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A workflow to facilitate three-dimensional geometrical modelling of complex poly-deformed geological units

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ABSTRACT

The three-dimensional (3D) geometry of complexly deformed regions is often beyond the scope of simple 2D and 2.5D representation in cross-sections and block diagrams. Methods must be developed for fully three-dimensional representation. A workflow for such three-dimensional modelling of structurally complex areas is presented. Data requirements are tailored to typical results of structural field work in strongly deformed rocks from mid-crustal levels. The workflow is based on data evaluation and data export using standard geographical information system and database management systems. Three-dimensional modelling in polyphase deformed areas is highly dependent on the correct interpretation of variations in the orientation of the dominant planar fabrics. The computer-aided earth-modelling software 3D GeoModeller is well adapted for managing this problem. It calculates the geometry of geological interfaces taking into account simultaneously the foliation data and location of lithological contacts. The workflow is based on iterative model refinement based on interactive editing of the geometry in section and map views with data assessment and pre-processing using GIS software. This approach assures internal consistency of the resulting three-dimensional models. Modelling of the Lower Lepontine Nappes in the Central Alps is used as an illustrative example from a complexly deformed terrain.

1. Introduction

Disentangling the polyphase deformation history in structurally complex areas is always a challenging task (e.g., Ramsay, 1967). This is especially true in mid-crustal levels where several successive ductile deformation phases entailing km-scale isoclinal recumbent folding and regional-scale thrusting may occur. Developing an internally consistent model of such areas can be very difficult (compare examples in Milnes, 1974; Steck, 1984; Brunel, 1986; Pognante et al., 1990; Spring and Crespo, 1992; Grujic and Mancktelow, 1996). Moreover, mid- and lower-crustal tectonic levels are generally dominated by magmatic or metamorphic crystalline basement rocks with typically rather low contrasts in their geophysical properties. Reflection seismic investigations are therefore limited in their ability to provide independent constraint on the scale of hundreds of metres or a few kilometres. However, it is specifically these tectonic levels that accommodate much of the deformation occurring during continental collision and they are key elements in understanding the geodynamics and kinematics of orogenic belts (e.g., Manatschal et al., 1998; Weijermars and Khan, 2000; Gerya et al., 2002; Stöckhert and Gerya, 2004). It is

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therefore crucial to establish the three-dimensional (3D) geometry of such regions as exactly as possible, in order to provide a reliable benchmark for models of continental collision.

In the absence of good geophysical control on the subsurface geometry of geological units, it is left to borehole measurements, tunnelling data, remote sensing and especially field observations to provide the information required to build a three-dimensional geological model. Boundaries between different lithological units (i.e., lines of outcrop), knowledge about possible correlations of these units (mainly from petrological examination) and recognition of geometric and kinematic constraints (from structural observations) are the principal inputs from field-based geological investigations. This information can be combined to develop a model of the geometry of the geology in three dimensions, often illustrated in a series of cross-sections or as a block diagram (e.g., see the description and instructive examples in Meyer, 1991; Steck and Hunziker, 1994 and Steck, 1998). Agreement with outcrop lines and internal consistency provide important visual cross-checks, but these are more readily and thoroughly controlled in truly three-dimensional models. Whereas a lack of data from areas that are difficult to access can be partially compensated by remote sensing (e.g., Alwash and Zakir, 1992), the insufficient density of subsurface data cannot normally be overcome, which generally leaves considerable freedom for different possible interpretations (Renard and Courrioux, 1994).

Two main approaches to modelling such complex geometries can be distinguished. *Explicit modelling* uses an explicit definition of each object in the model. Surfaces bounding the different formations are defined (for example with triangulated surfaces, two-dimensional grids, or parametric surfaces) and constructed by interpolation of the data (e.g., Renard and Courrioux, 1994). In this context, a wide variety of interpolation techniques are used including geostatistics (Chilès and Delfiner, 1999), splines, Bezier surfaces (de Kemp, 1999) or discrete techniques such as discrete smooth interpolation (Mallet, 1989). This last method can accommodate many different types of constraints involving a single object or relations between different objects (Mallet, 2002). *Implicit modelling* uses an implicit definition of the geological interfaces, which are defined as the iso-surfaces of one or several scalar fields in three-dimensional space. Orientation data represent normal vectors (dip direction, dip, younging direction/polarity) to these equipotential lines/planes and are thus regarded as the gradient of the corresponding scalar field. Again, the scalar field is obtained by three-dimensional interpolation, but one advantage of this approach is that it allows a set of surfaces accounting for all orientation data to be modelled simultaneously (e.g., Cowan et al., 2003; Lajaunie et al., 1997; Turk and O'Brien, 2002).

There are advantages and disadvantages in both approaches. Explicit modelling allows a great deal of interactive modification of each interface. On the other hand, the orientation constraints that can be regarded directly in an automated manner are restricted, because these data need to be related to a well defined surface. In order to overcome this problem, different approaches and tools providing a means for independent evaluation of large datasets prior to modelling have been presented (e.g., Cobbold and Barbotin, 1988; de Kemp, 1999; de Kemp, 2000; Gumiaux et al., 2003). The explicit approaches are implemented in computer programs like SURPAC or GOCAD. With implicit modelling, both contact locations and orientation constraints (not only on the contact surfaces) can be considered simultaneously. This approach provides less freedom to interactively modify individual surfaces once the model is set up and this can be a shortcoming if specific geometries are to be modelled. On the other hand, this can be a significant advantage because data updates or new constraints can be added easily. The computer programs 3D GeoModeller and (to some extent) EarthVision follow such an approach.

While these techniques are nowadays available in several computer codes, their application to a specific case study requires the collection and management of a large amount of data. The preparation of the data, their formatting, and their comparison or selection often requires a considerable amount of work. In practice, these tasks require the use of geographic information systems (GIS) and database management systems (DBMS) (Schetselaar, 1995; McCaffrey et al., 2005; Bond et al., 2007). In this paper, we present a workflow to facilitate the process of data acquisition, data management, and modelling of complex poly-deformed geological formations. The workflow is based on the use of GIS (ESRI ArcGis) for the data management and pre- and post-processing, and on computer-aided earth-modelling tools (CAEM; mainly 3D GeoModeller) for the three-dimensional modelling. The workflow is focused on implicit modelling with GeoModeller, since this program is the most convenient for handling the type of data that is collected and used in such complexly deformed terrains (e.g., Martelet et al., 2004; Talbot et al., 2004; Maxelon and Mancktelow, 2005; Joly et al., 2008). The main advantage of 3D Geomodeller is its interpolation method, which uses a potential-field approach (Lajaunie et al., 1997; Chilès et al., 2006; Calcagno et al., in press). The method defines a function $T(x, y, z)$ interpolated by co-kriging from points located on interfaces, considered as having a common (unknown) potential value for each interface, and directional data representing the gradient of T. Thanks to the dual form of the co-kriging, it is possible to solve the system just once, and then use it as an interpolator to estimate T at any point p in space. This property allows each interface to be defined as a specific isovalue of the potential field, using algorithms such as a marching cube. The approach is particularly powerful in modelling complex three-dimensional foliation trajectories, with only one point per trajectory (e.g., the grid coordinates and height of a lithological contact in the field) necessary to define a fully three-dimensional virtual interface that accords with the regional orientation measurements.

