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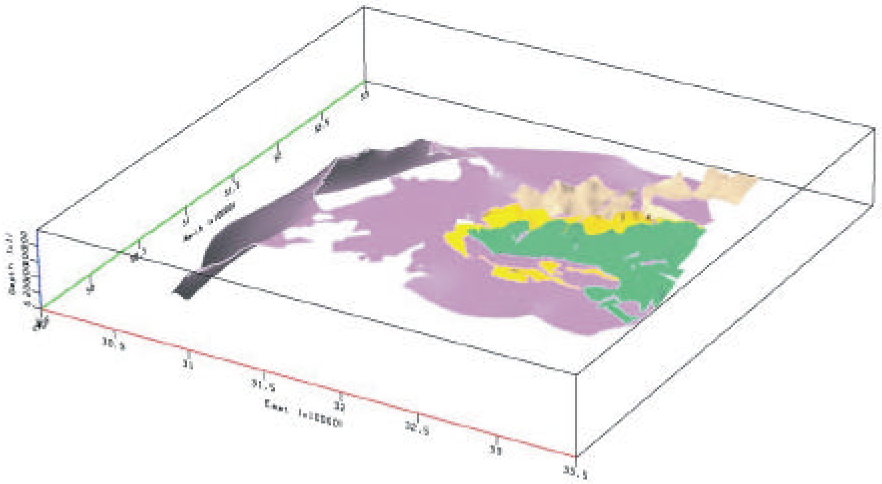
The Lake District DGSM

An overview of the model and best practice guidelines

DGSM Programme

Internal Report IR/04/114



BRITISH GEOLOGICAL SURVEY

INTERNAL REPORT IR/04/114

The Lake District DGSM

An overview of the model and best practice guidelines

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Front cover

Interpreted surfaces of the base Lower BVG, Scafell Caldera and Rydal successions, and the top surface of the bathoth.

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) into the possibilities of modelling three-dimensional subsurface geology base on two-dimensional subsurface interpretations.

As part of the DGSM Programme, the English Lake District was used as a test-bed on which to develop a methodology for constructing three-dimensional geological models of the subsurface in areas of the UK for which there are no subsurface data. Consequently the model and modelling techniques rely on subsurface interpretation and extrapolation of surface data.

This report describes and evaluates the Lake District DGSM and details a *Best Practice* methodology based on this work that can be applied to the construction of similar models in other structurally complex and data poor regions.

Acknowledgements

Of the many individuals who have contributed to this project, I would particularly like to thank:

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Summary

The Lake District Digital Geoscience Spatial Model (DGSM) represents a first attempt by the British Geological Survey to produce a three-dimensional geological model in an area of the United Kingdom where there are few directly observed measurements of the subsurface. Consequently, the model is based largely on two-dimensional interpretations of the subsurface and a thorough understanding of the geology of the area gained as a result of the complete resurvey at 1:10 000 scale of the region during the last twenty years. This report describes the construction of this model.

Modelling of the subsurface using interpretation, inference and geological understanding introduces issues of positional confidence for modelled horizons that are different from those encountered when modelling with directly observed measurements of the subsurface. A methodology for evaluating confidence in geological interpretations (Clarke, 2004) is applied to the DGSM. The resulting three-dimensional, subsurface horizons are a ‘weighted best-fit’ to the available interpretations, based on confidence in the data and methods used to construct each interpretation. This confidence is propagated from source through to model to express confidence in the final, three-dimensional model.

The structural geometry of the modelled subsurface horizons is compared with available measured surface data. Anomalies between modelled and measured structural geometries highlight the assumptions and implications of two-dimensional interpretative methods as well as with three-dimensional modelling using two-dimensional subsurface interpretations.

Based on the experience of building the Lake District DGSM, a *Best Practice* is introduced for the construction of three-dimensional subsurface models in analogous, complexly faulted areas of the United Kingdom.

1 Introduction

For a number of years, British Geological Survey staff members, under the guidance of the DGSM Programme, have explored methods of building three-dimensional, geological models of the subsurface (Monaghan, 2001; Ritchie et al., 2001; Jones, 2002; Kessler, 2002). These methods have used modern, numerical modelling techniques to produce three-dimensional interpolations of subsurface horizons between known, directly measurable (primary) data points. At the surface, these primary data can be collected from accurate field observation and in the subsurface they can be recorded from boreholes or mine plans. Such modelling has proved successful and modern numerical techniques allow the interpolation of subsurface horizons with a high degree of confidence.

In regions of the United Kingdom where primary subsurface data are few or unavailable, an understanding of the subsurface geology is gained by extrapolating surface observations to construct two-dimensional models such as cross-sections and contoured surfaces. This project explores the possibilities of constructing, and the limitations of, three-dimensional numerical models in such regions. The area chosen is the English Lake District, an inlier of Lower Palaeozoic rocks that has been resurveyed completely by the BGS and co-workers in various universities during the last twenty years. These detailed studies show that during late Ordovician (Caradoc) times a large subaerial, caldera-related volcano-complex was centred in the region and that this was underpinned by a granitic batholith (Millward, 2002). Volcanic systems of this type are rarely preserved in the geological record, and emplacement and preservation were substantially aided by faulting.

1.1 AIMS OF THE PROJECT

The Lake District DGSM attempts for the first time to build a three-dimensional geological model in a complexly faulted Lower Palaeozoic inlier for which there are few primary subsurface data. Within this objective, there are four aims:

- To develop a constrained, three-dimensional, subsurface, spatial, geological interpretation of the Ordovician *Borrowdale Volcanic Group* and the underlying Lake District batholith, using two-dimensional interpretations (cross-sections, contoured horizons, structural form-line maps, Generalised Vertical Sections, and potential-field geophysical data) as inputs. The model will be accurate at 1:50 000 scale and will rely heavily on assessments of confidence (uncertainty) in the input interpretations to resolve data conflicts.
- To evaluate the structural geometry of the model against surface observation and to assess the limitations of two-dimensional interpretation and their implications for three-dimensional modelling.
- To indicate confidence in the three-dimensional model of the Borrowdale Volcanic Group and the underlying upper surface of the batholith.
- To develop a best-practice methodology for the construction of three-dimensional geological models from subsurface interpretations, using the GoCAD modelling package, that can be applied to other structurally complex areas.

1.2 REPORT STRUCTURE

This report is divided into two sections. In the first, the construction of the Lake District DGSM is described and the model evaluated scientifically against the available data. Using the methodology that evolved during construction of this model, the second section provides a *best practice* for building geological models for analogous areas elsewhere in the UK. This methodology uses the GoCAD modelling platform as a base and the Lake District DGSM as an example. The two sections are largely independent and can be viewed independently.

1.3 BACKGROUND READING

References are included within this report as appropriate but a level of background understanding of the geology of the English Lake District, ArcGIS and GoCAD is assumed. Useful texts that should be consulted in parallel with this report include:

- Millward, D. 2002. Early Palaeozoic magmatism in the English Lake District. *Proceedings of the Yorkshire Geological Society*, Vol. **54**, 65-93.
- Millward, D, and 22 others. 2000. Geology of the Ambleside district. Geological Survey Memoir, England and Wales, Sheet 38.
- Woodhall, D.G. 2000. Geology of the Keswick district. Sheet Description of the British Geological Survey, 1:50000 Series Sheet 29 Keswick (England and Wales).
- The ESRI ArcGIS User Guides and support documentation (http://support.esri.com/).
- The GoCAD manuals and support documentation (http://gocad.ensg.inpl-nancy.fr/)

In addition, the methodology for the assessment of confidence within the Lake District DGSM follows that of Clarke (2004) and is based on investigations by BGS and external authors. The following texts are valuable background reading to this subject:

- Cave, M R, and Wood, B. 2002. Approaches to the measurement of uncertainty in Geoscience data modelling. BGS Internal Report IR/02/068.
- Clarke, S M. 2004. Confidence in Geological Interpretation A methodology for evaluating uncertainty in common two and three-dimensional representations of subsurface geology. *In preparation.*
- Funtowicz, S O, and Ravetz, J R. 1990. Uncertainty and Quality in Science for Policy. Dordrecht: Kluwer.
- Shrader-Frechette, K S. 1993. Burying uncertainty. Risk and the case against geological disposal of nuclear waste. University of California Press.

2 The Lake District DGSM

The DGSM for the English Lake District is the result of investigations into constructing a coherent and geologically valuable three-dimensional model using standard, two-dimensional interpretations (interpretative data) as inputs. This section gives a broad, generic overview of the model and its development. The background geology is reviewed, available datasets are described and model construction is detailed. Finally, the resultant model is evaluated against available structural data and the implications for three-dimensional modelling with two-dimensional subsurface interpretations are discussed.

2.1 MODEL AREA

The Lake District DGSM extends from the Cumbrian coast in the west to the M6 motorway in the east and from Windermere in the south to Keswick in the north (Figure 2.1). This area covers most of the outcrop of the Borrowdale Volcanic Group, along with parts of the Skiddaw Group and exposed components of the Lake District batholith (Millward et al., 2000). For the purposes of modelling, this area has been divided into three sub-areas delimited by the Coniston and Eskdale faults. These sub-areas are notionally termed the *Scafell Caldera* to the north of the Eskdale Fault and west of the Coniston Fault, the *Duddon Basin* to the south of the Eskdale Fault and west of the Coniston Fault, and the *Eastern BVG* to the east of the Coniston Fault (Figure 2.1).

This report is restricted to the modelling of the Scafell Caldera sub-area (Figure 2.2) that was completed in December 2003. The Duddon Basin model is due for completion in April 2004 and modelling of the Eastern BVG is ongoing. Although the Lake District DGSM is modelled as three separate sub-area models, the methodologies developed in the Scafell Caldera model are applied to the other two models in order to develop geologically consistent models that later can be combined along the Coniston and Eskdale faults.

2.2 BACKGROUND GEOLOGY

Magmatic events in northern England during Early Palaeozoic times resulted in the emplacement of two subaerial, upper Ordovician volcanic successions, underpinned by a substantial granitic batholith, comprising Upper Ordovician and Lower Devonian components. Preservation of subaerial volcanic sequences in the geological record is rare and the Lake District examples are thus significant. The andesitic Eycott Volcanic Group (EVG) crops out over about 50 km^2 along the northern margin of the Lake District Lower Palaeozoic inlier and has a thickness of 3200 m. The penecontemporaneous, caldera-related, andesitic to rhyolitic Borrowdale Volcanic Group (BVG) forms about 750 km^2 of the rugged fells in the central Lake District and is at least 6000 m thick. These voluminous, and at times highly explosive, volcanic episodes may have lasted for less than 5 Ma (Millward and Evans, 2003). The largely concealed batholith, covering an area of more than 1500 km^2, is thought to comprise mainly Ordovician components represented at the surface by the Eskdale and Ennerdale plutons. The Ordovician and Silurian rocks were deformed during the Acadian Orogeny late in Early Devonian times. Further components of the batholith, including the Skiddaw and Shap granites, were intruded during the waning phase of this episode.

The immense volumes of igneous rocks emplaced during very short intervals contrast with the deposition of marine sedimentary strata of the Skiddaw Group and Windermere Supergroup, which continued for much of this Early Palaeozoic period of nearly 100 Ma. The Ordovician (Tremadoc to lower Llanvirn) Skiddaw Group underlies the volcanic successions, crops out over about 530 km^2 and is at least 5000 m thick (Cooper et al., 1995). Overlying the volcanic rocks is the Windermere Supergroup of late Ordovician and Silurian age (Millward et al., 2000). The supergroup is more than 7000 m thick and has an outcrop of 1050 km^2. Regional unconformities separate the marine siliciclastic units from the volcanic successions.

During the last twenty years, the Lake District Lower Palaeozoic inlier has been resurveyed completely at 1:10 000 scale by the BGS and its university co-workers. Among other outcomes, this work has produced a modern understanding of the development of the BVG. In particular, the stratified products of volcanism accumulated within a number of major, spatially separated depocentres, some of which have been interpreted as calderas (Millward, 2002). One of the best-studied caldera systems within the BVG is that at Scafell (Branney and Kokelaar, 1994).

In the Scafell Caldera sub-area (Figure 2.3), the BVG can be divided into three major successions, which reflect stages in its development (Millward, 2002). At the base, the Lower BVG Succession comprises a stack of andesite sheets, mainly lavas, along with localised accumulations of pyroclastic and sedimentary rocks, representing the initial stages of volcanism. The overlying Scafell Caldera Succession comprises a stratified sequence of welded andesitic to rhyolitic ignimbrites of the Whorneyside, Airy's Bridge and Lingmell formations, produced during very large magnitude, paroxysmal pyroclastic eruptions that led to the formation of a piecemeal caldera during the climactic phase (Branney and Kokelaar, 1994). The uppermost, Rydal Succession comprises the mainly volcaniclastic sedimentary infill to the caldera and a later welded ignimbrite that was centred elsewhere in the Lake District. Basin-scale extensional and volcanotectonic faulting played a vital role in the accumulation and preservation of the volcanic rocks (Millward, 2002 and references therein). The caldera basin was subsequently deformed during the Acadian Orogeny to form the Scafell Syncline, a major structure in the Lake District (Millward, 2002).

2.3 AVAILABLE DATASETS

The resurvey of the Lake District Lower Palaeozoic rocks has provided a wealth of primary (directly measured) surface structural data and a robust understanding of the geology of the area. Interpretations of the subsurface from newly published BGS maps (BGS, 1996; 1999a; 1999b, 2004), combined with raw surface measurements form the bulk of the data on which this model is based. All available datasets, both measured and interpretative, are combined in the three-dimensional modelling environment to help constrain the subsurface geometry and position of key surfaces within the BVG and of the upper surface of the batholith.

2.3.1 Primary (measured) data

Within the area modelled, no primary data relate directly to the subsurface geology. All primary datasets relate to the topographical surface. Such datasets employed in the construction of Lake District DGSM include:

- Topographical contours.
- Topographical spot heights.
- Direct observations of geological contacts / exposures etc.

2.3.2 Interpretative data

Within the area modelled, the subsurface geology is represented by a number of two-dimensional interpretations and extrapolations of measured surface data. These interpretative datasets include:

- Geological maps
- Cross-sections
- Geophysical interpretations

- Generalised Vertical Sections.
- Structural interpretations (form-line maps and contoured horizon plots).

2.4 A STRUCTURAL FRAMEWORK

Unlike modelling with primary subsurface data, the three-dimensional form and position of subsurface horizons within an interpretative model are not constrained by measurements. In order to develop and constrain a three-dimensional interpretation of the BVG it is necessary to construct a geological *structural framework* within the three-dimensional environment. The framework is a projection or interpretation of the available two-dimensional interpretative data in three dimensions and provides a constraining model on which to interpret the form and position of the BVG.

The structural framework for the Lake District DGSM consists of a number of key horizons:

2.4.1 Surface Digital Terrain Model (DTM)

All available primary data relate directly to observations made at the topographical surface. Within the structural framework the topographical surface is represented as a three-dimensional DTM (Figure 2.4) generated specifically for this work from Ordnance Survey topographical contours and spot height data. The topographical surface, combined with measured field data, provide the greatest constraint on the DGSM. To achieve maximum accuracy at the scale of the model (1:50 000), Ordnance Survey *Landform Panorama* contours and *Landform Profile* spot heights have been combined with elevation information taken from mountain summits, roads, railways, rivers and lakes (from the same datasets) in order to further constrain the local maxima and minima of the DTM. The coastline (0 m) is taken as the low-water mark (as defined by the Ordnance Survey) and subsurface lake contours have been added where available.

A well-constrained DTM provides a control surface onto which map-based information can be referenced. Raster format information such as the Ordnance Survey cultural base map or the geological map can be ‘draped’ (projected in the Cartesian ‘z’ vector) on to the DTM to provide a three-dimensional impression of the map (Figure 2.4). Vector data such as the trace of fault outcrops or lithostratigraphical polygons (from DigMapGB) can be projected onto the DTM to interpolate a Cartesian ‘z’ (elevation) component and give them true, three-dimensional form.

The scope of the Lake District DGSM project does not extend to projecting geological contacts above the land surface to model present day erosion of the sequences. Thus, the DTM provides a ‘ceiling’ to the model and an upper limit to the BVG interpretation.

2.4.2 Fault surfaces

The BVG is intensely cut by faults of varying lengths and displacement magnitudes. These fault surfaces divide the BVG into blocks ranging from a few tens of metres to many hundreds of metres across. Each block has a separate geometry and relationship to the DTM and a displacement relationship to the contiguous blocks. For these reasons, the fault network is a fundamental element in the structural framework.

Within the Lake District DGSM, most of the faults within the Scafell Caldera have a volcanotectonic origin and so are represented as vertical surfaces (Figure 2.5). Over the full, vertical extent of a fault surface this is structurally unrealistic, but the majority of the field evidence shows near-vertical dips and, within the confines of the BVG and the scale limitations of the DGSM, the assumption of vertical fault surfaces is acceptable. Five of the most extensive faults are not represented as vertical surfaces (Figure 2.2), because field evidence suggests that the surfaces are inclined and that they originated as extensional or reverse structures with a complex history of reactivation (Millward et al., 2000; Millward 2002). Structural contours have been constructed for these fault surfaces based on outcrop patterns to constrain their geometry in the subsurface (Figure 2.6):

- The Coniston and Eskdale faults (Figure 2.1) divide the Lake District DGSM into sub-areas. The outcrop traces of the Coniston and its component splay fault (Figure 2.2) indicate that they have a dip of 50–60° to the west (BGS, 1996; 1999b and component 1:10 000-scale standards) and this is supported further by seismic evidence (Wright and Richards, 1995). The Eskdale Fault dips between 60° and 90° to the north (BGS, 1996).
- The Whillan Beck Fault cuts the outcrop of the Lake District batholith giving a topographical expression that suggests a dip of 45°–50° to the west.
- The Langdale Fault, exposed in the south of the model, is thought to have originated as a volcanotectonic fault, but it was subsequently reactivated as a reverse structure during the Acadian Orogeny (Millward et al., 2000). Structural field data suggest a dip on this fault of 40–50° towards the north.

2.4.3 Cross-sections

Detailed cross-sections published on recent BGS 1:50 000 and 1:25 000 scale geological bedrock maps of the English Lake District (most notably BGS, 1996; 1999b; 2002) provide excellent constraints on the subsurface geometry and depth of the geological formations along the line of section. The cross-sections use surface information along to the line of section, and projected at depth using surface data from contiguous areas and expert knowledge of the unit thickness variations gained during the survey. The upper surface of the batholith has been constrained at depth using interpretations of the potential field data (Lee, 1989). Sections 029 and 038 (from BGS, 1996; 1999b), shown in Figure 2.7, cross the Scafell Caldera sub-area and are projected into their correct orientation in three dimensions for modelling purposes.

2.4.4 Lake District batholith

The Ennerdale and Eskdale intrusions, that crop out in the west of the region, are exposed elements of the Lake District batholith, which underlies the Scafell Caldera sub-area DGSM at relatively shallow depth. Detailed geophysical (gravity and magnetic) investigations of the Lake District in the late 1980s (Lee, 1989) allowed the development of numerous detailed, two-dimensional models from which the depth to the top surface of the batholith could be estimated. A contoured, three-dimensional interpretation was then formed by combining these two-dimensional models. In the DGSM, this plot (Figure 2.8a) was combined with the outcrops of the Ennerdale and Eskdale intrusions to form the input for the three-dimensional interpretation of the top surface of the batholith (Figure 2.8b).

The top surface of the batholith constrains the maximum depth of the Lake District DGSM. BVG surfaces were then modelled where they exist above this.

2.4.5 The Integrated Framework

The DTM, fault surfaces, cross-sections and top surface of the Lake District batholith combine to form the structural framework that delimits the extent of modelling and constrains the BVG interpretation (Figure 2.9). The Coniston and Eskdale faults are shown to cut the batholith in keeping with the most likely geological interpretation (Millward et al., 2000) and, in this DGSM, limit the extent of the batholith to the south and east. The depth to which the Coniston and Eskdale faults extend below the top of the batholith is unknown and is defined arbitrarily within the model as 500 m in order to demonstrate diagrammatically this relationship at 1:50 000 scale. All other faults are shown to cut the batholith by 100 m as a diagrammatic representation of possible, small offsets of the top batholith surface on these faults, though it is known that many have throws of much less than this figure and some probably entirely pre-date emplacement of the batholith. All modelled surfaces are cut by, and limited to, the DTM.

2.5 RESOLVING CONFLICT IN INTERPRETED DATA

Two-dimensional, geological interpretations, such as those that form the basis of the structural framework of this DGSM, are produced using various geological techniques, are based on a specific set of geological theories and use different types of available measured data as inputs. In regions in which there is little subsurface control from measured data, these differences in approach may result in a number of equally valid interpretations that show markedly different spatial positions or geometry of subsurface horizons. These disparities need to be resolved in order to combine the two-dimensional interpretations into a structural framework for three-dimensional modelling.

Because of differences in geological theory, available data quantity and quality, data vintage and geological experience of the interpreter, *confidence* in the interpreted position of a geological horizon may be higher in one interpretation than in others. Therefore, it is not acceptable to simply 'average-out' mismatches. A rigorous approach to evaluating confidence in each interpretation must be conducted in order to determine the most likely subsurface position of a given horizon. Furthermore, evaluations of confidence should be carried through the modelling process from input, two-dimensional interpretations to resultant, constrained, three-dimensional surfaces (section 2.6.3). In this way, confidence in the final model can be expressed and the effects of supporting or refuting evidence (independent interpretations that agree or conflict on the position of an horizon) incorporated. A 'weighted best-fit' solution is produced, based on confidence in the original interpretations and this can be considered the most likely interpretation of the subsurface geometry, rather than an average fit with inferior geological value.

In the Lake District DGSM, confidence has been evaluated for each interpretation used, based on the methodology of Clarke (2004). In this section, this method is briefly reviewed and its application to the interpretations comprising the DGSM is discussed.

2.5.1 Confidence

A geological model is an attempt to represent the geology of an area based on interpretations of measurements and observation, combined with informed judgement. The need for a *model* implies that we do not (and cannot) know everything about that which we are trying to represent (in this case the three-dimensional form of subsurface geological horizons). Therefore, inevitably, the geological model is uncertain.

Uncertainty is not the same as *error*. Error in data measurement can be defined numerically by an error margin, dependent on the measuring method and measured entity, such that the true value of the measured entity lies within the error margin. By contrast, uncertainty arises from the interpretation, interpolation and extrapolation of measured data under the influence of informed judgement, and cannot be quantified in the same manner. The degree of uncertainty (and therefore confidence in interpretation) within the model may vary spatially and will be dependent on many factors related to the base-line data, the modelling process and the experience of the modeller (informed judgement).

Confidence in the interpolated, three-dimensional models of geological surfaces based on primary Cartesian point data, such as borehole or mine-plan data, is largely the result of data density if there has been no expert influence in the construction (Cave and Wood, 2002). In these models, areas of the surface for which there are many, closely spaced data points have a higher confidence than those areas that have been interpolated from sparse data points. In practice, confidence in such models is also related to the second derivative of the surface (rate of change of dip), in addition to data density (Cave and Wood, 2002). This is because the measured Cartesian point data, from which the surface is modelled, represent a sample of that surface.

Surfaces that have abrupt spatial changes in dip are less likely to be correctly represented by a sampled dataset than those that show near constant dip.

Confidence in surfaces modelled from primary data can be quantified using statistical re-sampling techniques (Iman and Helton, 1988; 1991; McKay et al., 1979; Meinrath et al., 2000; Davison and Hinkley, 1997; Efron, 1979; Efron and Tibshirani, 1993; Wehrens et al., 2000; Young, 1994). The modelled surface is recomputed using a sub-sample of the original data and compared with the original model. The variation of interpolated surface points with different subsets of the full dataset can be used to indicate confidence in that point in the modelled surface (Cave and Wood, 2002).

Confidence in the spatial position of a particular point on a surface is usually expressed using a coloured scale rather than numerical quantities (Clarke, 2004). Numerical quantities imply error rather than confidence and assigning values to confidence can be misleading. In practice, and for computational reasons, confidence is usually assigned to a normalised scale such that 1 (one) represents *total confidence* and 0 (zero) represents *total uncertainty*. It is taken as read that the end members should never be achieved within the model because total confidence cannot be achieved (usually due to measurement error and sampling) and total uncertainty implies no geological thought or measurement was employed in the construction of the model and it is based on nothing at all!

2.5.1.1 CONFIDENCE IN INTERPRETATIVE DATA

The uncertainty associated with three-dimensional modelling of geological surfaces from interpreted data is related to many additional factors other than data density and surface curvature. In practice, data density and surface curvature are the two factors with the lowest contribution to uncertainty given that interpretative datasets, by their very nature, often have an even density of data, such as contour lines, or the data density is such that it is designed to capture the subtle, perceived variations in surface geometry (Clarke, 2004). Given that the ‘data’ are themselves an interpretation, issues of data density become largely irrelevant to assessments of confidence.

The factors that govern confidence in models derived from interpretative data are (Clarke, 2004):

- The quantity and quality of the original observed and measured data on which the interpretation was based.
- The expert knowledge of the interpreter and the extent to which this knowledge is accepted theory and tested practice.
- The auditability and fitness of the interpretation to the original data.
- The extent to which the interpretation can be validated by independent methods.
- The exclusivity of that interpretation.
- The objectivity (or lack of) in the approach adopted.
- The effects of vintage (i.e. the extent to which the interpretation and its process has been supported, or refuted, by additional data collected since the interpretation was made, and/or by evolution of accepted theory or practice).

The quantification of confidence using these factors is much less clear-cut than that for models constructed from measured data and cannot be evaluated using statistical re-sampling techniques.

2.5.2 Modelling confidence

To incorporate the effects of the interpretative process on confidence, a linguistic ‘fuzzy logic’ approach has been adopted (Funtowicz. and Ravetz, 1990). Following the method of Clarke

(2004), sources of uncertainty in a given two-dimensional interpretation are established. Each unit area of the interpretation is assessed for both the *quantity* of primary data on which the interpretation is based and the *quality* of both the data and the interpretive process. In this way, a measure of confidence for each unit area of each two-dimensional interpretation can be determined. Where interpretations overlap in space, individual evaluations of confidence can be used to determine dominant interpretations in regions of conflict.

In the Lake District DGSM, confidence evaluations are based on a horizontal grid with 1 km spacing with the British National Grid as an origin, and a vertical grid of 500 m spacing with Ordnance Datum as an origin, defining a geocellular 'confidence volume' of elements 0.5 km^3 (1 km by 1 km by 500 m). The individual, two-dimensional grids imposed on a specific interpretation are spaced to fit this cuboid architecture.

2.5.2.1 CONFIDENCE IN BEDROCK GEOLOGY INTERPRETATION

One of the major interpretative data sources for the Lake District DGSM is the interpretation of the bedrock geology (the geological map, Figure 2.3). This interpretation provides surface control on the position of BVG interpretation, but confidence in that position (and indeed the map as a whole) is not constant over the extent of the DGSM. Many factors govern confidence in the bedrock interpretation including the extent of superficial, vegetation and urban cover, constraints from geological theory and the possibility of equally valid interpretations, amongst others (Clarke, 2004).

For each map square kilometre of the bedrock interpretation, the *quantity* of available data was assessed based on the *percentage of bedrock geological exposure* in that square kilometre, using twenty percentile steps to define five categories ranging from *'very-low'* to *'very-high'* (Clarke, 2004).

