GIS and 3D geological reconstruction of the Zuccone gravitational deformation, Val Taleggio (Southern Alps)

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ABSTRACT

This work aims to show how geological maps can be used for the 3D modelling of complex geological bodies. Geological data must be organised in a Geographic Information System and then imported in GOCAD, a software which allows the creation of 3D surfaces, solids and grids using points and linear elements. A deep-seated slope gravitational deformation developed in the Triassic sedimentary cover of the Southern Alps (Val Taleggio, BG) has been reconstructed. This phenomenon occurs in a complex structural setting comprising thrust faults crossed by strike-slip and normal faults. 3D modelling is mainly based on topographic, geological, structural, and morphological linear features.
In this way a direct control of bi-dimensional interpretations is possible, leading to a better understanding of complex geological bodies, and as a base for geomechanical modelling.

AIMS

- To demonstrate that geological maps and field structural data can be used in 3D reconstruction starting from a GIS database.
- To show how GOCAD can build complex geological objects.
- To illustrate the procedure for 3D modelling through the use of topographic data and point and linear features previously stored in a GIS.
- To define the structure of a deep-seated slope gravitational deformation developed in a complex structural setting.
- To reconstruct the 3D distribution of mechanical properties in a complex slide involving rocks with a very different rheology.

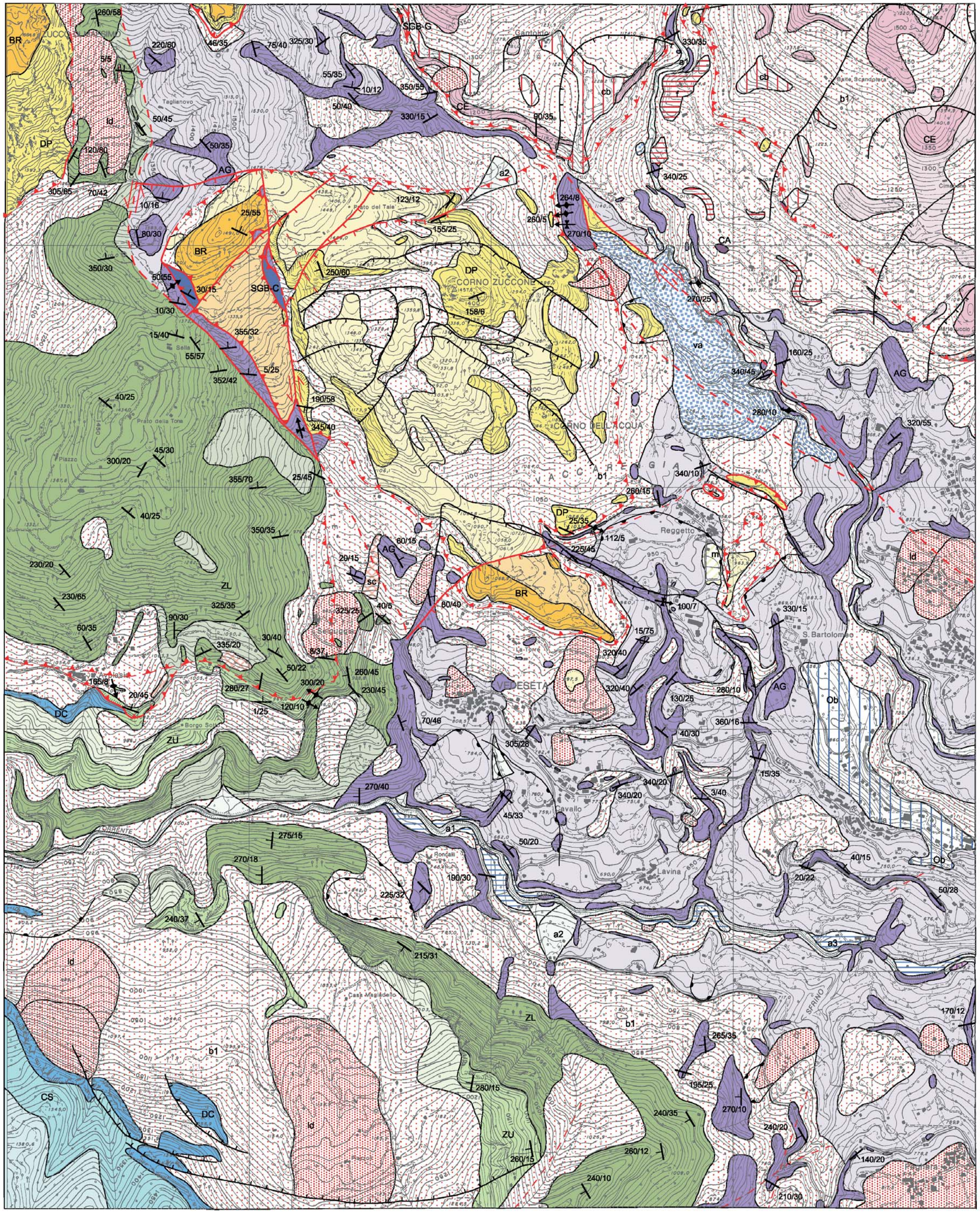
KEY WORDS

3D reconstruction, geometrical modelling, structural geology, Geographic Information System, geological mapping, deep-seated slope gravitational deformation, Southern Alps, sedimentary cover, Triassic.

RIASSUNTO

L'obiettivo di questo lavoro consiste nel mostrare come la cartografia geologica, organizzata in un Sistema Informativo Territoriale possa essere utilizzata per la modellazione 3D di corpi geologici complessi. Tali ricostruzioni sono state effettuate con gOcad, un software in grado di ricostruire superfici 3D, solidi e griglie a partire da elementi puntuali e lineari. La procedura è stata applicata alla ricostruzione di una deformazione gravitativa profonda di versante sviluppata nella copertura sedimentaria triassica del Sudalpino (Val Taleggio, BG), deformata da un sistema di sovrascorrimenti e successivamente da faglie trascorrenti e normali. La ricostruzione 3D è basata essenzialmente su dati topografici, geologico-strutturali e morfo-strutturali di dettaglio.