After presenting an overview of the workflow, the paper describes more precisely the different aspects of the proposed approach, from the database structure to the

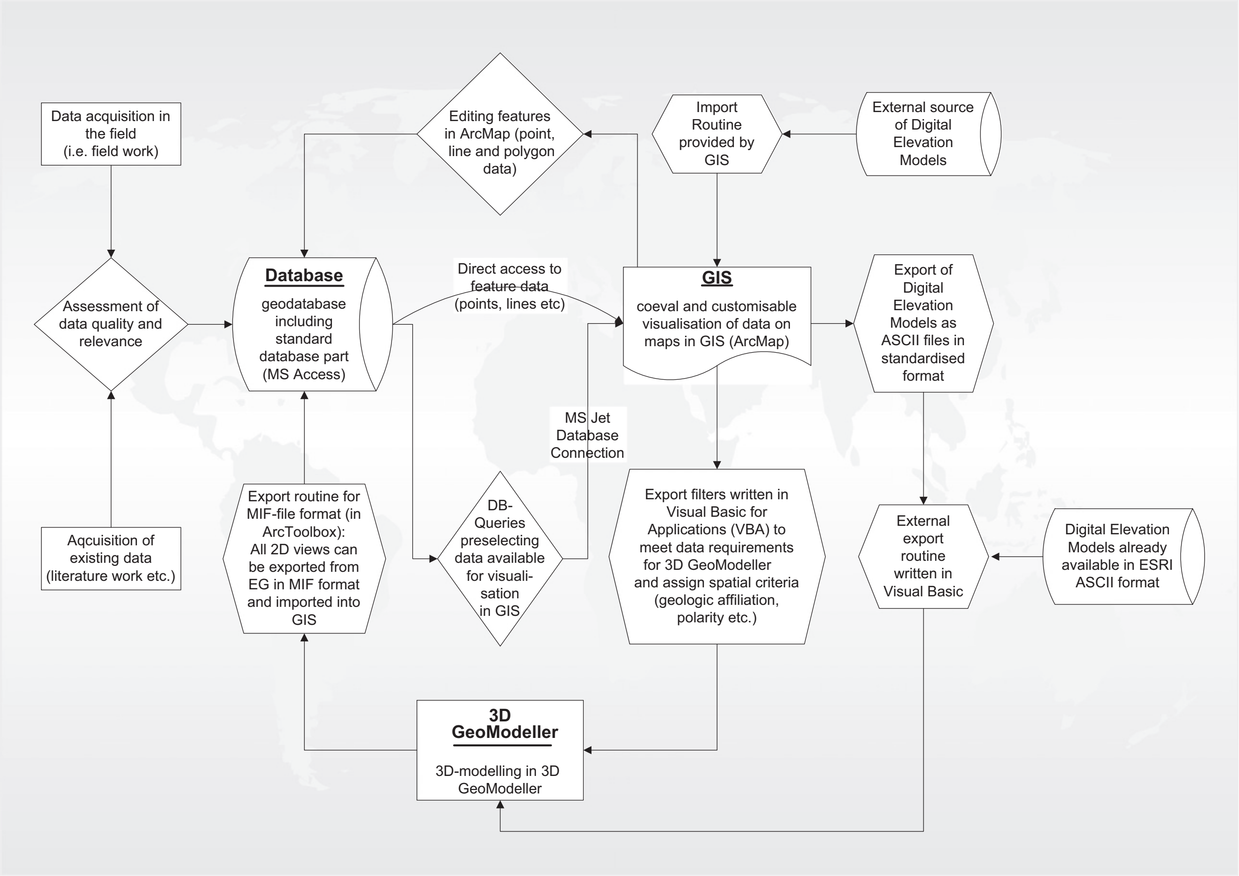

Fig. 1. Flow-chart describing our complete three-dimensional modelling procedure. Single processes are discussed in the text. Process labelled 3D GeoModeller is described more precisely in Fig. 8.

different stages involved in building a three-dimensional model. The different steps are illustrated with an example from the Pennine zone in the Central Alps, which is probably the most extensively studied example of a refolded mid-crustal nappe sequence, with a very extensive database of observations, maps and orientation measurements reflecting over 150 years of research.

2. Workflow overview

The proposed workflow (Figs. 1 and 8) facilitates the three-dimensional modelling of geological formations that have been affected by polyphase deformation, resulting in a tectonostratigraphy that is characterized by a pervasive planar fabric. This planar fabric is assumed to have formed coevally with the principal tectonic event (normally regional isoclinal folding or thrusting) and to have obliterated older tectono-stratigraphic limits. Such problems can be addressed by a two-stage modelling procedure, which first assesses the orientation field and subsequently outlines geological limits according to the orientation field, constrained by further information (e.g., younging direction, cleavage/bedding intersection, vergence of parasitic folds).

The basic workflow (Fig. 1) uses available software (ESRI ArcGis, MS Access, and GeoModeller), complemented by a set of programs and macro-routines for data preparation, data exchange and necessary data interfaces, where these are not provided by the software packages themselves.[1]

Typical field-derived measurements and interpretations are made consistent through the definition of a data structure implemented in a DBMS. Interpretations, mostly introduced as cross-sections, are used to constrain the model. MsAccess and ArcGIS are used for central data organization, for editing features in two dimension, such as field data points, lines and polygons, as well as for pre-processing of the data. The GIS provides data interfaces to import raw georeferenced one- and two-dimensional data through integrated database connections. Tabular data in ASCII- or .dbf-format specifying x- and y-coordinates and other characteristic attributes (e.g., measurements) provide another import possibility.

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[1] Maxelon, M., 2004. Some tools for three-dimensional modeling in structural geology and tectonics. Available online through: http://e-collection.ethbib.ethz.ch

3. Data source and data structure

The diversity of data types that contribute to a three-dimensional model accentuates the need for a clear data structure. In the rest of this paper, the word data will be used in a broad sense to describe any information used and stored to build the three-dimensional model and includes both measurements and interpretations. Not only do data differ in types of geometry (points, lines, areas), they can also have a vectorial meaning (lineations, cleavages) or only be relevant for specific steps in the modelling process (e.g., different generations of foliations). A further distinction should be made with respect to the origin of the data: they can originate from field work (and are thus raw data) or from preliminary interpretation (e.g., cross-sections). Furthermore, digital elevation models play an important role and need to be incorporated in the workflow.

3.1. Field observations

Field observations are collected and stored in an MsAccess database as geographically referenced data assigned to one single point in space (i.e., a location defined by its coordinates and height above sea level). They consist of planar measurements (e.g., foliation), linear measurements (e.g., lineation), and parasitic folds (Fig. 2).

One- and two-dimensional features (i.e., outcrop lines and areas on a map) are then derived from interpretation of several outcrop points and from vector-based interpolation between them (i.e., an additional assessment of orientation measurements that determines how the line between two points is to be drawn). These objects are stored independently from the field measurements, as lines and areas in ArcGIS. Note that they are composed of interconnected points and consequently points remain the most important geometrical type for three-dimensional models, either as constituents of outcrop lines or as a geographic reference for any kind of information (e.g., lithology).

The structural measurements (planar or linear) contributing to the geometrical understanding of an area are usually represented by vectors and stored as a unique dip direction and dip angle (Fig. 2). Typical vectors (in part illustrated in Fig. 3) are the dominant bedding/foliation and younger planar fabrics (e.g., fold axial plane, newly formed foliation) and the plunge direction and plunge angle of linear fabrics, such as stretching lineations