Furthermore, the *quality* of interpretation in each square kilometre of the bedrock interpretation was assessed using the assessment criteria of Clarke (2004), and combined with the quantity measurement to derive a *confidence* score (Clarke, 2004). Maps of *quantity*, *quality* and *confidence* in the bedrock geological interpretation are shown in Figure 2.10.

2.5.2.2 CONFIDENCE IN GEOLOGICAL CROSS-SECTIONS

Both of the geological cross-sections incorporated into this DGSM (Figure 2.7) are potentially of great use in delimiting the BVG interpretation over a significant part of the model. For the surface expression of each cross-section, *quantity*, *quality* and *confidence* evaluations are propagated from the bedrock geological map. Assessments of the subsurface are calculated from these values. Whilst, in general confidence in cross-sectional interpretations should decrease with depth (Clarke, 2004), a number of anomalies exist in the cross-sections of the Lake District DGSM. The structural architecture of the geology crossed by both sections strongly influences subsurface confidence. Both limbs of a synclinal structure are exposed in Section 038 and this, combined with measured outcrop thickness, tightly constrains the subsurface interpretation of the syncline. Therefore confidence in this area is significantly increased above what may be considered a representative confidence decay with depth. Similarly, the strong variations in dip-magnitude over the extent of the sections (particularly Section 038) have an influence on confidence (Clarke, 2004).

The cross-sections of the Lake District DGSM represent a rare example of the use of extra subsurface data, in addition to surface observations, to constrain the position of horizons on the sections. For both sections included within the model, the geophysical data and interpretations that form the top surface of the batholith (Lee, 1989), have been used in the original cross-section interpretations. It is important that effect on confidence of this is only captured once and that the position of the batholith surface on the cross-sections is not used as supporting evidence for the batholith interpretation itself and vice versa in a circular reference manner (Clarke, 2004).

The effects on confidence of using the geophysics in the cross-sectional interpretations have been included (rather than ignored) in the confidence evaluation of the cross-sections. Therefore, this evaluation can be propagated to the confidence analysis of the batholith surface but not used as supporting evidence to increase confidence in framework interpretation at points where the sections and batholith interpretation are coincident. The resulting confidence evaluation of the cross-sections is shown in Figure 2.11.

2.5.2.3 Confidence in the fault network

The fault network interpretation is based on the surface interpretation of fault lines and, in the case of the Coniston, Eskdale, Langdale and Whillan Beck faults, on the interaction of the interpreted fault outcrop and the topography. For each of the major faults that indicate a significant structural dip (Coniston, Eskdale, Langdale and Whillan Beck faults), the confidence in the interpretation of the outcrop line on the bedrock geological interpretation has been evaluated using the 'quantity-quality' approach of Clarke (2004). The *quantity* of data is assessed, per kilometre grid square, for the fault alone based on percentage of exposed trace across the grid square, and is not therefore necessarily the same assessment as that for the bedrock interpretation as a whole (although it is related to it). Assessments of *quality* take into account the constraints on information about exposures of the faults, or on the outcrop position from the surrounding geology and the possibility of other, viable interpretations.

In the subsurface, the structural geometry of fault surfaces is determined by propagating the geometry implied from outcrop patterns linearly with depth, hence, the confidence of interpretation decays rapidly with depth below the topographical cut. The confidence interpretation of the Coniston Fault is shown in Figure 2.12.

2.5.2.4 Confidence in the top surface of the batholith

The top surface of the batholith is a three-dimensional interpretation based on two-dimensional geophysical studies across the Lake District (Lee, 1989). Though older than other interpretations used in the DGSM, Lee (1989) detailed the methodology used and discussed possible confidence in the interpretation. His three-dimensional interpretation is a simple, linear interpolation between the component two-dimensional geophysical sections; some out-of-plane data are included and the surface is constrained by expert knowledge. Hence, confidence is related to the geophysical sections. Once again, the 'quantity–quality' approach of Clarke (2004) is adopted in order to incorporate confidence in the top surface of the batholith into the structural framework for the DGSM.

The two-dimensional, geophysical sections are interpreted from gravity and magnetic data collected from a number of stations across the Lake District and interpolated to a 0.5 km model spacing along the sections. For this reason, the presence of four or more gravity/magnetic measurement points within one map grid unit (square kilometre) through which the section passes is taken to be the *ideal scenario* (Clarke, 2004) and given a quantity score of *'very-high'* on the five-category scale. Each square kilometre of the section trace is evaluated in the same way. Quality scores based on the interpretation of the position of the top surface of the batholith in the geophysical sections are elicited, using the approach of Clarke (2004) for each square kilometre along the sections. Quantity and quality evaluations for the interpretation of the top surface of the batholith on the cross-sections (Section 2.5.2.2) are propagated to the batholith interpretation along the lines of intersection between the two and, similarly, quantity and quality evaluation for the bedrock geology are propagated to the batholith surface at points of outcrop. Finally, all these data are linearly interpolated over the remainder of the geophysical interpretation to produce a complete confidence assessment (Figure 2.13).

2.5.2.5 CONFIDENCE IN THE STRUCTURAL FRAMEWORK

The approach to confidence, outlined above, defines a ‘geocellular confidence cube’ for the structural framework of the DGSM. Where input interpretations coincide in space their confidences can be used to define a preferred interpretation (that should be used to define the position of a surface at that point), but their relative confidences can be used to support or refute that interpretation, and can be combined accordingly (Clarke, 2004). As a result, a coherent structural framework is generated and the ‘confidence cube’ can be used as a basis for confidence in the final three-dimensional model.

In practice, this approach has shown that it is possible, at specific spatial points within the model, to prioritise the various interpretations that are used to construct the structural framework:

- At the topographical surface, the geological map has a higher confidence level than the geophysical interpretation of the batholith or the cross-sections: i.e. the outcrop position has priority at the topographical surface;
- Where the top surface of the batholith has not been incorporated in the interpreted cross-section, the geophysical interpretation of the surface position has a higher confidence level and therefore has priority;
- For those faults that are not interpreted as vertical, the geometrical interpretations in the lines of cross-sections are based on both surface data and outcrop structure (unit thickness and fault-block dip etc) and therefore have a higher certainty than the fault surfaces contours interpolated from surface dip alone. In regions of conflict between fault surface and cross-section fault position, the cross-sections are given priority.

2.6 THE THREE-DIMENSIONAL INTERPRETATION OF THE BVG

Other available geological data and interpretations may be constrained by the structural framework (Figure 2.9) to construct a three-dimensional model of the BVG. These data include: surface structural measurements and their interpretation, and an interpretation of the lithostratigraphy of the BVG.

2.6.1 Structural form of the BVG

Abundant bedding dip measurements across the Scafell Caldera area were collected during the resurvey. These define a broad synclinal structure, known as the Scafell Syncline (Millward et al., 2000), with its axis trending east-north-east through the mountain summits of Scafell (Figure 2.14). In parts, the syncline is intensely faulted with blocks up to several hundreds of metres across; the dip vector in contiguous blocks is commonly not coincident, a feature that is important to the piecemeal collapse interpretation of the Scafell Caldera (Branney and Kokelaar, 1994).

Interpretations of structural data for the BVG are given by Soper and Moseley (1978), and Millward (2002, figure 6). The latter is a rigorously constructed bedding form-line map, originally made at 1:50 000 scale (Figure 2.14). The form lines were interpolated parallel to the strike of bedding-related fabrics (see Akhurst et al., 1998 for discussion of this topic, particularly with reference to ignimbrite fabrics) at any given point and their spacing is proportional to dip. Form lines are not structural contours because they have no absolute elevation and do not represent any particular surface within the BVG. Their spacing is based on an outcrop width for an assumed true bed thickness of 100 m; thus vertical dips can be represented. However, though this map represents the best available two-dimensional representation of the regional structure it has two major assumptions that imply that this technique is not wholly applicable:

- The assumption of 100 m bed thickness implies that unit thickness is constant over the area; in reality there are abrupt changes in bed thickness on all scales;

- The use of surface data to convey subsurface form implies similar folding in the subsurface to that exposed at the surface. The structure of the area has been determined by caldera collapse and subsequent tightening during Acadian Orogeny and the folds seen are not similar in type.

However, accepting these constraints, the structural form-line map can be used in part to interpolate the structural geometry of subsurface horizons within the BVG.

2.6.2 Construction of three-dimensional surfaces for the BVG

The bedding form-lines of Figure 2.14 must be converted to an elevation contour plot map before they can be used as a basis for constructing three-dimensional surfaces representing specific horizons within the BVG. The form lines within each fault block are reduced to points and given a 'z' (elevation) value that is relative to the highest form line of that block (assumed to be at OD). The relative elevation is calculated from the spacing of form lines in a normal direction at each point. In this way, the structural form is reduced to a cloud of data points for each individual fault block, relatively positioned in Cartesian space, but not based on any given surface and with no relationship shown between fault blocks.

Within the Scafell area three surfaces are modelled, based on the successions established by Millward (2002). The successions are the *Lower BVG Succession*, comprising formations older than the Whorneyside Formation, the *Scafell Caldera Succession*, comprising the Whorneyside, Airy's Bridge and Lingmell formations, and the *Rydal Succession*, comprising the Seathwaite Fell and Lincomb Tarns formations (Figure 2.3). The base surfaces of these successions are modelled. The base of the Lower BVG succession marks the base of the BVG in the area and crops out in the northern part of the model. The base of the Scafell Caldera succession is defined by the base of the Whorneyside Formation, or where this is absent by the base of the Airy's Bridge Formation; this crops out in the north, south and west of the model. The base of the Rydal succession is marked by the base of the Seathwaite Fell Formation and crops out through the central part of the model.

The outcrop traces of the base of the successions provide absolute elevation reference points for these surfaces in many of the fault blocks and the form lines are used to construct the surfaces. Fault blocks without outcrop lines were then constrained using calculated fault throws between blocks. Using this approach it is possible to define these BVG surfaces in Cartesian space over the extent of the model. The structural framework (Section 2.4) is then used to further constrain the position of the BVG surfaces within the model. The surfaces are adjusted to fit with interpretations on cross-sections and relationships to the fault network and the top surface of the batholith. In areas of conflict between the interpreted positions of BVG surfaces in different elements of the structural framework, evaluations of confidence (Section 2.5) are used to determine the final position of the three-dimensional BVG surface. The coherent model is shown in Figure 2.15.

2.6.3 Confidence in the BVG Interpretation

For a complete model, confidence evaluations for the structural framework should be carried forward to the BVG surfaces in order to convey confidence in this interpretation.

For fault blocks in which the BVG surfaces intersect elements of the structural framework (cross-sections, outcrop lines, the batholith surface), confidence in the BVG surfaces at the points of intersection is derived from these elements and interpolated to the remainder of BVG surface within that fault block. For fault blocks where BVG surfaces do not crop out and are not well constrained by other elements of the structural framework, confidence in the BVG surfaces can only be derived from assessments of confidence in calculated fault throws and unit thickness between these and contiguous fault blocks. Clearly, confidence in the interpretation of BVG surfaces in such fault blocks is significantly lower as a result. In fault blocks in which the position of a BVG surface is refuted by two or more data, the confidence assessments of all supporting and refuting data are incorporated into the confidence assessment of the BVG following the method of Clarke (2004).

Confidence in the interpretation of the BVG surfaces can be reviewed using the digital model. A figure is not provided here as it is not possible to capture the three-dimensional variations in confidence in one view. In general, interpretation of the base of the Scafell Caldera and Rydal successions, in the area between the two cross-sections included in the structural framework, is in the upper range of confidence. Strong confidence in the elements of the structural framework in this area, combined with good control from outcrop lines and a small number of relatively large fault blocks serve to constrain the interpretation. Elsewhere, confidence in the BVG interpretation is dependent largely on the confidence in the geological interpretation (Section 2.5.2). Confidence levels are generally moderate to low in the peripheral areas of the model where confidence in the Lake District batholith surface is low, or where the fault blocks are particularly small, numerous and without outcrop constraint.

2.7 THE LAKE DISTRICT DGSM

The full DGSM for the Scafell sub-area is shown in Figure 2.16. The base of the Lower BVG Succession is present only to the north of the Burtness Comb Fault. Immediately to the south of this fault, which has a very large throw (Millward, 2002), the base is thrown down below the top of the batholith and therefore is not shown. Though strata of the Lower BVG Succession also crop out in the south and west of the model (Figure 2.3) the base in these areas is also below the top of the batholith and therefore is not modelled.

The base of the Scafell Caldera Succession is modelled in the north, west and south flanks of the Scafell Syncline. Beneath the Rydal Succession it dips, or is thrown down, below the top surface of the batholith. The base of the Rydal Succession is modelled in the subsurface in the central and eastern area of the DGSM, and crops out along a line forming a loop from the Coniston Fault in the east around the mountain of Scafell in the west.

The Scafell Caldera and Rydal successions describe the Scafell Syncline as broad and flat-bottomed, with an axis trending east-north-east through Scafell (Figures. 2.15, 2.16). This is clearly evident from the base of the Rydal Succession illustrated in Figure 2.15c, where both the north and south-facing limbs are present and their structural geometry is only slightly disturbed by local fault displacement. The Scafell Caldera Succession emphasises the synclinal form to the north, west and south of the Rydal Succession, though in the south the effects of individual fault-block rotation on the local synclinal geometry are much more apparent. The north-western-most modelled surface segments of the base of the Lower BVG Succession dip to the south in keeping with the synclinal form of the BVG but, by contrast, the north-eastern-most surface segments show strong control from local faulting and form a small local synclinal structure extending over three fault blocks (Figure 2.15c).

2.8 EVALUATION

Given that there are no directly observed subsurface data in the extent of the model, evaluation is difficult. However, the large amount of surface-related, structural data available have not been used directly in the construction of the BVG surfaces, though some of these data have been incorporated into interpretations used in the modelling process. A comparison of the DGSM against the available surface data will allow limited model evaluation.

Figure 2.17 shows the distribution of sample points over the extent of BVG outcrop for which structural dip vectors are known. These points were plotted as three-dimensional graphs of map (x, y) position against dip-magnitude and dip-azimuth. Best-fit surfaces were then interpolated to these data. Such surfaces are projections in the dip-magnitude or dip-azimuth domain (the ‘z’

Cartesian component is dip-magnitude or dip-azimuth respectively, rather than elevation) and their geometry can be compared with the distribution of dip-magnitude or dip-azimuth over the extent of surfaces in the DGSM. In practice, the best-fit surfaces in the dip domains are composed of separate segments that have the same map plane geometry and extent as the individual faulted blocks of the BVG surfaces. In this way the best-fit surfaces are discontinuous at faults and structural data from one fault block do not affect the geometry of the best-fit surface segment in a contiguous fault block.

By constructing dip-magnitude and dip-azimuth domain surfaces it is possible to reduce the effects of numerical interpolation and best-fit (smoothing) on the comparison of measured and modelled data. The same interpolation algorithm parameters are applied to the dip domain surfaces as to the BVG surfaces in the space domain model.

2.8.1 BVG dip azimuth

Figure 2.18 shows the spatial variation in dip azimuth over the extent of the BVG surfaces in the Scafell Caldera model, compared with that predicted from measured data. The general regional correlation is strong indicating that, over the extent the area, modelled BVG surfaces strike and dip in directions concordant with field evidence. However, there are a number of anomalies in the finer detail in Figure 2.18:

- Fault blocks marked ‘A’ show constant dip azimuth over their lateral extent in the measured data plot compared with lateral variations and often markedly different orientations in the modelled surface plot. These disparities result from a lack of measured data in these fault blocks with which to construct best-fit surfaces in the dip-azimuth domain. These disparities can be ignored in this and subsequent plots.
- The fault block marked ‘B’ appears to show dip-azimuth values at opposing ends of the spectrum between the measured data plot and the modelled surface plot. This apparently large disparity is an artefact of the colour scale and represents very small variations in dip azimuth about north, leading to azimuth values at either end of the numerical range.

Figure 2.19 shows the spatial rate of change of dip azimuth (or azimuth curvature) obtained from the model and from observed data. High values indicate rapid spatial changes of dip azimuth and low values indicate spatially near-constant dip azimuths. This plot is particularly useful at highlighting the position of fold axes, because here there are rapid changes in dip azimuth (over a range of approximately 180°) from one fold limb to the other. The axis of the Scafell Syncline is clearly evident in both the azimuth curvature plot of the model and that of the best-fit surface to the measured structural data. Comparison between to the two is very strong, particularly towards the western end of the syncline demonstrating that the position of the modelled synclinal axis is strongly supported by field data (Figure 2.19).

2.8.2 BVG dip magnitude

Figure 2.20 shows the spatial variation in dip magnitude in the DGSM compared with that predicted from measured data. Once again the regional correlation is strong, indicating that the modelled BVG surfaces dip with similar magnitudes to those recorded from field observation. However, there are a number of anomalies in the finer detail:

- Fault blocks marked ‘A’ show anomalies arising from lack of measured data and can be ignored (see Section 2.8.1).
- Fault blocks marked ‘B’ show a disparity in the magnitude of dip between the measured data plot and the modelled surface plot, though the relative distribution of value over the extent of individual fault blocks is largely in agreement.

- The area marked 'C' shows marked variations between the dip magnitude of the modelled surfaces and measured data plot. For the fault blocks marked 'C_1' and 'C_2', the measured field data appear to suggest a constant dip magnitude over the extent of the fault blocks (orientated towards the south-east). Fault block C_1 is very steeply dipping (~70°) and C_2 dips at a shallower angle (~40°). However, the modelled surfaces show a spatial variation in dip magnitude in both fault blocks with steep (~70°) dip near the outcrop of both surfaces, shallowing rapidly with depth and distance towards the south-east. The measured data suggest flat, planar, surfaces with constant dip and the modelled surfaces are curved.

Figure 2.21 shows the spatial rate of change of dip magnitude (or curvature). High values indicate tight folding and low values indicate board, open folding. The differences in surface curvature between the modelled BVG surfaces in fault blocks C_1 and C_2 and those predicted from measured data become more apparent. The curvature plot of the modelled surfaces clearly shows two zones of rapid changes in dip magnitude in fault block C_2 with areas of constant dip between them. The measured structural data suggest little spatial variation in curvature over the extent of the BVG surfaces within fault block C_2.

2.8.3 Discussion

The modelled BVG surfaces of the base of the Lower BVG, Scafell Caldera and Rydal successions together describe the Scafell Syncline as broad and flat-bottomed, with an axial trace trending east-north-east through Scafell. This orientation and overall structural form is in strong agreement with that suggested by the surface measured data. A strong correlation exists between measured and modelled spatial variations in dip azimuth and the large-scale structural shape and orientation of the DGSM is supported by field observation.

The subsurface geometry of the base Scafell Caldera Succession and base Rydal Succession on the northern limb of the Scafell Syncline are significantly different from those suggested by field evidence. The curvature of the BVG surfaces in fault blocks C_1 and C_2 results in part from the geometrical control of cross-section 038, which passes through these fault blocks, with additional influences from cross-section 029 to the west. Subsurface interpretations in these cross-sections are based on bed thickness at outcrop, geophysical information and expert knowledge of local structural style, in addition to surface structural data. The computed best-fit surfaces to the surface structural data cannot incorporate the effects of unit thickness, geophysical information and expert knowledge, and are a direct interpolation of surface structural measurements only. Confidence in the cross-sectional interpretation is high and the positions of zones of tight fold curvature on the modelled BVG surfaces (Figure 2.21) are a direct consequence of the propagation of this high confidence geometry from the sections to the three-dimensional interpretation. The incorporation of high confidence cross-sectional data into the resultant model explains the disparity between the geometry of modelled surfaces and that predicted from surface structural data. Using surface structural data to infer structural geometry in the subsurface implies similar folding. The cross-sectional interpretations indicate that this is clearly not the case in the Scafell Syncline and this assumption produces a discrepancy between modelled and measurement-inferred structural geometries.

Rigorous assessments of confidence, performed as objectively as possible, for all input interpretations can aid decision making where there are conflicts in interpretation and can be used as an indication of overall confidence in the model. However, given the absence of directly observed subsurface data, the accuracy of the absolute position of the modelled BVG horizons cannot be assessed, though they are well constrained by outcrop data and the three-dimensional framework of the model.

2.9 CONCLUSIONS

The Lake District DGSM has demonstrated that it is possible to construct three-dimensional, geological models from interpretative datasets, but the resultant model is only valuable if modelling is combined with rigorous assessments of confidence in input datasets. Only by evaluating confidence in the input data can conflicts between data be resolved and a geologically valuable model constructed. Without evaluations of confidence the result model is a best-fit average solution to data conflicts, lacking in geological value. With evaluations of confidence the model becomes a weighted best-fit solution that incorporates the relative strengths and weaknesses of interpreted data and methods.

Constructing three-dimensional models from two-dimensional interpretations in this manner highlights some of the limitations of the two-dimensional world. Extrapolating surface structural data to subsurface horizons can be misleading. Surface measurements of dip azimuth and fold axes can be extrapolated into the subsurface reliably but measurements of dip magnitude require projection that agrees with the fold style. The structural form map (Figure 2.14) is a reliable indication of subsurface structural geometry in rotated fault blocks, and of strike orientation and a fold axis position in folded sequences, but the projection of surface data with depth implies similar folding and in areas where this assumption is not justified the structural form map is not a reliable indication of subsurface spatial variations in dip-magnitude.

Cross-sections on geological maps are constructed using surface data, but take into account deformation style, unit thickness and expert judgement on the geological relationships. In this way the confidence in geometry of subsurface horizons indicated on sections can be high. However, cross-sections give no indication of the variations in geometry out of plane of the section and may be over simplified as a result.

3 Modelling with interpreted data - a best practice methodology

The Lake District DGSM (Section 2) attempts to model the three-dimensional, subsurface position of horizons in a region of the UK for which there are few, primary (directly measured), subsurface data. This exercise has lead to the development a methodology for building such models that can be applied to similar, structurally complex terranes in the UK. The modelling of Beinn Udlaidh Fold complex in the south-west Highlands of Scotland (the Glen Lochy DGSM) is a current example of the application of this approach. This section details a *Best Practice* methodology for three-dimensional modelling of this type and uses the District DGSM is used as an illustrative example.

3.1 DIGITAL MODELLING REQUIREMENTS

Three-dimensional, numerical modelling of sub-surface horizons using interpreted data is fundamentally different from modelling with primary subsurface data. In the latter case, most of the data employed in the modelling process represent discrete subsurface points (within the scale limitations of the model) as Cartesian data, with or without attributes as appropriate, and much is in digital form (e.g. borehole data from BGS digital databases). Primary subsurface data may be augmented with interpreted data (outcrops etc.) to constrain horizon interpolations at the surface (Monaghan, 2001) but these data are usually reduced to Cartesian points and act as an addition to, or refinement of, the original dataset rather than the principle data sources themselves.

When the principle datasets (or indeed all of them) used in the interpolation of subsurface horizons are interpretative in nature a different approach to modelling is required because:

- Interpreted datasets are not usually Cartesian point data. They are lines, polygons and sometimes volumes. Cartesian point datasets are rare in such modelling and usually represent primary data that can be used to augment interpretations.
- Interpreted datasets provide a wealth of information about the position of subsurface horizons at a specific point, relative to a specific surface (such as DTM) or in a specific plane (cross-sections) and little or no information at points laterally or vertically between them. This uneven and biased spread of data is often much more of a modelling issue when working with interpreted data than with primary data.
- Interpretative datasets from different sources or vintages, interpreted using different principles and theories or dependent on the extrapolation of different measurements are far less likely to agree on the Cartesian position of a subsurface horizon at a given point.
- In many cases, interpretative datasets are hardcopy format and need to be captured in a manner suitable for digital modelling.

Owing to the points above, modelling with interpretative datasets is much more subjective than modelling with primary data. In the latter, the subsurface position of a horizon is known and true (within the measurement and scale error of the data) at given points and therefore the final interpolation of the surface must adhere to these known points. This is not the case when modelling with interpretative data, which usually requires a greater input of ‘expert knowledge’ and a much greater reliance on introducing ‘interpreted points’ (Monaghan, 2001) into the model. This often necessitates the use of constraining rules on the interpolation algorithm (such as “interpretation of horizon ‘a’ must always be above horizon ‘b’ by ‘n’ metres”) and requires direct visualisation and manipulation of the interpretative data within the modelling environment. That is to say, reduction of the interpreted input data to Cartesian point data is not a practical way forward.

Given the wide-ranging types and formats of interpreted data, and the desire that such data are represented and manipulated within the three-dimensional modelling environment, suitable software packages are required.

3.1.1 Software

Experience of three-dimensional modelling has led the BGS to define the GoCAD modelling package as the standard for DGSM modelling with interpretative data. GoCAD is particularly suited to this role as it can handle point, line, polygon and volume data and is fully equipped with routines to manipulate the geometry of these. It is essentially a three-dimensional 'surface' modelling environment not specific to the field of geology, although many 'geologically driven' functions and manipulation routines are included.

Whilst GoCAD is a suitable three-dimensional modelling package it is not suitable for the accurate manipulation of map (x, y or x, y, attribute) data. A GIS package, such as ESRI ArcGIS, is much more suitable for the preparation of data prior to input into GoCAD.

This *Best Practice* for the construction of three-dimensional models from interpretative data uses GoCAD as the modelling package with ESRI ArcGIS8 (ArcMap) as the GIS support software. Currently, the use of Arcview3.2 is also required as the BGS-written, *ESRI shape-file format to ASCII column-based format* export filter is only available as a bolt-on to Arcview3.2. This export is required to convert map-based data into three-dimensional Cartesian point data where necessary. A future development of such an export filter for ArcGIS8 will negate the use of Arcview3.2.

3.1.2 Data storage

The construction of any three-dimensional model from interpreted data inherently generates many data files, some representing the simple conversion between formats of raw data, others representing various manipulations of those data. This presents significant problems of data storage, integrity and tracking. The need for a data storage methodology and associated metadata was highlighted by Monaghan (2002) in relation to modelling with primary data. This need is equal, if not greater, when modelling with interpreted data and cannot be over emphasised. The correct management of large volumes of data for modelling requires the implementation of two concepts; the data storage structure (discussed here) and the recording of metadata (discussed in Section 3.1.3).

The issues of data storage were discussed in detail by Monaghan (2002). She developed a robust data storage structure for data files generated for, and by, the modelling of subsurface horizons from primary data using Earthvision on the UNIX platform. This data structure is adopted here, with minor modifications for the PC platform and to incorporate aspects unique to GoCAD modelling. The details of this data structure are discussed at length by Monaghan (2002) and only briefly reviewed here with emphasis on the additions for GoCAD modelling.

Two concepts are at the core of the data structure: firstly a hierarchical and highly structured directory system for the storage of files and, secondly a rigid naming convention for files. These allow the intuitive locating of data, the determination of data file contents (from the filename) and help to prevent the miss-location of data, which can lead to their incorrect use in the three-dimensional model.