Le ricostruzioni 3D di tale tipo contribuiscono alla comprensione delle strutture analizzate, permettendo una rigorosa verifica delle interpretazioni bidimensionali e possono servire come base per modellazioni geomeccaniche di tipo numerico.

GEOLOGICAL MAP OF THE CORNO ZUCCONE AREA



QUATERNARY DEPOSITS

a1 **Alluvial deposits**
Coarse gravels and sands along the Enna river and the Valle dell'Acqua talweg. (Holocene)

a2 **Alluvial fan deposits**
(Holocene)

b1 **Slope deposits**
Loose debris and colluvium. (Holocene)

a3 **Terraced alluvial deposits**
Loose gravels and sandy gravels forming terraced deposits along the Enna river. (Holocene)

m **Marsh deposits**
(Holocene)

ld **Landslide deposits**
Poorly sorted coarse grained loose heterometric gravels with big boulders, often embedded in a fine matrix. (Late Pleistocene-Holocene)

sc **Slope cemented breccias**
Cemented slope deposits with carbonatic angular clasts. (Late Pleistocene)

Ob **Olda Breccia Unit**
Breccia with poorly rounded to angular clasts up to 20 cm in size including different lithologies from several formations (Angolo, Buchenstein, Esino, and Argillite di Riva di Solto). Cross laminations and coarse bedding locally present, suggesting a very proximal "alluvial fan" environment. Fine grained lacustrine beds occurring at the base. No relationship with present-day morphology (Middle Pleistocene ?)

f **Fraggio Unit**
Coarse grained loose or poorly cemented gravels with large blocks and boulders of Calcare di Esino, cropping out around Fraggio, forming suspended terraces along the main valley. The unit was mainly deposited in an alluvial environment. (Early-Middle Pleistocene ?)

va **Valle dell'Acqua Unit**
Very coarse grained poorly rounded and strongly cemented breccia. The unit mainly consist of heterometric clasts of Calcare di Esino; huge blocks of Calcare di Angolo in front of Fraggio. Main outcrops along Valle dell' Acqua; no relationships with present-day morphology. The unit may suggest an upper fan alluvial environment. (Early Pleistocene ?)

cb **Cantoldo-Bruco Unit**
Well cemented angular breccias with clasts of Calcare di Esino deposited along a paleo-slope. Main outcrops around Cantoldo and around Corno del Bruco. No relation with present-day morfology (Early Pleistocene ?)