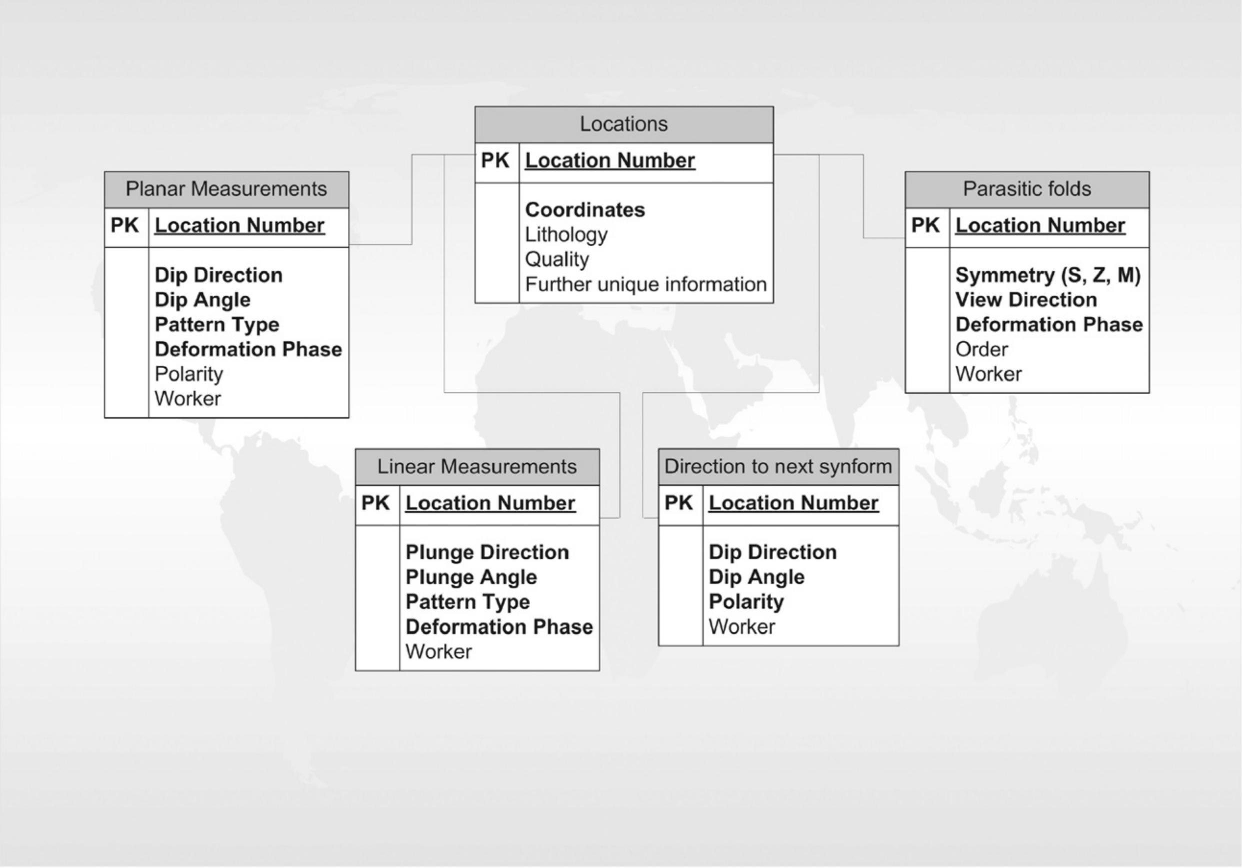

Fig. 2. One-to-many relationship for field-derived measurements, which can be represented in a simple database. Boxes represent different tables, primary keys are labelled PK. All data are uniquely identified by location numbers. Bold parameters should be considered as required information. Meanings of some linear and planar parameters are illustrated in Fig. 3.

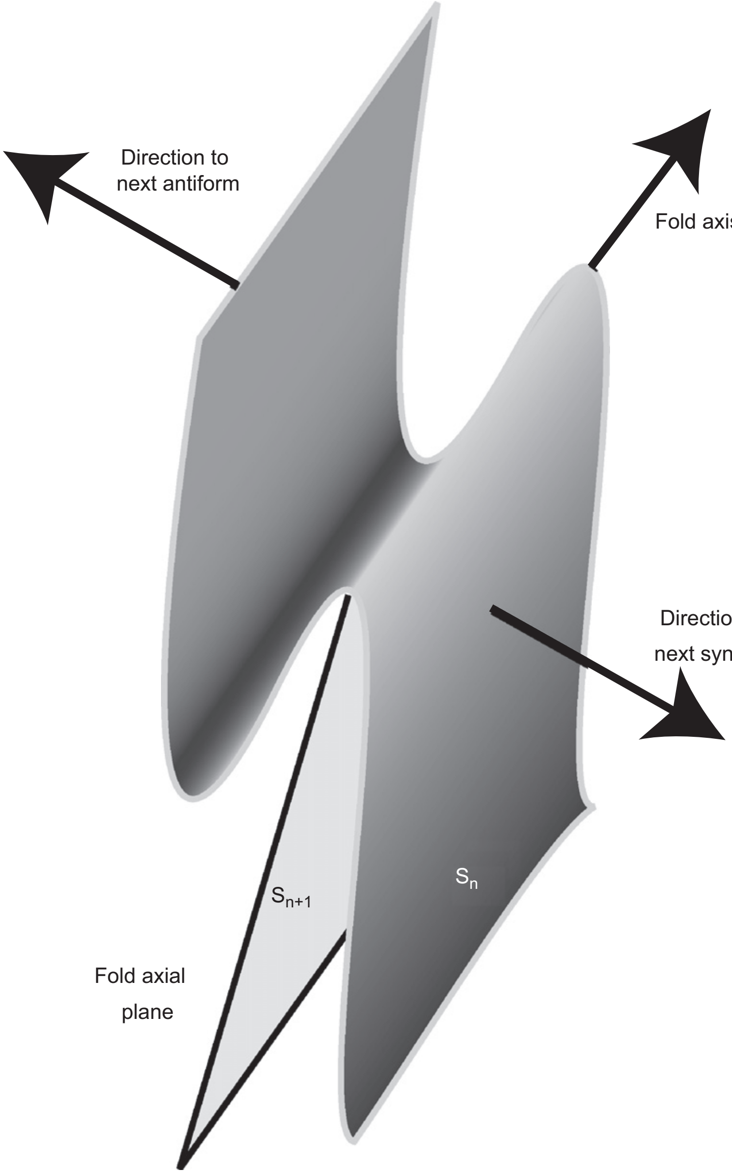

Fig. 3. Relevant parameters to be recorded during field data acquisition with respect to an isoclinal parasitic fold. Direction to adjacent major syn-and antiforms, fold axis, fold axial plane (parallel to a possible newly formed foliation Sn+1) and dominant orientation of folded planar fabric (Sn) are illustrated. Sketch shows a situation after deformation phase Dn+1.

(also providing kinematic information) or fold axes (providing geometric information). Often a great deal of such information is referenced to only one single location. As a consequence, multiple property assignments to a single location are the rule.

In addition, there may be information about symmetry/asymmetry and geometry on a larger scale (cleavage/bedding intersections, parasitic folds; Figs. 3 and 4). This information is again represented by vectors, for example indicating the direction either to the next relevant syn- or antiform (as indicated in Fig. 3). Similarly, during the process of data preparation, planar measurements must be complemented by a declaration of their polarity (or younging direction), since describing planar measurements in terms of dip direction and dip angle does not in itself indicate if bedding or layering is overturned or not. These data dependencies are represented as a simple one-to-many data relationship in the database (Fig. 2). The coexistence of several generations of the same observation type (e.g., foliations assigned to different deformation phases; *S*1, *S*2, etc.) at one single location requires that the respective deformation phases must also be recorded. Finally, it is quite common to have several measurements of the same feature (e.g., fold axis of 2nd phase parasitic folds) taken at one location. In this case, a decision has to be made as to how a single representative piece of

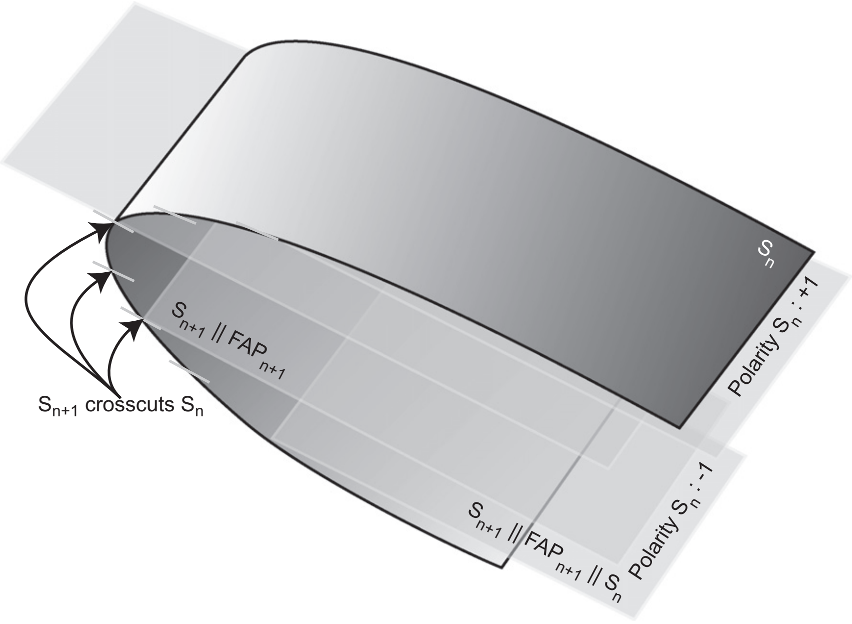

Fig. 4. Schematic sketch showing a folded older planar element (Sn; bedding or fabric) crosscut by a younger planar fabric (Sn+1) parallel to the fold axial plane (FAPn+1) in an hinge region of the fold. In limb regions, Sn+1 approximately parallels Sn, but Sn has opposite younging directions (polarities). Such folds often result in the identical geological interface occurring at two elevation levels (duplicate assignment of a *z*-value to an (*x*,*y*)-coordinate pair) and are therefore difficult to visualize in 3D GIS viewers like ArcScene.

information can be derived from these multiple data assignments (e.g., component-wise calculation of an arithmetic mean).

