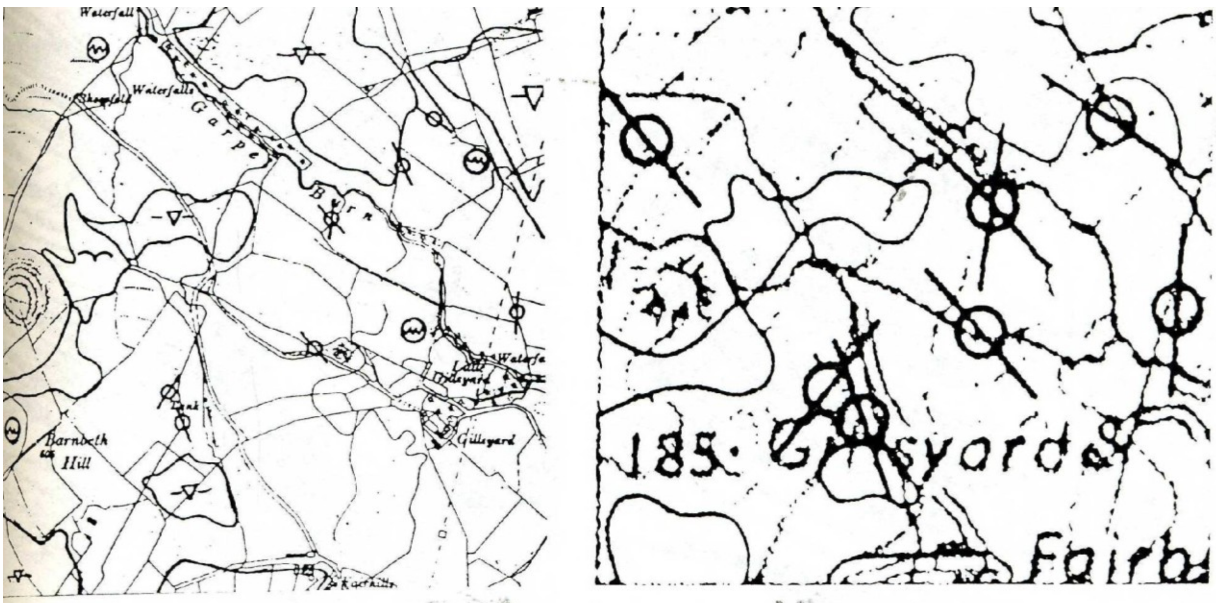
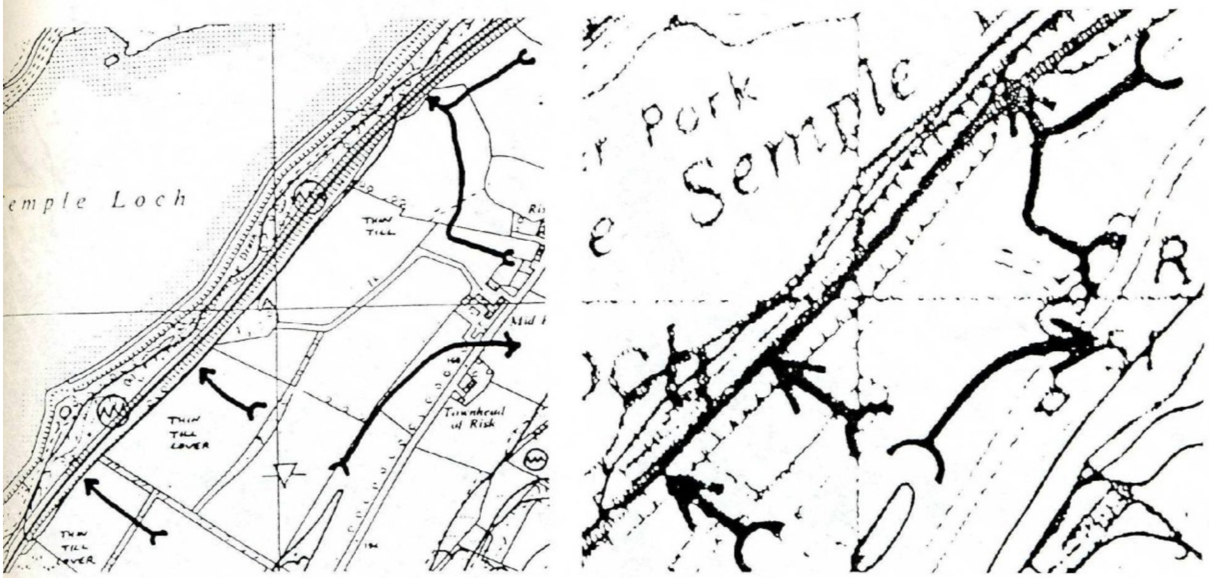


Figure 1: Nine generalisation techniques, as illustrated by Mackaness (1991, page 219).