CORNO ZUCCONE - MAESIMO TECTONIC UNIT (ZM)

DP-int / DP, BR-int / BR **Dolomia Principale (DP)**
Massive recrystallized dolostones with intraformational breccias (BR). DP- int and BR-int: interpreted. (Late Carnian - Lower Norian)

SGB-C **San Giovanni Bianco Formation (SGB-C)**
Cataclastic yellowish bedded dolostones, marls and carniolas at the base of the thrust along the Chignolo Valley. (Carnian)

CORNO DEL BRUCO TECTONIC UNIT (BU)

SGB-G **San Giovanni Bianco Formation (SGB-G)**
Deformed whitish gypsum lenses at the base of the thrust along Valle dell'Acqua. (Carnian)

CE-int / CE **Calcare di Esino (CE)**
Gray massive limestones with breccias, evinosponge, cements, corals and tubiphytes. CE-int: interpreted. (Ladinian)

CA **Calcare di Angolo (CA)**
Well bedded and laminated or bioturbated gray limestones at the base of the thrust around Fraggio. (Lower Middle Anisian)

TALEGGIO-IMAGNA TECTONIC UNIT (TIU) (Parauthocthonous auctorum)

CS-int / CS **Calcare di Sedrina (CS)**
Well bedded grey micritic cherty limestones, passing upward to oolitic and bioclastic calcarenites; thickness: 100m. CS-int: interpreted. (Upper Hettangian p.p.)

DC **Dolomia a Conchodon (DC)**
Massive peloidal micritic limestones with oolitic calcarenites, locally dolomitized. Thickness: 100m (Lower Hettangian) .

ZU-int / ZU **Calcare di Zu, upper part (ZU)**
Includes cyclic marly and limestone repetitions covered by a carbonate platform horizon rich in corals (Zu3). Well bedded limestones at the top (Zu4). Thickness: 300m. ZU-int: interpreted (Raethian)

ZL-int / ZL **Calcare di Zu, lower part (ZL)**
Includes blackish marls, marly limestones (Zu1) passing upward to fossiliferous massive limestones with patch reefs (ZU2). Thickness: 200m. ZL-int: interpreted (Late Norian-Raethian)

AG-int / AG **Argillite di Riva di Solto Formation (AG)**
Upper member: regular intercalations of shales, marly limestones and calcilutites, 250m thick. Lower member: black shales and marly shales with slumpings and subordinate micritic limestones. Thickness:150m. AG-int: interpreted. (Late Norian).

CZ **Calcare di Zorzino (CZ)**
Well bedded black micritic limestones. (Middle Norian).

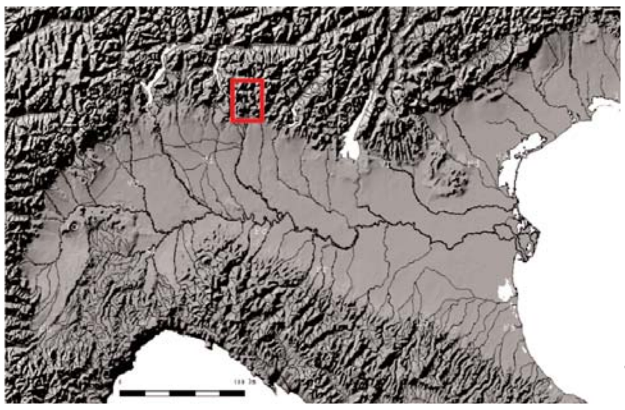
SYMBOLS

Main scarps and counterscarps related to DSSGD, inferred
Landslide scarp, inferred
Fault, inferred
Normal fault, inferred
Strike-slip fault, inferred
Thrust fault, inferred.