Point data from different workers are stored in the database the same way as personal data are stored, with a location number uniquely identifying the point and the worker's name mentioned in the appropriate category (Fig. 2).

The proposed database structure for field observations (Fig. 2) has been kept very simple and limited for the purposes of the present work. Note however that there is a considerable amount of existing work (see McCaffrey et al., 2005) providing more general data models for the digital collection of geological observations.

3.2. *Existing maps and cross-sections*

Interpretations from previous studies (e.g., outcrop lines and cross-sections) are important pieces of information that need to be stored in the database. Scanned images of geological maps are georeferenced in the project coordinate system. Outcrop lines are then digitized in an appropriate file format (e.g., Shape file, MapInfo file). For cross-section data, it is necessary to have the profile defined by its start and end points (and intermediate points if need be), whereas the interpretations (lines on the cross-section) themselves are recorded in a (u,v)-coordinate system, defined by distance from the origin of the cross-section (abscissa) and height above sea level (ordinate). Geometries digitized in this way can then be imported into 3D GeoModeller either to add additional constraints to the model or for comparison purposes.

3.3. *Digital elevation models*

The digital elevation models (DEMs) provide vital information about exact positions of georeferenced data in the three-dimensional space. Advanced remote sensing techniques (e.g., Franklin and Giles, 1995; Zomer et al., 2002) have made them available also in less developed countries and in areas difficult of access. DEM data are mostly provided in formats that are compatible with standard GIS software.

With the aid of the DEM, preliminary three-dimensional assessment is possible by calculating a hill shade and combining it with polygon geometries representing the respective geological units (two-dimensional image with shading, see Fig. 5). Alternatively, the DEM can be used as a source for elevation data that are then assigned to the respective points of the two-dimensional geometries in the three-dimensional space (Fig. 6).

4. Data processing using GIS

The data described in the previous section are made available by database connections between ArcGIS and MsAccess and can be exported in the appropriate file format using customized macro-routines (e.g. see footnote 1). Export from the GIS software works in two directions: backward into the DBMS and forward into the CAEM tool. The former case offers the opportunity to store additional information (like polarities) and newly compiled geometries (like fold axial traces) in the database. The latter provides the data input interface for introducing raw, pre-processed data, or interpretations into the CAEM tool.

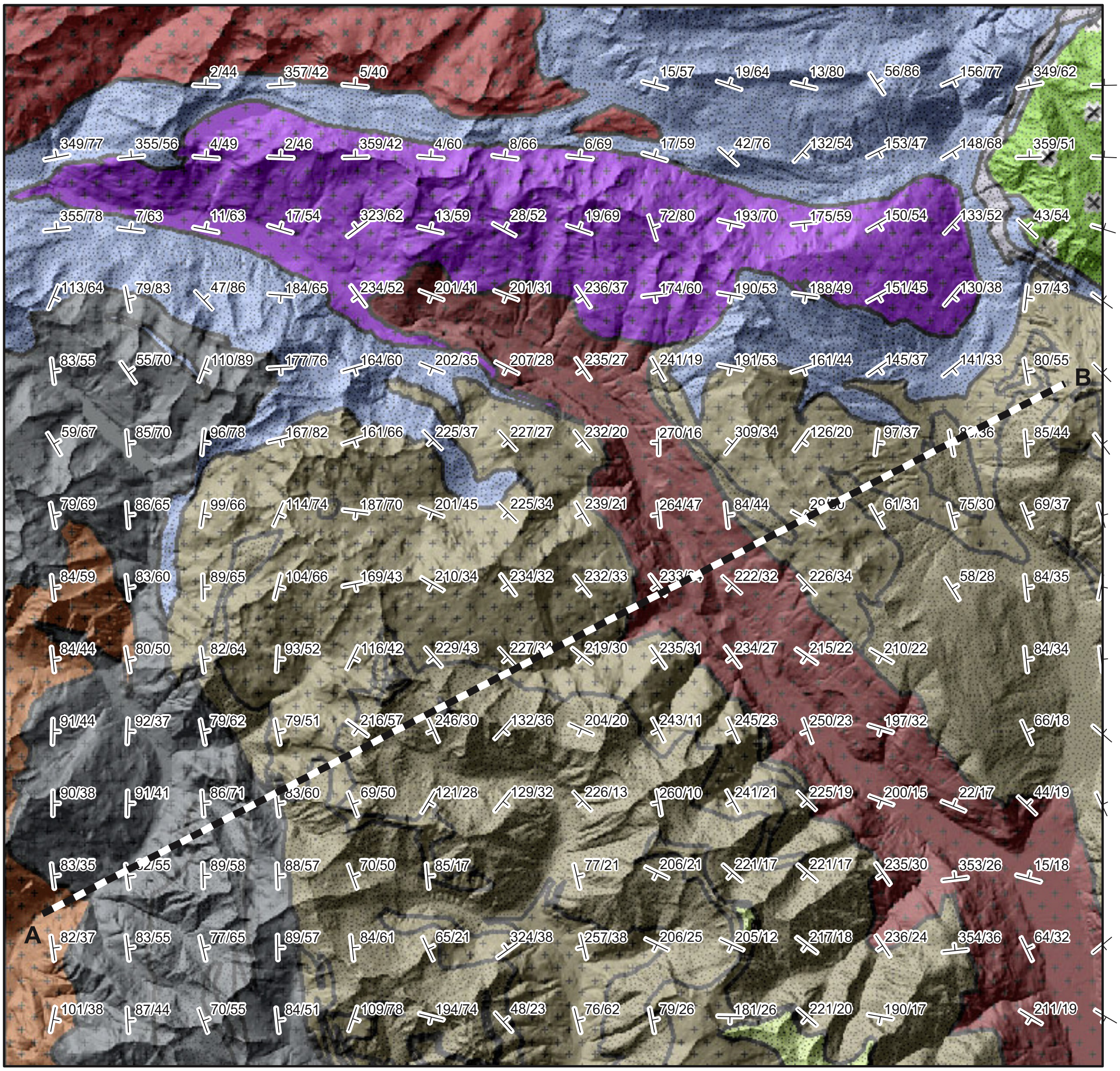

Fig. 5. Inset of a tectonic map from the Central Alps of Switzerland (simplified after Preiswerk et al., 1934), combined with a hill shade calculated from corresponding DEM. Easier correlation of outcrop lines in space (compared to standard map views) facilitates a first visual three-dimensional assessment. Orientation data are spatially averaged from a set of 2964 measurements with the VBA macro *Profile Calculation* (see footnote 1). SW–NE trending line indicates location of cross-section shown in Fig. 7.

Furthermore, data evaluation within GIS using either the built-in tools or the custom-made routines allows preliminary assessment of structural data. This variety of data management and processing tools makes GIS a convenient data distributing centre for comprehensive three-dimensional modelling.

4.1. Data analysis and preparation in GIS

Data management in GIS software involves two important aspects. On the one hand, data can already be efficiently analyzed there, saving time during the later modelling process. Such work takes advantage of the possibility to display several different data types synoptically and then process them with Visual Basic for Applications (VBA) routines. On the other hand, topological relationships allow properties to be assigned to single points, which is necessary for later processing during the three-dimensional modelling (e.g., younging direction, geological affiliation).

4.2. Structural assessment and profile construction

A basic understanding of the geometry of the area at the beginning of the actual three-dimensional modelling procedure provides important insights for ensuring consistency and trustworthiness of the later modelling results.

Two VBA routines (see footnote 1) help to envisage structural relationships and speed up typical tasks during tectonic assessment. The routine *Orientation Averaging* produces an evenly spaced grid of average orientations calculated from measurements situated within a given distance (also inverse distance weighted if required). Fig. 5 shows an example of the application of this tool. The routine *Profile Calculation* automatically creates a cross-section considering both the underlying DEM and the different geological units crossed by the profile trace (Fig. 7). Averaged orientation values can be calculated from measurements situated within a given circular region (i.e., a buffer) around those points along the profile trace. Furthermore, they can be assigned to the cross-section at equal intervals, also accounting for their apparent dip angle (e.g., Flick et al., 1972).