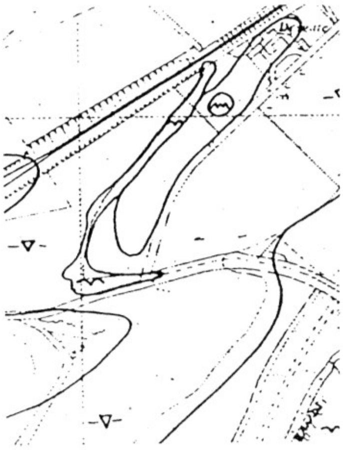


2b



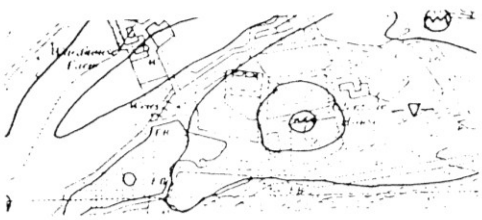
2d

Figure 2: Greenock Drift Sheet 30W: Extracts from the 1:10 000 maps are shown in 2a, 2c, 2e, 2g and 2i. Corresponding areas of the published 1:50 000 map, enlarged to approximately the same scale, are shown in 2b, 2d, 2f, 2h and 2j. See text for details.



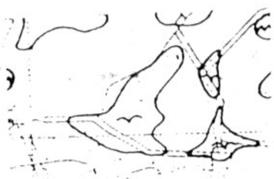
2e

2f



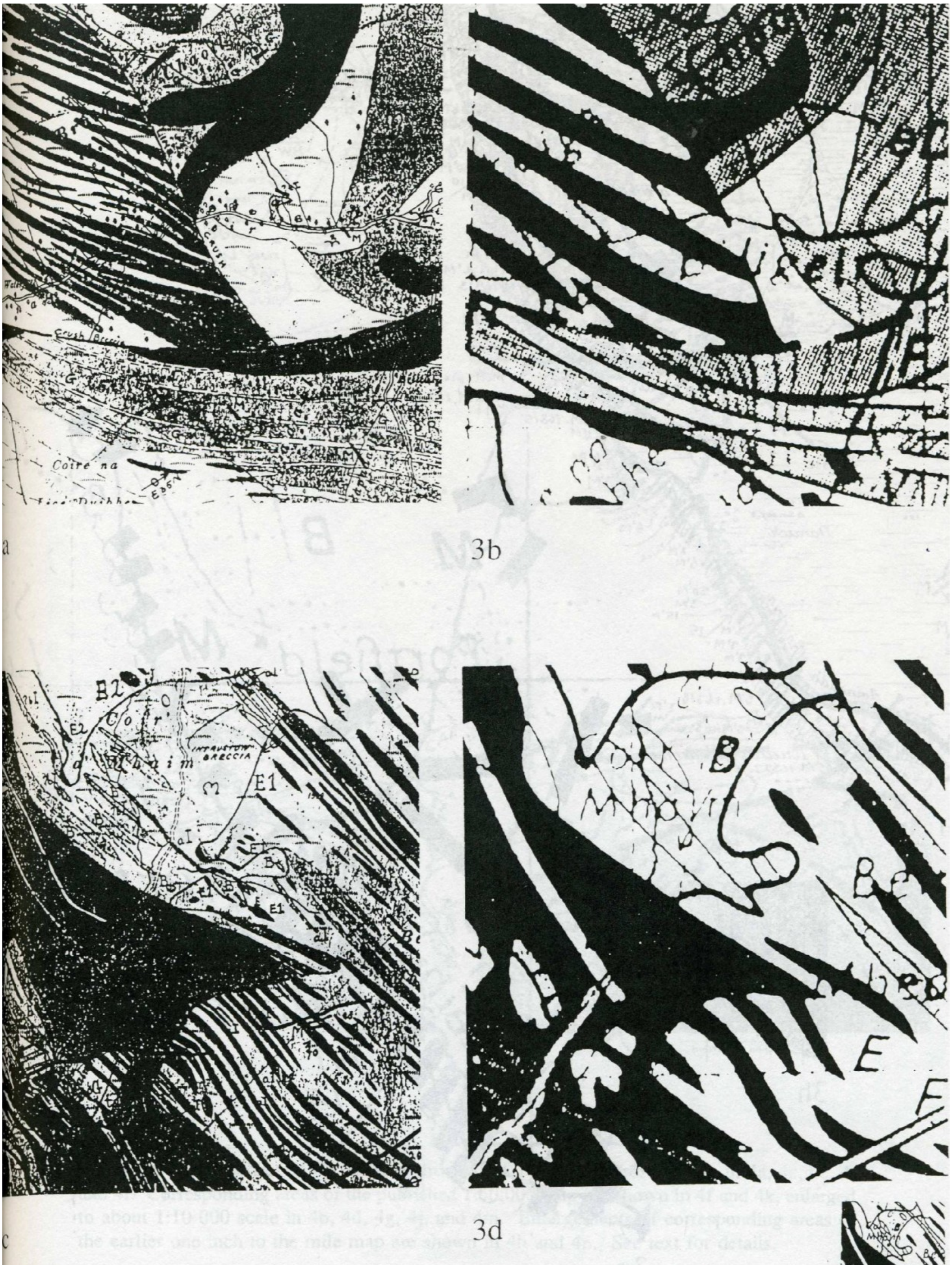
2g

2h

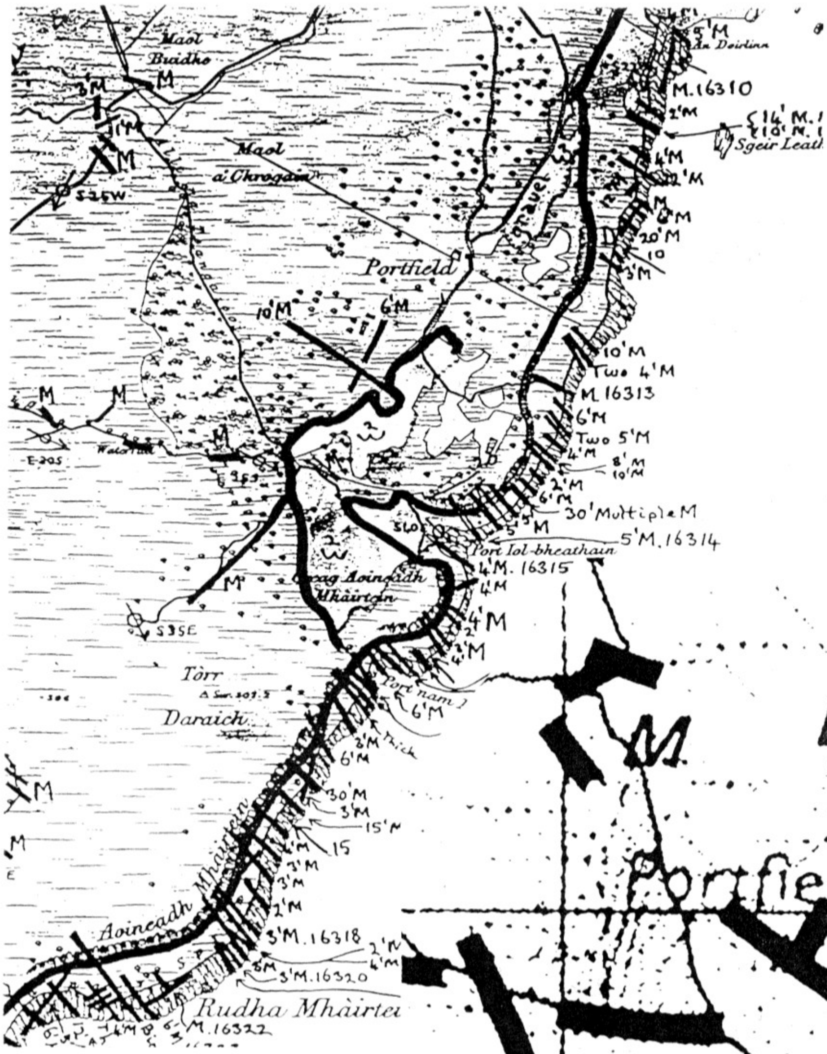


2i

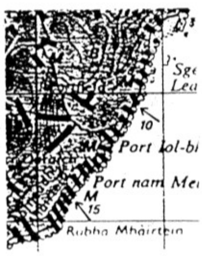
2j