Bedding
Overturned bedding
Syncline axis
Anticline axis

0 0.5 1 km

Fig. 1 - *Geological map of the Corno Zuccone area*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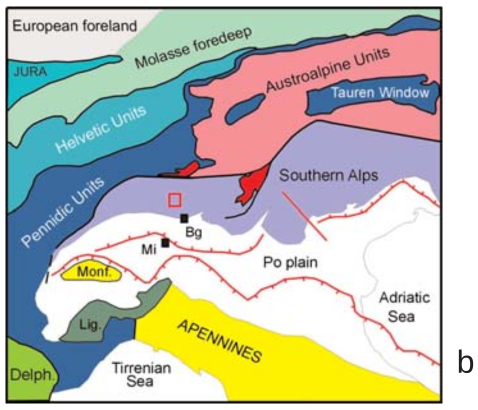

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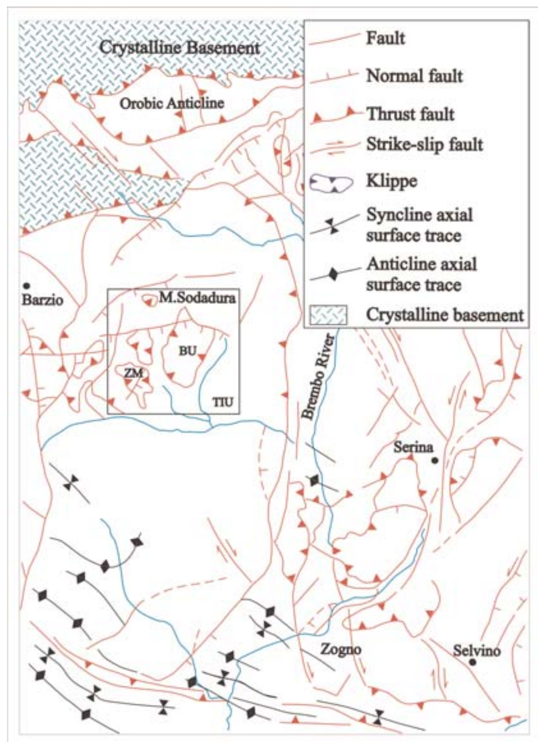

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Fig. 2 - a) *Shaded relief map of the Alps;*
b) *Structural scheme of the Alps showing the main domains. The box highlights the study area;*
c) *Structural map of the study area (modified from AA.VV., 2000).*