4.3. Polarity assignments

In structurally complex areas characterized by mainly ductile deformation, regional-scale recumbent isoclinal folding is frequently observed (e.g., Milnes, 1974). Such deformation typically entails the development of a new pervasive planar fabric (Sn+1) parallel to the fold axial planes of the respective folds (Fig. 4). If this new foliation is the dominant foliation, which is often the case, the limits of the folded unit (i.e., Sn) are easily obliterated. However, in regionally important hinge zones, the older fabric (or the bedding) is sometimes preserved and the position and orientation of regional hinges can then be determined in the field. In limb regions, the younger fabric is often parallel to the older fabric (Fig. 4), but with respect to this older fabric a change of the polarity has to be taken into account. Therefore correct planar measurements can only be obtained in such regions if the position relative to regional fold structures is known (e.g., from parasitic fold vergences or Sn/Sn+1 relationships; Figs. 3 and 4).

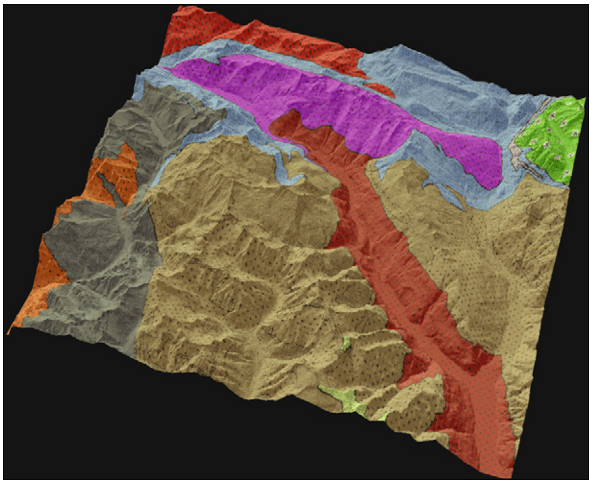

Fig. 6. Perspective view of two-dimensional map also shown in Fig. 5. Polygons corresponding to geological units are draped onto DEM.

The axial traces of regional-scale folds are linear features that can usually be established in some detail during a field study. Foliation measurements from either side of such an axial trace are assigned a different polarity reflecting their position on opposite limbs and polygons defining such areas of different polarity can be easily constructed in Arc Map. The result is a series of bands of different polarity separated by the axial trace of folds, which may even be isoclinal. This tedious work can be readily done by a VBA routine (e.g., routine *Export Planar Measurements*, see footnote 1). Such a routine allows topological relationships between planar measurements (i.e., point data) and areas of a constant property (i.e., polygons) to be considered and assigns geological affiliations and polarity information to the respective planar measurements (or other point data).

5. Three-dimensional modelling

For polyphase deformation, including regional development of a new pervasive planar fabric, a two-step approach is suggested. First, the younger deformations recorded in regional orientation pattern of planar measurements are investigated. Then, these results are combined with information about older deformation phases, coeval with the formation of the dominant foliation, so as to develop a comprehensive model of the tectono-stratigraphic relationships. The three-dimensional modelling part of the workflow (Fig. 8) will be discussed considering the map in Fig. 9 as an example.

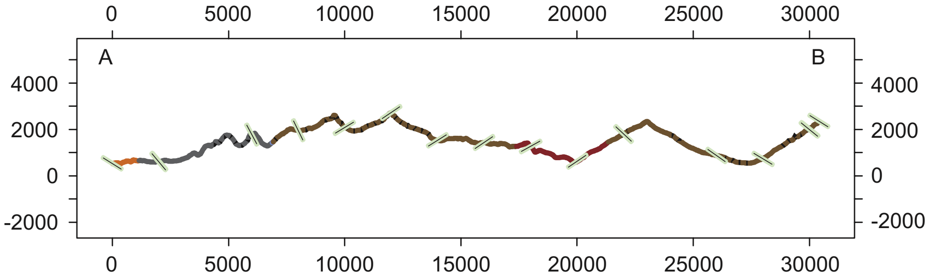

Fig. 7. Cross-section calculated with routine *Profile Calculation* developed in Arc Map (see footnote 1). Profile trace is indicated in Fig. 5. Affiliation with different geological units (i.e., different colours in the section) and orientation indicators (i.e., black lines underlain in green) were produced automatically. Units are metres.

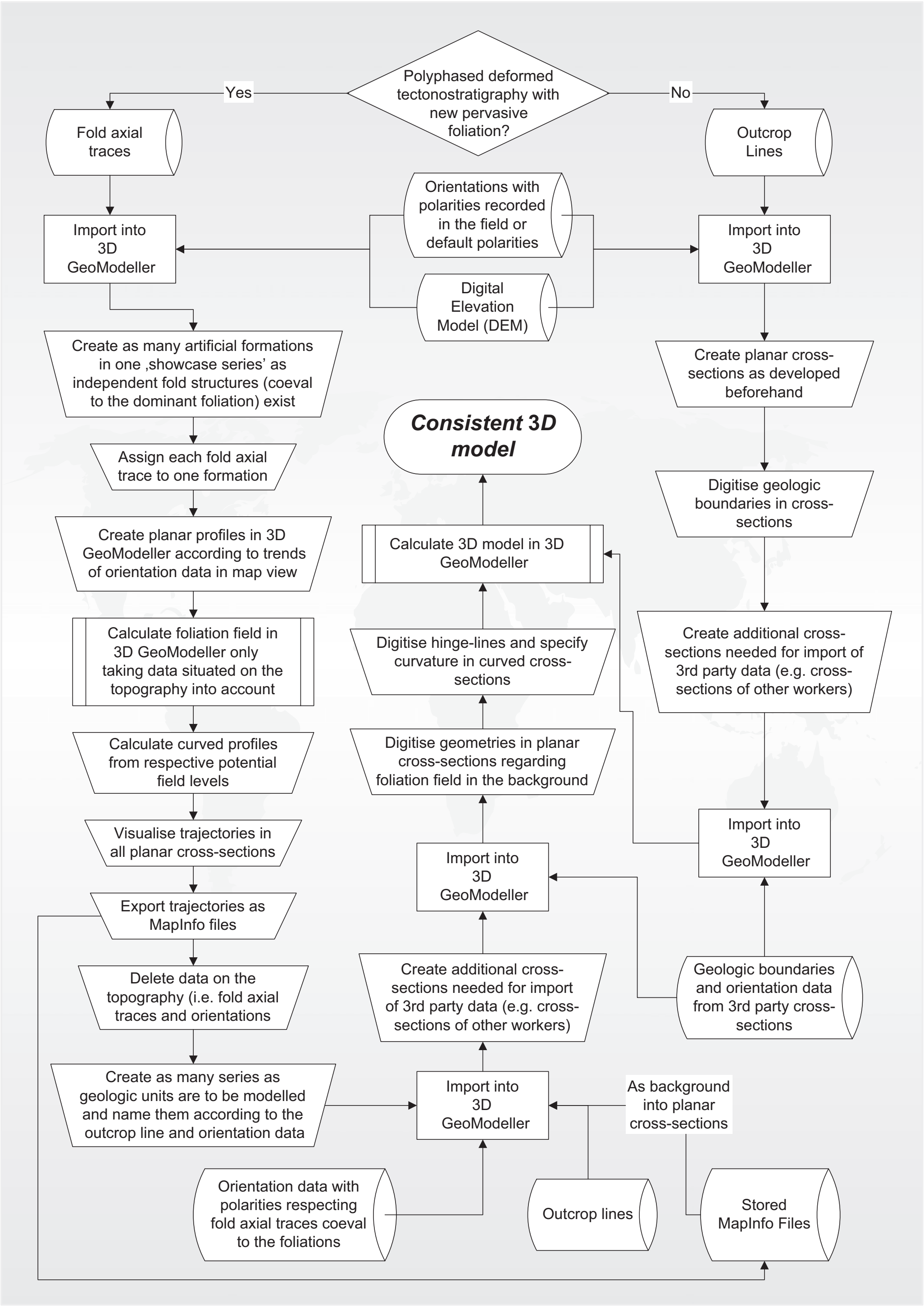

Fig. 8. Flow-chart of modelling procedure inside 3D GeoModeller. Data exchange to other software and data preparation outside GeoModeller are not regarded in this diagram. Processing chain illustrated here corresponds to process labelled 3D GeoModeller in Fig. 1.