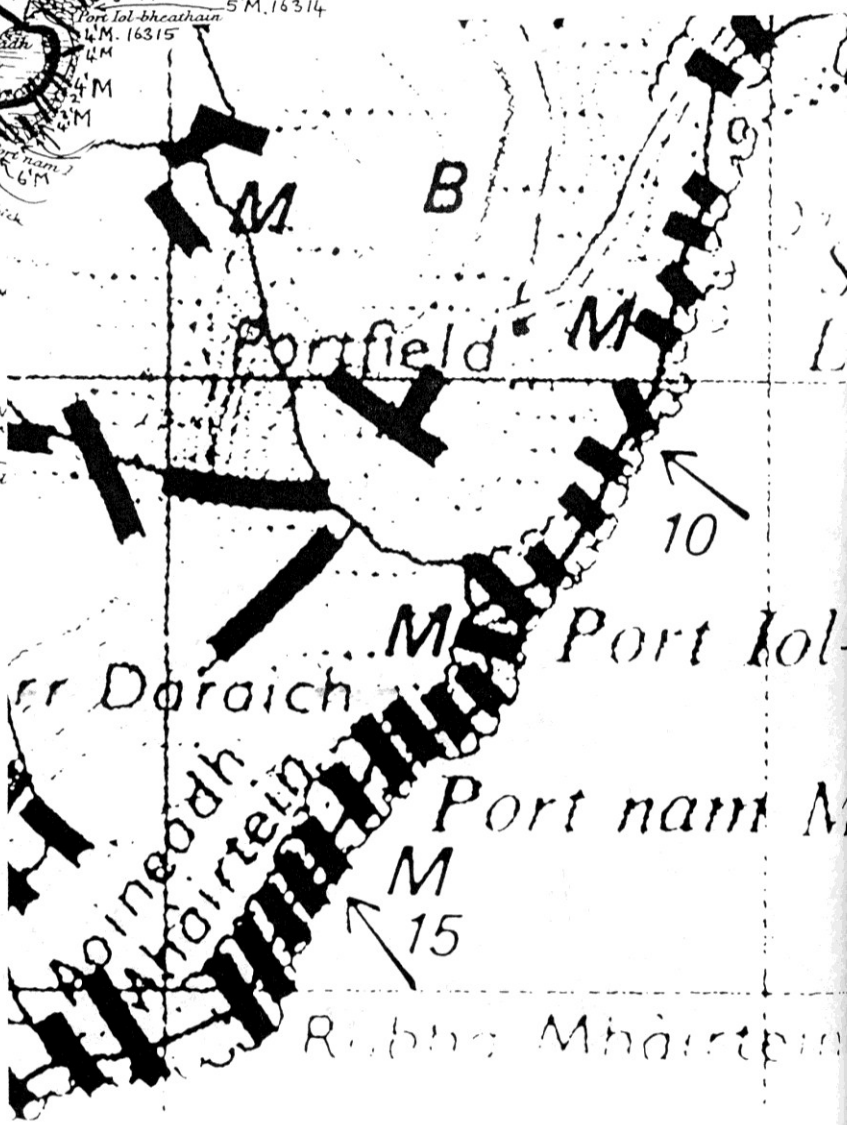
gure 3: Eastern Mull Sheet 44W: Extracts from the 1:10 000 maps are shown in 3a, 3c
d 3f. Corresponding areas of the published 1:50 000 map are shown in 3e and 3h, enlarged
approximately 1:10 000 scale, in 3b, 3d and 3g. See text for details.