3.1.2.1 Directory structure

An example of the directory architecture of the data storage structure on the PC is shown in Figure 3.1. This example is from the Lake District DGSM, but a similar structure can be employed for other DGSM projects using GoCAD. The directory structure should be set up as follows:

1) A large project workspace for the DGSM should be allocated on a shared drive and represented by a project root directory suitably named (in Figure 3.1 the root directory is called 'Lake_District').
2) Subdirectories of the root directory should be created for each sub-area of the DGSM (each area that will be modelled separately). This could be separate OS 1:10 000 scale quarter-sheets named accordingly or, as in the Lake District example, sub-areas of 'north-west', 'south-west' and 'east' Lake District (represented by directory names 'NW', 'SW' and 'E' respectively).
3) In addition to these subdirectories for each modelled sub-area, subdirectories of the project root directory should be created called:
   - 'ProjectGIS' to hold the GIS that will support the DGSM and data pertaining directly to it
   - 'Support' to hold supporting documents, presentations and reports etc.
   - 'Working' to provide a temporary 'scratch disk' area for modellers working on the project
4) An optional 'Local' directory may be added as a subdirectory of the root directory to store data relevant to the whole of the DGSM (i.e. all the sub-areas) should this be required.
5) All DGSM sub-area directories (including 'local') should contain a subdirectory named 'GOCAD', and a subdirectory for each of the horizons to be modelled. Horizon directories should be named with standard LEX codes if appropriate or standard recognised abbreviations (in capitals). In the Lake District example (Figure 3.1) these directories are for data pertaining to the Topographical surface, the Borrowdale Volcanic Group and the Lake District batholith and are named DTM, BVG and LDB respectively.
6) Each horizon directory (DTM, BVG and LDB in Figure 3.1) is given at least two subdirectories called 'Draft' and 'Checked'. A third, called 'Issued' can be added at the set-up or later as it will not be needed until the completion of the project. The purpose of these directories will be made clear in Section 3.2.1.3 – QC procedures.
7) The 'GOCAD' directory should also contain 'Draft', Checked' and 'Issued' subdirectories along with a forth called 'History'. The purpose of these directories will be made clear in Section 3.2.1.3 – QC procedures.
8) Each 'Checked' directory from whatever parentage contains a subdirectory called 'Obsolete', the purpose of which will be come clear in Section 3.2.1.3 – QC procedures.
9) The child directory structure of the 'ProjectGIS' and 'Support' directories is not constrained and these directories can be divided as required.
10) The 'Working' directory should be divided with subdirectories for each of the modellers working on the project (using their usernames – Figure 3.1) and the child structure of these subdirectories is the responsibility of the modeller.

General points:

- the use of capital letters in filenames is not critical to the PC operating system (or GoCAD) and therefore it is not critical that any convention is adhered to. However, the final model may be stored on systems that are case-specific and some form of convention should be adopted. The best practice recommendation is that capitals are used for the DGSM sub-area directories (in the Lake District example; NW, SW and

E), and for the horizon directories (DTM, BVG and LDB) as these are then consistent with DGSM's subdivided by quarter-sheet and in keeping with BGS Lexicon computer codes. The GOCAD directory should also be named in capitals. All other directories should be in lower-case with an initial capital. See also the recommendations on filename conventions (Section 3.2.1.2)

- cross-sections (or data pertaining to them) do not fit directly into this directory structure since they usually contain information relating to more than one modelled surface. In this situation, a directory named 'Sections' can be added to each of the sub-area directories, or added to a 'Local' directory whichever is the more appropriate. The child directory structure of a 'Sections' directory is not constrained

3.1.2.2 File naming convention

The recommended file naming conventions follow those of Monaghan (2002). Each filename (see Figure 3.1) follows a rigid structure composed of parts that define:

1. The DGSM sub-area to which the file relates.
2. The horizon to which the data in the file relate.
3. Any sub-area, division or qualifying label related to the data (if appropriate).
4. Scale code (if necessary).
5. Data type code.
6. Dot and normal file extension.

General points:

- the qualifying label and scale code can be used to distinguish between files that are subsets of each other or sampled at different scales, given that all other parts of the filename will be identical (following the standard naming convention). Figure 3.1 gives an example of the breakdown of two filenames from the Lake District DGSM
- the filename (not the extension) may be post-fixed with an underscore (_) and a combination of numbers and letters to represent the status of the file (see Section 3.1.2.4 – Quality Control)
- capital letters are not critical on the PC platform but it is recommended that a convention is adhered to in order to limit problems with other platforms. Best practice recommends that the sub-area part is capitalised and the remainder of the filename is lower case. See examples in Figure 3.1

The format of the filename is designed for two purposes. It conveys information about the data contained in the file and, by virtue of the sub-area and horizon parts, it defines where the file should be stored in the data structure. This helps to locate files and identify miss-located files.

3.1.2.3 Metadata

Metadata are the descriptive data associated with scientific data that detail their derivation, use, limitations, processing, scale, applicability etc. The importance of metadata cannot be over emphasised. Scientific data without metadata is, at best, limited in application outside that for which it was originally recorded and, at worst, completely useless. Metadata recording systems introduced by Monaghan (2002) for recording metadata details in connection with Earthvision modelling with primary data are adapted here.

Microsoft™ Excel spreadsheets are used to store metadata relating to each and every file contained within the DGSM directory structure. For convenience, the metadata spreadsheets are divided into three identical tables to store details of raw data files, GoCAD models and objects (surfaces etc.) derived from GoCAD models separately. The details of the metadata table fields are covered by Monaghan (2002) and not repeated here. Much of the information recorded in metadata files can be lifted and transferred directly to the metadata structure of the GLOS and GSF upon completion of the DGSM.

To set-up and record Metadata proceed as follows:

1) Make a copy of the latest QC metadata spreadsheet for each sub-area within the DGSM and store it in that sub-area directory. The file should be named ****qc_0n.xls such that '****' is replaced with DGSM project name and sub-area name (in accordance with the file naming conventions detailed in Section 3.1.2.2) and 'n' is replaced with the version number of the QC metadata base file. The metadata spreadsheet format evolves and the latest version is 02.
2) For each data file stored, complete one column of the metadata spreadsheet in accordance with descriptions provided by Monaghan (2002).

General points:

- there is no requirement to store metadata relating to files in the Support or Working directories. Files contained in the former do not fit the metadata recording structure and should have self-explanatory filenames, and files in the latter are temporary data
- metadata files should be completed at the time of file creation. It is very difficult to complete them retrospectively and following such a practice leads to errors

3.1.2.4 QUALITY CONTROL

Three-dimensional model construction inherently requires the manipulation of a large amount of raw data derived from many different sources. The potential for introducing errors into the modelling process as a result of accidents, typographical errors or bad scientific practice is immense. In interpretative modelling this potential is vastly increased by the nature of the data. Much of the original data are in a format that cannot be used directly and require digitising or tabulating. Small errors at this stage are compounded throughout the modelling process to result in large errors in the final model. The metadata system is designed to reduce the risk of data misuse by storing details of the limitations and manipulation of data but it does not allow quality control of the data *per se.*

Quality control procedures have been implemented in other three-dimensional modelling exercises (Monaghan, 2002) and should be followed strictly in interpretative modelling.

1) Completed data files are first stored in the appropriate 'draft' directory, assigned the appropriate filename and details entered into the metadata tables by the modeller responsible for the file generation.
2) The file and metadata are checked by another team-member to specifically look for errors. It is not intended that the second team-member should effectively repeat the methodology of the first, since good scientific practice and attention to detail by the modeller are assumed and repetition by the second team-member is a waste of time. The second team-member should specifically look for spikes in the data or mismatches between the data and metadata. This can be achieved efficiently and effectively by displaying spatial data graphically and visually inspecting them, or by sorting lists of numbers to highlight anomalously high or low values.
3) The file is signed-off and dated as checked by the second team member in the associated metadata table.
4) Once checked, the data file is moved to the appropriate 'Checked' directory and the filename appended with _01c in accordance with the file naming conventions of

Monaghan (2002). The ‘01’ signifies version number and the ‘c’ signifies that the file has been checked.

5) Should the data in the file be superseded by new data resulting in the subsequent regeneration of that file, the same process is followed with the exception that the new checked file is appended with ‘02c’. The old checked file is appended with ‘o’ (*_01co*) and moved to the obsolete subdirectory of the checked directory. The necessary obsolescence metadata should be entered into the metadata listing for the old file.

6) At the end of the DGSM project, checked files required for entry into the corporate GLOS/GSF, or to be made available to customers, are signed off as issued by the project leader and should be moved to an ‘Issued’ directory and appended with ‘i’ (*_01ci*). Metadata files should be updated accordingly.

General points:

- only files with ‘checked’ status should be used in the next stage of the modelling process. Draft files should not be used. This limits the potential for compounding errors
- only files with ‘issued’ status should be uploaded to the corporate GLOS/GSF, released for customer use or used in other BGS projects. Issuing files is the final sign-off on the quality of the data by the project leader and is usually applied only to those files required for GLOS/GSF upload or release
- superseded files should not be overwritten but marked as obsolete and handled as detailed above
- there is no formal quality control applied to intermediate and transient files held by the modeller in his/her working directory. These are the responsibility of the modeller
- ArcGIS8.3 links-in data files. Changes to the contents of files will be automatically reflected in the Project GIS. Files that gain ‘checked’, ‘issued’ or ‘obsolete’ status, and consequently are moved within the directory structure and therefore the links to those files within the project GIS will require updating
- GoCAD embeds data. It does **not** link-in data files. Errors in raw datasets spotted and corrected in the GoCAD environment are not automatically propagated to the source data files. It is imperative that the team members manually propagate any such corrections to the underlying data files, using the obsolescence procedures if necessary, to maintain data coherence

3.2 THE DGSM MODELLING ENVIRONMENT

The modelling environment defines the Cartesian limits and resolution of the resultant three-dimensional model. It provides a spatial framework for both data manipulation using ArcGIS and three-dimensional modelling/visualisation using GoCAD. Both these environments require configuring according to the specifications of the modelling environment.

3.2.1 Model parameters: limits, scale and projection

The modelling environment requires the definition of three important parameters; *model limits, model limiting scale and model projection.* Model scale and limits are usually a trade-off with each other as both affect the computational size of the model.

The model limits define the maximum extent of the model (both in the map plane and in elevation). They may be defined conceptually, using the OS quarter sheet or 1:50 000-scale sheet boundaries, geographically using land features, geologically using outcrop/fault limits or arbitrarily using polygonal shapes. The model limits need not describe a boundary parallel to Cartesian directions. It is important that the map (x, y) limits are defined so as to encompass all the area that is to be modelled (but not unnecessary area) as it is difficult to change these limits later. The elevation limits (z) are less important and can evolve with the project.

The model limiting scale defines the resolution at which the three-dimensional model is considered accurate. The ability to fly-through three-dimensional visualisations of models is a well-known paradox. It has the advantage of allowing maximum interrogation and appreciation of the model but the disadvantage of allowing interrogation and appreciation at unreasonable scales right down to 1:1! The model limiting scale should be stated clearly at the initiation of the project as it defines the resolution to which input data may be sampled. Data from 1:50 000 scale sources cannot be used in 1:10 000 scale models as they are not accurate at the limiting scale of the model. The reverse scenario is acceptable; hence the limiting scale of the model is usually defined by the smallest scale of the input data. The limiting scale is not to be confused with model uncertainty (Clarke, 2004). The limiting scale defines the positional accuracy and detail level (and therefore error margins) of the original input data and therefore the modelling that results from them. In the same way that a pecked line on a 1:10000 scale map implies positional uncertainty but does not change the scale accuracy of the map, the limited scale of the model is unaffected by uncertainty in interpretation. The limiting scale defines the accuracy of the input data and the level of spatial detail of the modelled surfaces. Limiting scale and confidence analysis (Clarke, 2004) together define the reliability of the model.

The projection of geographical data within the GoCAD environment is not possible. The software uses Cartesian co-ordinates as its reference frame. Given the limited spatial extent of DGSM models, issues with projection are usually irrelevant although it is important to note that, as GoCAD works in Cartesian co-ordinates, a decimal projection co-ordinate system must be used. The most practical for the UK is the British National Grid (BNG) although systems based on decimal degrees can also be used. Projection systems that do not use a decimal base for the fractional part (e.g. degrees and minutes) cannot be used as a decimal base will be assumed by GoCAD.

3.2.2 Configuring the GIS workspace

Using defined parameters of model limits, scale and projection, the GIS workspace to support the DGSM project may be configured as follows:

1) Define a new ArcMap8.3 project, in the correct projection and save it to the ‘ProjectGIS’ directory.
2) Link-in all necessary Ordnance Survey (OS) maps for the project area from corporate drives.
3) Generate a shape-file called ‘****modellimit.shp’ to hold a polygon defining the model limits, where ‘****’ represents the DGSM name (and sub-area name if appropriate) following the naming conventions in Section 3.1.2.2. This shape file should hold just one polygon for one limit, as it will be used in GoCAD. The polygon may be derived from OS data (e.g. a quarter-sheet boundary) or digitised directly.
4) Store the shape-file in ‘ProjectGIS’

3.2.3 Configuring the GoCAD workspace

GoCAD will allow the placement of Cartesian co-ordinate data at any point from a true arbitrary origin (0, 0, 0). In order to provide a point of reference it is good practice to define a viewing box or *voxet* that delimits the model.

The GoCAD environment can be configured as follows (Figure 3.2):

1. Define a new voxet from corner points (Voxet Mode – New – From Corners).
2. Enter an origin as the BNG co-ordinates of minimum easting and minimum northing of the model limit, and minimum elevation (negative depth) for the model.
3. Enter east and north maximum extents as vectors 'point_u' and 'point_v' respectively.
4. Enter maximum elevation as 'end z value'.

General points:

- voxets that are not parallel to Cartesian co-ordinates can be specified in GoCAD. This is not recommended as it conflicts (visually) with easting- and northing-based map data
- the advanced tab can be used to label the axes accordingly (Figure 3.2)

3.2.3.1 GoCAD metadata – tracking manipulation

GoCAD allows powerful manipulation of data. It is relatively simple to reconfigure spatial data or to re-compute surfaces. Therefore, it is important that the manipulation of the data and the model within the GoCAD environment is recorded such that the steps taken to arrive at a given model can be determined (and repeated).

To track manipulation in GoCAD:

1. At the start of a working session set up GoCAD to record all operations using File – Record Commands In... (version 2.07) or File – Save History As... in earlier versions.
2. Save the history file to the history directory of the appropriate GoCAD directory within the directory structure (Section 3.1.2.1).
3. The file should be named with the DGSM project and sub-area (if appropriate) and given the extension '.his'.

General points:

- the history file is ASCII text and can be read by any text editor
- GoCAD will overwrite a history file rather than append it therefore subsequent sessions should have different filenames for the history file. Multiple history files for the same model from different working sessions can be combined in any text editor

3.3 DATA COLLATION

The interpreted data for three-dimensional models may exist in many forms. Modern surface geological data is usually in digital GIS format. Much other data may be proprietary formats or hardcopy. Suitable, corporate datasets for modelling specific surfaces are discussed in Section 3.5, but general data preparation issues and importing data into the GoCAD environment are covered here.

3.3.1 Data preparation in ArcMap

All data required for the DGSM must be prepared in a suitable form for ArcGIS manipulation. Much modern digital data (e.g. DigMapGB) will exist in a suitable form and can be imported directly into the project GIS. Other proprietary forms such as 'x, y, attribute' tabulated data can be imported and converted, and hardcopy data can be digitised using third-party techniques or directly from within ArcGIS.

ArcGIS uses a map-and-attribute spatial framework. That is to say, all data points are represented by an 'x' and 'y' co-ordinate and a number of attributes. GoCAD will interpret such data as Cartesian data with co-ordinates (x, y, 0). In some cases this is ideal, but in many others (such as spot-height data) one of the shape-file attributes may represent the Cartesian 'z' co-ordinate. GoCAD cannot interpret this and these datasets require exporting as tabulated Cartesian data for use in GoCAD.

Data for modelling can be prepared as follows:

1. For all datasets required for use in the DGSM, produce an ArcGIS shape-file clipped to the model limits and stored with the appropriate filename and in the appropriate place in the directory structure.
2. Each shape-file should be linked to the project GIS.
3. For datasets that are required as three-dimensional Cartesian data in GoCAD:
    - add the shape-file to a temporary Arcview3.2 project
    - use the BGS Earthvision export filter to export the shape-file as column-based Cartesian points with a 'z' point defined by a selected attribute field. The filename for this export should correspond to that of the shape-file but with the extension '.xyz'

General points:

- the BGS Earthvision export filter will only export three columns (x, y and attribute representing z). However, the filter will always export the points from a given dataset in the same order. Column-based, attributed, three-dimensional, Cartesian co-ordinate data can be generated by exporting the same shape-file a number of times with different attributes specified as 'z' and then combining them into one file using Microsoft™ Excel or a similar spreadsheet package

3.3.2 Importing data into GoCAD

Suitably prepared modelling data can be imported into GoCAD using various techniques based both on the nature of the data and the representation of the data in GoCAD.

3.3.2.1 GIS-BASED DATA (XY POINTS, LINES AND POLYGONS)

Two-dimensional data can only be represented in the map plane but may be important to the modelling process as they are attributed with important values or they can be interpolated with a 'z' co-ordinate using other data in the model (see Section 3.4.3). Examples include fault outcrop trace lines and DigMapGB polygons.

ArcGIS shape-files can be imported directly into GoCAD using:

1. File – Import – Arcview ESRI (shape-file).

General points:

- the easting and northing will be converted to 'x' and 'y' Cartesian co-ordinates respectively
- the 'z' co-ordinate will be assigned zero
- all attributes will be ignored
- the topology or the original shape-file (points, lines or polygons) will be preserved
- polygons are imported as lines and are not closed by default

3.3.2.2 Column-based data (points)

ASCII column-based (point) data may be in two or three dimensions, with or without attributes and can be imported using:

1) Import Objects – Raw Files – Pointset – Column Based (Figure 3.3).

Using this approach, any number of columns (attributes) can be imported by adding new column headings to the 'property parameters' box and assigning column numbers to them.

General points:

- columns with property parameters 'X', 'Y' or 'Z' (note the capitals) will be automatically interpreted as the respective Cartesian co-ordinates; all others will be interpreted as properties
- two-dimensional, column-based data (with or without attributes) can be imported by specifying 'X' and 'Y' properties but no 'Z' property. The Cartesian 'z' attribute will be assigned zero automatically

3.3.2.3 Column-based data (lines and polygons)

Column-based datasets representing points on a specified line (such as contours), for which the representation of the line itself (and therefore the association between points) is important, can be imported using:

1) Import Objects – Raw Files – Curve – Column Based.

Attributes can be added by specifying additional column names and column numbers in the 'Property Parameters' box, in the same manner as for point data (see Section 3.3.2.2). However, a property parameter called SEGID will be interpreted as specifying a column that represents the connectivity of the points into lines.

General points:

- if SEGID is not specified all points will be connected into one line
- polygons are interpreted as lines and will not be closed by default
- two-dimensional, column-based line data, with or without attributes, can be imported by specifying 'X', 'Y' and 'SEGID' properties but no 'Z' property. The Cartesian 'z' attribute will be assigned zero automatically
- the 'SEGID' property will not be recognised in GoCAD 2.07 and the points will always be interpreted as one line. This is a bug

3.3.3 GoCAD object naming conventions

All datasets in GoCAD are represented as objects and identified by names in the object table. Imported datasets will assume the filename of the original file by default. This is advantageous as it 'soft-links' the dataset in GoCAD to the original file. Datasets generated from within the GoCAD environment have user-specified names.

Suggested best practice for GoCAD generated datasets is that they should be named following the standard file naming conventions as detailed in Section 3.1.2.2 but with the addition of a type definition prefix 'p_', 'c_', 's_' or 'v_' to specify the data type (points, curves (and polygons), surfaces or voxets respectively). In this way, the data type is specified in the object's name. This is useful to the modeller as many menu options in GoCAD will list both points, lines and polygons and it is useful to tell between them. It also allows datasets representing the same horizon, but in different forms, to have a filename that differs only by the prefix. The type definition is prefixed to the object name rather than post-fixed to force alphabetical sorting by object type within dialog boxes in GoCAD.

3.4 GOCAD GEOLOGICAL HORIZON CREATION

The creation of geological horizons from input data within GoCAD relies on mathematical interpolation (and in some cases extrapolation). The geometry of the resultant surface is therefore partly dependent on the interpolation algorithm and the parameters applied to that algorithm. Surfaces representing specific types of horizon within the model, such as the DTM, fault surfaces or lithostratigraphical surfaces have particular scientific characteristics that influence the interpolation algorithm. These are discussed in Section 3.5. However, there are general approaches, applicable to the interpolation of any three-dimensional surface and these are discussed here.

3.4.1 Interpolating surfaces

Within GoCAD three-dimensional surfaces can be generated from a variety of data in a variety of ways. This section is not an exhaustive review of all possible methodologies, but experimentation has shown that two different methods are the most applicable to the generation of geologically sensible, three-dimensional surfaces and these methods are recommended best practice.

3.4.1.1 POINT-SET AND OUTLINE METHOD

The most practical method of interpolating three-dimensional surfaces is to use a set of Cartesian points (a *point-set*) that constrains the interpolated geometry and an outline curve that constrains the extent of interpolation. Using this approach, GoCAD will interpolate a surface through the point-set by triangulating between points of the point-set and points on the outline as appropriate.

To generate a three-dimensional surface:

1. Combine all datasets representing the surface into one point-set with an appropriate name prefixed by ‘p_’.
2. Fit an outline to the point-set using: Curve Mode – New – Convex Hull – Of Object.
3. Edit the fit of the outline using: Curve Mode – Edit – Fit to Points or the GoCAD node editing tools as appropriate.
4. *Densify* (Curve Mode – Edit – Densify) the outline such that the point spacing of the outline curve is roughly similar to the data density (spacing) of the point-set.
5. Use Surface Mode – New – From Point-set & Curve to generate a surface.

General points:

- if the density of points in the outline is not roughly that of the point-set, GoCAD will produce large or irregular-shaped triangles at the edges of the resultant surface. This is undesirable and has adverse effects on later manipulation of the surface
- surface densification types of ‘homogeneous triangles’ or ‘enforce adding points’ appear to work best with randomly sampled geological data
- the surface densification factor can be used to reduce the density of the triangles in the resultant surface compared with the density of the point-set if the latter is too dense
- by default, surface generation using this method uses a vertical (z) normal to the surface. This can produce undesirable effects when generating surfaces that are near vertical, such as faults. Un-check ‘use normal’ under the advanced tab of the ‘create surface…’ dialog

- the resultant triangular mesh of the surface can be 'improved' by re-interpolating and/or smoothing the surface. See Section 3.4.2

3.4.1.2 Closed curve and modifying point-set method

In some cases, it is beneficial to generate a three-dimensional surface by interpolating a planar surface in one of the Cartesian planes and then warping this surface to fit a point-set. This method is particularly favourable over the previous method in situations when:

- the outline of the resultant surface is of a specified shape, such as a county boundary, rather than a best-fit curve to the point-set
- the point-set data are sparse and do not cover the entire area to be represented by the surface, so fitting an outline to the data is inadequate
- the point-set data are irregularly distributed or do not represent the gradient trends of the surface adequately. Using this method can give an even distribution of triangles over the full extent of the surface irrespective of the point-set data resolution

To generate a three-dimensional surface:

1. Combine all input data into one point-set.
2. Import a curve to represent the outline of the surface.
3. Clean the curve for duplicated or zero length segments.
4. Close the curve into a polygon by bridging the extremity nodes (note that ESRI shape-files are not closed by default when they are imported into GoCAD).
5. *Densify* (Curve Mode – Edit – Densify) the closed curve to a resolution that is similar to the desired linear dimensions of triangles in the resultant surface.
6. Use Surface Mode – New – From Closed Curve to generate a surface.
7. Use Surface Mode – Edit – Fit – To Point-set to warp the surface to the point-set.

General points:

- a constant warping direction of movement can be specified in the 'fit to points' dialog. In most geological scenarios this will be vertical (z) or horizontal for fault surfaces
- 'insert points' should be checked to avoid 'step' effects in surfaces that have sparse controlling data
- *constraints* can be used to restrict the movement of points on the outline or within the surface. Outline points are normally restricted to movement in the warping direction only
- the resultant triangular mesh of the surface can be 'improved' by re-interpolating and/or smoothing the surface. See Section 3.4.2

3.4.2 Smoothing surfaces

Three-dimensional surfaces generated by the point-set and outline method will be linear interpolations to the dataset and contain sharp gradient changes. Surfaces generated using the closed curve method may show smoother gradient changes, but with irregular and unconstrained 'bumps' in places where controlling data are sparse. These issues can be resolved using smoothing techniques.

It is important to consider the geoscientific implications of applying smoothing routines to three-dimensional surfaces. Most geological surfaces will show trends to the variation in gradient and thus smoothing can be justified. Obvious exceptions are surfaces that are faulted or subaerial erosion surfaces (both present day and palaeo-topography) that show rapid abrupt changes in gradient.

To apply smoothing to a surface:

1. Use Surface Mode – Interpolation – On Entire Surface.
2. Check the 'smooth' box to apply smoothing.

General points:

- the number of iterations has a logarithmic relationship to the quality of the resulting smoothed surface
- if no constraints are set on the surface (see Section 3.4.2.1), smoothing will dampen gradient variations in the surface towards an average gradient and move the outline of the surface towards a best-fit ellipsoid

3.4.2.1 HONOURING DATA

For most geological surfaces modelled, it is desirable to force the surface to honour selected data and/or to honour the given outline. In these instances GoCAD *constraints* (Figure 3.4) can be used to constrain the motion of specific surface points during smoothing.

To honour surface data points:

1. Use the options under Surface Mode – Constraints – Control Nodes to define nodes of the surface that should not move during interpolation or smoothing (Figure 3.4a).
2. Follow the procedures in Section 3.4.2.

General points:

- nodes on the edge of the surface can be constrained to move in the vertical plane only. This is the desirable option for surfaces created using 'closed curve and modifying point-set'. Use Constraints on Border – Set on Straight Line (Figure 3.4b)

3.4.3 Projecting 2D data onto 3D surfaces

Lines taken directly from maps, such as outcrop lines and fault traces, have spatial (x, y) co-ordinates, but no elevation (z) co-ordinate. Such data are effectively two-dimensional and GoCAD will assign zero to the 'z' Cartesian co-ordinate (see Importing Data – Section 3.3.2). It is often useful to project two-dimensional lines into three dimensions so they can form part of the input data to a three-dimensional surface. If a three-dimensional surface to which the data relate exists within the model (e.g. a DTM for outcrop lines and fault traces), map-based lines can be projected along a vector to intersect with this surface.

To project 2D line data into 3D:

1. Select Curve Mode – Edit – Project – On Surface.
2. Specify the curve to project and the target surface.

General points:

- a separation between target surface and projected curve can be set using the thickness value or property
- the default projection vector is vertical (i.e. projecting map data). This can be redefined under the 'advanced' tab
- if the topological relationship of the projected curve with the target surface is of importance (rather than the curve's component points), the point density of the curve

should be greater than that of the surface. A curve with a lower point density than the target surface will appear to weave in an out of the surface due to under-sampling problems

- the ‘Project’ option is only available in advanced mode

3.5 INTERPRETATIVE MODELLING – A STRUCTURAL FRAMEWORK

To build coherent, three-dimensional models of subsurface geological horizons from two-dimensional interpretations rather than primary data, it is necessary to construct a three-dimensional structural framework (Section 2.4). The framework consists of all available interpretative data projected into three dimensions and provides spatial constraints on the interpolation of subsurface horizons. This section covers the specific issues on constructing the most common elements that comprise the structural framework, based on the best practice for general surface construction outlined in Section 3.4 above.

3.5.1 Digital Terrain Model (DTM)

A *Digital Terrain Model* (topographical surface) is the most significant constraining surface within the three-dimensional structural framework. A large amount of input data is derived from geological maps and therefore relates to the topographical surface. The DTM should be constructed to reflect the topography as accurately as possible within the confines of the model scale.

