An Integrated Approach to the Generalisation of Geological Maps

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ABSTRACT
The British Geological Survey is recognising the consumer’s need for customised ‘built-for-purpose’ geoscientific data sets. It is witnessing a move away from being merely producers of standard scale cartographic products. This research proposes an automated tool for the generalisation of geological maps, which may assist the organisation in meeting these demands. The research shows that in order to derive a coarse scale geological map from a fine scale geological database there is a requirement for contextual sensitivity. To achieve an appropriate result the interaction between the themes represented on the map must be considered and should reflect the interaction of geological objects in the real world. A case study is presented which illustrates how standard cartographic generalisation operations can be combined, using a rule base, into a partially automated process to generalise a geological data set from 1:50,000 to 1:250,000 scale. Independent geoscientific professionals evaluated the encouraging results from the case study. The tool provides consistency and traceability in the generation of multiscale geoscientific data. The evaluation suggests that, with further research, higher levels of autonomous generalisation are achievable. In its current form it is a highly useful tool as 1) a testbed for defining generalisation requirements in geological mapping, 2) an aid to the production of standard scale maps and 3) a basis for creating customer specific data sets.

KEYWORDS
Automated Generalisation, Geological Maps, Scale Reduction, Theme Integration

1. GEOLOGICAL MAPS AND GENERALISATION
A geological map is a complex document that attempts to describe the geological structure both at and below the earth’s surface. They divulge a wealth of information, including: the distribution of rock types, geological structures and mineral deposits. In this sense, a geological map attempts to represent what is largely unseen (Nickless and Jackson, 1994). They can be regarded as an approved illustration of the considered interpretation of an experienced geologist (Loudon and Humphries, 1994). Their production is dependent upon the skills of the geologist in interpreting the limited available data. A sample of a geological map is shown in Figure 1.
When reducing the scale of a geological map it is necessary to emphasise essential geological detail whilst repressing the unimportant. This process of abstraction, termed generalisation, is acknowledged to be subjective, but nevertheless must attempt to maintain the logical and unambiguous relations between map objects, showing the salient features, possibly in a simplified form, whilst removing unnecessary detail (Loudon, 2000). Reducing the scale of a geological map without some form of generalisation would result in a cluttered, extremely complex map. The document would be unintelligible, unable to communicate to its user effectively and therefore be of diminished value. Experience has shown that manually generalising a digital geological map can be a time consuming and difficult operation, often beyond the scope of the task in hand. The ability to easily and quickly generalise such data sets would be highly advantageous, particularly in the context of current digital frameworks.

This research takes an initial step in determining whether it is possible to derive geological maps from a single detailed spatial database at a range of scales. It is concerned with automating the generalisation of geological maps. The major theme of the research is one of an integrated approach. It will be shown that to achieve the goal of deriving a coarse scale geological map from a fine scale database, there must be consideration of geological philosophies and how geological objects interact in the real world.

1.1 Objectives and Case Study
The principal research aim was to derive a 1:250,000 scale geological map (the target scale) from a 1:50,000 scale geological database (the source scale). The research was conducted in close association with the British Geological Survey (BGS), the UK’s principal compiler of digital geoscientific data and publisher of geological maps. The BGS provided a source scale data set comprising the Morpeth area solid geology and faults. The area was chosen for two reasons: the range of complex forms, and access to geological and cartographic personnel deeply familiar with this area. A target scale map of the same area was provided in order to illustrate how the BGS currently represent the geology at that scale.
Figures 2 and 3 show the source and target scale maps. With respect to Figure 2, note how small areal units become imperceptible and linear elements become dense and cluttered; hence the need for generalisation.

**Figure 2** The Morpeth data set shown at target scale, illustrating the need for generalisation. Licence 2001/60 British Geological Survey. ©NERC

**Figure 3** Target data set, shown at the target scale of 1:250,000. Licence 2001/60 British Geological Survey. ©NERC
The research aimed to answer the following questions:

- Can a set of algorithms be established to successfully generalise the selected elements of a geological map?
- Can the algorithms be combined into a generic rule-based procedure to enable the automated generalisation of a geological map series?
- Can the real world interaction of geological objects be modelled cartographically, thereby providing a solution conforming to geological principles or mapping styles?
- What degree of automation is achievable and what is the context of use for such a tool?