Maol Buidhe
Maol a' Chrogain
Portfield
M.16310
Sgeir Leath
10'M
Two 4'M
M.16313
Two 5'M
30' Multiple M
Port Iol-bheathain
5'M.16314
4'M.16315
Tòrr
Daraich
3'M.16318
3'M.16320
Rudha Mhàirte
M.16322

3f


Port Iol-bi
Port nam Me
Rubha Mhàirtein

3h


B
M
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M
10
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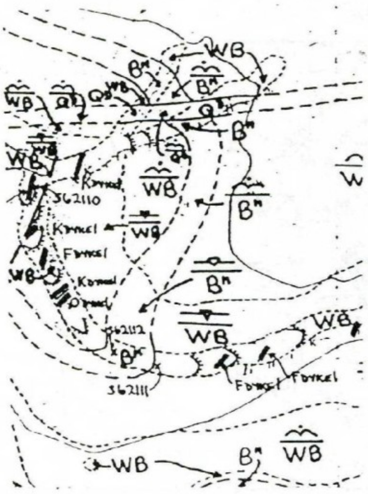
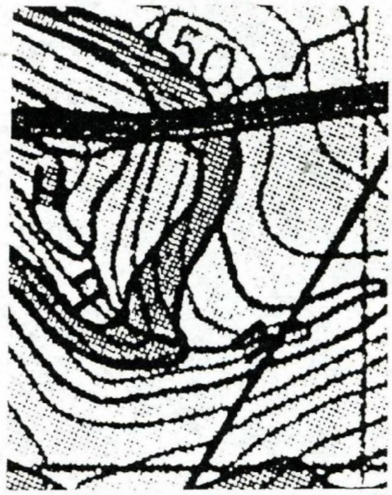
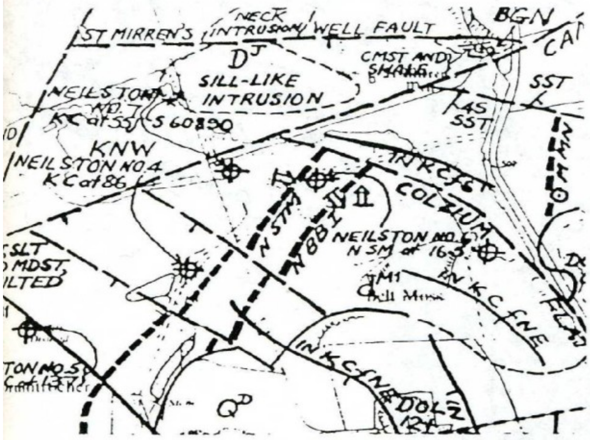
Daraich
Port nam M
M
15