3.5.1.1 DATASETS

DTM datasets for the UK do exist. However, most of these are represented as gridded elevation data and therefore do not necessarily reflect local topographical variations accurately, particularly local maxima and minima. The best datasets for the construction of DTM surfaces for use in interpretative modelling are:

- Ordnance Survey *Landform Profile* contour line data for models of a few square kilometres accurate to 1:10 000 scale or *Landform Panorama* contour line data for larger area models accurate to 1:50 000 scale. OS metadata sources give details on these datasets
- spot height data from the Landform Profile dataset to constrain mountain summits
- rivers and lake boundaries from the Landform Panorama dataset. These data contain an elevation attribute and can be used to further constrain valley bottoms and undulating upland areas
- the low-water mark from the Landform Panorama data should be used as a coastline even though it has the somewhat inaccurate elevation attribute value of zero metres. The high-water mark is unsuitable as it has the same elevation (zero) and therefore causes conflict with coastal spot height data

3.5.1.2 SURFACE INTERPOLATION

The data suggested in Section 3.5.1.1 effectively defines all local topographical variations within the resolution of the model scale. In mountainous areas the spacing of the contours is such that the density of data is roughly even in the x and y Cartesian directions. The DTM surface should be interpolated using the ‘point-set and outline’ method without smoothing.

In low-lying areas of the UK, contour spacing may be sparse and in these situations the *closed curve* method of surface interpolation produces a better result. The ‘closed curve’ method should also be used when a defined outline to the DTM (such as a county boundary) is required.

3.5.1.3 Raster drapes

To express the three-dimensional relationships of map based data, aid model interpretation and construction, or to convey model form to an audience it can be useful to project an image of the topographical surface (cultural or geological maps, aerial photos etc) onto the three-dimensional DTM. This technique is know as *raster draping.*

To drape a raster image onto a three-dimensional DTM:

1. Import a suitable image using File – Import Objects – Picture – As 2D Voxet.
2. 'Georeference' the image using Voxet Mode – Edit – Resize with Points and provide an origin (minimum easting and northing) and corner point co-ordinates.
3. Under the 'texture' field of the attributes for the DTM surface, specify the voxet containing the image and select 'visible' to visualise the drape.

General points:

- to avoid distortion, the image should have edges parallel to the Cartesian axes (north and east)
- the voxet corner points in the 'z' Cartesian direction should differ by a nominal amount (e.g. one metre) to give the voxet a thickness. An image in a voxet with no thickness can cause display problems

3.5.2 Faults

The fault network of an interpretative model is usually the second most important constraint (after the DTM) on the interpolation of subsurface horizons. Fault positions define the limits of, or breaks in, lithostratigraphical horizons and fault deformation vectors control relationships between horizons in neighbouring faulted blocks. In interpretative modelling, three-dimensional lithostratigraphical surfaces are tied to, and truncated by, the fault network. It follows that a well-constrained fault network in three dimensions is of paramount importance in interpretative modelling. Fault surfaces may be considered vertical if this is a valid assumption within the scale and spatial limitations of the model, or they may be considered to have variations in dip vectors over their extent like any other three-dimensional surface.

3.5.2.1 Datasets

Datasets recommended for use in fault surface construction are:

- DigmapGB50 or DigmapGB10 fault outcrop lines
- structural contour plans of fault surfaces (dipping faults only)
- field structural data (dipping faults only)

3.5.2.2 Vertical fault surface construction

Fault surfaces that can be considered vertical within the scale and spatial limitations of the model can be interpreted from outcrop lines alone, using a built-in GoCAD surface construction wizard:

1. Project DigMapGB lines into three-dimensions onto the DTM (see Section 3.4.3).
2. Use the GoCAD wizard Surface Creation – Fault Construction – Create Vertical Fault (fig. 3.5).
3. Smooth resultant surface using the projected DigMap lines as fixed constraints (Section 3.4.2).

General points:

- the lower elevation level for the vertical fault should be set to the maximum depth of the model and the upper limit should be set high enough such that the fault intersects the DTM fully (it will be trimmed later; Section 3.7)
- DigMapGB lines usually require cleaning for duplicated and zero length segments to avoid interpolation problems

3.5.2.3 Non-vertical fault surface construction

Non-vertical faults can be constructed in a similar manner to any other three-dimensional surface:

1. Project DigMapGB data into three-dimensions onto the DTM.
2. Combine all available datasets, including DigMapGB data into one point-set.
3. Use Point-set and outline method to construct a surface (Section 3.4.1.1).
4. The resultant surface can be smoothed using the DigMapGB data as fixed constraints (Section 3.4.2).

3.5.3 Cross-sections

Cross-sections are a two-dimensional representation of geological relationships along a specific line on the ground. This line may be straight or it may have changes in orientation along its length. Interpolating cross-sections into three-dimensions is a mathematical interpolation between the co-ordinates of the end (or corner) points. This requires specialist software outside the scope of GoCAD and is an operation that can be performed by the Drawing Office, or suitably tabulated datasets can be derived from cross-sections via the *DGSM Portal*.

3.5.3.1 Datasets

The Drawing Office (or the DGSM Portal) can supply tabulated (Microsoft™ Excel) data files representing the corner co-ordinates of polygons that form the geology represented on the cross-section. The most recent format of theses files is suitable for direct importation into GoCAD. Older, dxf format files contain corner point data as columns of Cartesian co-ordinates, but grouped into rows of points that represent one lithostratigraphical unit bound by a Lexicon code qualifier and the word ‘END’.

GoCAD cannot use dxf format directly. Attributes within GoCAD relate to the nodes of line or polygon elements rather than to the elements themselves; thus each Cartesian point that comprises a line or polygon boundary requires a Lexicon code attribute value. Furthermore, GoCAD attributes are numerical, not alpha-numeric. Lexicon codes cannot be assigned as attributes directly.

To circumvent these problems:

1. Add a fourth column to the tabulated data file to contain the Lexicon attribute.
2. Assign an integer number to each node that represents the Lexicon code.
3. Keep a separate look-up table of lexicon code numbers.

3.5.3.2 Surface construction

Each separate lithostratigraphical unit of each cross-section must be created as a vertical surface:

1. Import the tabulated corner-point co-ordinate file using the method described in Section 3.3.2.3, specifying an attribute field for the Lexicon code.

2. Clean imported lines for zero length and duplicated segments.
3. Close lines to form polygons.
4. Create a surface for each polygon using Surface Mode – New – From Closed Curve.
5. Combine all surfaces from one section into one surface using Surface – New – From Parts.

General points:

- the Lexicon field can be used as the SEGID field for GoCAD import (as the Lexicon code is the same for all points that form one polygon). The SEGID feature does not work in version 2.07 and if not used will result in all polygons connected by their ends
- the density of nodes on the edges of polygons will control the density of triangles in the interpolated surfaces. Given that the surfaces are vertical and planar, the default minimum number of nodes (corner points only) will produce a surface with the minimum number of triangles

3.5.4 Contoured subsurface horizons (Lake District batholith)

A three-dimensional structural framework with which to constrain the subsurface interpretations of specific horizons may include other well defined surfaces in addition to the DTM, faults and cross-sections. In the example of the English Lake District DGSM (Section 2), the top surface of the Lake District batholith was modelled as part of the structural framework and provided a limiting maximum depth constraint to the BVG interpretation.

Surfaces that may contribute to the structural framework, such as the Lake District batholith are commonly defined in three dimensions by structural contour maps derived from remote sensing and/or outcrop studies. Subsurface horizons can be constructed from these maps and used as elements in the structural framework.

3.5.4.1 Datasets

The datasets required for building three-dimensional models of contoured horizons are:

- ESRI (ArcMap) format shape-files of surface contours as lines or as points
- ESRI (ArcMap) format polygon of surface extent
- DigmapGB50 or DigmapGB10 outcrop lines (if any)
- DigmapGB50 or DigmapGB10 fault lines

3.5.4.2 Surface construction

1. Export the contour file(s) as Cartesian points using BGS Earthvision export filter and ArcView3.2.
2. Import contour file using the method outlined in Section (3.3.2.2).
3. Import DigMapGB data and surface extent outline as shape-files using the method outlined in Section 3.3.2.1.
4. Interpolate 3D form of outcrop lines and faults using method outlined in Section 3.4.3.
5. Create one point-set from all data (except extent outline).
6. Filter zero length and duplicate segments from extent outline and close to form a polygon.
7. Densify (Curve Mode – Edit – Densify) outline to suitable node spacing.

8. Create surface following the method in Section 3.4.1.2.

General points:

- if the surface represents a unit top (such as the Lake District batholith), the outcrop extent of the unit should represent a hole in the top surface. The outcrop line can be used to create a vertical surface using the GoCAD built-in wizard (see Section 3.5.2.2) with which to cut the top surface and remove the outcrop area (Section 3.7)

3.6 CONSTRAINING INTERPRETATION IN 3D

The structural framework (Section 3.5) provides spatial constraints (at specific points) on the interpolation of three-dimensional surfaces. The combination of the structural framework with available raw data can help delimit the position of subsurface horizons in three-dimensions. This approach was used in the English Lake District DGSM to create the BVG surfaces (Section 2).

Poorly constrained subsurface horizons can be interpreted within the three-dimensional environment, using the structural framework as a constraint and following the procedures below.

3.6.1 Datasets

Important datasets necessary for constraining three-dimensional, subsurface interpretation are:

- relevant DigMapGB outcrop lines and faults
- cross-section lines and faults

Additional data that may relate to the surface to be interpreted can be imported as appropriate to further constrain the interpretation. These data may include:

- surface spot-heights (logged depths to horizons in wells)
- surface contours
- form lines describing structural form but not absolute position

3.6.2 Constraining subsurface interpretation

Any data pertaining to the surface to be interpreted that is in absolute co-ordinates can be used directly in the interpolation. Other data such as form lines may require translation (particularly in depth) to tie it into the structural framework. This can be achieved using Surface Mode – Compute – On Object to translate the full object or object part along a specified Cartesian vector.

To construct an interpreted three-dimensional surface proceed as follows:

1) Combine all available surface data into one point-set (including outcrop lines and section lines).
2) Import or generate a closed horizontal polygon representing the outline of each fault block in map view.
3) Densify the polygon outline to appropriate node spacing and generate a surface from it.
4) Specify the edge constraints for the surface as allowing vertical movement only.
5) Warp the surface to the surface point-set.
6) Using the outcrop line (and the section lines if appropriate) as fixed constraints, smooth the surface.
7) Trim the surface to fit fault surfaces and other surfaces within the structural framework as appropriate, using Surface – Edit – Cut – By Surfaces.

General points:

- if the resultant surfaces are not quite extensive enough to join with other surfaces of the model, they may be increased in size using Surface Mode – Edit – Borders – Extend

3.7 THE COMPLETED MODEL

The final stage of model building is to trim all surfaces by each other as appropriate to construct a tidy and structurally sound model. In particular all surfaces should be cut by the DTM to remove their aerial extent:

1) Surface Mode – Edit – Cut – By Surfaces.
2) Surface Mode – Edit – Part – Remove Selection.

General points:

- trimming surfaces with surfaces can result in untidy trimmed edges, particularly if the trimmed and trimming surfaces are of different triangular densities. Use Surface Mode – Edit – Border - Simplify and Surface Mode – Edit – Beautify – Remove Bad Triangles to improve the trimmed border topology
- any other surfaces can be trimmed against each other in the same way

Finally, it is good practice to create a finished version of the DGSM model that has only the required surfaces within it and not the intermediate data objects (point-sets, lines etc). The modelled surfaces should also be exported as GoCAD objects (stored in the appropriate place in the directory structure – Section 3.1.2.1) for loading into the GLOS.

3.8 EVALUATION

Interpretative modelling of the subsurface is inherently difficult to evaluate given the lack of primary, subsurface data. However, whilst the subsurface position (in terms of depth) of interpreted surfaces remains largely un-testable, the geometry of the surfaces can be evaluated against available surface structural data.

3.8.1 Derivation of structural data from GoCAD surfaces

GoCAD surfaces are constructed from a mesh of triangular elements. Triangles are planar in three-dimensional space and, as a result, dip vectors can be determined for any point on the surface. GoCAD is equipped with an automatic function to determine dip vectors on three-dimensional surfaces. These data are stored as surface attributes and can be exported in tabular form.

To derive structural data from three-dimensional surfaces:

1. Use Surface Mode – Compute – Azimuth/Dip Information.
2. Provide a name for the dip-magnitude and dip-azimuth properties that will store the computed information.
3. Use File – Export Objects – Surface – Properties to Excel to export tabulated dip vectors to Microsoft™ Excel.

General points:

- positional properties (X, Y, Z) must be specified for export, along with the dip vector properties as these are not included by default
- the sampling rate can be used to reduce the quantity of data exported by linearly re-sampling the surface data.

3.8.2 Creating surfaces in non-space domains

The variation in dip vectors over the extent of a modelled surface can be compared with field measurements by building three-dimensional surfaces in non-space domains. In the space domain the ‘z’ Cartesian co-ordinate represents space (elevation). In non-space domains the ‘z’ Cartesian co-ordinate represents some other property such as time, or in this case dip-azimuth or dip-magnitude. Surfaces interpolated through data in non-space domains are effectively three-dimensional graphs of the variation in a specific property over the lateral (x, y) extent of the model.

To compare dip vectors from modelled three-dimensional surfaces with measured dip vector data:

1. Export structural data from GoCAD surfaces (Section 3.8.1).
2. Import both structural data derived from modelled surfaces and measured field data into GoCAD as different point-sets using the method outlined in Section 3.3.2.2. The Cartesian ‘x’ and ‘y’ co-ordinates should be assigned to columns representing the spatial position of the data, but the ‘z’ Cartesian co-ordinate should be assigned to a structural property of the data such as dip-magnitude, defining a non-space domain projection for the data.
3. Import the outline polygons for the surface modelled (or surface parts if the surface is faulted).
4. Close and *densify* (Curve Mode – Edit – Densify) polygons as appropriate.
5. Construct a horizontal planar surface using just the outline polygons (Surface – New – From Closed Curve).
6. Copy the planar surfaces to generate a second set.
7. Set the border constraints to a vertical line for each surface (Figure 3.4b).
8. Warp one set of surfaces to fit the modelled structural data point-set.
9. Warp the other set of surfaces to fit the measured structural data point-set.
10. Apply smoothing as appropriate to both sets of surfaces using the same algorithms and parameters.

General points:

- dip-azimuths around north can cause misleading anomalies in the dip-azimuth domain because of the rapid fluctuations between minimum dip-azimuth (1°) and maximum (359°)
- separate fault blocks should be modelled as separate surface parts to avoid the possibility of data from neighbouring fault blocks affecting the interpolation of data in a particular fault block

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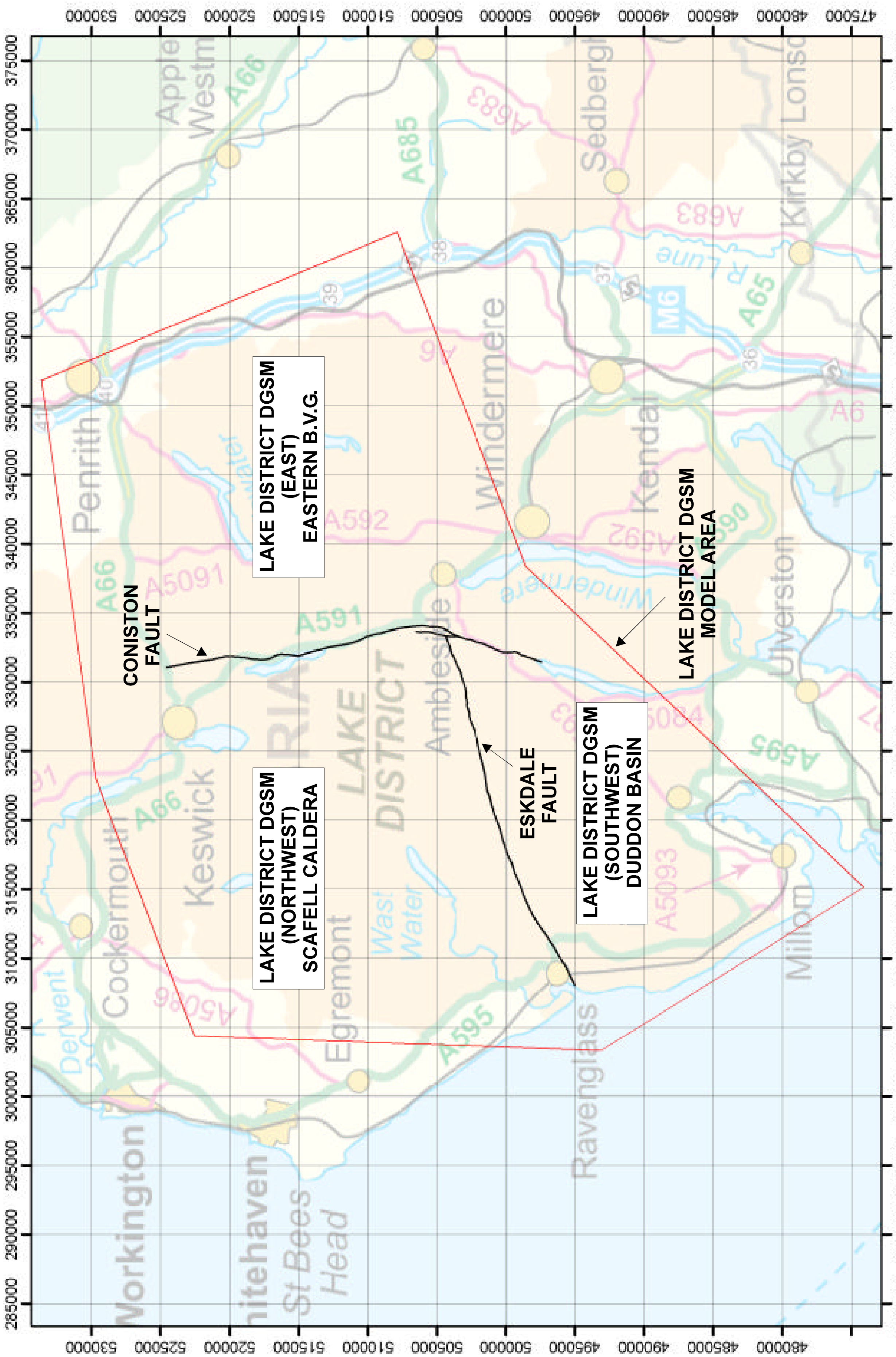


Figure 2.1. The Lake District DGSM study area is divided into three sub-areas by the surface outcrops of the Coniston and Eskdale Faults. Each area ismodelled separately. This report covers the modelling of the Scafell Caldera sub -area.

Figure 2.1

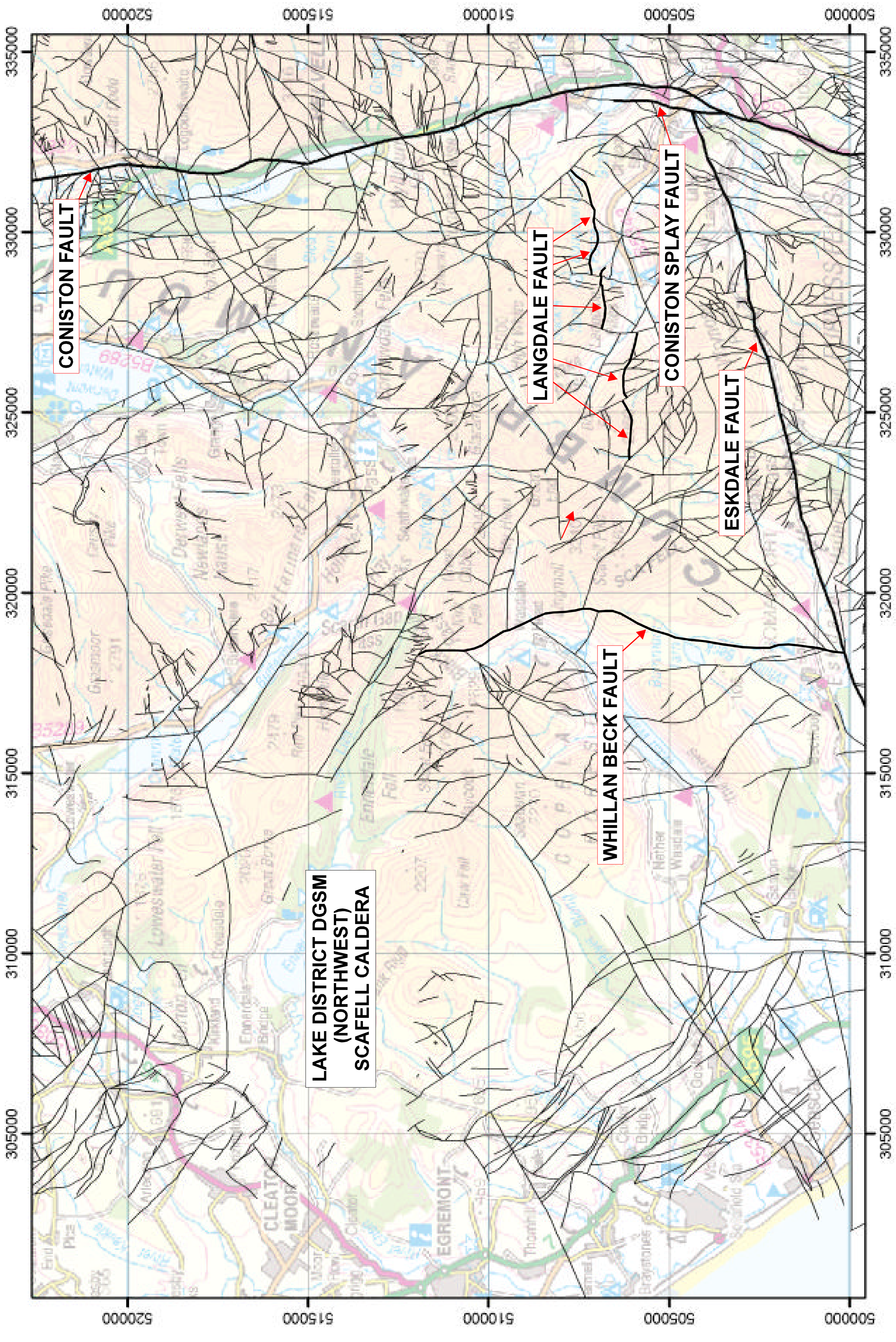


Figure 2.2. The Scafell Caldera sub-area showing the fault network withmajor, non-vertical faults highlighted.

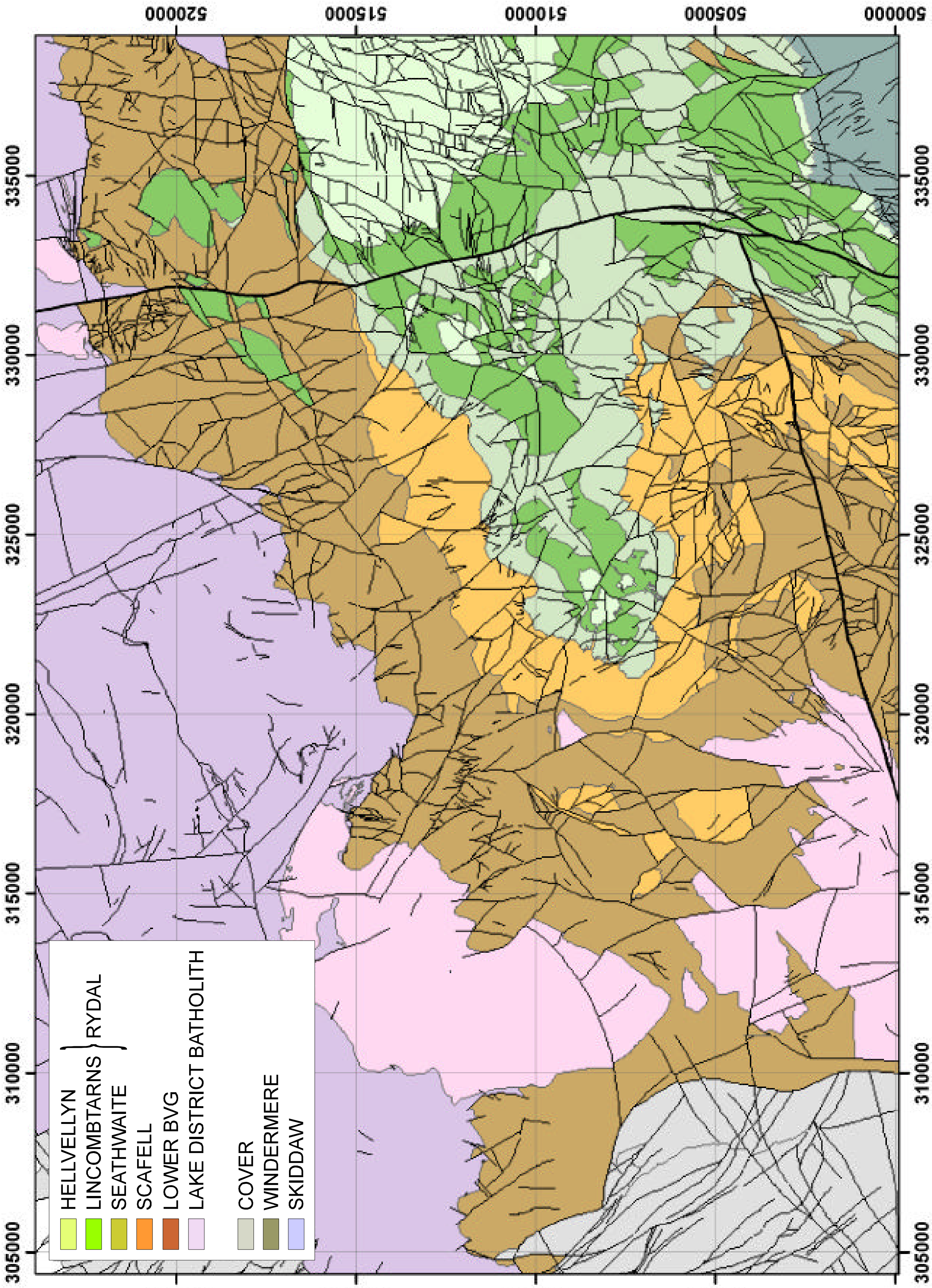


Figure 2.3. The bedrock geology of the Scafell Caldera sub-area of the LakeDistrict DGSM.