5.1. *Step 1—visualization of the foliation field*

In 3D GeoModeller, a three-dimensional model can be calculated considering all available planar measurements (i.e., typically foliations), but with only one (more or less arbitrarily chosen) outcrop point per tectonic or lithological unit fixing its structural level. To establish this, all geological entities must be defined in the software as

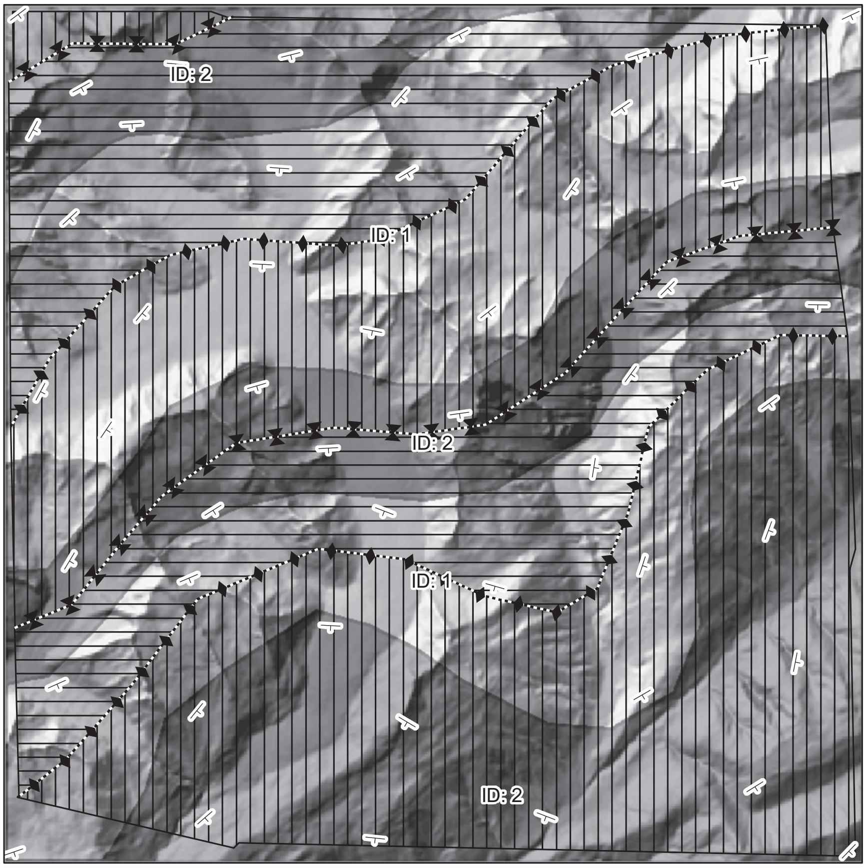

Fig. 9. An example of a geological map, illustrating two hypothetical geological units (light and dark grey, corresponding to ID1 in footwall and ID2 in hanging wall). They are draped upon a hill shade that was calculated from a DEM. Line patterns indicate regions of identical younging direction (horizontal lines: overturned (i.e., polarity -1); vertical lines: not overturned (i.e., polarity 1). Indicated foliations are coeval with development of folds (i.e., they are axial plane to these folds).

formations and be assigned to one combined series. All foliations are then considered in the calculation regardless of their geological affiliation. The resulting modelled surfaces represent the regional trend of the foliation field in three dimensions, passing through the single chosen outcrop point. The intersection of a subset of such surfaces with the topography results in a typical foliation trajectory map as illustrated in Fig. 10a.

Instead of being defined by one arbitrary outcrop point, the surfaces representing the foliation field can also be forced to contain more than one point, namely a line defined by several connected points. This possibility is relevant for modelling a fold structure coeval with a pervasive foliation. If the line corresponds to a fold axial trace on the topography, the surface created in this manner will represent the fold axial plane of the respective fold (compare Figs. 4, 9 and 10b). Thus it provides an important constraint with respect to the possible fold geometry in three dimensions.

In the much simpler case where the regional trend of the dominant planar fabric is defined by the limits of geological units, it is obvious that a surface complying with the orientation field and forced to follow an outcrop line will immediately represent the boundaries of geological units. It therefore immediately provides an initial, valid, though probably preliminary, three-dimensional model.

5.2. *Step 2—confining the model*

If the boundaries between geological units in a study area are obliterated by the dominant foliation, their geometry can be determined only by careful mapping of lithological limits. Unfortunately, mapping of boundaries may be equivocal in gneissic units from typical basement terrains and correlations or distinctions between multiply deformed and possibly polymetamorphic units are therefore uncertain. In such terrains, structural data (Figs. 3 and 4) are crucial for interpreting the geometry. In particular, the three-dimensional trends of fold axial planes, as outlined in the previous section, can provide strong geometric constraints throughout a whole volume. Such information helps to identify valid geometric interpretations in cross-sections, which can be created in 3D GeoModeller in two ways.

(1) Planar profiles are straight cuts through a given volume. Their intersection with a horizontal surface results in a straight line, completely described by a

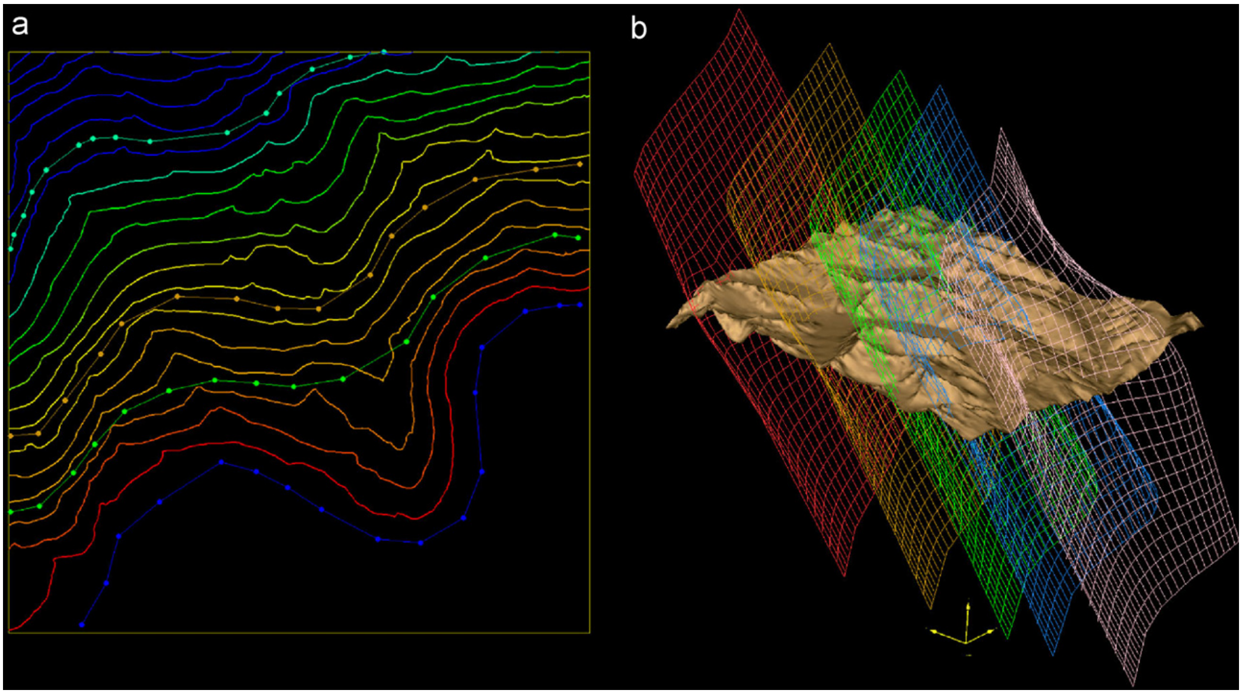

Fig. 10. (a) Foliation trajectories calculated from planar measurements shown in Fig. 9. Connected point lines correspond to outcrop lines shown in Fig. 9. Colouring is arbitrary. (b) Surfaces indicating trend of foliation field in three dimensions. Intersections of red, ochre, green and blue meshes with shaded topography correspond to fold axial traces depicted in Fig. 9.

finite number of points. Typically they are constructed as vertical cuts, with a trace defined by only two points.