1.2 Justification and Benefits

Different applications require maps at different scales, showing different representations of geoscientific information. For example, in the mineral exploration industry, coarse scale maps (e.g. 1:250,000) are used for recognising regional trends in the geology, which would aid in defining prospecting regions. Finer scale maps (e.g. 1:50,000) give a more localised interpretation of the geology, and could assist in the positioning of drill holes. National Mapping Organisations, such as the Ordnance Survey and French IGN, are setting their sights on maintaining a single detailed database, from which it is possible to derive a number of cartographic products at a range of scales (Ordnance Survey 2001, Ordnance Survey 2002) and the BGS is no exception.

Publishing the source and target scale maps used in this case study requires the maintenance of two different geological databases. Alternatively the use of a single detailed database has a number of advantages including (Nickless and Jackson, 1994):

- the ability for continuous revision of maps at all published scales by updating a single database once;
- the provision of scale independent data in a digital format to external organisations for integration with other modelling and GIS software;
- to allow the generation of non-standard, customer specific output and,
- to ensure data consistency between cartographic products of the same area at different scales.

The BGS are recognising the need for customised, purpose built data products. The organisation is rapidly becoming a provider of multiscale ‘built for purpose’ digital data sets. That is not to say there will no longer be a need for the traditional standard scale paper map, but a tool such as the one proposed in this research could provide great benefits in meeting the new demands for geoscience data provision.

2. METHODOLOGY

In order to conduct the research, a conceptual model of map generalisation was adopted. The model, first suggested by Brassel and Weibel (1988), provided a framework consisting of five separate phases for generalisation in a digital environment. Figure 4 illustrates the five-phase process and the research tasks necessary for achieving each phase. The five phases are discussed in the subsequent sections.
2.1 Structure Recognition

The aim of structure recognition is to identify, through empirical evaluation, the specific objects and their spatial relations that are important to achieving the generalisation objectives. Throughout this research, modelling, evaluation and tuning of the generalisation process was achieved through empirical observation in close consultation with field geologists and cartographers at the BGS. This process of visual inspection and comparison of source and target scale maps enabled the identification of the principal geological objects requiring generalisation, namely:

- areal patches representing solid geology units and,
- linear elements representing faults.

This research concentrated on these elements, though it is readily acknowledged that generalisation also includes other tasks such as text placement, symbolisation and the addition of other thematic layers. A review of developments in these areas is given by Muller et al. (1995), and Brassel and Weibel (1988). A current review of generalisation methodologies is given by Ruas (2002).

2.2 Process Recognition

Process recognition determines exactly what is to be done with the elements recognised in the previous phase in order to achieve generalisation. In doing so the essential generalisation operations and the order in which they are applied to the source data are established. This experimental phase was achieved through detailed discussion and visual inspection of source and target scale maps, both with cartographers and field geologists. The following key steps in transformation were identified:

- For geological units, the areal units describing the solid geology are amalgamated. Firstly, according to a class hierarchy based on geological principles and secondly through geometrical considerations. The second step is required to remove area patches that will be imperceptible at target scale.
Specific geological units are then exaggerated. This is a common technique used in geological mapping to emphasise relatively small, yet important features such as igneous intrusions.

The final step is to smooth the boundaries between geological units.

A fourth step is to select a subset of the faults (fault attenuation). This is done by first ranking the faults by ‘importance’ according to a range of factors (such as length of fault, and the number of geological units they cross) and retaining the most important up to a calculated threshold.

2.3 Process Modelling

Process modelling involves the design of rules controlling generalisation and the algorithms behind the generalisation operations. Wherever possible it was intended to employ existing algorithms, therefore an extensive review of previous research was conducted. A rule base system was used to control the generalisation operations. Rules were constructed using an ‘IF… THEN…’ syntax, whereby if a condition is met a generalisation operation is triggered. Measures determining when objects are amalgamated, simplified or exaggerated were established by evaluating system output against hand produced results at a comparable scale.