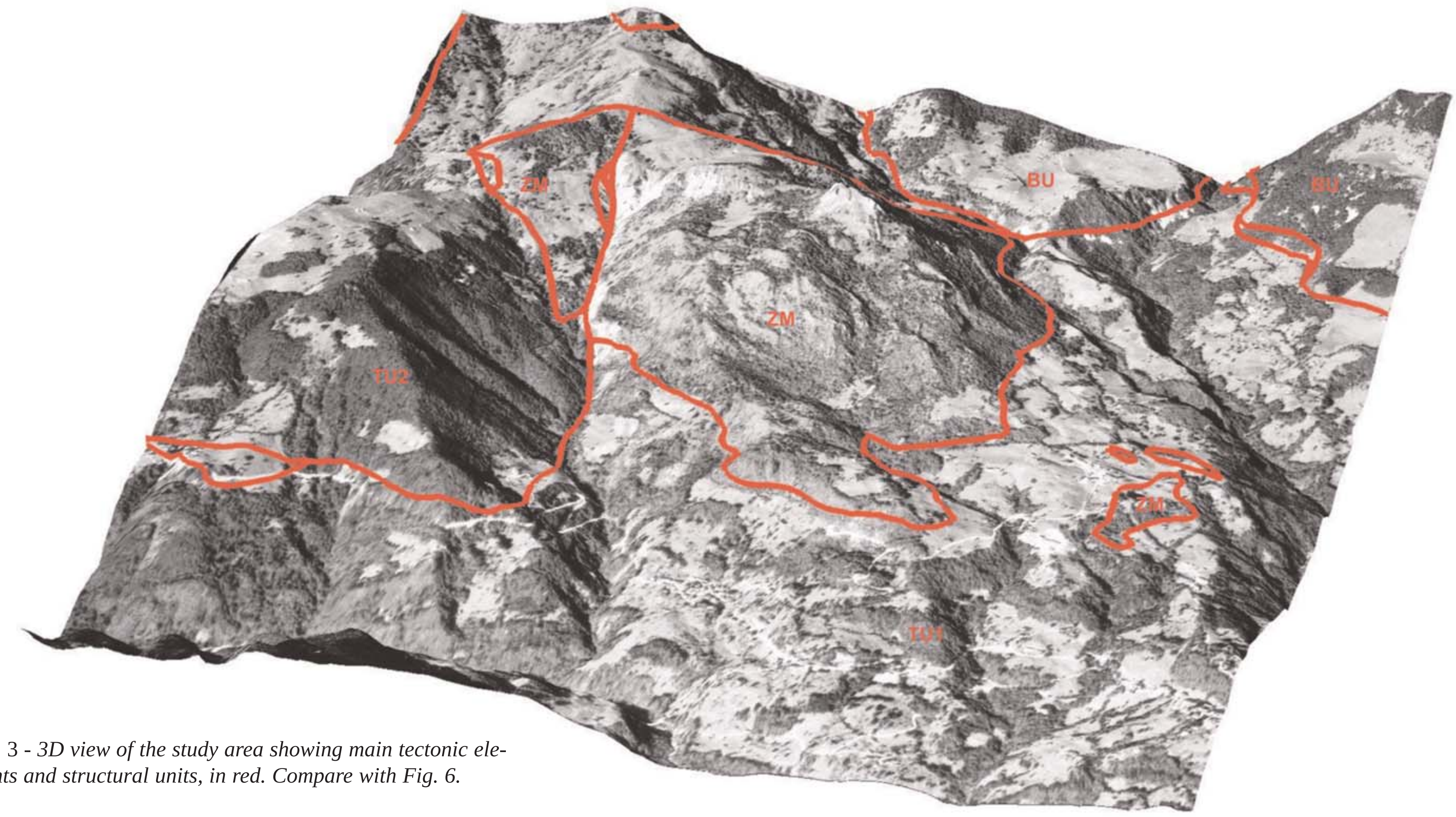


Fig. 3 - *3D view of the study area showing main tectonic elements and structural units, in red. Compare with Fig. 6.*

INTRODUCTION

A geological map is one of the best tools available to show the geometrical relationships between geological bodies. Their extent may be moreover appreciated in three dimensions by applying geometrical techniques (Ramsay & Huber, 1987; Powell, 1992; de Kemp, 2000), when topographic and structural data are also available.

The aim of this work is to show how, by using a special procedure, geological cartographic data stored in a Geographic Information System (GIS) can be used for the 3D modelling of complex geological bodies (Sterlacchini & Zanchi, 2001; Zanchi *et alii*, 2002, 2003). 3D reconstruction has been performed in GOCAD, a software based on a discrete smooth interpolator (Mallet, 1997) which makes possible the creation of 3D surfaces, volumes and grids starting from simple features, such as points and lines.

These techniques have been applied to the reconstruction of the Corno Zuccone deep-seated slope gravitational deformation (Crosta *et alii*, 1999, Zanchi *et alii*, 2002, 2003) developed within the sedimentary cover of the Southern Alps, in Italy (Fig. 1). The DSSGD occurs within a complex thrust stack (Schonborn, 1992; AA.VV., 2000) (Fig. 2), later affected by strike-slip and normal faults. These structures have been modelled on the basis of detailed structural, morphostructural and geological data (1:5,000-1:2,000). All required data were first stored and integrated within a GIS, to be later generalized and imported into GOCAD. The 3D model was reconstructed in several steps, which will be illustrated in the next sections.

GEOLOGICAL SETTING

The study area (Fig. 3) consists of Middle Triassic to Early Jurassic successions deposited in the Lombardian basin and stacked in a south-vergent imbricated thrust pile between the Cretaceous and Miocene (AA.VV., 2000). The lowermost tectonic unit, (Taleggio Imagna Unit: TIU) includes a complete succession spanning from the Calcare di Zorzino to the Calcare di Sedrina. The unit shows important tectonic repetitions around Avolasio (TIU1 and TIU2). The Zuccone-Maesimo (ZM) and the Corno del Bruco (BU) tectonic units cover the TIU. They both consist of strongly fractured carbonatic masses gently dipping southward. The ZM includes a few small Klippen of Dolomia Principale, which are the remnants of a continuous thrust sheet dismembered by N/S left-lateral strike-slip faults.

The largest klippe forms the massif of Corno Zuccone, which is the main object of the 3D reconstruction. The BU mainly consists of the Calcare di Esino. NW-SE right-lateral strike-slip faults separate the two upper units. A large part of the Mesozoic substratum is covered by continental deposits which testify to several important morphogenetic cycles during Quaternary.