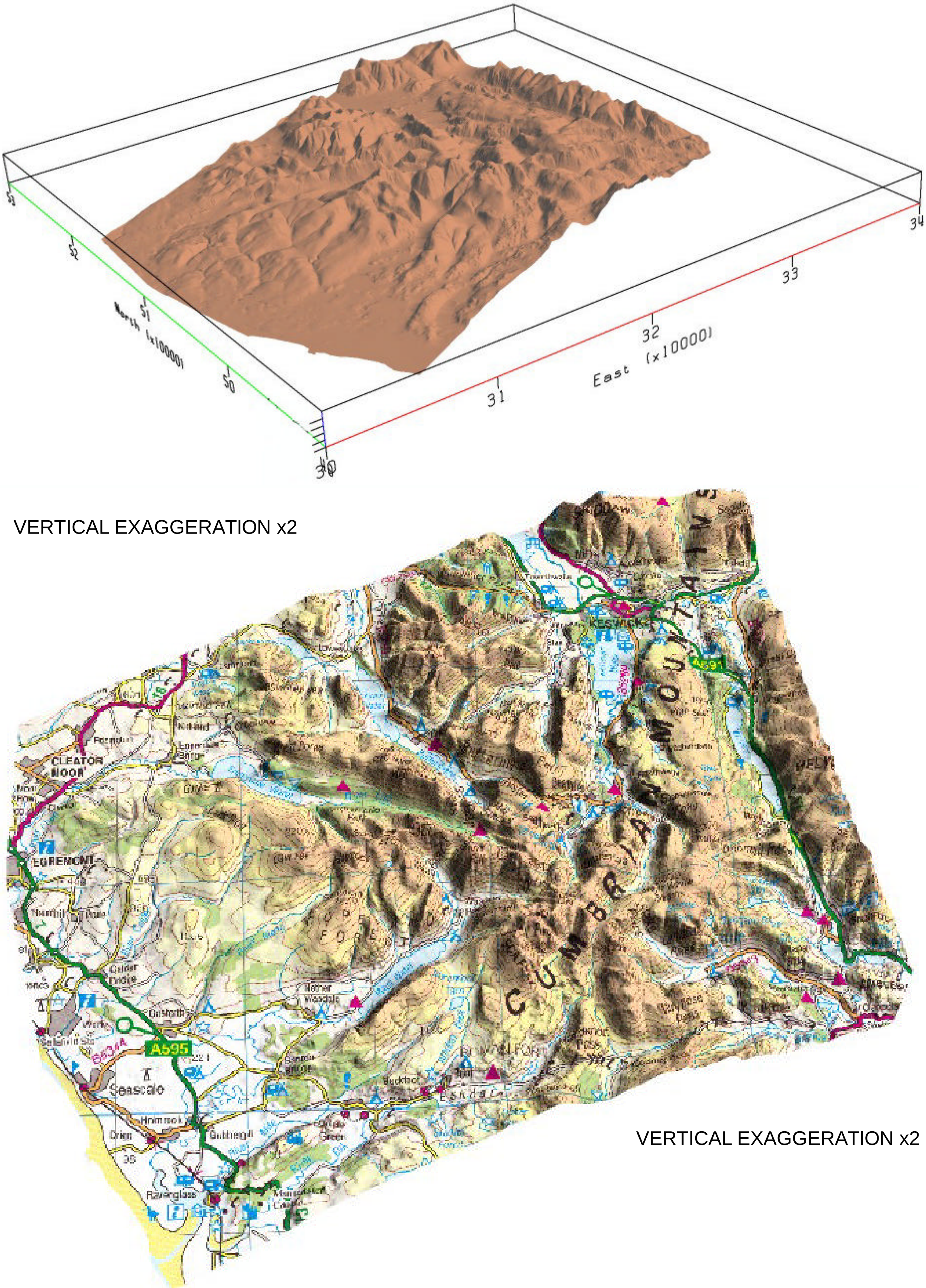
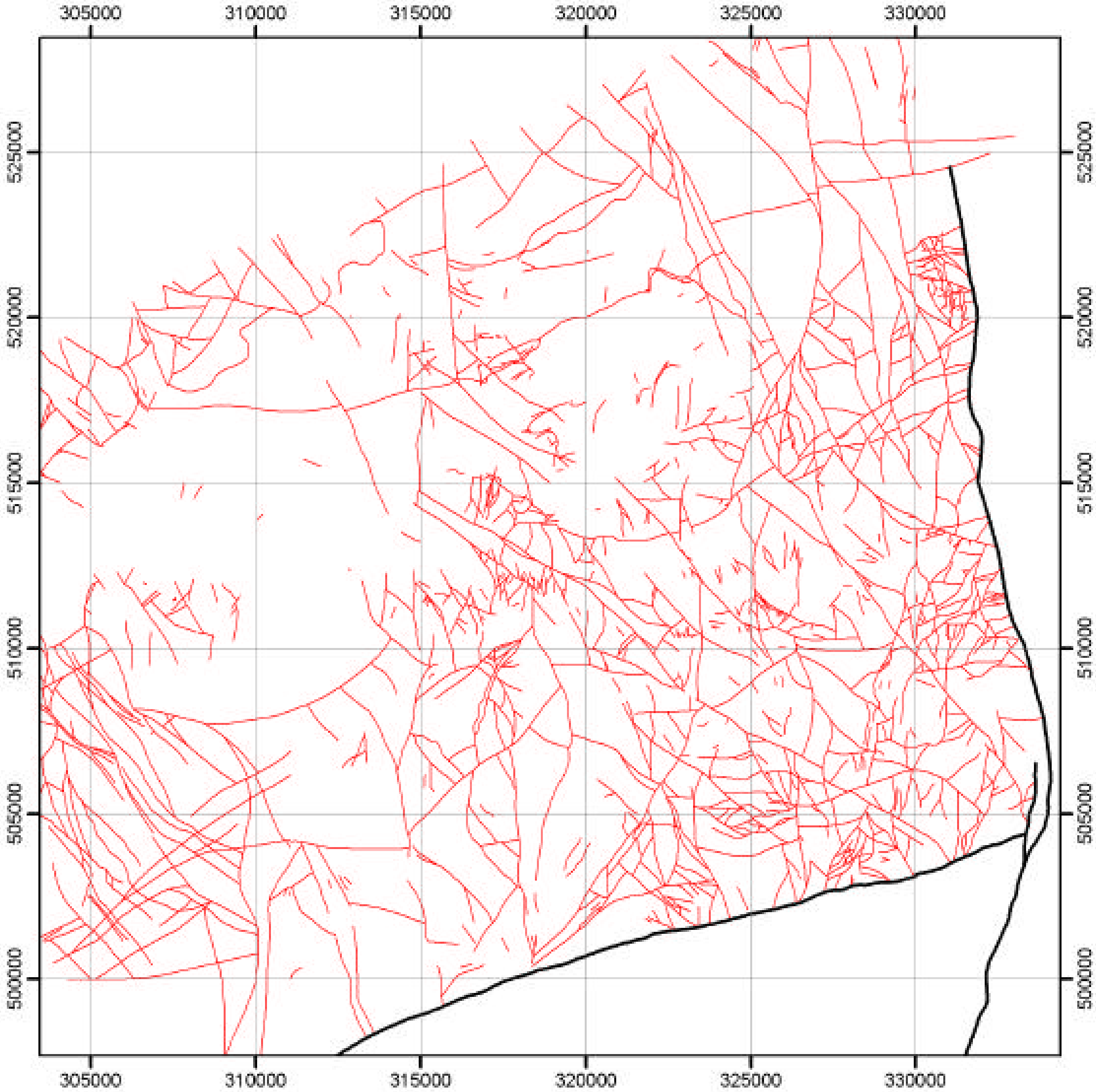
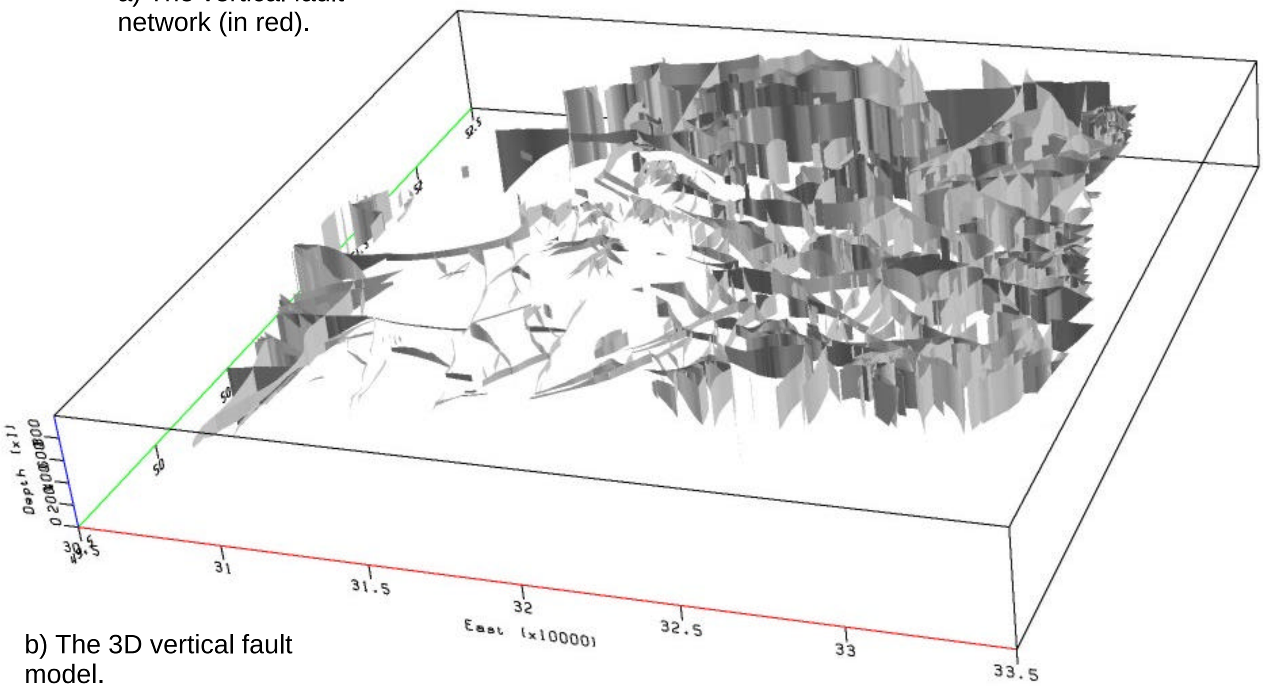


Figure 2.4. Three-dimensional DTM for the Scafell Caldera sub-area showing Ordnance Survey topography drape. The DTM is one of themostimportant elements of the structural framework.

Figure 2.4



a) The vertical fault network (in red).



b) The 3D vertical fault model.

Figure 2.5. The vertical fault network. All faults shown in red in (a) are interpreted as vertical within the scale and resolution limitations of the Lake District DGSM. b) The resultant three-dimensional fault network model.

Figure 2.5

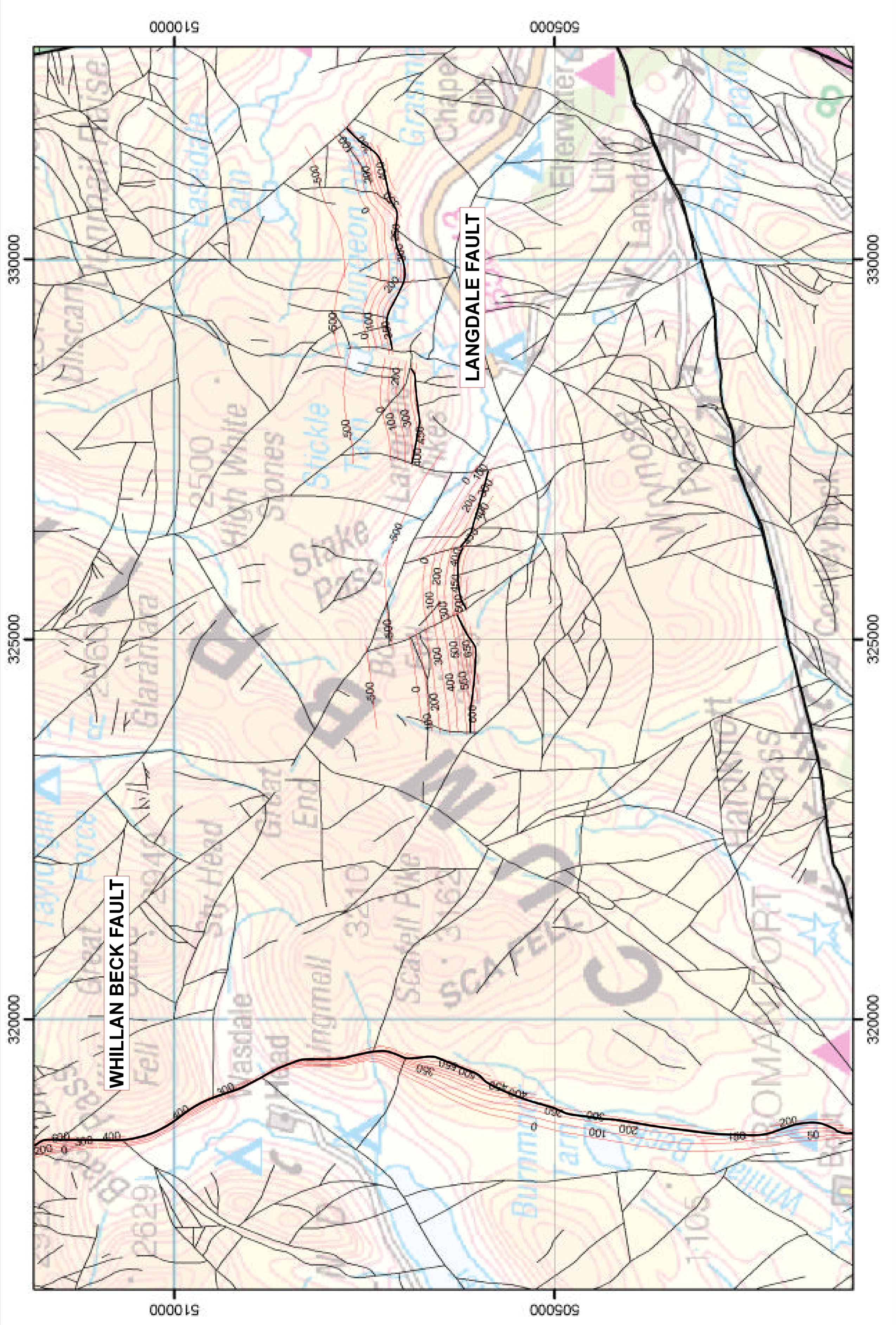


Figure 2.6. Interpreted structure contours on the Langdale and Whillan Beck faults (red). All contours are based on surface outcrop and extrapolated linearly into the subsurface. Contour labeling inmetres OD.

Figure 2.6

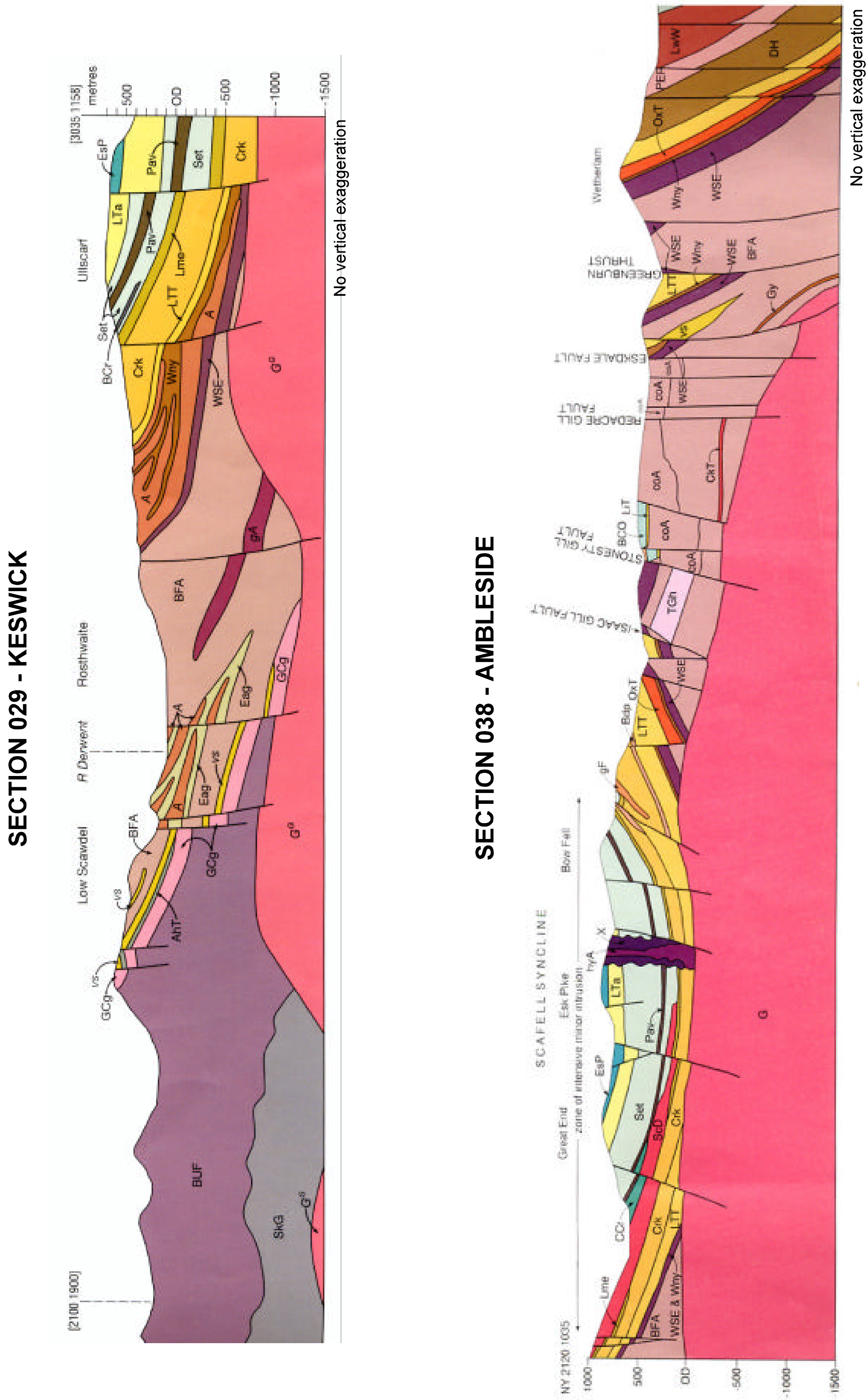
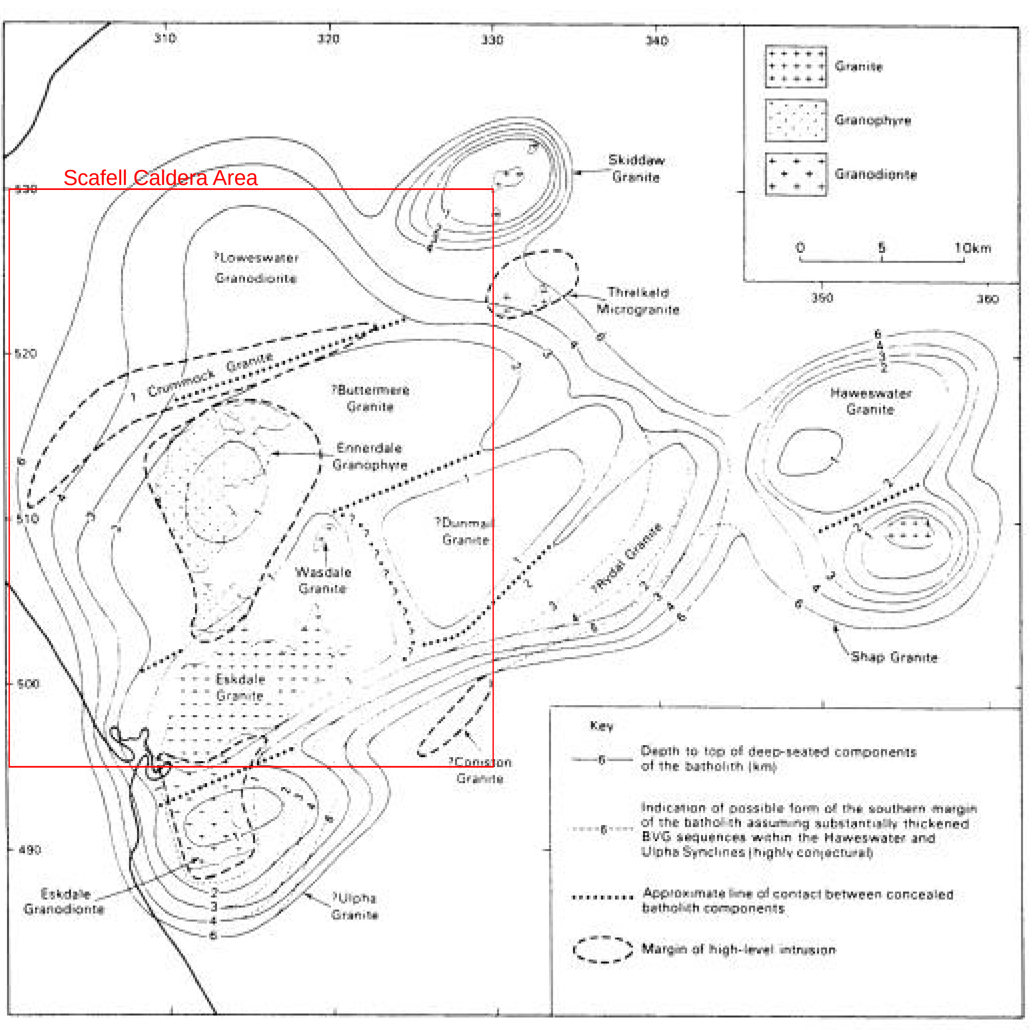
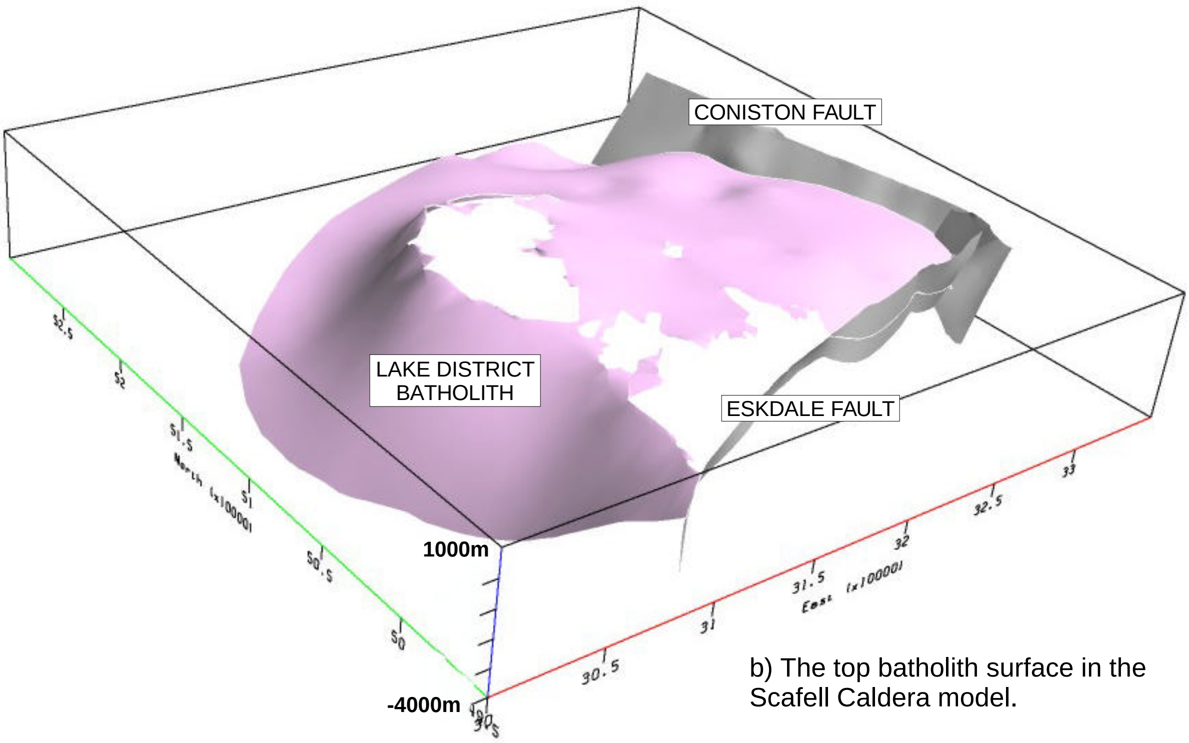


Figure 2.7. Cross-sections 029 (Keswick) and 038 (Ambleside) that cross the Scafell Caldera sub-area of the Lake DistrictDGSM. Reproduced from BGS 1996;1999. For key to symbols see BGS 1996;1999 orMillward et al., 2000.

Figure 2.7

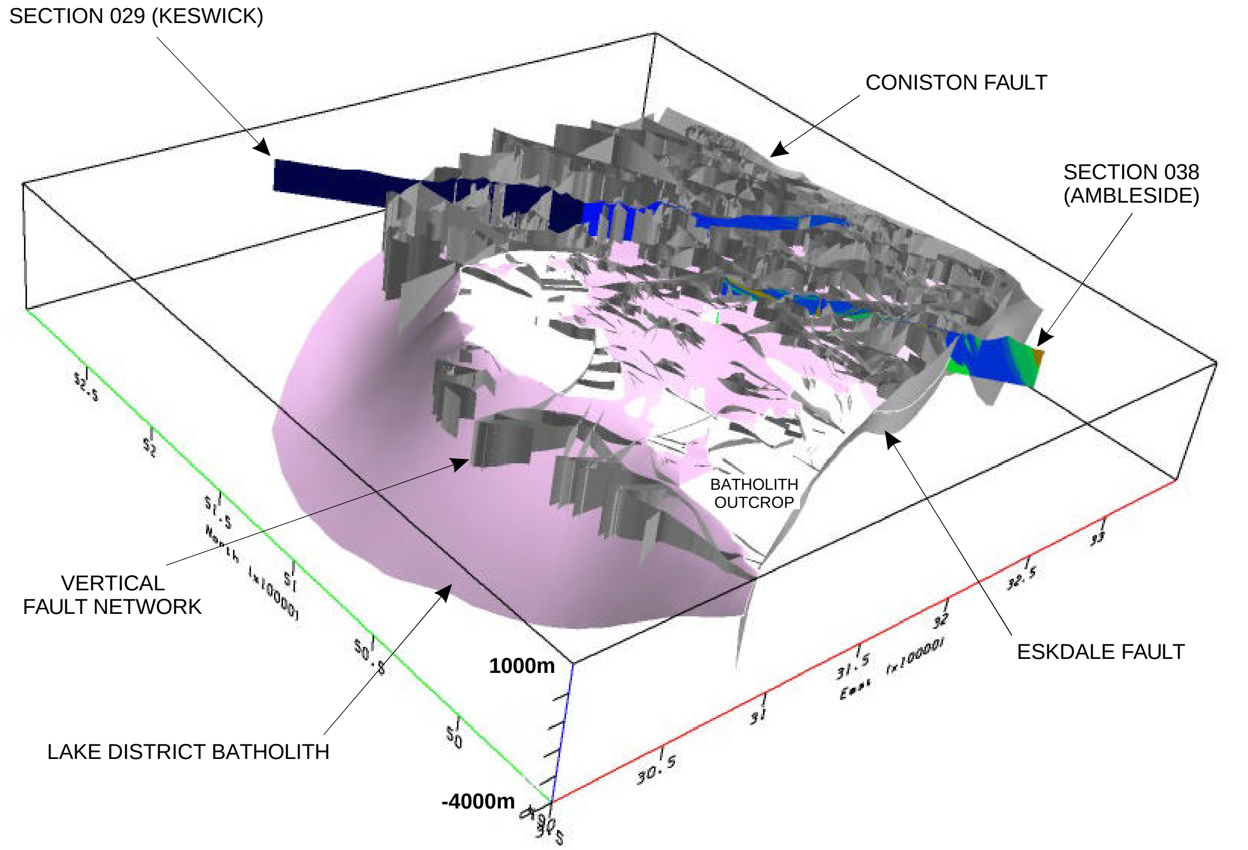


a) Geophyscially derived depth to top batholith (Lee, 1989).



b) The top batholith surface in the Scafell Caldera model.

Figure 2.8. a) Geophysically derived contour plot of the top Lake District batholith surface and various components (reproduced from Lee, 1989). b) Three-dimensional model of the Lake District batholith surface in the Scafell Caldera sub-area produced from geophysics and outcrop measurements (only the top main batholith has been modelled - not individual components.