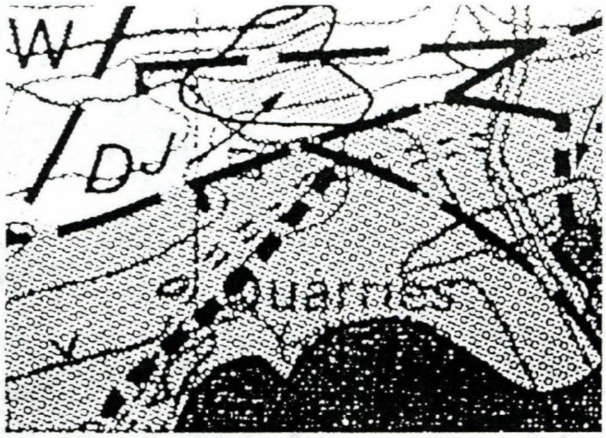


4a



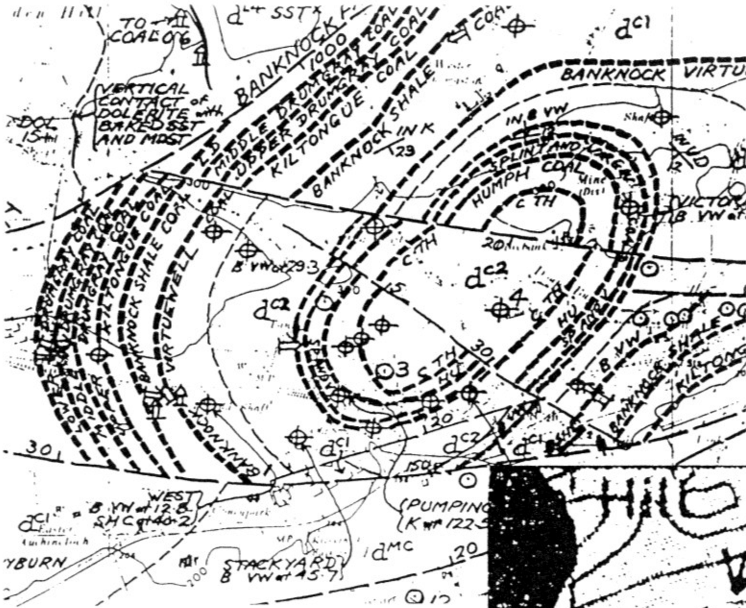
4b





4d

Figure 4: Airdrie Sheet 31W: Extracts from the 1:10 000 maps are shown in 4a, 4c, 4e, 4i and 4l. Corresponding areas of the published 1:50 000 map are shown in 4f and 4k, enlarged to about 1:10 000 scale in 4b, 4d, 4g, 4j, and 4m. Enlargements of corresponding areas of the earlier one inch to the mile map are shown in 4h and 4n. See text for details.

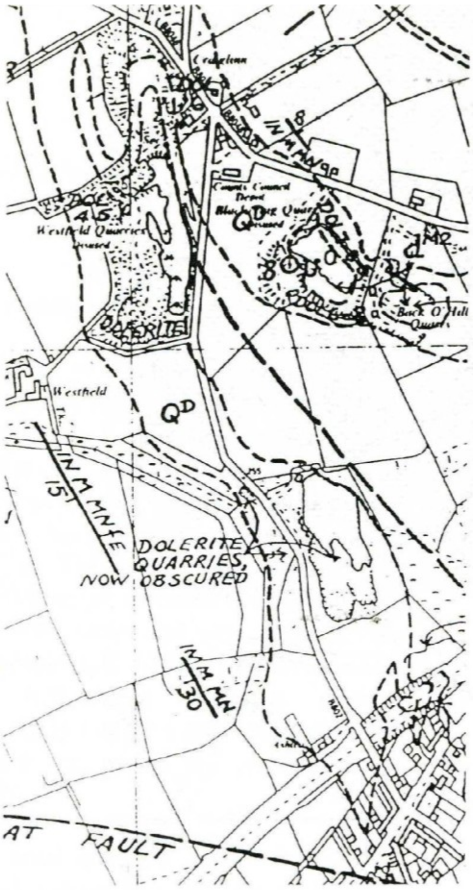

VERTICAL CONTACT of DOLERITE with BAKED SST AND MDST
BANKNOCK
MIDDLE DRUMGRAY COAL
UPPER DRUMGRAY COAL
KILTONGUE COAL
BANKNOCK SHALE
BANKNOCK VIRTU
HUMPH COAL
STACKYARD
PUMPING
WEST