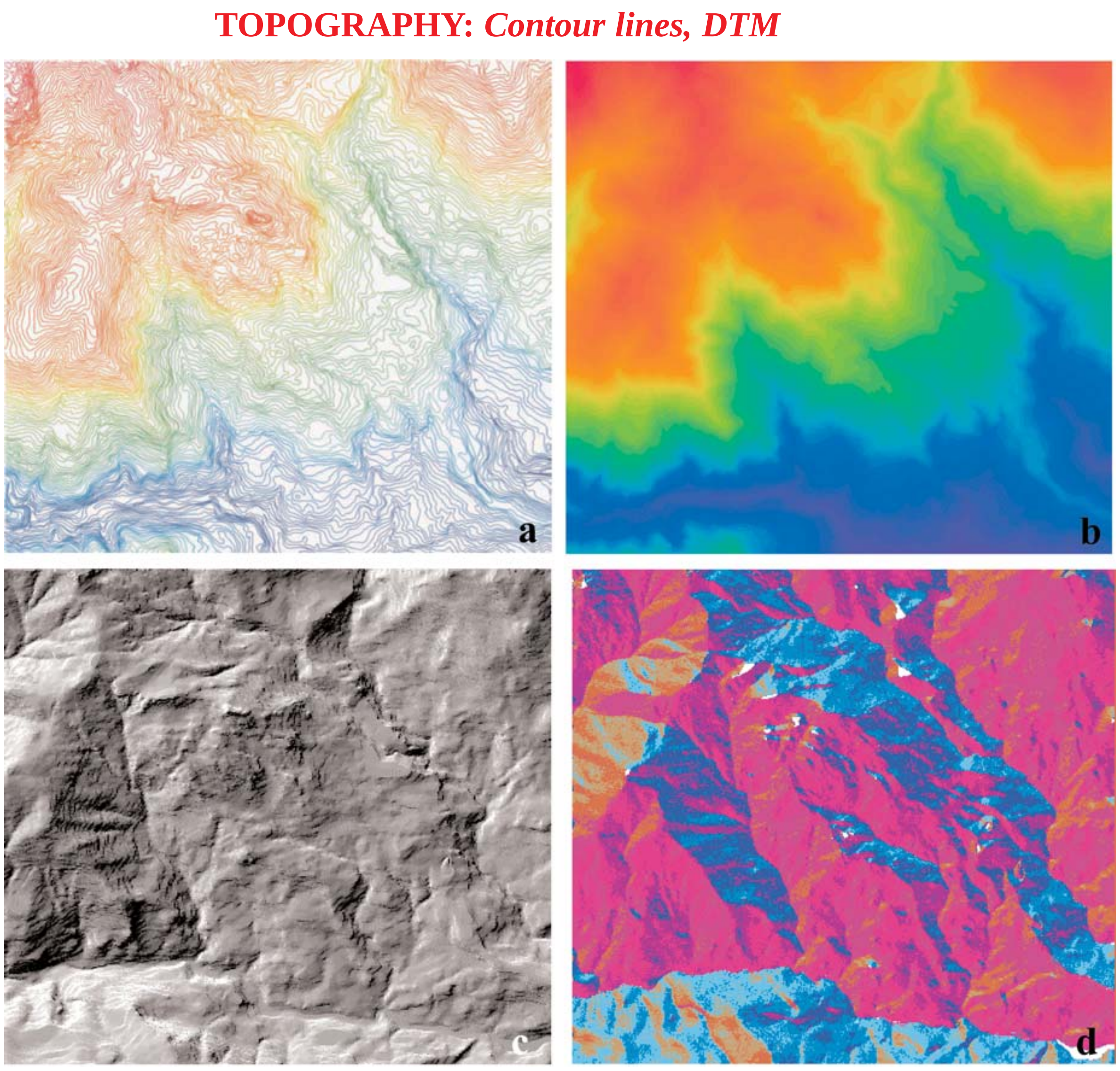


Fig. 4 - *Topographic data for 3D modelling:* a) *the contour lines (10 m) have been obtained in a vector format from a detailed 1:10,000 topographic map (CTR, Regione Lombardia);* b) *the Digital Elevation Model, DEM, (pixel size 2.5 m) has been directly realized in the GIS using the Burges algorithm for distance interpolation. The hill shaded relief map* (c) *and the aspect map* (d) *have been obtained from the DEM. These are 2.5 representations which can be used for morphological analysis. After resampling the DEM with a different pixel size (12.5 m), about 90,000 points will be extracted to create a 3D topographic surface in GOCAD.*