(2) Curved profiles follow a contorted surface through a given volume. In 3D GeoModeller, the geometry of such cross-sections can be defined in three-dimensional space as an isosurface from a previously calculated orientation field. Their intersections with a horizontal surface are mostly curved. They are generally more complicated than those of planar profiles, and are normally not sufficiently described by a small number of connected points.

5.3. Planar profiles

The trend of planar profiles should be defined with respect to the regional trend of planar features in the study area. Generally it is more convenient to work on cross-sections that run (sub-) perpendicular to the dip directions, because the effect of apparent dips along the profile is then minimized (Flick et al., 1972; Meyer, 1991).

After a foliation field has been calculated, the respective foliation trajectories can be visualized in a planar profile, stored in a MapInfo file, and then re-imported as a background for the section (Fig. 11b). Such a background aids digitization of geological units, because it depicts the trend of regional-scale fold axial planes or their parallel translations intersecting the cross-section.

Curved profiles calculated with special attention to fold axial traces are an especially helpful feature, because their intersection with the planar cross-sections provides an excellent guideline for delineating the trace of regionally important fold axial planes (Fig. 11c).

In the workflow, several planar cross-sections should be constructed in this way. They will act as principal constituents of the actual modelling. Personally constructed cross-sections can be complemented by cross-sections from other workers. Fig. 11a shows an example of one such cross-section, while also presenting the three-dimensional modelling result in the subsurface. However, fold structures as shown in Fig. 13 often have rather irregular and ragged hinge lines in models calculated on the basis of planar cross-sections exclusively. This geometric shortcoming can be corrected with curved profiles (Fig. 12).

5.4. Curved profiles

As mentioned before, curved profiles are created from previously calculated foliation fields. Interface points specifying different levels of this foliation field can be grouped upon the fold axial traces coeval with the development of the dominant planar fabric. Then the resulting curved profiles calculated from these levels will correspond to the fold axial planes themselves. For example, the intersections of the meshed surfaces shown in Fig. 13a with the topography correspond to the fold axial traces delineated in Fig. 9 (also compare Fig. 10b).

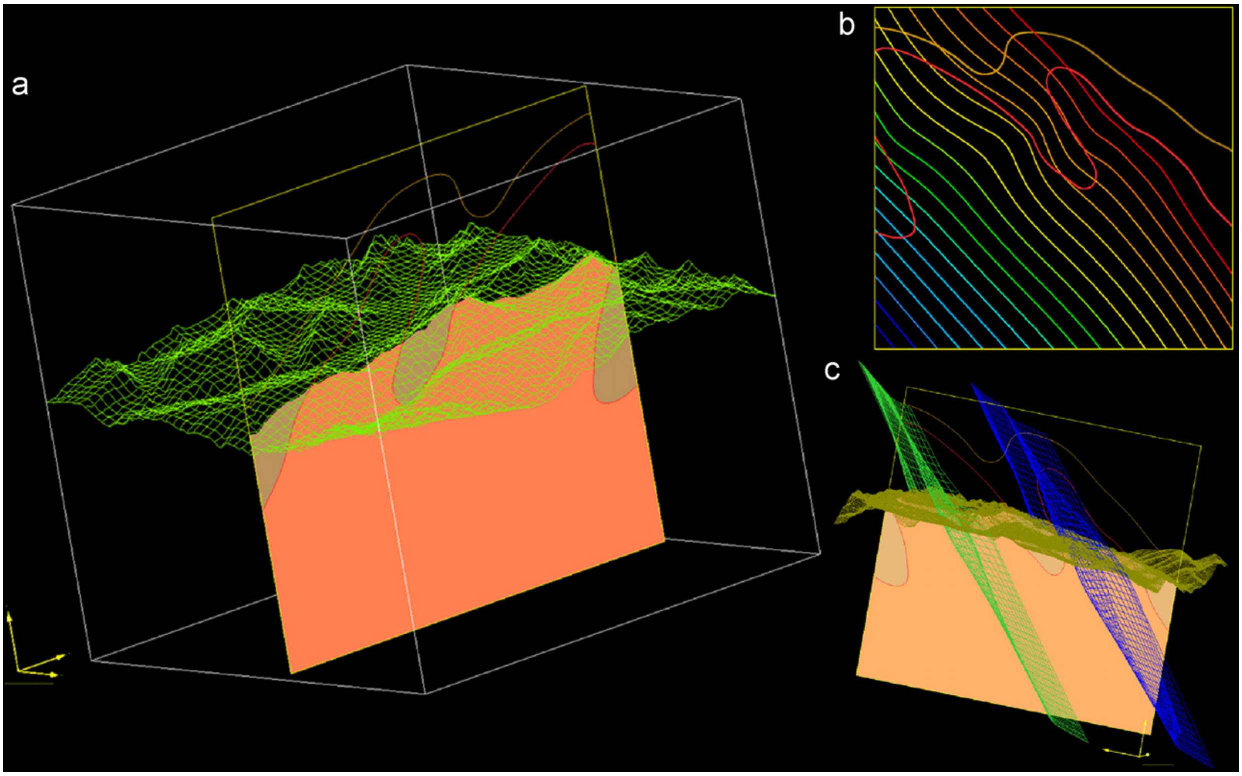

Fig. 11. (a) Three-dimensional view of a planar cross-section through the model. (b) Intersection of foliation field shown in Fig. 8 with cross-section of (a). "Real" outlines of units are digitized in planar profile, considering foliation trajectories shown in three dimensions in Fig. 10b. (c) Cross-section in three-dimensional space. Two meshes following the foliation field correspond to fold axial planes of digitized antiforms and were used as curved profiles.

Two parameters of geometric significance for a fold can be digitized on such cross-sections: hinge lines and the curvature of hinges.

Hinge lines can be digitized as a series of equipotential points, because in such a profile hinge lines correspond to intersections of the geological boundaries with the cross-section. Furthermore, irregularities in the trend of such a hinge line can be smoothed out in this way. The lower limit of a folded series in the hinge region is usually defined by the hinge of the next unit below (like ID1 defines the lower limit of ID2 in Fig. 13b).

The curvature of hinges (and therefore the geometry of the folds) can additionally be specified by either one or two opening angles (angle α in Fig. 12). For each opening angle, the distance along the fold axial plane at which the two points situated symmetrically on opposite limbs and defining the angle must also be specified (distance D in Fig. 12).

However, the parameters provided have to be checked to ensure that they are not in contradiction with the fold geometries implied by the digitized forms in the (typically perpendicularly trending) planar profiles. In other words, digitizing an open fold in a planar profile and specifying angular and distance parameters that define an isoclinal fold in a curved profile will obviously result in unrealistic three-dimensional geometries.

5.5. *Calculating the three-dimensional geometries*

Once all planar and curved profiles are set up, the model can be calculated considering all necessary cross-sections and the map section. The detailed workflow within 3D GeoModeller (Fig. 8) distinguishes two cases: (1) deformation without regional development of a new pervasive planar fabric, and (2) deformation associated with regional development of a new pervasive planar fabric parallel to fold axial planes of coeval regional fold structures. The second case requires the assessment of additional information about the regional geometry (e.g., vergence of parasitic folds, younging directions) and entails more steps than the first case.

In case (1) (right part of Fig. 8), the trend of geological boundaries corresponds to the orientation field defined by the planar fabrics. Therefore the model can be calculated immediately after all necessary data (e.g., outcrop lines, planar measurements, DEM) have been imported into 3D GeoModeller.