2.4 Process Execution

Process execution involves the design and implementation of the generalisation operations and rule base. The procedures were prototyped and tested on samples of the data set, and subsequently applied to the whole data set. The software was developed using Laser-Scan’s object oriented topologically structured GIS database technology which facilitated, in an intuitive way, the rapid prototyping and integration of the various components of the algorithm (Hardy 1999).

2.5 Data Display

The final process involves displaying the target scale data set and evaluating it. Visual evaluation by a team of geological cartography professionals was carried out to determine how successful the process and operations had been in meeting the research objectives. Areas for potential further research were also identified during this phase.

3. PREVIOUS RESEARCH

There is limited published research specifically concerned with the generalisation of geological maps. In fact, Bonham-Carter and Broome (1997) called for greater research in this area. Artioli et al. (2000) did attempt to automatically generalise a geological map. Their encouraging results indicated that an automatic generalisation procedure might be possible. However, their process was limited, with numerous procedures being carried out manually. These conclusions echo those of Loudon and Humphries (1994), who suggest that given the subjective nature of generalisation, an automated generalisation procedure can only follow an amplified intelligence approach (Weibel, 1991). One that takes advantage of the coupling between the higher level decision making of the human, and the application of semi autonomous generalisation algorithms such as the one developed in this research.

Little mention is made in the geological literature of the actual modelling necessary to support generalisation, nor the specific operations that would be required. However, there is a great deal of relevant research with respect to generalising other categories of maps in the digital environment (Muller et al., 1995; McMaster and Shea, 1992). This and other relevant literature is included in the following discussions.

3.1 Rock Units

A geological map is categorical in nature. The distribution of different rock types throughout a region is represented by means of coloured areal units. These areal units define the outcrops of geological formations, which have been mapped as separate entities in the field (Roberts, 1982). The polygons describing the geological distributions are linked to a legend containing a hierarchical combination of stratigraphic and lithological nomenclature. Categorical maps display a unique characteristic; they are a
space exhaustive tessellation of space (Edwardes and Mackaness, 2000b). This infers that if the size of a polygon is reduced or enlarged through a generalisation process, the neighbouring polygons must be altered to accommodate the change.

Molenaar (1998) discusses the generalisation of vector structured categorical data with respect to geometrical considerations. He suggests, for reasons of visual perception and resolution, a minimum permissible area threshold should be defined. Theoretically objects with an area below this threshold can be treated in one of three ways; either conversion to point objects or line objects, or merging with adjacent objects. It is somewhat counter intuitive to treat regions as lines or points, and in geological mapping it is invariably the case that geological units are only displayed as areal features. Three options for merging small areas are generally considered:

1. Ignore them completely. Suitable for isolated small objects, their area will be substitutively merged into a large neighbour (even though it may be thematically completely different).
2. Clusters of mutually adjacent small objects could be aggregated to form a large (greater than the area threshold) object, only with objects that are thematically similar.
3. Small objects can be merged with a larger adjacent object that is thematically similar.

Peter and Weibel (1999) discuss the generic cartographic constraints governing categorical data. A constraint describes explicitly which information should be maintained in terms of content during the generalisation process (Ruas, 1998). Constraints can form the basis of a rules-based approach to automated generalisation. A geological formation can, through stratigraphy, be shown to belong hierarchically to a larger group of formations. The hierarchy can be based on different controlling factors such as rock age (chronostratigraphy) or rock type (lithostratigraphy). Geological maps at smaller scales show rock units belonging to a higher order in the hierarchy than for larger scales. Table 1 illustrates the hierarchy for some of the rock units occurring on the source scale map used in this research. Each is shown to belong to a higher order parent geological unit.