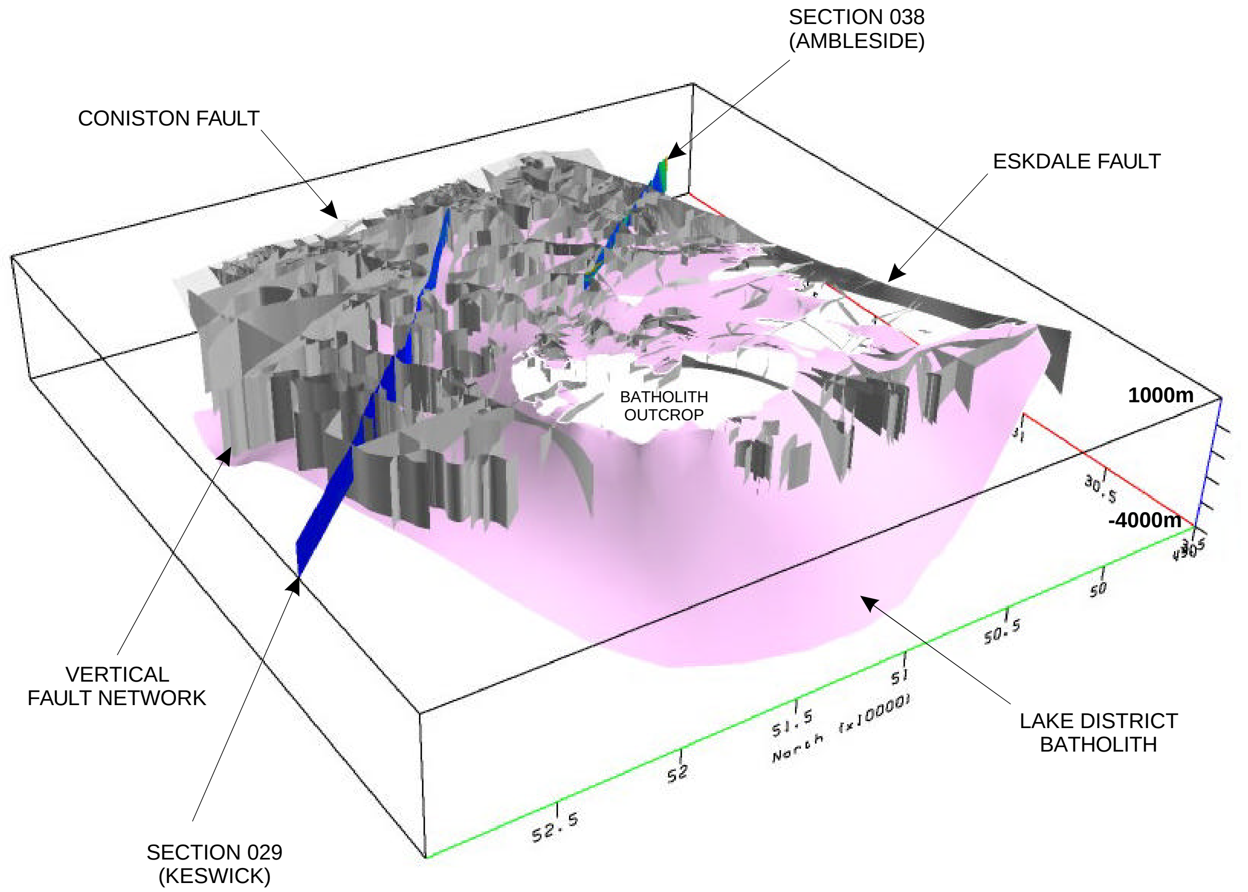
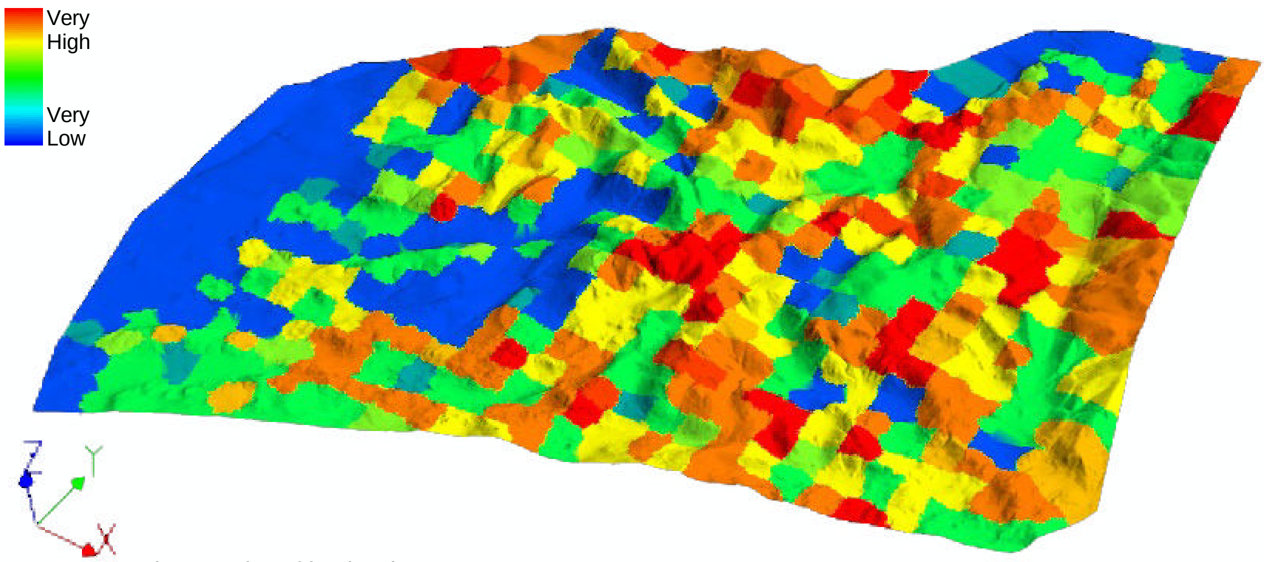
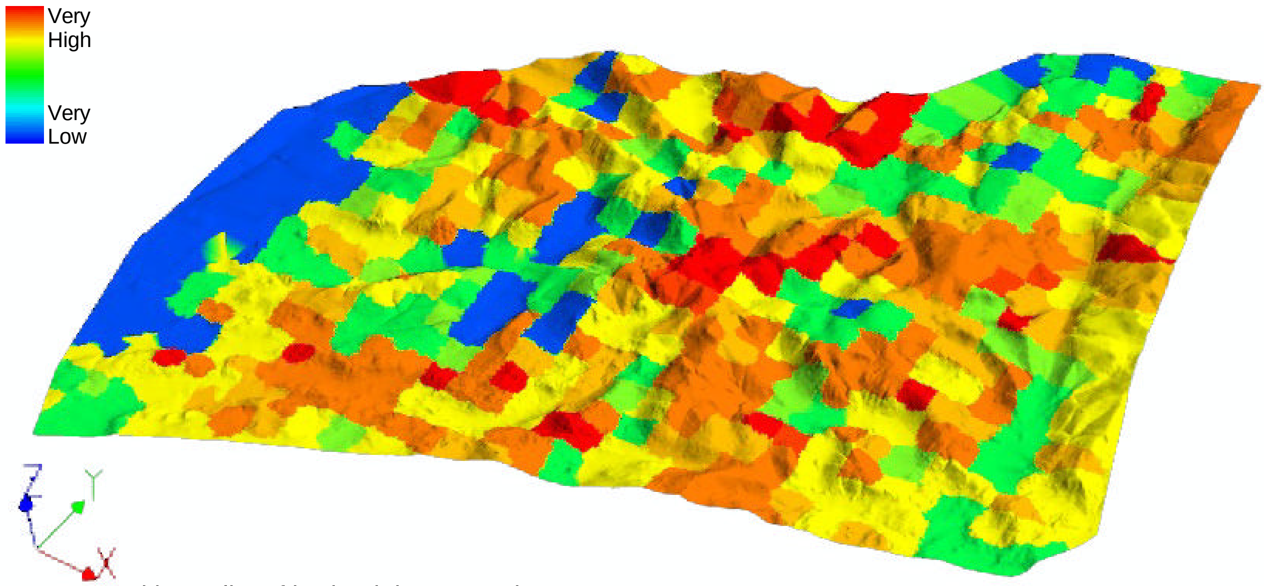


Figure 2.9. The Lake District DGSM (Scafell Caldera sub-area) Structural Framework. All elements that comprise the structural framework are shown (with the exception of the DTM).

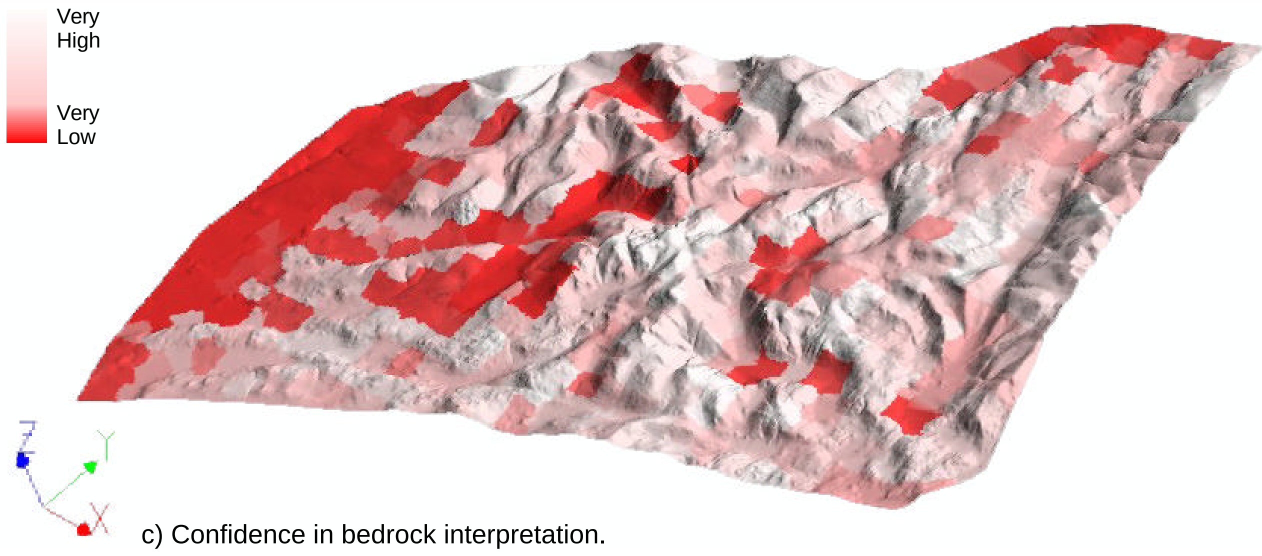
Figure 2.9



a) Quantity of bedrock exposure.



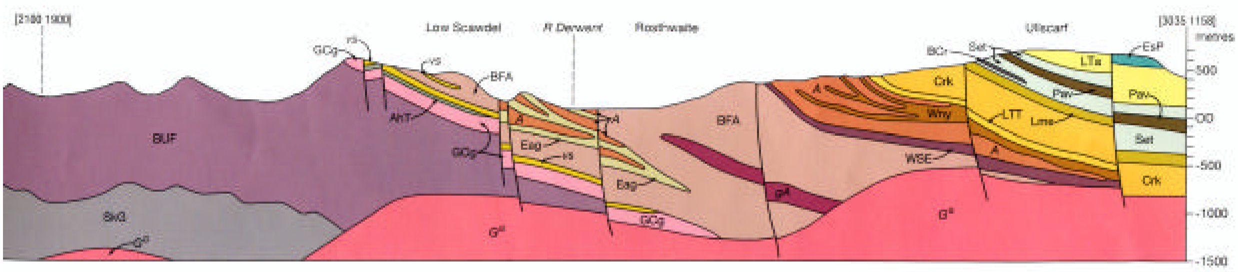
b) Quality of bedrock interpretation.



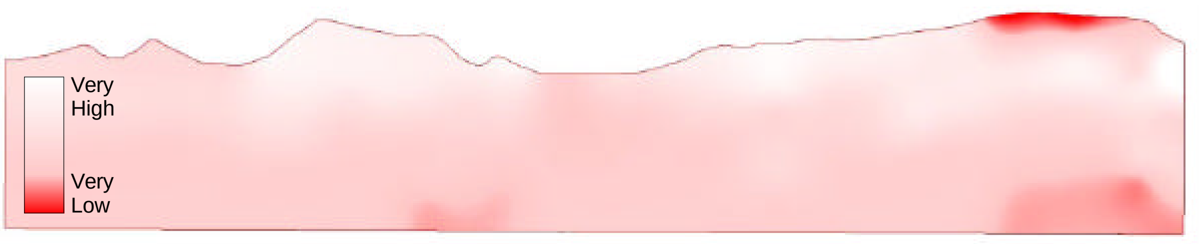
c) Confidence in bedrock interpretation.

Figure 2.10. The Confidence in the geological bedrock interpretation of the Scafell Caldera sub-area. Confidence (c) is a combination of the quantity of bedrock exposure (a) and the quality of interpretation (b). Note how areas of high confidence coincide with maximum exposure and areas of low confidence coincide with areas of cover and urban settlement

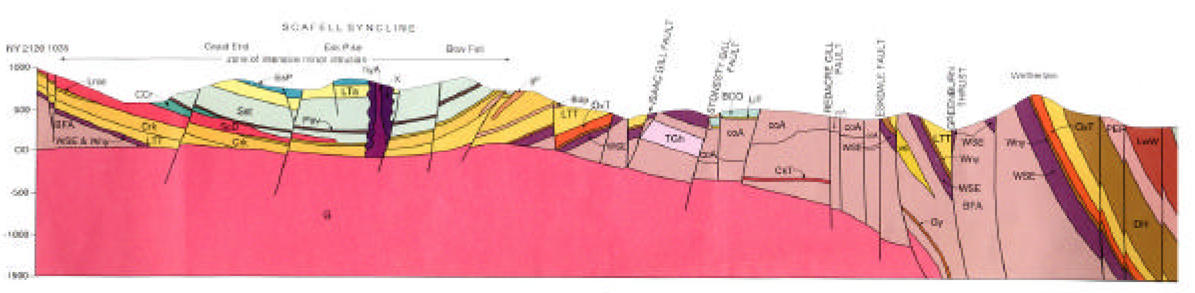
SECTION 029 (KESWICK)



SECTION 029 (KESWICK) - CONFIDENCE



SECTION 038 (AMBLESIDE)



SECTION 038 (AMBLESIDE) - CONFIDENCE

Figure 2.11. Confidence in the interpretative sections used in the Lake District DGSM (Scafell Caldera sub-area). 1:50000 Sections taken from BGS (1996;1999b).

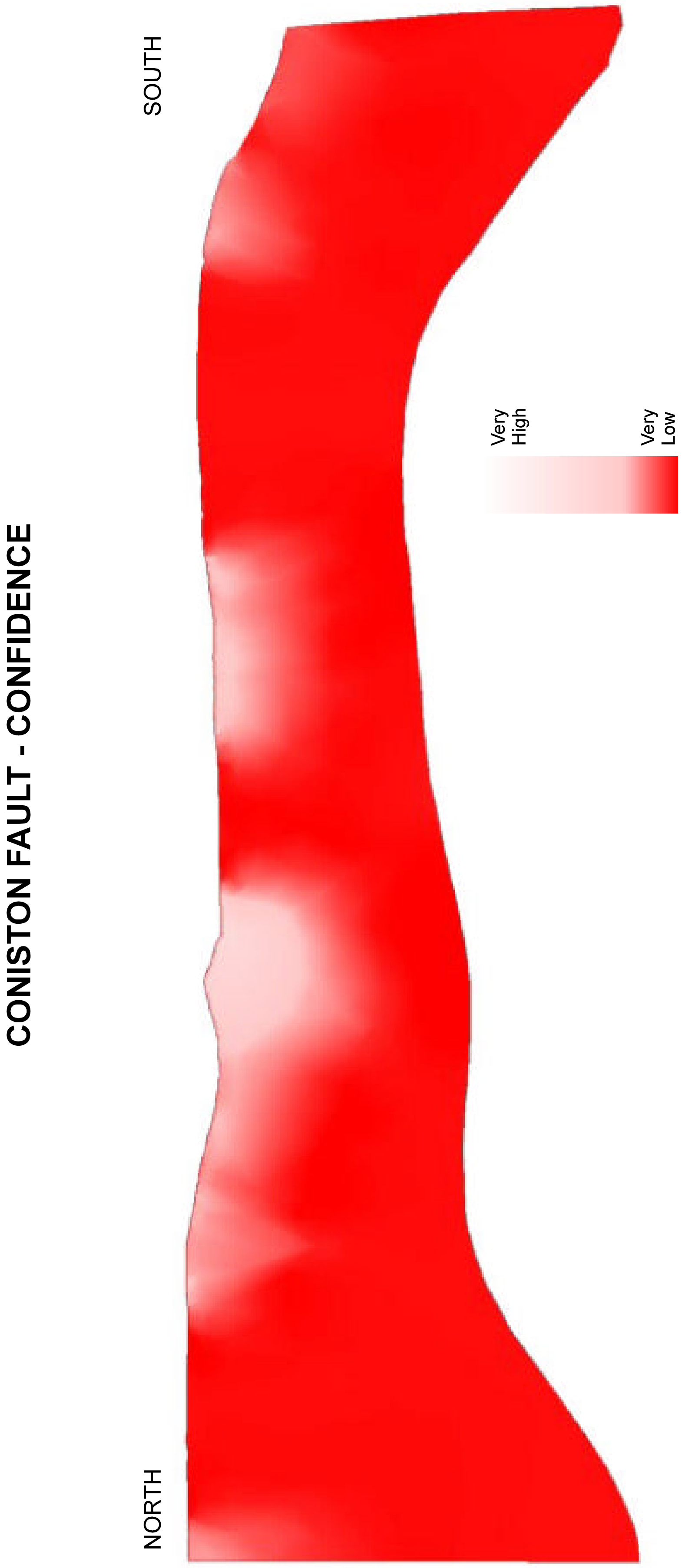


Figure 2.12. Confidence in the interpretation of the Coniston Fault. Note how confidence decays rapidly below the topographical cut as the fault surface at depth is simply an extrapolation of surface dip data. Confidence varies laterally at the surface (and therefore at depth as well) as a result of the level of exposure.

Figure 2.12

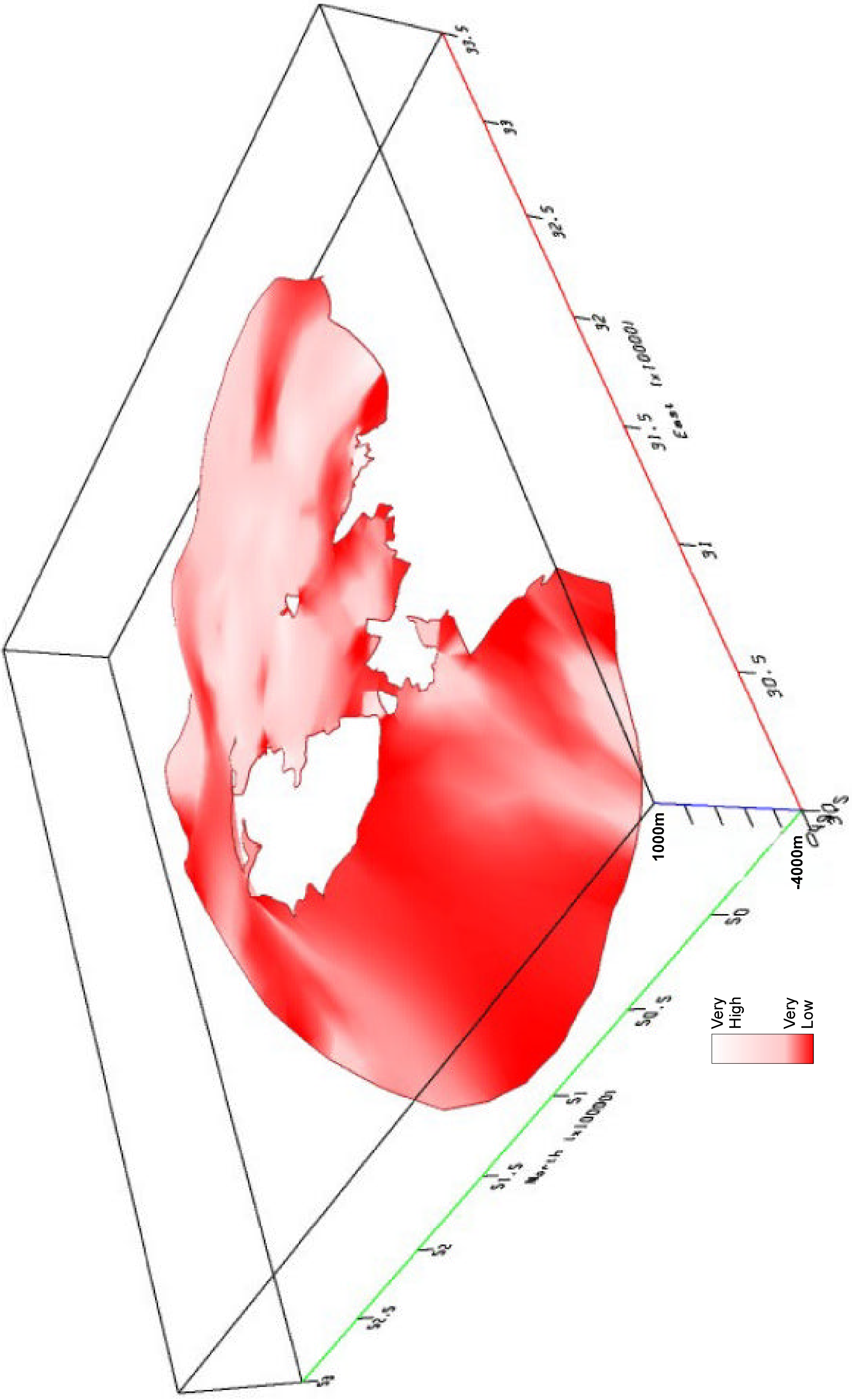


Figure 2.13. Confidence in the top Lake District batholith surface based on the gravity and magnetic modelling work of Lee (1989).

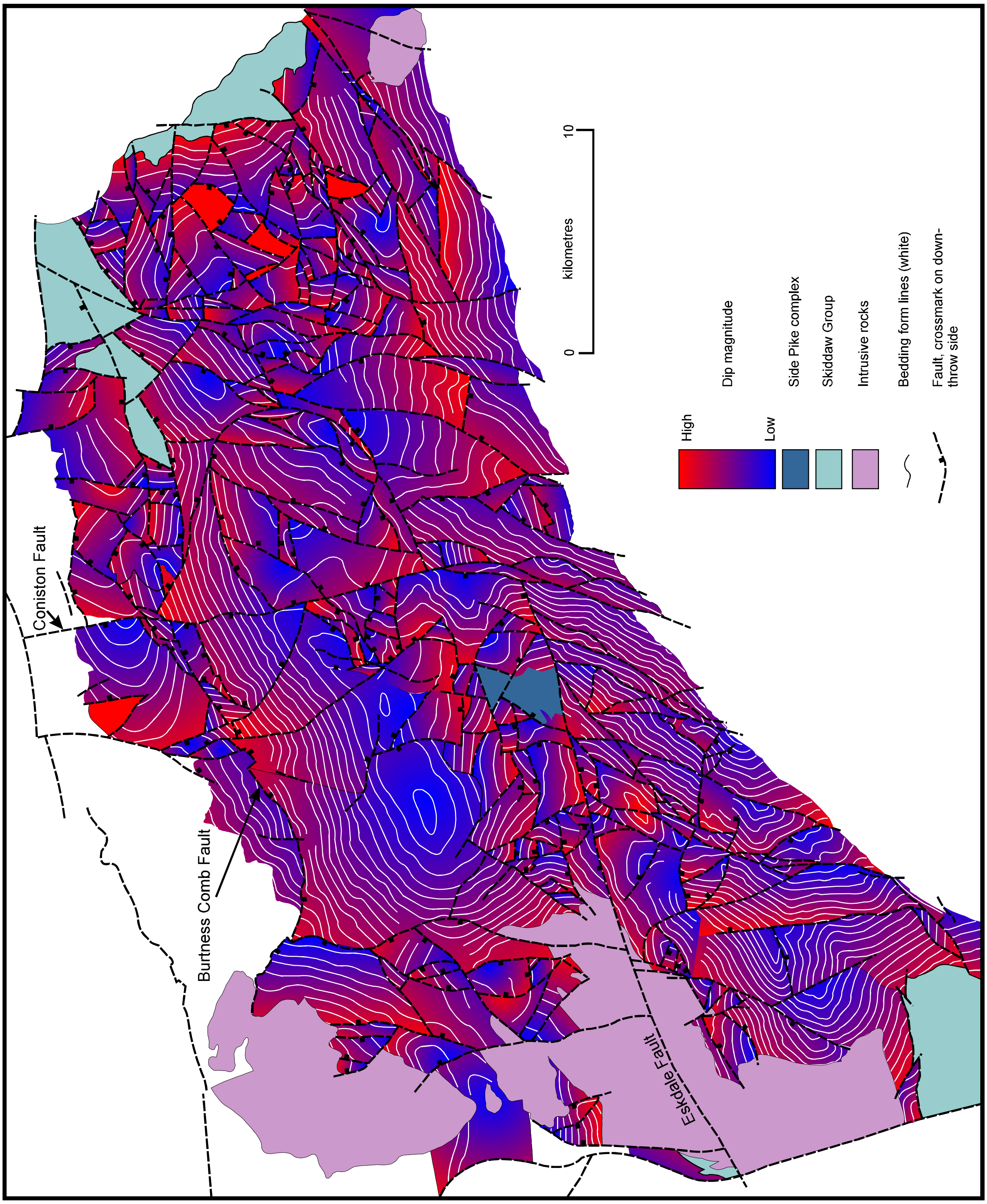
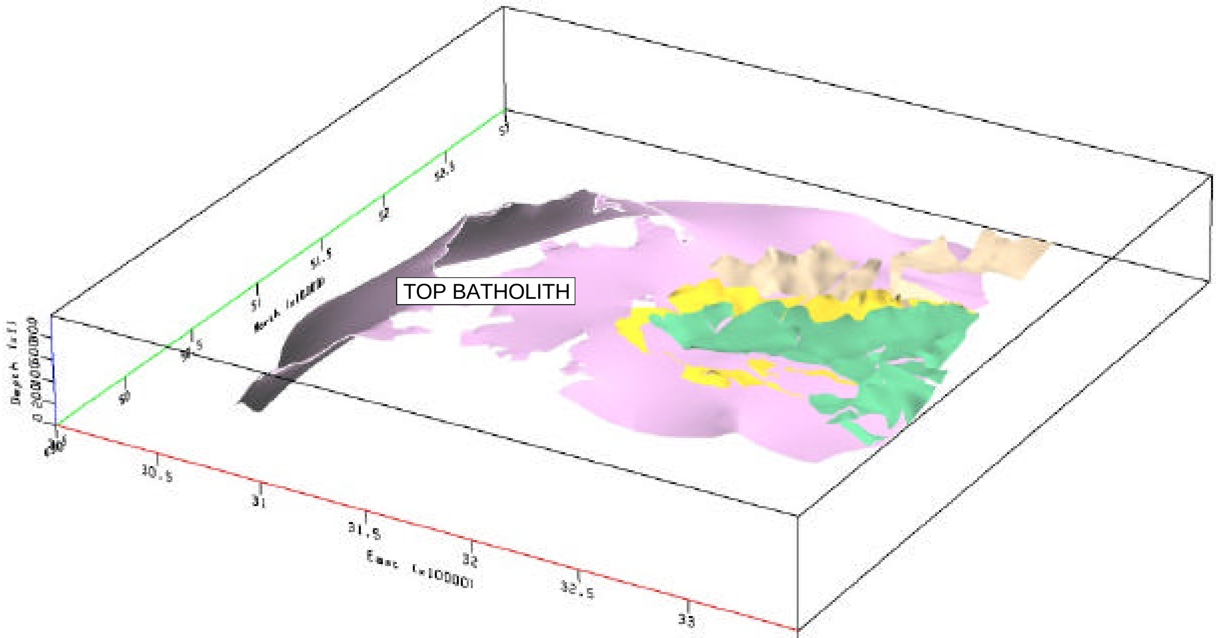
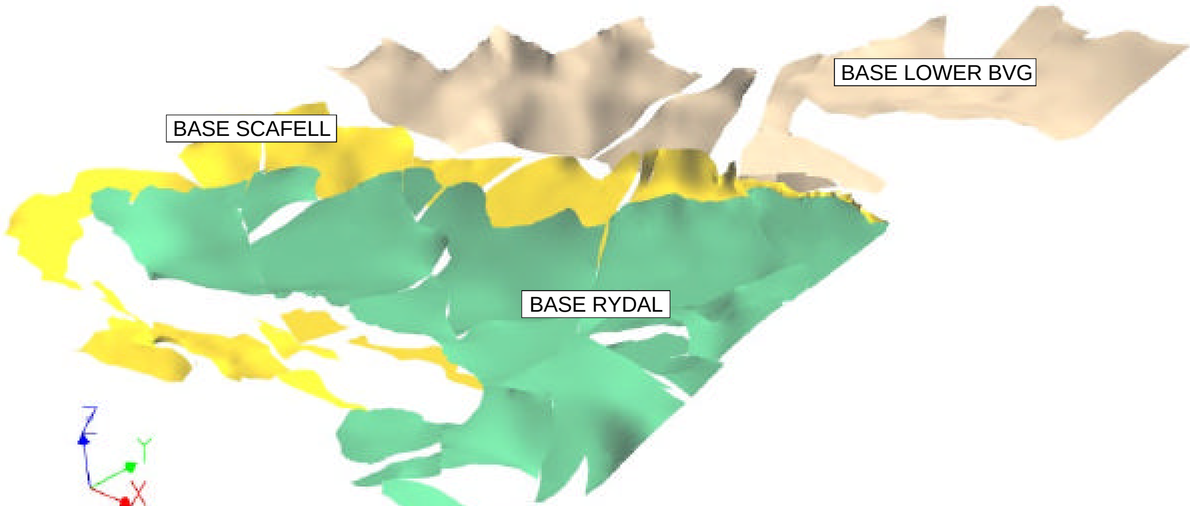