4e

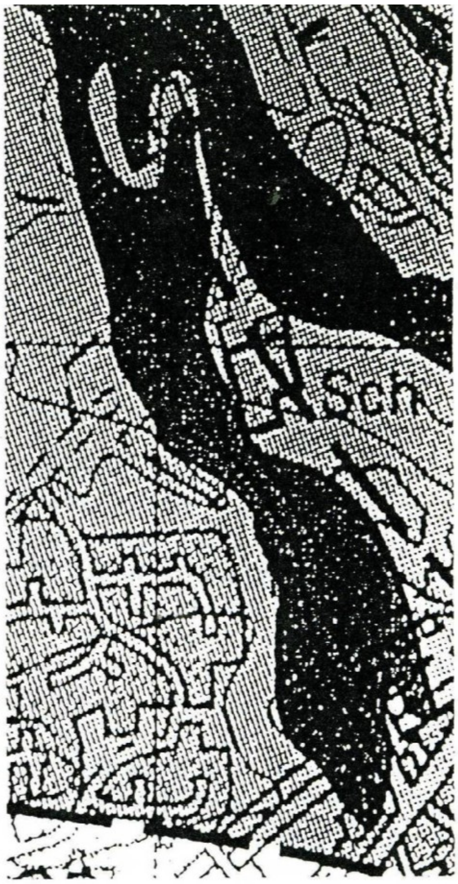
4f

4g

4h

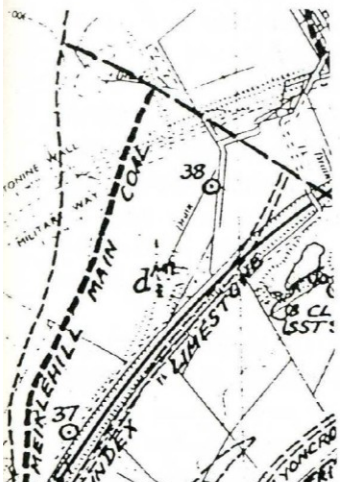

Westfield
QD
DOLERITE
DOLERITE QUARRIES, NOW OBSCURED
FAULT

4i


Sch

4j

4k


38
37
HEIRLEHILL MAIN COAL
INDEX LIMESTONE
QD

4m

4n

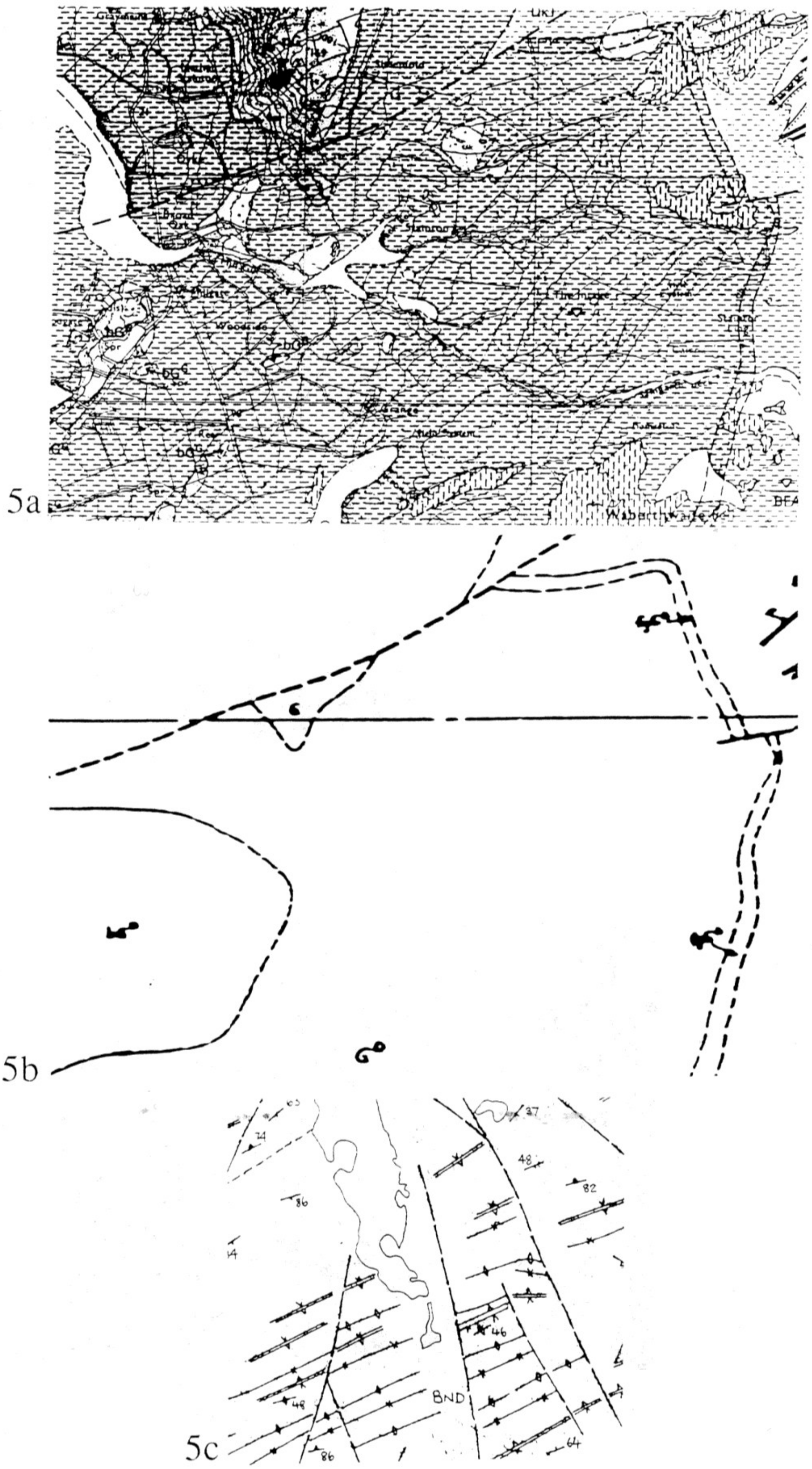


Figure 5: Ambleside Sheet 30 and Special Sheet SD19 (1:25 000). The geological lines in 5b have been enlarged from 1:50 000 to approximately the same scale as 5a (1:25 000). See