<table>
<thead>
<tr>
<th>Rock Unit Name (Lexicondes)</th>
<th>Rock Type</th>
<th>Parent Geology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belsay Dean Limestone</td>
<td>Limestone</td>
<td>Stainmore Group</td>
</tr>
<tr>
<td>Corbridge Limestone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dalton Limestone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Great Limestone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Little Limestone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stainmore Group</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stainmore Group</td>
<td>Sandstone</td>
<td></td>
</tr>
<tr>
<td>Rothley Grits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shaftoe Grits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eelwell Limestone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower Bath-House Wood Limestone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Redhouse Burn Lower Limestone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Redhouse Burn Middle Limestone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shotto Wood Limestone</td>
<td>Limestone</td>
<td>Liddesdale Group</td>
</tr>
<tr>
<td>Upper Bath-House Wood Limestone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Redhouse Burn Upper Limestone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liddesdale Group</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liddesdale Group</td>
<td>Sandstone</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 An example of the geological hierarchy used for the case study
Richardson (1994) recognised the importance of hierarchical class generalisation in reducing object densities for coarser scale representations. Molenaar (1998) discusses hierarchical generalisation in terms of a class driven process, in the context of land use type. A generalised land use map could be achieved by amalgamating mutually adjacent objects belonging to the same hierarchically higher class. This would result in no two adjacent regions belonging to the same class. Class generalisation affords a degree of flexibility by being able to provide alternative representations at coarser scales.

The generalisation process should filter out local effects and reveal the broader geological pattern more clearly (Loudon and Humpheries, 1994). However, small features with special significance must be preserved. Geologists employ cartographic techniques to emphasise critical features of the map. For example, a dyke or a sill may be exaggerated in size at the target scale. Muller and Wang (1992) suggested an automated technique for generalising area patches with the same semantic meaning (lakes in their example), based on geometric considerations. Their methods emphasise the large patches at the expense of smaller ones. The principle should not be applied without cartographic nuance however. Muller and Wang (1992) suggested that a collection of small close areas should be allowed to ‘survive’ in order to preserve the overall cartographic pattern.

A geological map should be designed in such a way that it records those critical features which would assist another geologist to reconstruct the main aspects of the conceptual geological model that it describes (Loudon and Humpheries, 1994). At a small scale there is no need to represent the boundary between geological units as intricately as is shown on large-scale maps. For this reason, the boundaries between geological units are simplified. This can be achieved through the use of standard linear generalisation operations such as those proposed by Douglas and Peucker (1973) or Lang (1969).

### 3.2 Fault Lines

Edwardes and Mackaness (2000a), in studying the generalisation of road networks, demonstrated the use of an algorithm that would systematically ascertain which road provided the most superior continuation with another road, based on the principle of *good continuation* (Thompson and Richardson, 1999). This principle regards a set of linear elements as *strokes*, emulating the hand of the cartographer. Their algorithm examined the angles described by the proximal ends of pairs of roads in order to determine whether good continuation existed.

Thompson and Richardson (1999), using the principle of *good continuation* for the generalisation of road networks, showed that linear elements could be ranked according to the length of the continuous stroke, thus providing a simple, yet effective method for determining which roads should be retained at target scale. Both these ideas were utilised in this research. The ideas of Topfer and Pillewiser (1966) were utilised in determining how many of the ranked faults should be retained at the target scale (discussed in finer detail in section 4.2).

### 4. GENERALISATION OPERATIONS

#### 4.1 Lithological units

Class and geometry driven generalisation operations were used to amalgamate the rock units. The algorithm was based on the research of Lonsdale (1999) who examined the generalisation of soil maps. Soil maps display similar characteristics to geological maps, in that they are both categorical. In essence amalgamation was modelled as a recursive process in which, for any given unit, the class of its adjacent units was used as a basis for reclassification. *Adjacency* between geology units occurs when two units share part of the same boundary. By removing the mutual boundary, we can combine the two units to create a larger one.
The recursive nature of the algorithm is illustrated in Figure 5. The first geology unit, numbered 1 (Figure 5a), is selected as the seed. All of the adjacent units attributed to the same parent are then selected (in this case, units 2, 3 and 4). Unit 2 becomes the new seed; its geometry is combined to that of unit 1. The algorithm then calls itself, determining which units, not previously selected, are adjacent to the new seed. This process continues until there are no longer any adjacent units, which in this case, is when unit 7 is reached. The algorithm then returns to the last seed unit that still has adjacent units not yet considered, which in this case, is unit 2. The procedure continues with the next adjacent unit, number 8, which then becomes the seed. This continues until all adjacent units with the same parent have been selected. Unit number 12 is not amalgamated because of the lack of adjacency.