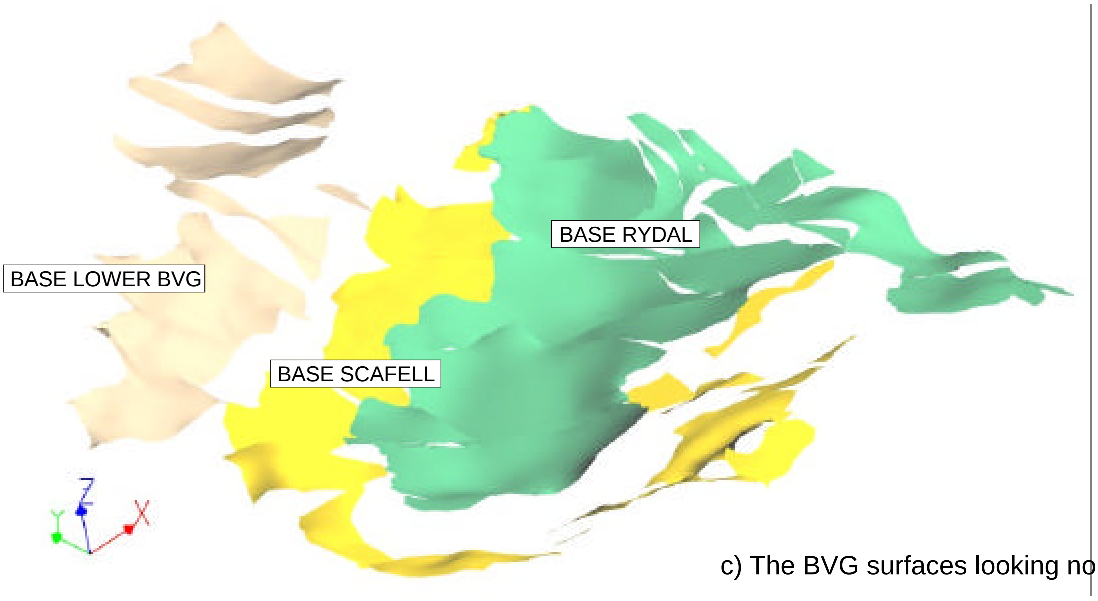
Figure 2.14 - The structural form of the BVG within the Lake District DGSM (modified from: Millward, 2002, fig. 6). Colour shading indicates direction of dip within fault blocks such that red is steep and blue is relatively shallow. Form lines assume a unit with a nominal thickness of 200m.



a) The intrpreted surfaces of the base Rydal, Scafell and Lower BVG with the top Batholith surface



b) The BVG surfaces looking northwest



c) The BVG surfaces looking northeast

.Figure 2.15. The modelled B.V.G. surfaces of the Rydal, Scafell and Lower B.V.G. successions. In (a) the top batholith surface is shown to help in locating the BVG interpretation. The synclinal form to the B.V.G. is clearly visible in the base Rydal and Scafell surfaces (b & c). In all figures, 'X' points east, 'Y' points north.

Figure 2.15

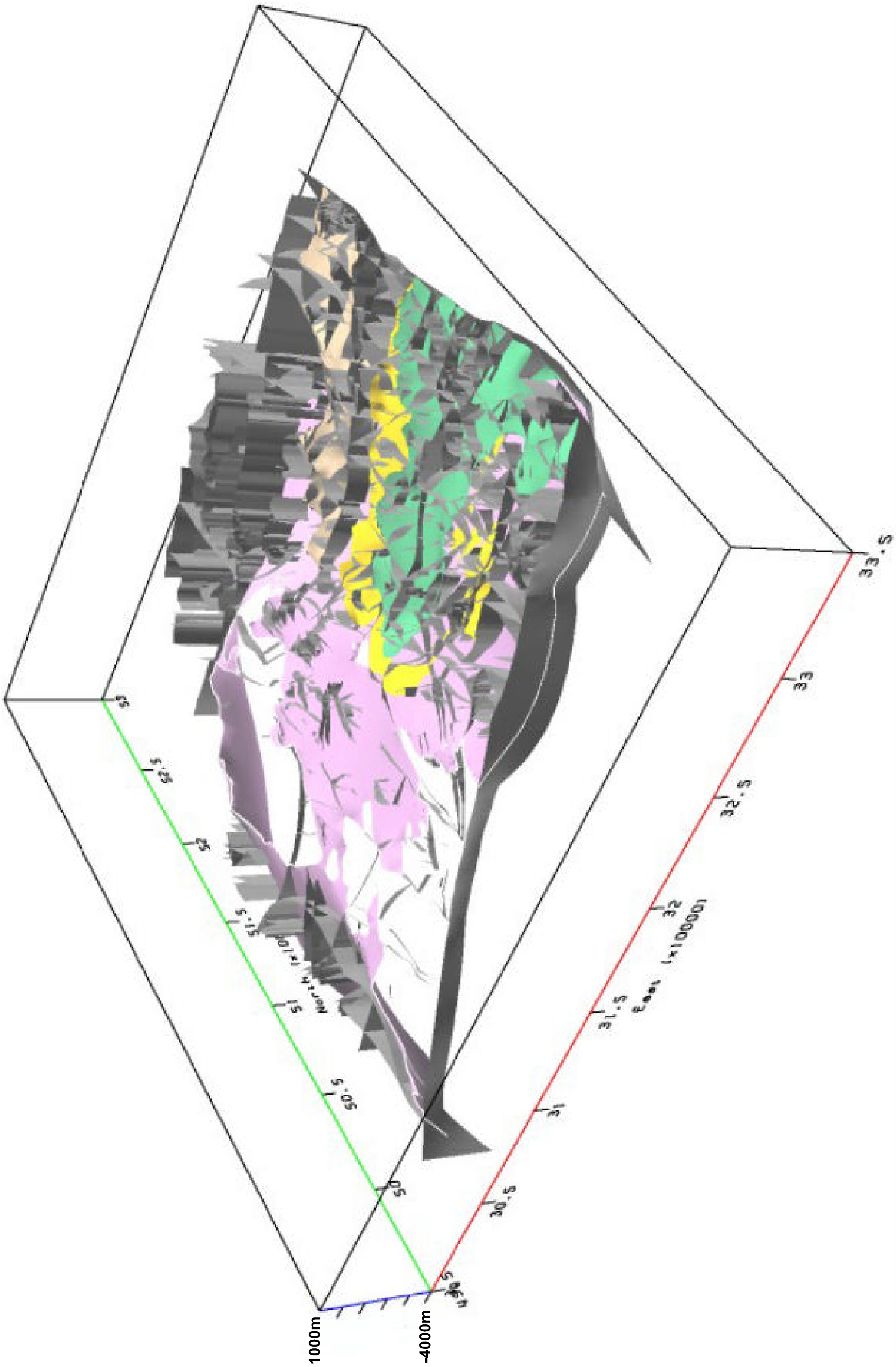


Figure 2.16. The full Lake District DGSM (Scafell Caldera sub-area) Model. All surface colours are as per figures 2.15 and figure 2.4.

Figure 2.16

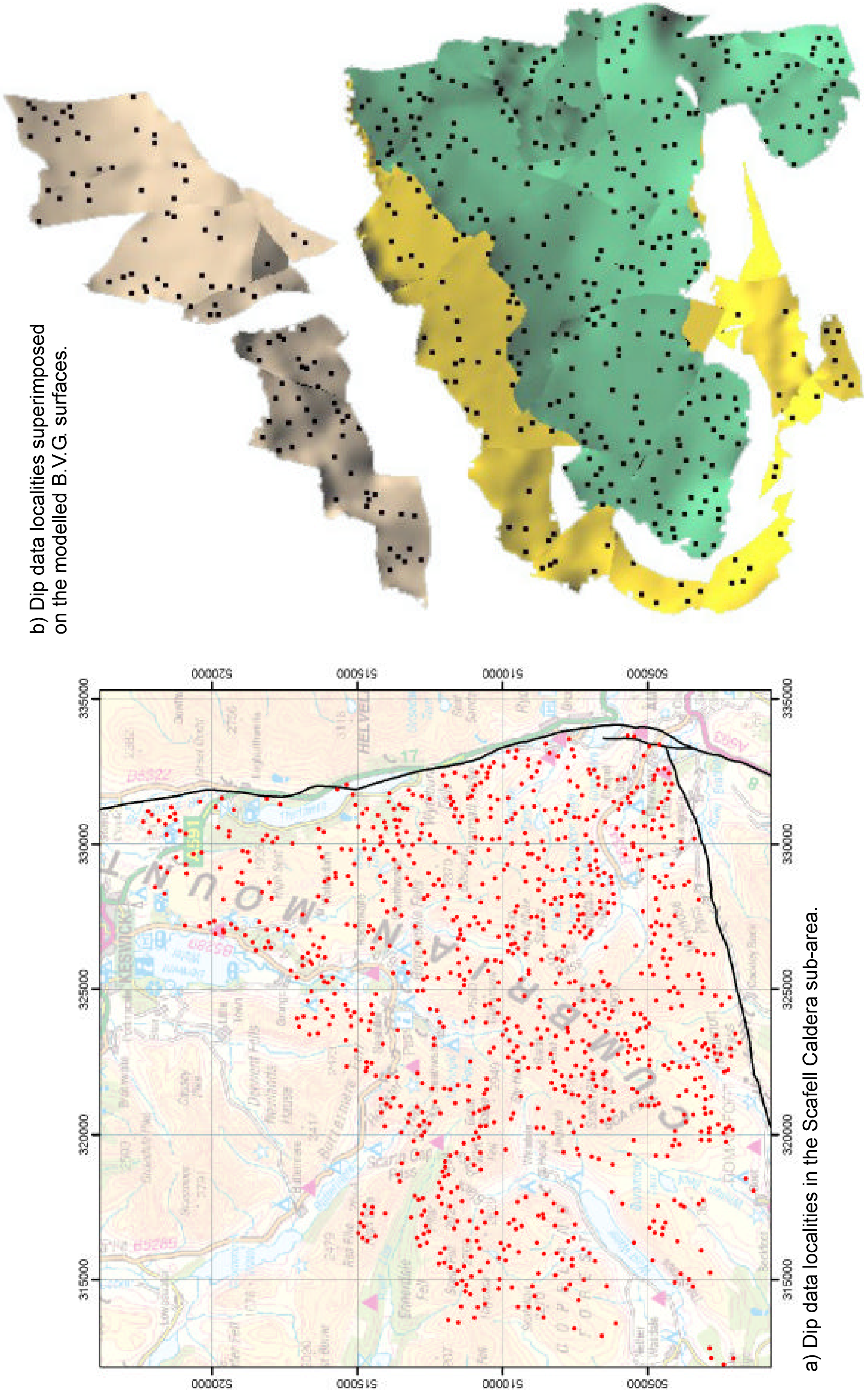
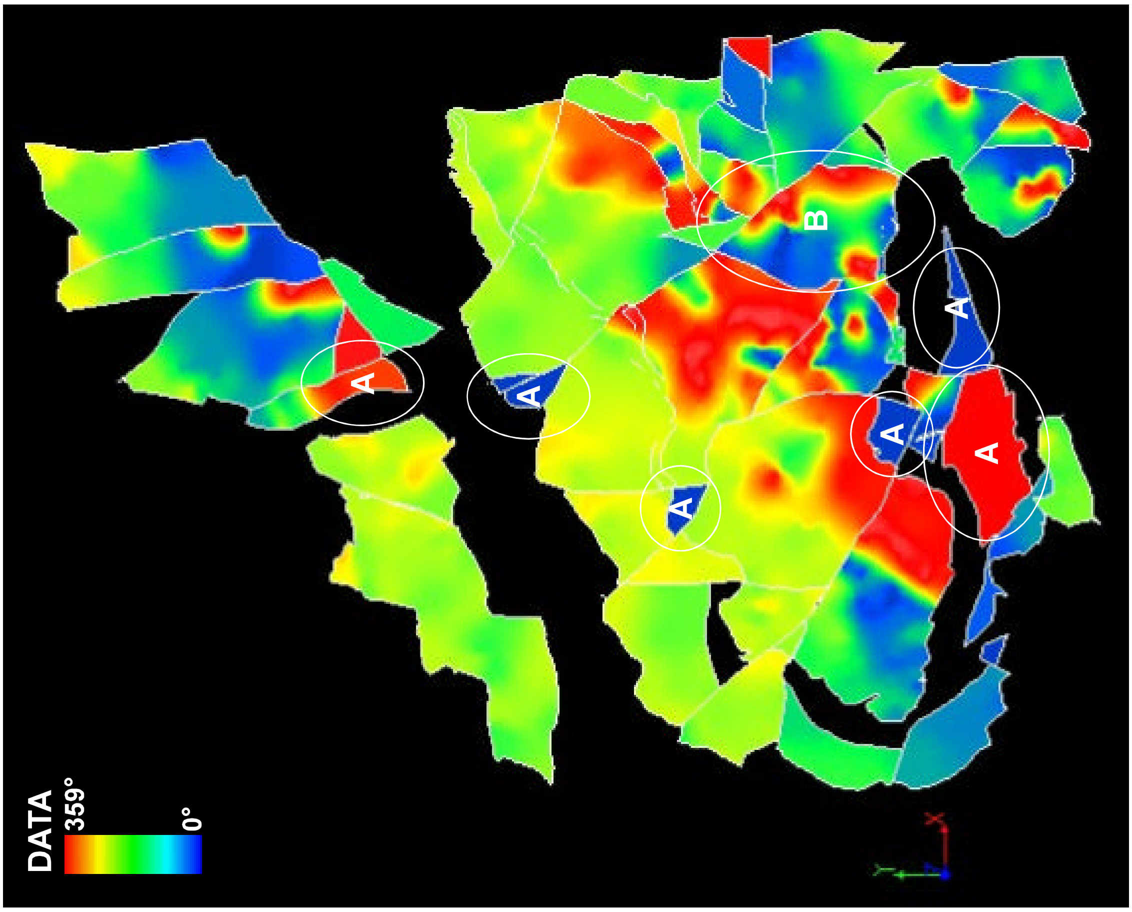


Figure 2.17. a) Sample points over the Scafell Caldera sub-area for which structural dip data of the BVG successions are known. (b)The sample points superimposed onto the modelled surfaces of the BVG successions.

Figure 2.17



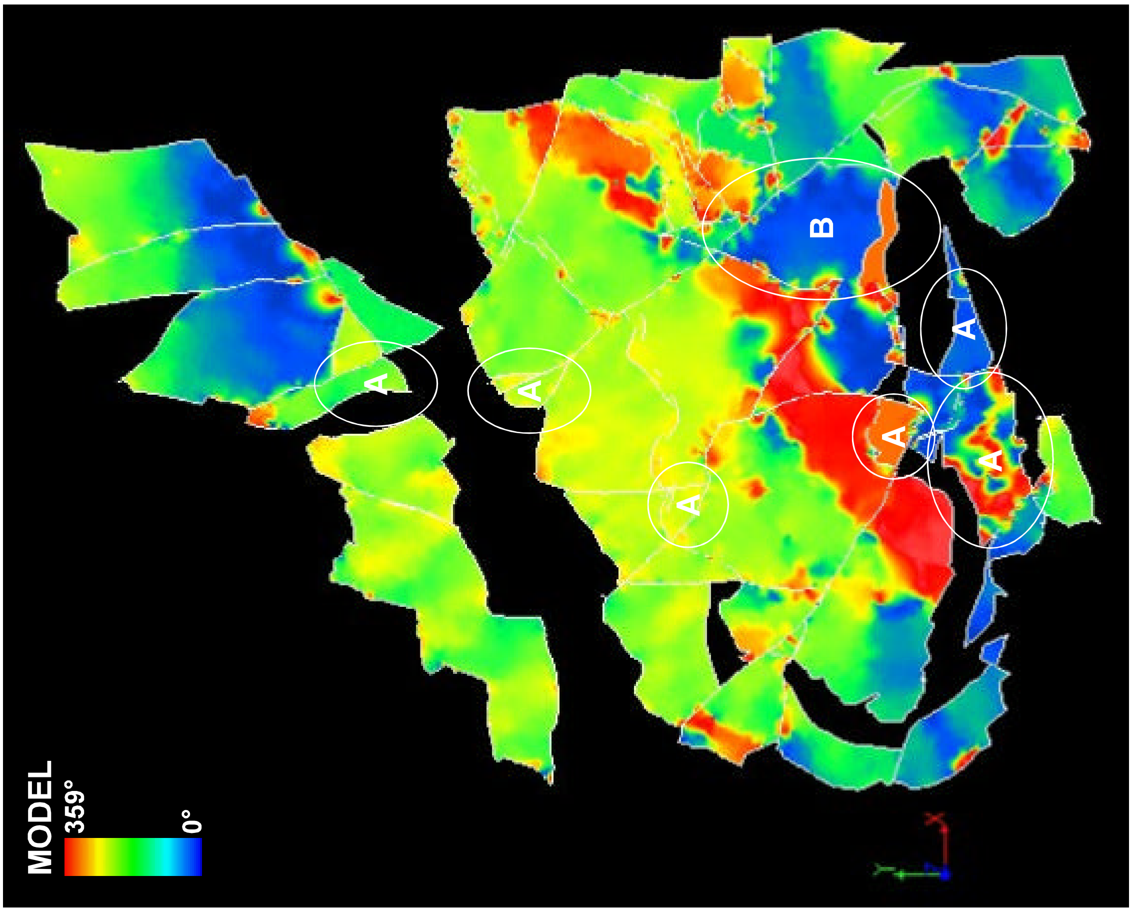


Figure 2.18. The dip-azimuth of modelled B.V.G. surfaces (MODEL) compared to measured surface structural dips (DATA) interpolated over the same map areas. Differences in areas marked 'A' are the result of lack of data.

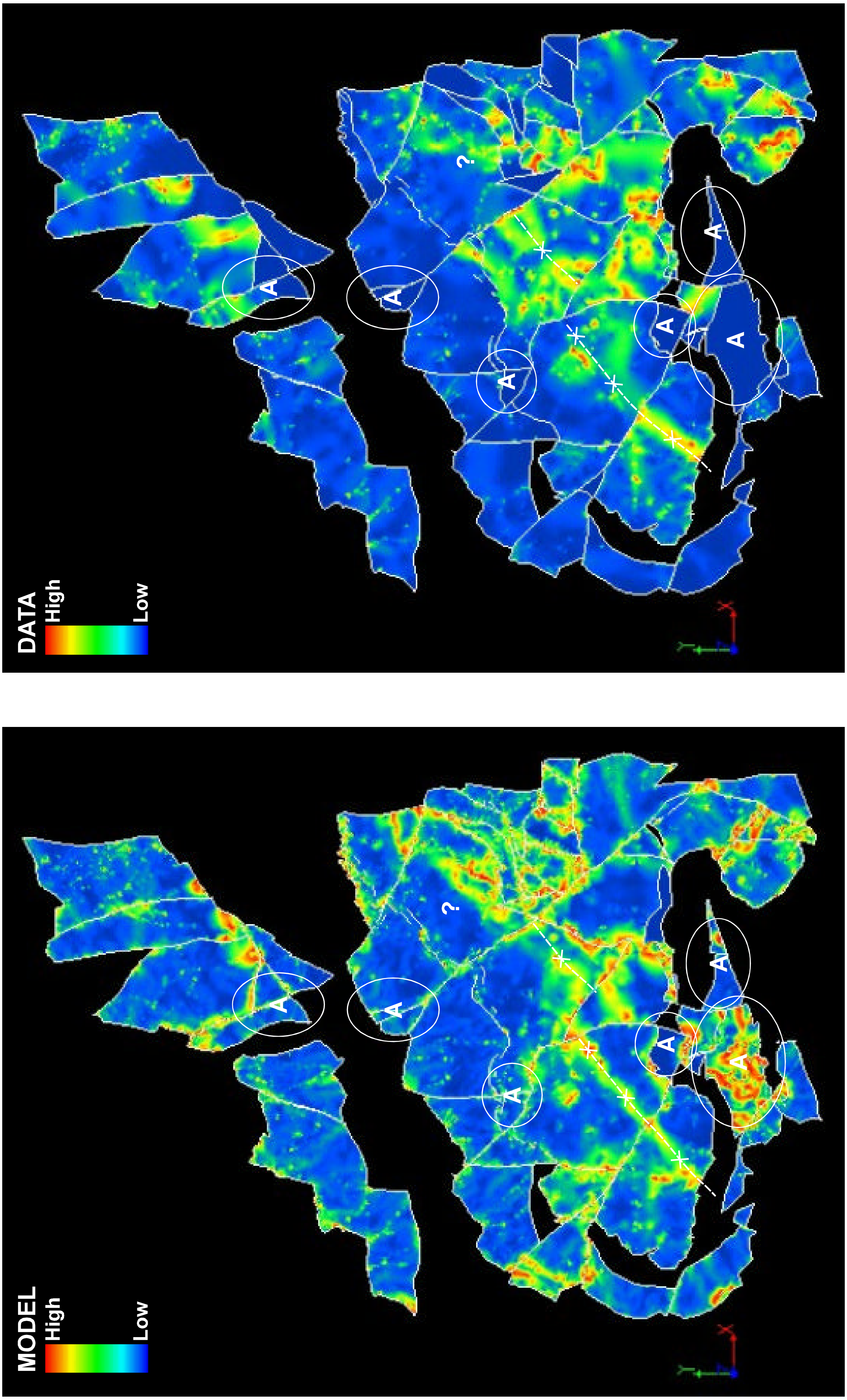


Figure 2.19. Dip-azimuth curvature of the modelled B.V.G. surfaces compared to that predicted from surface data. The dip-azimuth curvature highlights the areas of rapid changes in dip-azimuth; i.e. fold axes. The position of the Scafell synclinal axis is clearly visible and correlates betweenmodelled surfaces andmeasured data.