In case (2) (left and central part of Fig. 8), the orientation field defined by the planar fabrics crosscuts geological boundaries in the hinge regions of regional folds. However, it defines the regional trend of coeval fold axial planes. Therefore the model cannot be calculated before the orientation field (including the

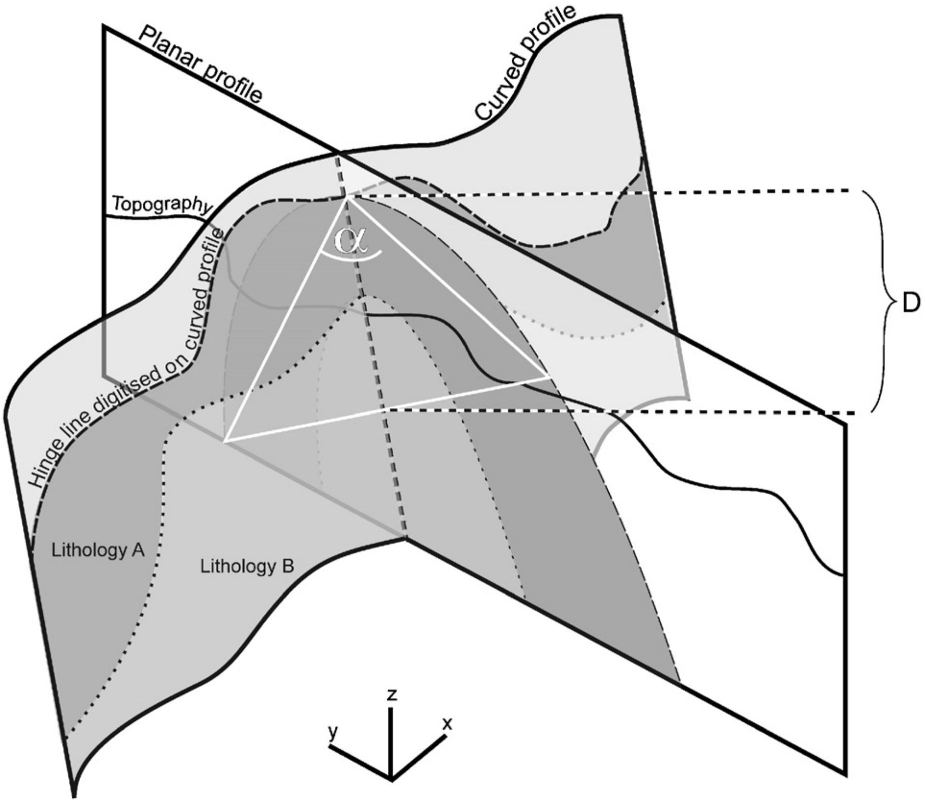

Fig. 12. Schematic sketch of a curved and a perpendicular planar profile with a folded sequence of two lithologies (labelled A and B). Topography is indicated only in planar profile. On the curved profile, the hinge line of the fold can be digitized. Fold shape is determined by (a) the geometry of lithological units in planar profile as well as (b) by the opening angle α and distance D along the corresponding fold axial plane. Up to two such opening angles, each of them referring to a specific distance D from hinge, can be defined and assigned to one digitized hinge in 3D GeoModeller.

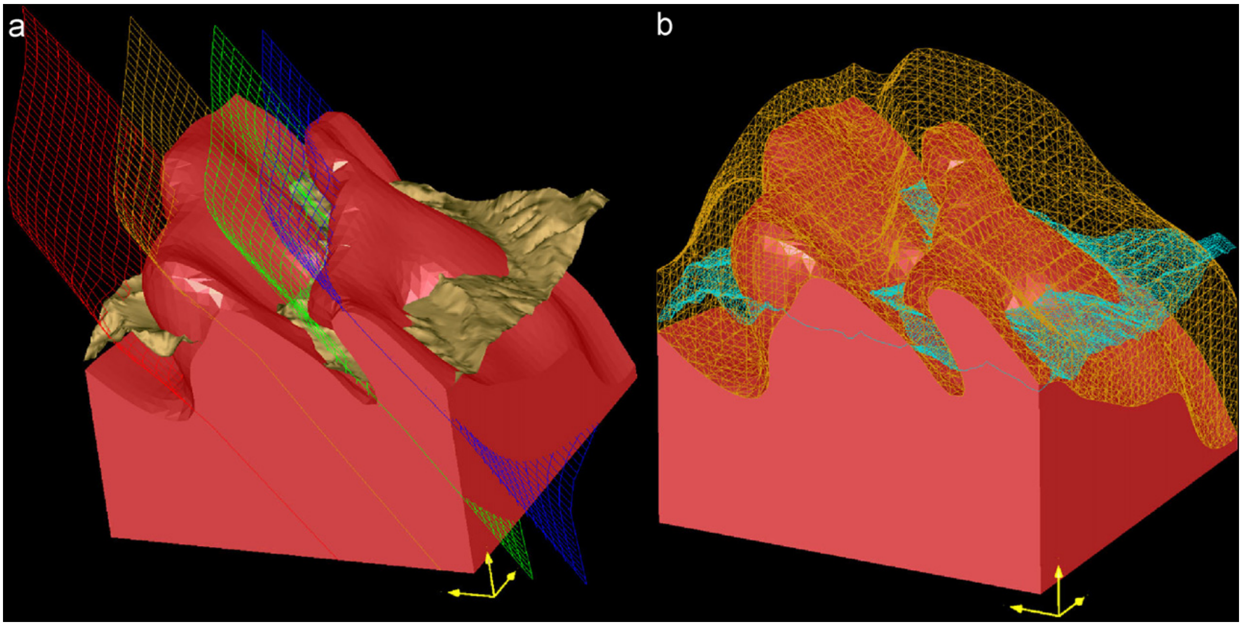

Fig. 13. (a) Three-dimensional model of lower unit indicated in Fig. 9 (ID1). Mesh represents foliation trajectories in three dimensions and corresponds to fold axial planes of isoclinal folds affecting lithologies. Topography is shown as an ochre shaded surface. (b) Three-dimensional model of both units indicated in Fig. 9 (ID1 and ID2). ID2 is shown as a light brown mesh to preserve visibility of topography (turquoise mesh).

three-dimensional trend of fold axial planes) has been calculated regionally from foliation measurements and axial traces (Fig. 10). Cross-sections regarding this result are then constructed (Fig. 11b) and combined with additional information like outcrop lines or fold structures. Finally these "intermediate results" have to be incorporated in the calculation of three-dimensional geometric models of geological units (Fig. 13).

For the showcase model illustrated in Fig. 13, the curved profiles shown in Figs. 10a and 11, the outcrop lines indicated in Fig. 9, as well as five north–south trending planar cross-sections (the one explained in Fig. 11 and two parallel translations of it to the east and west, respectively) were considered. Digitization in these profiles was supported by trajectories of the foliation field displayed as a background. Comparing Figs. 9 and 13 clearly illustrates the correspondence between the outcrop lines derived from mapping and those produced by the three-dimensional model.

6. Conclusion

Poly-deformed geological areas represent a challenge for three-dimensional modelling because of their complex geometries, which display little regularity or symmetry. In addition, the complexity of the relationships linking the different structural field observations requires specific approaches to develop a consistent three-dimensional model. The workflow proposed in this paper is one attempt to develop a systematic procedure: (1) to cope with the intricate geometric relationships typically found in such mid-crustal levels, and (2) to ensure internal consistency between the different structural data available. The workflow is based on a simple database allowing the storage of field data, previous interpretations and digital elevation models. This workflow is intended to help geologists dealing with such complex three-dimensional geometries. The workflow is complemented by a number of tools to prepare and analyze available data before modelling the geometry.

A number of features are not considered in this workflow and can be developed further in future. One important aspect is uncertainty. Currently, the workflow aims to provide a unique deterministic model that should be a rather good representation of the hidden underground geometry, constrained by the available data and reasonable interpretations. However, because of the lack of sufficient underground data, the complexity of the geometry, and the different possible interpretations of the observations (e.g., as noted above, with regard to correlation of lithological boundaries), it would be useful to build models in a probabilistic framework (Renard, 2007). This is already partly possible because the geostatistical kernel of the implicit approach can be used in a stochastic manner (Chilès et al., 2006). However, what still needs to be done is to distinguish carefully during the different steps between information that is really a field observation and information that is derived from an interpretation that could be replaced by another equally probable interpretation. Because interpretations are typically interdependent, such an approach would require a very different type of database structure. This would most likely be based on a tree-like structure, which could be explored in a semi-automated manner to build a series of possibly radically different but still realistic three-dimensional models.

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