![Algorithm Flowchart](image)

**Figure 5** A demonstration of the class driven generalisation operation.

The next issue is how to deal with small imperceptible area patches that remain after this class driven generalisation has taken place. Based on Lonsdale’s research and drawing heavily on Molenaar’s (1998) principles, an isolated unit is either ‘consumed’ by the underlying geology unit, or amalgamated to the largest adjacent unit that displays similar lithological characteristics. This idea is represented in the form of a decision flow diagram in Figure 6.
The small geology unit is an 'island'

Amalgamate small geology unit into surrounding unit

START

Select all geology units with an area below the

Select next small geology unit

Number of adjacent geology units?

1

The small geology unit is an 'island'

Amalgamate small geology unit into surrounding unit

END
If no more small units

>1

Select the largest adjacent unit

DO any adjacent geology units display similar lithological characteristics?

NO

END
If no more small units

YES

How many?

1

Select the adjacent unit

Select the largest adjacent unit

>1

Select the adjacent unit

AMALGAMATE SMALL GEOLOGY UNIT IN

the adjacent unit

END
If no more small units

Figure 6 Flow diagram for the geometrical amalgamation of geology units.

With respect to the case study data, sills and dykes were considered to be geologically important, since they indicate the occurrence of a major geological event. These features were treated in different ways.
Dykes were either removed or exaggerated, according to an area threshold. Sills with an area below a lower area threshold were removed. Those with an area between the lower threshold and a higher threshold were exaggerated by scaling. Sills with an area greater than the high threshold remained unchanged. The operation used a simple buffering action to exaggerate the geometries of dykes and sills. A key geological concern was the role played by faults before, during and after the intrusion of a dyke or sill. For example, the dyke in Figure 7a has been intruded along an existing fault. The map at target scale must communicate this important chronological aspect. It was therefore necessary to model the interaction of faults adjacent to igneous intrusions undergoing exaggeration. The solution is illustrated in Figure 7b-d. First the dyke was buffered (Figure 7b), so that it straddled the fault. The fault was then used to ‘split’ the buffered dyke into two pieces (Figure 7c). Finally, the smaller of the two pieces was removed and the surrounding country rock adjusted to accommodate the exaggerated dyke (Figure 7d).

![Figure 7](image-url) Dyke exaggeration using a simple buffer and trim operation.

The geological boundaries were simplified using an implementation of the Lang algorithm (Lang 1969). The Lang algorithm, a constrained local processing routine, uses two tolerance values to control the simplification of the line. Simplification is based on a distance tolerance control that ignores points on the line that fall within the tolerance value for various sections of the line (McMaster and Shea, 1992). It was found to produce perfectly acceptable results in the context of this research.

However, careful consideration needed to be given to boundaries that included sections of fault as part of the boundary (as in Figure 8a). If the fault is retained at target scale then cartographically speaking, the geological boundary must follow the fault (as in Figure 8b). An incorrect solution to the same problem is shown in Figure 8c. Alternatively, if the fault were not retained at target scale then the solution would be of the form shown in Figure 8d.
The solution to this requirement was achieved by simplifying each of the constituent arcs that forms a geological boundary. If, through topological inspection, an arc was shown to be shared with part of a target scale fault then that section of the boundary was not simplified.