Figure 2.19

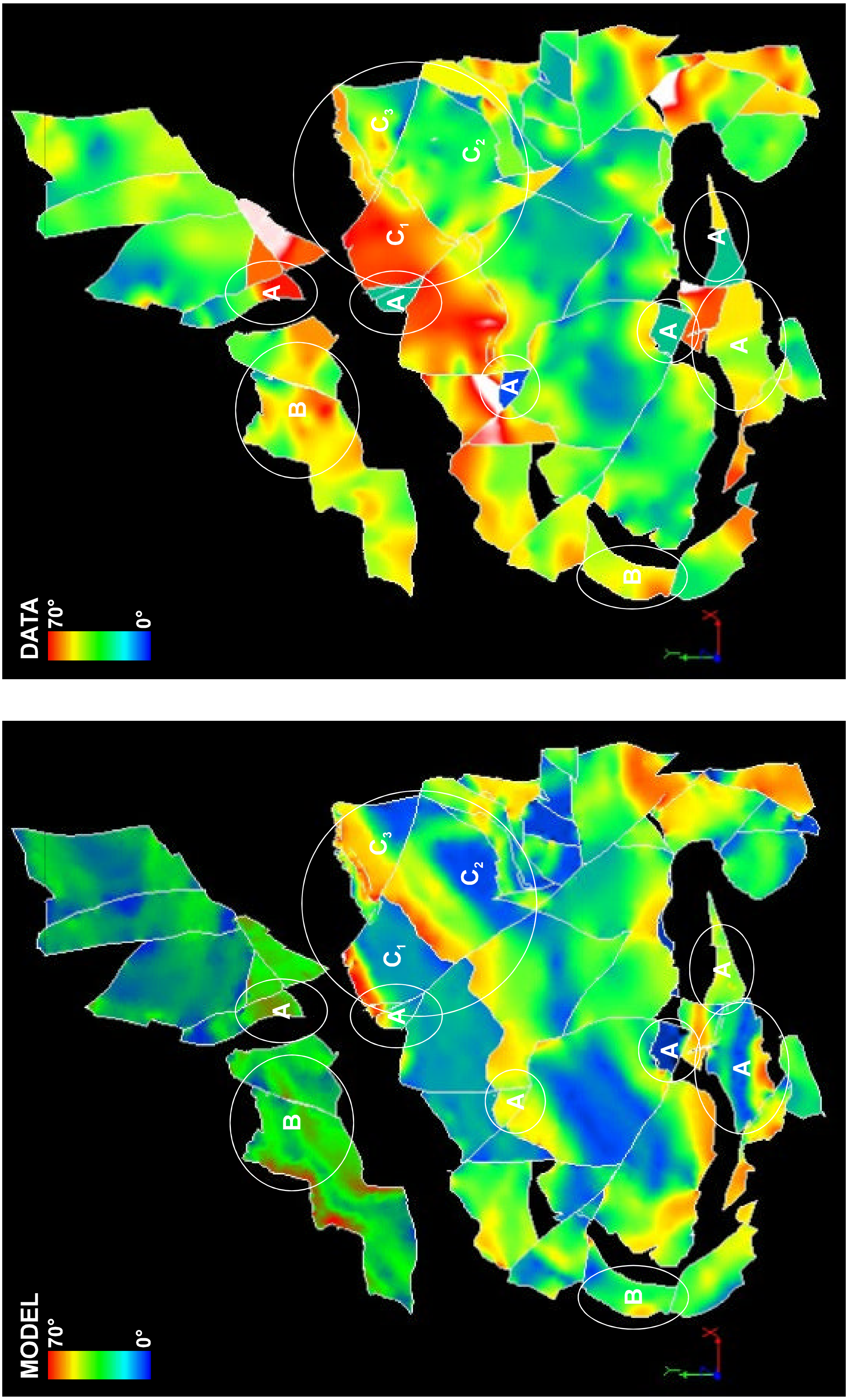
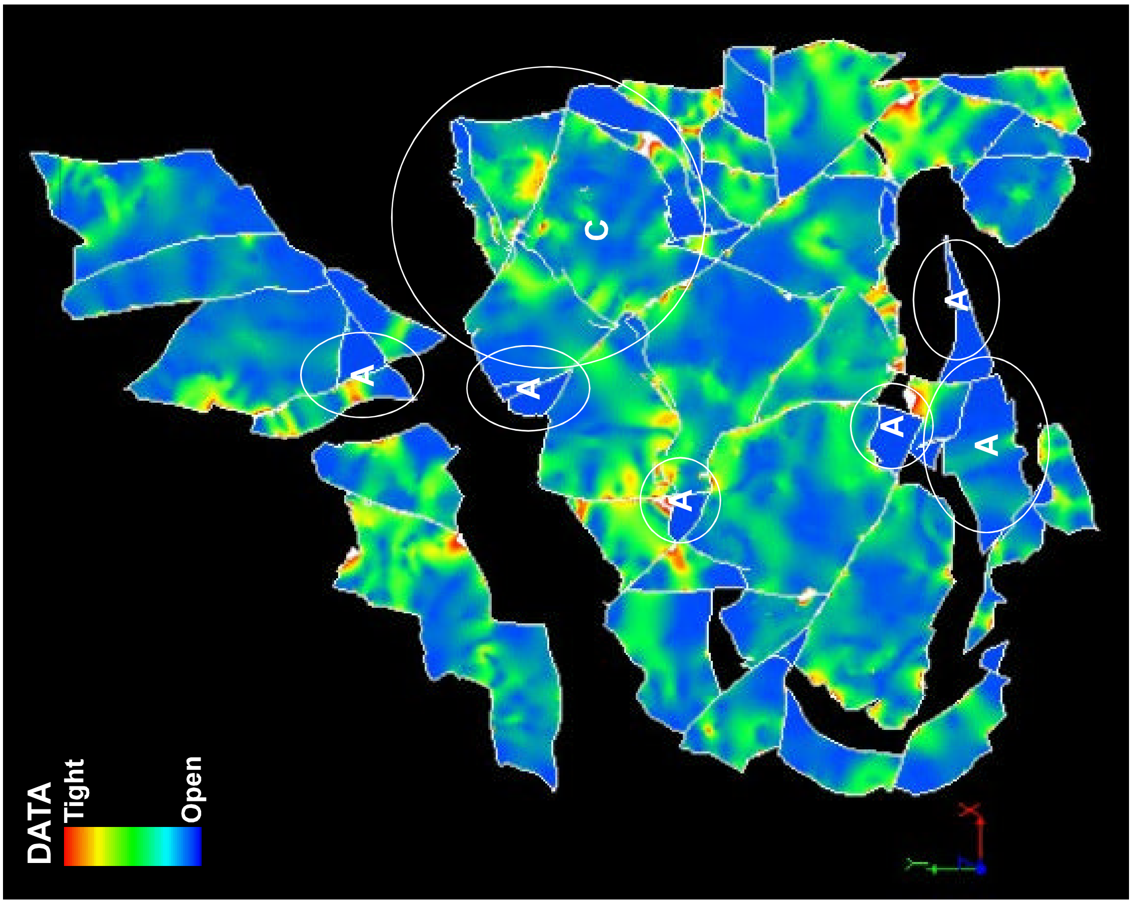


Figure 2.20. The dip-magnitude of the B.V.G. surfaces compared to measured surface data. The areas marked ‘B’ show differences in value but similarities in distribution of dips-magnitudes. The area marked ‘C’ shows markedly different structural styles. Themodelpredicts curved surfaces and the data predicts planar surfaces.

Figure 2.20



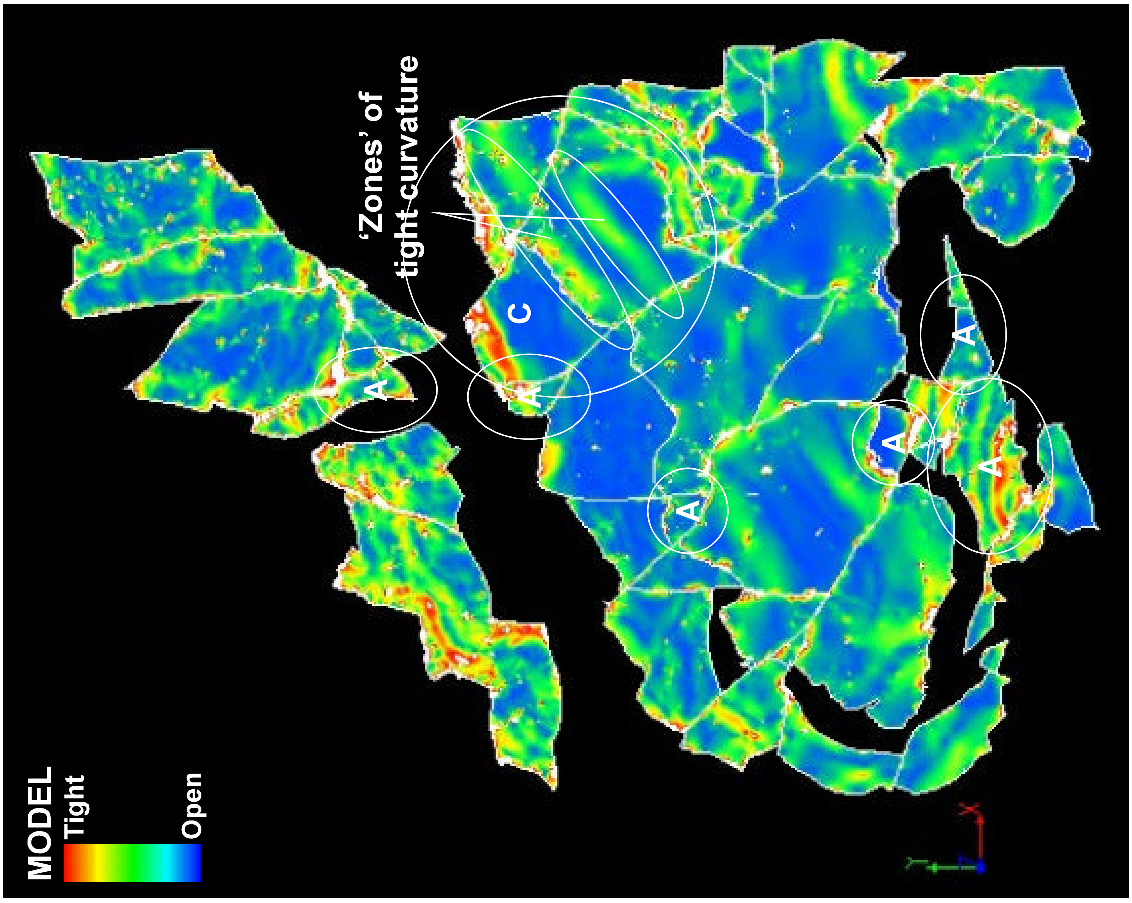
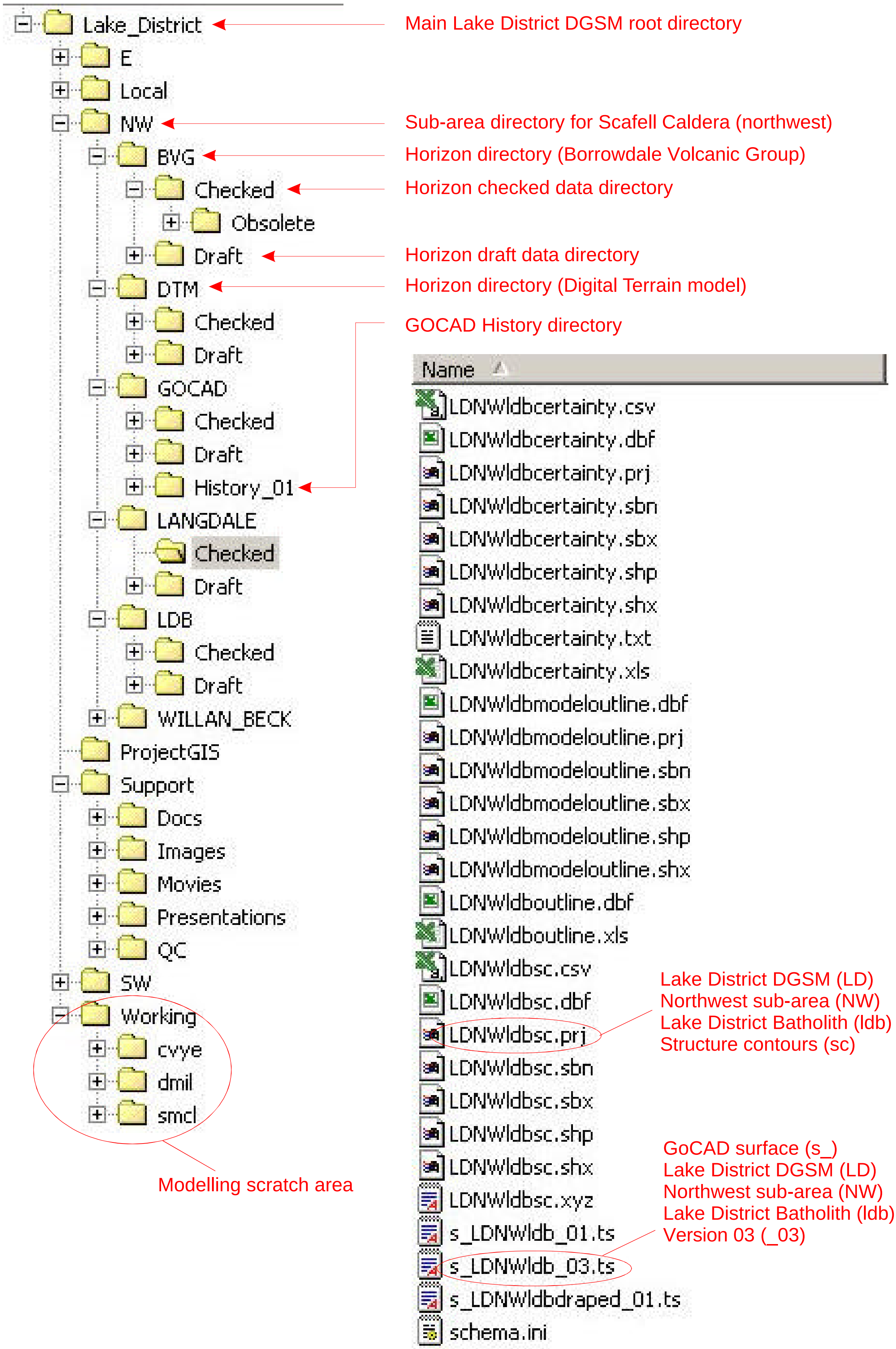


Figure 2.21. The dip-magnitude curvature of themodelled B.V.G. surfaces compared to measured surface data. Note that the modelled surface show clear zones of tight curvature between planar segments in area 'C' but the measured data showsmoreconstant, open curvature changes in dip-magnitude.

Figure 2.21



.Figure 3.1. The Lake DistrictDGSMdirectory structure and file naming conventions. Some examples of the breakdown of the file names are given.

Figure3.1

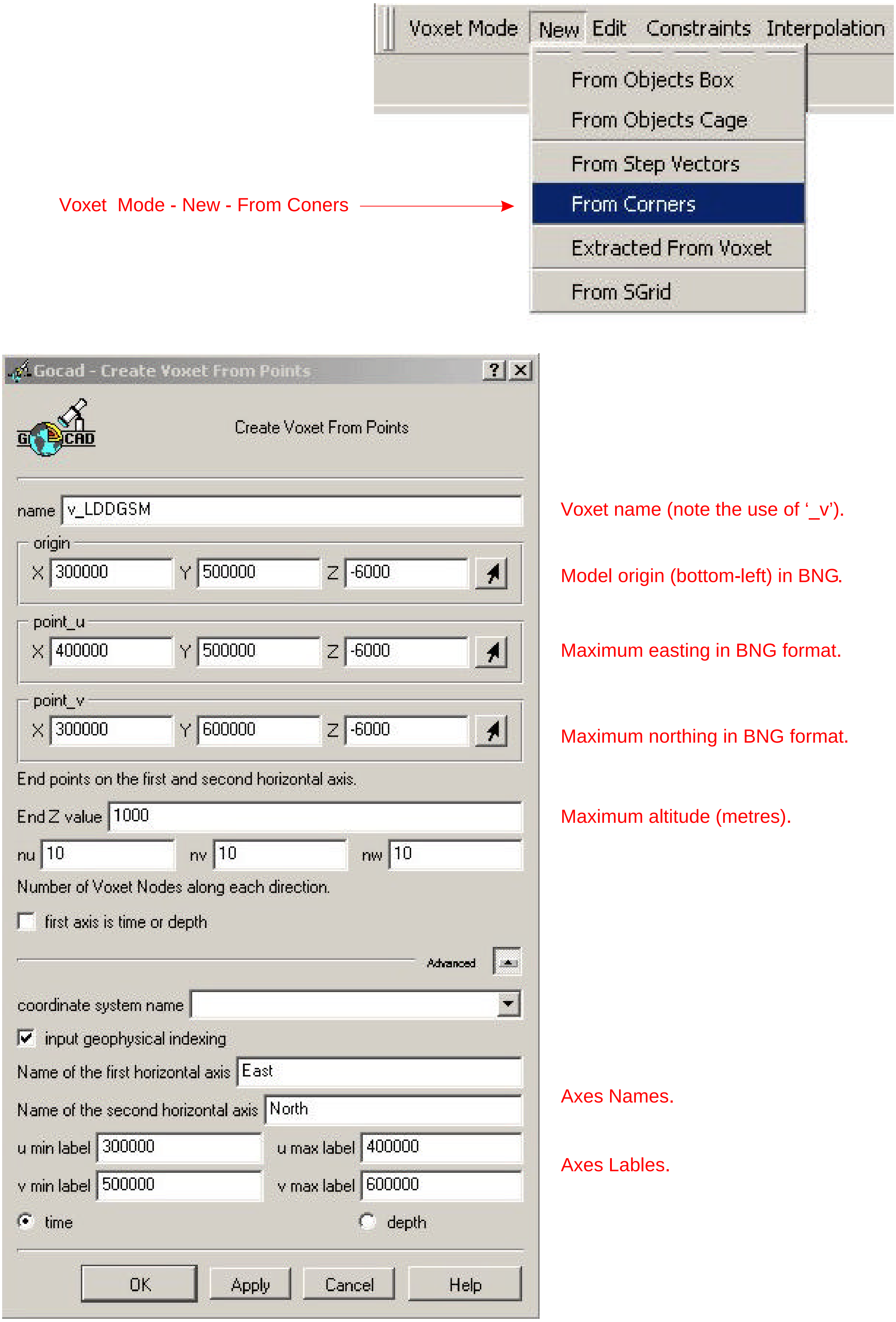


Figure 3.2. Setting up the model workspace in GoCAD by defining a model 'Voxet' based on the British National Grid coordinate system.

Figure 3.2

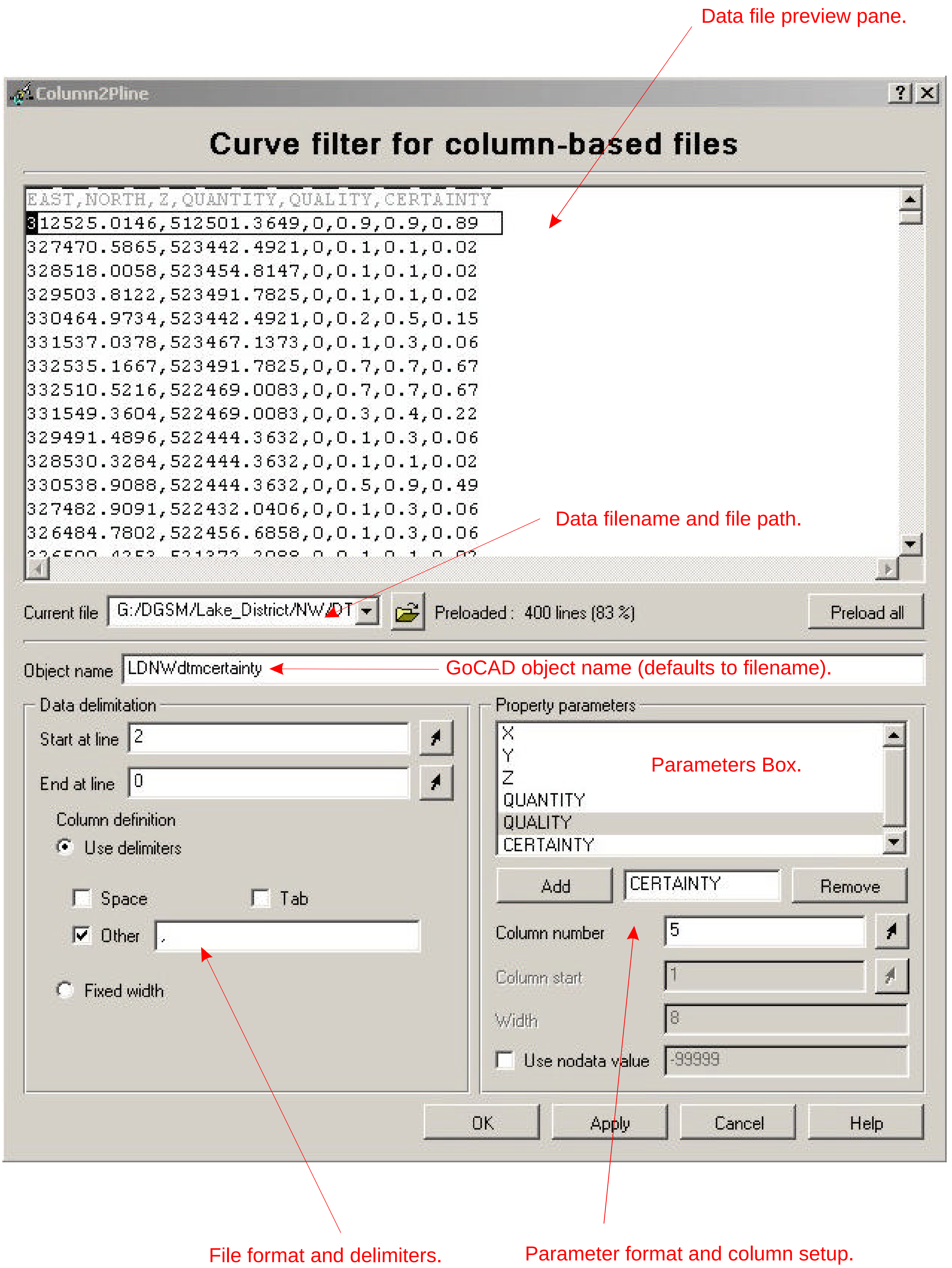


Figure 3.3. The text format raw data file import filter used for importing both lines and points into GoCAD. Attributes (properties) can be imported at the same time by adding property fields to the parameters box. For lines, the property SEGID should be included that defines the segment ID of the point. points with the same segment ID will be connected into the same line.

Figure 3.3

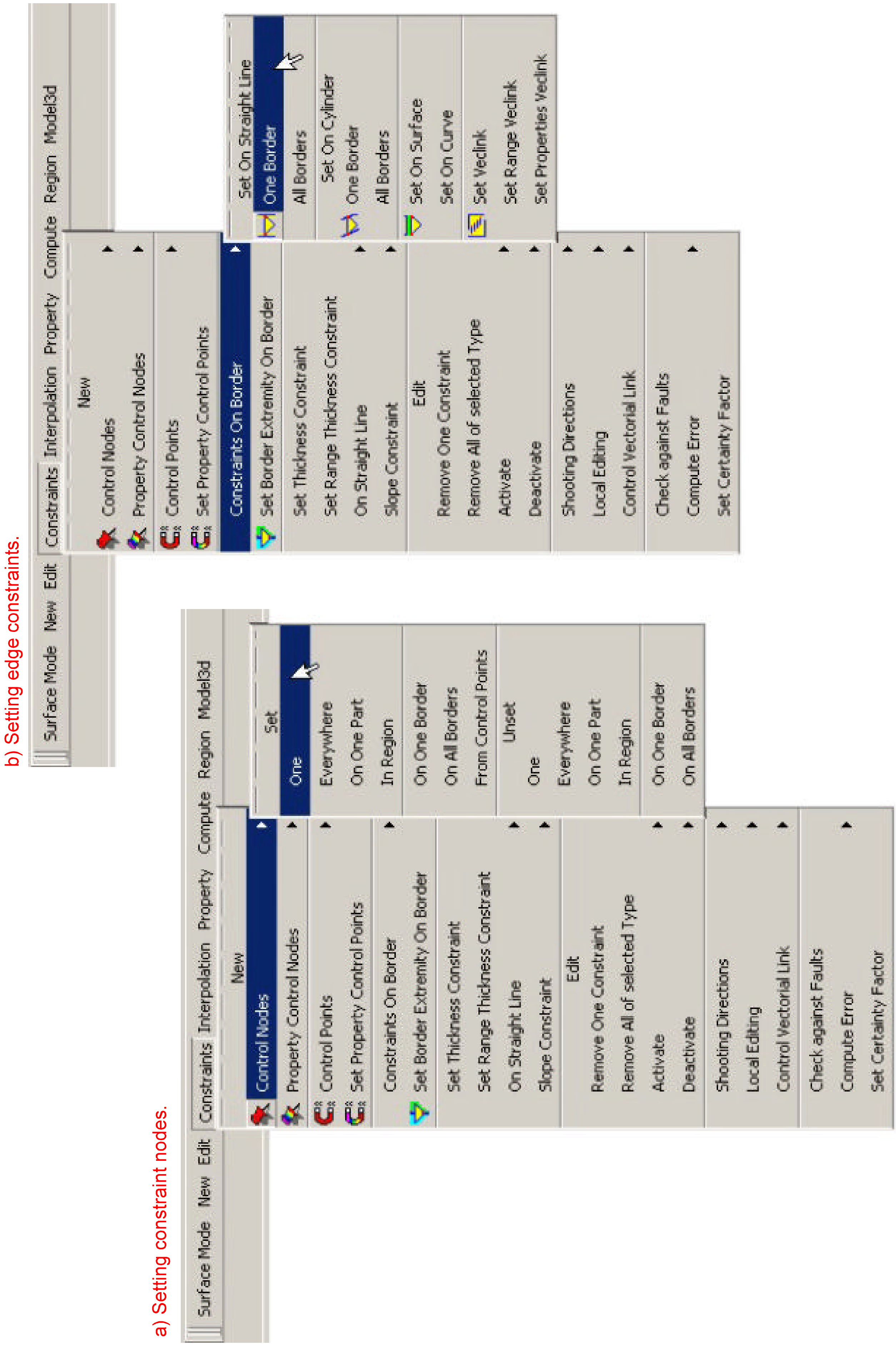


Figure 3.4. Setting node and edge constraints in GoCAD. a) Points set as nodal constraints will not move durring interpolation or smoothing. Edge points set as shown in (b) will only move in the vertical (z) sense.

Figure 3.4

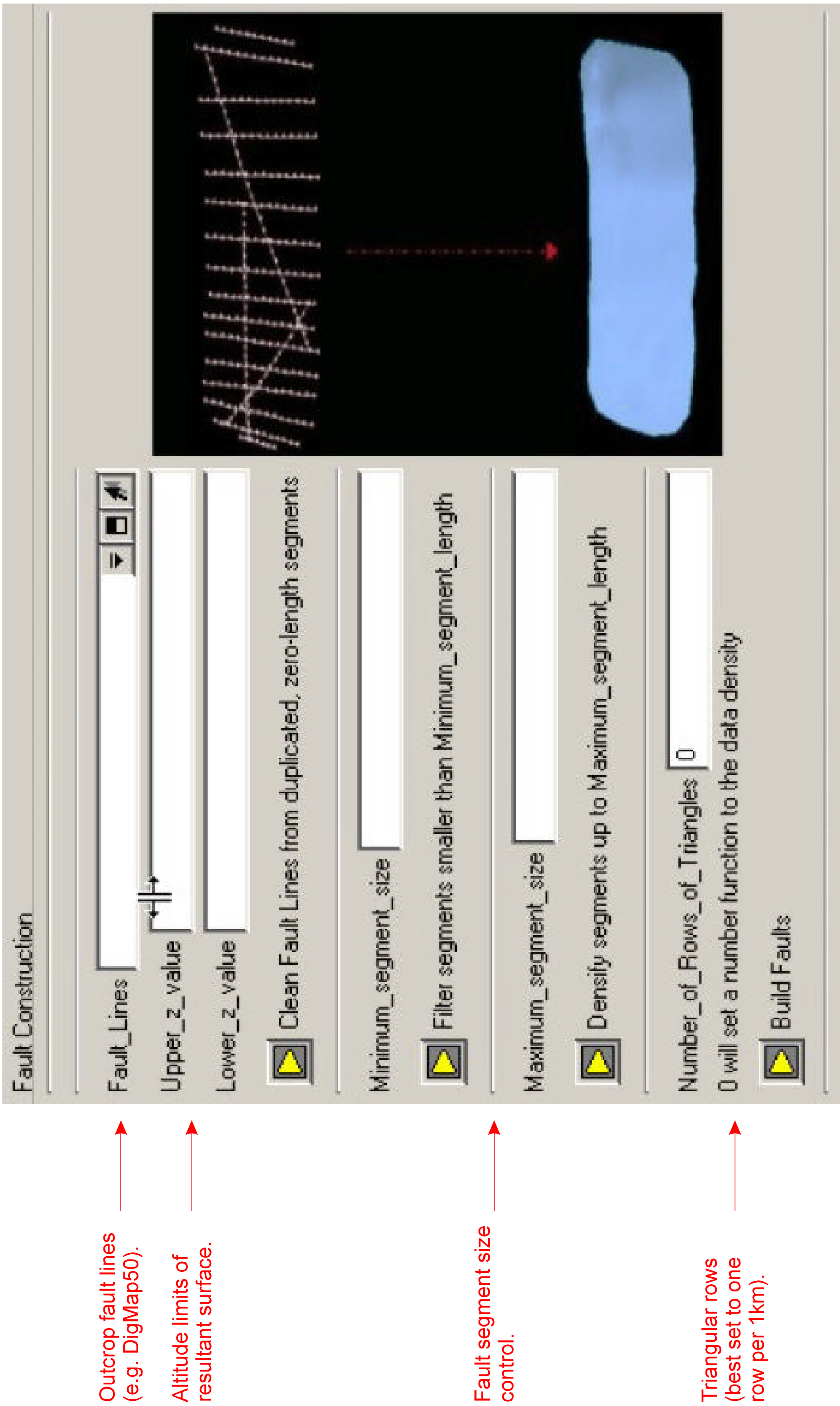


Figure 3.5. The vertical fault construction wizard.