4.2 Fault lines

The case study fault lines were originally digitised as short pieces of ‘spaghetti’ as opposed to continuous arcs, and an operation was therefore required to join the faults in the most geologically appropriate manner prior to ranking and attenuation. The operation first determined if there were any faults with a potential for being joined, then selected the most suitable and joined them. Following ideas of good continuity, faults were joined if they were ‘close’ and of a similar trend. Figure 9 illustrates the conditions used in determining whether or not a fault was suitable for joining. A proximity search, controlled by a search radius, determined if there were any faults close to either end of the selected fault. The size of the search radius was a parameter that could be set within the code. By experimentation, a value of 125m was arrived at, and was used to achieve the results shown in this paper. Faults that were entirely outside of the search radius were not considered as candidates for joining, as is the case for fault 2 in Figure 9. Faults with neither end point within the search radius were also ignored, such as fault 4. The trends of the proximal ends of a potential fault and the selected fault were then compared. If the difference between the two was greater than a pre-specified trend tolerance the fault was ignored, such as fault 1 in Figure 9. By experimentation, a trend tolerance value of 20 degrees was found to achieve the desired results. If there was still more than one fault at either end suitable for joining then the fault with the least difference in trend was selected.
This solution was considered acceptable as it attempts to join the faults by selecting the smoothest continuous stroke, whilst still allowing for occasions where one fault may have displaced another.

It was then necessary to rank the faults prior to determining which should be retained at the target scale. The source data faults had no attribution such as fault name or throw. Such attribution would provide a geologically appropriate method of ranking, ensuring the most important faults were retained. As no other information was available, it was decided to rank the faults according to the product of their length (after being joined) and the number of different rock types lying either side of the fault (Figure 10). Thus long faults that had a relatively large number of rock units lying either side were ranked highest and short faults crossing relatively few rock units were ranked lowest. This approach was intended to give precedence to faults of greater regional importance.

![Figure 9](image1.png)

**Figure 9** The constraints determining whether one fault is joined to another.

![Figure 10](image2.png)

**Figure 10** Ranking faults according to the number different rock types lying either side.
Once the faults have been joined into continuous strokes and subsequently ranked it was necessary to determine how many faults should be retained at the target scale. Topfer and Pillewizer’s (1966) Radical Law provides a means for determining the number of source scale objects belonging to a particular theme that should be retained on a map undergoing scale reduction (Dutton 1999). Similar scale based relationships have previously been derived for managing the selection of areal features (Muller and Wang, 1992).

Topfer’s radical law, plus two other ‘purpose built’ methods were experimented with in order to design a method for determining the number of faults that should be retained at target scale. The ratio of scales method (Figure 11a) reduces the number of objects at target scale by a factor equal to the ratio of the source and target scales. When a map’s scale is reduced the available area on the paper is reduced accordingly. The relative density (Figure 11b) method reduces the number of objects by preserving the same density of objects for a given area on a map sheet.

\[
\begin{align*}
\text{(A) Ratio of scales} \\
n_t &= n_s \left( \frac{M_s}{M_t} \right)
\end{align*}
\]

where
- \( n_t \) is the number of objects at target scale,
- \( n_s \) is the number of objects at source scale,
- \( M_s \) is the source scale denominator,
- \( M_t \) is the target scale denominator.

\[
\begin{align*}
\text{(B) Relative density} \\
n_t &= \left( \frac{A_s \times A_t}{n_s} \right)
\end{align*}
\]

where
- \( n_t \) is the number of objects at target scale,
- \( n_s \) is the number of objects at source scale,
- \( A_s \) is the area available on the source scale map,
- \( A_t \) is the area available on the target scale map.

Figure 11 Alternative methods for calculating the number of selected objects at target scale.

Inspection of the source data (Figure 2) shows that there are distinctly different densities of faults across the sheet; a higher density to the east compared to the centre and western sections. The differing densities reflect both the degree of geological processes that have occurred and the level of mapping, knowledge and understanding that there is for an area. These aspects should be communicated at target scale. This aspect was met by dividing the map into separate regions. Each region was delineated by the amalgamated parent geology units that were generated during the class and geometry driven operations. The number of faults to be retained at target scale was then calculated for each individual region, resulting in those areas with a high number of faults at source scale having a relatively higher number at
target scale. This was done by first ranking the faults belonging to a parent geological unit, and selecting a subset of the highest ranked, up to the number $n_t$.

5. IMPLEMENTATION

When implementing the generalisation operations on the source data there was call for careful consideration of the order in which each operation was applied. For example, if the geology boundaries were simplified before the fault selection took place, the resulting boundary could be left with fault artefacts. For the case in Figure 12a, a low ranking fault is removed after generalisation (Figure 12c) whereas the convention is for no trace of the fault to be left (as in Figure 12b). This illustrates the need for fault removal prior to generalisation.

![Geology units boundaries before simplification](image)

(a) Geology units boundaries before simplification

![Correct boundary simplification](image)

(b) Correct boundary simplification. No trace of the fault remains.

![Incorrect boundary simplification](image)

(c) Incorrect boundary simplification. Evidence of the fault remains as an 'artefact'.

Figure 12 The need for applying generalisation operations in the correct order, with respect to fault attenuation and geology boundary simplification.

These and other cases highlight the interdependence of generalisation operations and the need for care in their sequencing. For example faults can be joined, but their ranking includes inspection of the adjacent solid geology in order to take account of the number of units they intersect. The class and geometry driven amalgamation of units must happen prior to calculating regional densities of faults since it forms the basis for defining such regions. Only once it is known which faults will be retained, is it possible to simplify the boundaries of such regions. These interdependencies are summarised in Figure 13, (coloured arrows), thus illustrating the way in which the interdependencies and contextual interactions that exist between the fault and geological units govern the sequence of generalisation operations.
Figure 13 Generalisation operations flow diagram indicating the required interaction between themes.
5.1 Geology units

Figure 14 illustrates the result (on the right) of applying class driven generalisation operations to the source data (on the left), followed by the geometry driven generalisation operation. The effects of the exaggeration operations applied to igneous intrusions are also highlighted.

![Figure 14 The effects of the geometry driven generalisation operations.](image)

5.2 Faults

Three different methods for determining the number of faults to be retained at target scale were investigated (section 4.2) and compared with the BGS' representation (Figure 15b). Each image reflects different cut off points for the faults ranked in each region. Through visual comparison and detailed discussion with experts, it was decided that the scale ratio method (Figure 15c) provided the most adequate solution in that it preserved the relative densities of faults within and between different regions (Downs 2001).
6. RESULTS AND EVALUATION

The final generalised version of the case study data is presented in Figure 16, shown at the target scale of 1:250,000. This map was produced using the generalisation operations in the sequence described earlier.

Figure 15 Fault selection scenarios. Licence 2001/60 British Geological Survey. ©NERC
The evaluation of the generalisation operations and final cartographic results was performed in a subjective manner by a panel of geoscience professionals employed by the BGS. The panel’s expertise covered the disciplines of geology, cartography and information science. This form of evaluation was considered highly appropriate because of the specialised nature of geological maps, in that they document geological models based on the philosophies, interpretation and inference (Loudon and Humphries, 1994) of a skilled professional; the geologist. A direct visual comparison of Figure 3 with Figure 16 suggests a highly appropriate and significant result with respect to the case study data set (Figure 2). The BGS geologist responsible for the Morpeth area and an evaluation panel member supports this assertion stating: ‘I believe that the result for the Morpeth sheet would be entirely satisfactory as a 1:250,000 [scale] map.’ (Lawrence, 2001). The generalisation routine has been shown to address ‘the difficulty of over selection in areas of complex geology and numerous faults’ (Akhurst, 2001) and in doing so has ‘removed some (all?) of the apparent subjectivity, which geologists apply to generalization’ (Lawrence, 2001). These comments suggest that the application of this tool across a large area can guarantee that a standardised, traceable procedure for generalisation has been used (Laxton, 2001). This is advantageous because it will ensure consistent generalisations from one map to another.

The generalisation routine was applied to a second 1:50,000 scale data set (the Newcastle sheet). This phase of the evaluation was carried out in order to assess how generic the operations are when applied to other data sets. The operations were applied in exactly the same sequence using the same rule base as for the case study data. Though the source data is not shown, an annotated result is provided in Figure 17. Lawrence (2001) states: ‘The results shows a fair representation of the generalised geology at target scale of a complex map.’ This comment suggests that the routine does have potential for application to areas other than that used for the case study. It has been recognised that further work, cartometrically evaluating numerous map sheets, would be required to ensure a truly generic rule base.
Figure 17 Evaluation of the generalisation operations when applied to a second data set. Licence 2001/121 British Geological Survey. ©NERC

Figure 17 illustrates some of the shortcomings of the generalisation routine in its current state and indicates where further research can be directed. The shortcomings shown in Figure 17a-c principally arise from reasons of resolution and perception. An example of incorrect fault joining and selection is shown in Figure 17d. A fault running along the boundary between two geological units (in the source scale data set) should have taken precedence over the fault shown. Figure 17e illustrates a need to consider the geology beyond the edge of an individual map sheet. If a fault continues on to the next map it must be shown to abut the edge of the map. Further to this, relatively short faults abutting the edge of a map may be part of a longer, relatively important fault on the adjacent map. In which case the short end of the fault should be shown at target scale. The continuity of faults from one map to the next could be addressed by placing a ‘buffer’ around the map being generalised, incorporating the edges of adjacent sheets. A real world distance of 2km has been suggested for the size of such a buffer (Akhurst, 2001).

The flexibility of the generalisation tool was evaluated by attempting to use it to produce different representations of the case study geology. Variation in the use of Topfer's law has already demonstrated that it is possible to control the number of faults that are shown at the target scale (Figure 15). Figure 18 shows that a different representation of the solid geology can be achieved. This map is the result of amalgamating the solid geology according to a different geological hierarchy; the rock lexicondes entry for each unit was used instead of the parent geology. This was achieved by simply altering the amalgamation code, set in the class driven generalisation operation.
Figure 18 An alternative representation of the case study data, generated using the generalisation tool. Licence 2001/60 British Geological Survey. ©NERC

Note how this representation shows a different selection of faults to that shown in Figure 16. This reflects how dividing the map into sections, based on the amalgamated geology units, enables control in the fault selection process. With regards to Figure 18 Lawrence, (2001) states: ‘The selection of different rock units is a good facility to meet different user requirements’. A tool such as this can provide the cartographer with an ability to choose and change rules, to allow for quick appraisal of potential generalisation solutions at an early stage in the map production process (Mennim, 2001).

7. CONCLUSIONS

Of overwhelming importance to the successful design of generalisation tools is the need to consider the interdependencies between the themes represented in a map and we have therefore argued for an integrated approach – one that is capable of modelling the various design objectives of the cartographer. The research has demonstrated how a number of existing generalisation operations can be combined into a ‘rules based’ procedure in order to automatically derive a 1:250,000 scaled product from a 1:50,000 scaled database. The resulting tool has the potential to provide the geologist with a simple yet flexible method for generating alternative representations of an area’s geology. A more comprehensive evaluation among a group of cartographers would highlight further improvements and extensions to the existing algorithm. In particular the algorithm needs to be tested against a more complete set of case studies and over larger geographical extent in order to establish a more generic rule base that will give satisfactory generalisation results for a suite of maps of similar geology. Though qualitative in nature, the initial sets of results are, nevertheless, very encouraging.

There are good reasons for applying localised styles to regions of differing geology. Equally, for reasons of quality control and meaningful comparison between such regions, there are good reasons for adopting automated solutions that are predictable and consistent. The ‘tension’ between these needs became apparent during the research, and led to the belief that whilst high levels of automation may be achievable, there remains a critical role for the human in the map design process. In creating more
autonomous solutions, an optimal balance in decision making must be struck between the human and the machine (Long and Whitefield 1989). Results indicate that for areas that are geologically 'simple' a minor check by geologists of the resulting map would be sufficient but that for complex areas the procedure may have to be applied several times and require greater intervention by the operator. In either event, the human would remain an integral part of the design process.

This generalisation tool has the merit of introducing standardisation and ‘traceability’ into a procedure that is acknowledged as being subjective and in need of quality control and management. To this end, the British Geological Survey has expressed an interest in taking this research further, suggesting that in the first instance it has potential as an interactive generalisation tool. In providing insight into the generalisation process it also has value as a teaching tool (reflecting back to the user those criteria deemed to influence the generalisation process). In the longer term, a more robust version of the algorithm could be used as a basis for creating ‘built for purpose’ digital data sets for specific customers.

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