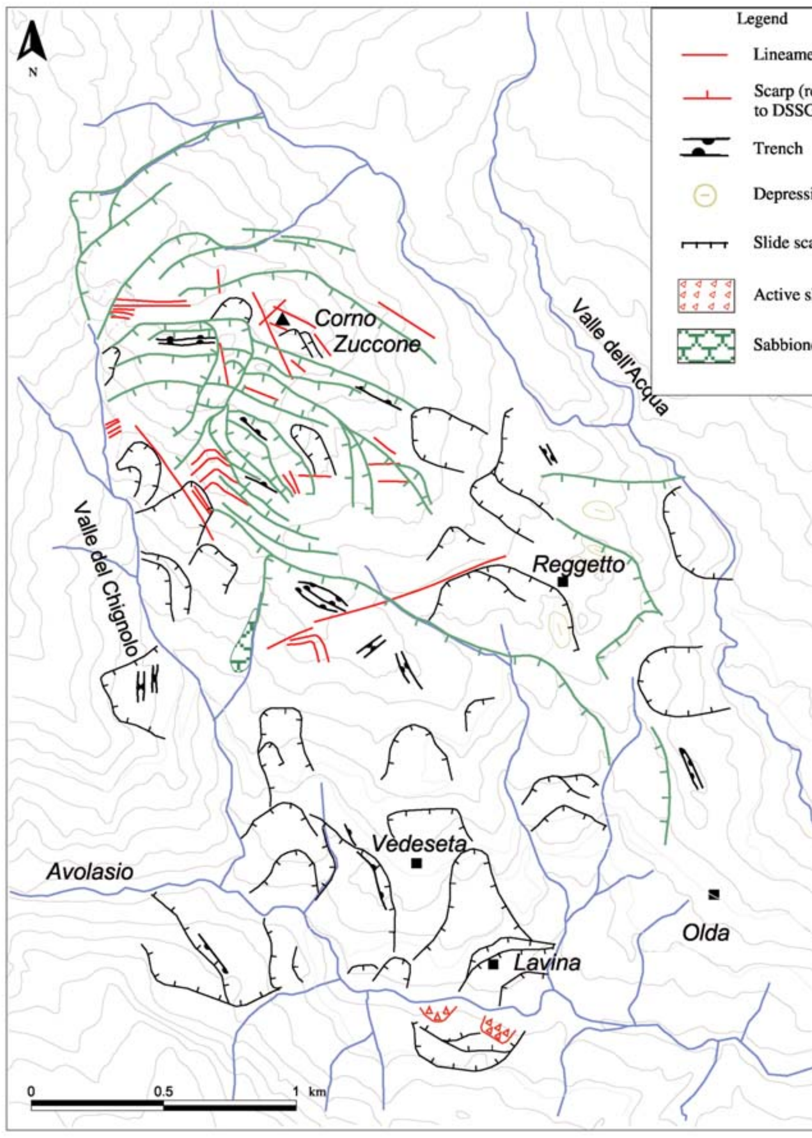
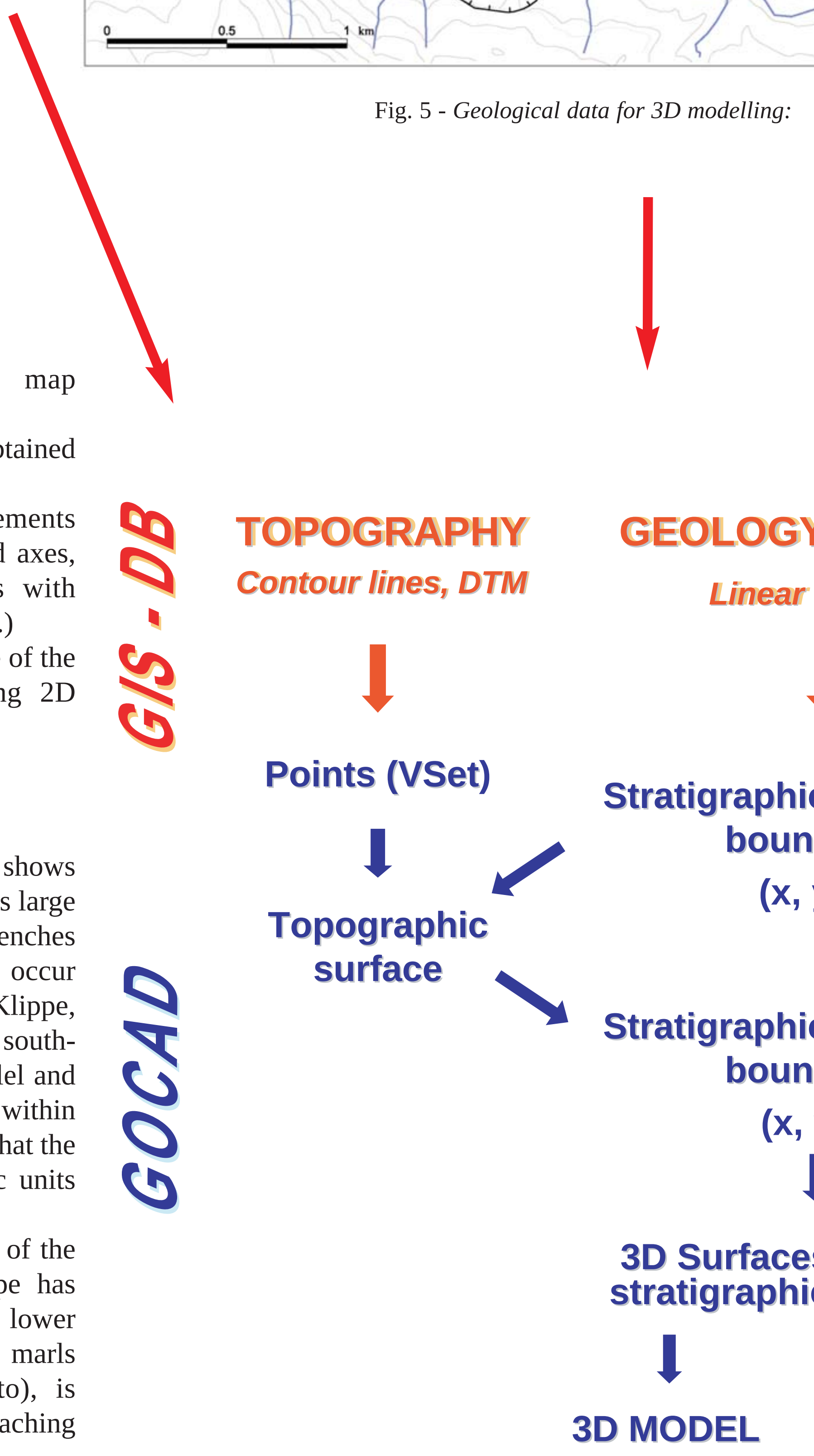


Fig. 5 - *Geological data for 3D modelling:*



CREATION OF THE GEO-DATABASE

The diagram on the right shows in synthetic fashion the procedure used for 3D geological modelling.

The first step concerns the creation of a geological database including all the information needed for 3D modelling (red part of the diagram). This step has been realized using a GIS, the best tool for the storage and management of cartographic data. The following data layers have been built in the geo-database:

- topographic data (Fig. 4), including 2D elevation contour lines and single points. Digital Elevation Models (DEM) have been obtained in the GIS by interpolation of the topographic elements, to be used later on for the creation of the 3D topographic surface in GOCAD;
- stratigraphic and tectonic boundaries (2D lines). These features have been obtained by generalizing the detailed geological map surveyed in the field (Fig. 5b);
- morphostructural elements (2D lines) obtained from photo interpretation (Fig. 5a);
- mesoscopic field structural measurements (Fig. 6) (attitude of bedding, faults, fold axes, lineations, etc.) represented as points with properties (dip, dip-direction, plunge, etc.)
- geological cross-sections (Fig. 7). Some of the sections have been reconstructed using 2D balancing techniques.

THE CORNO ZUCCONE DSSGD

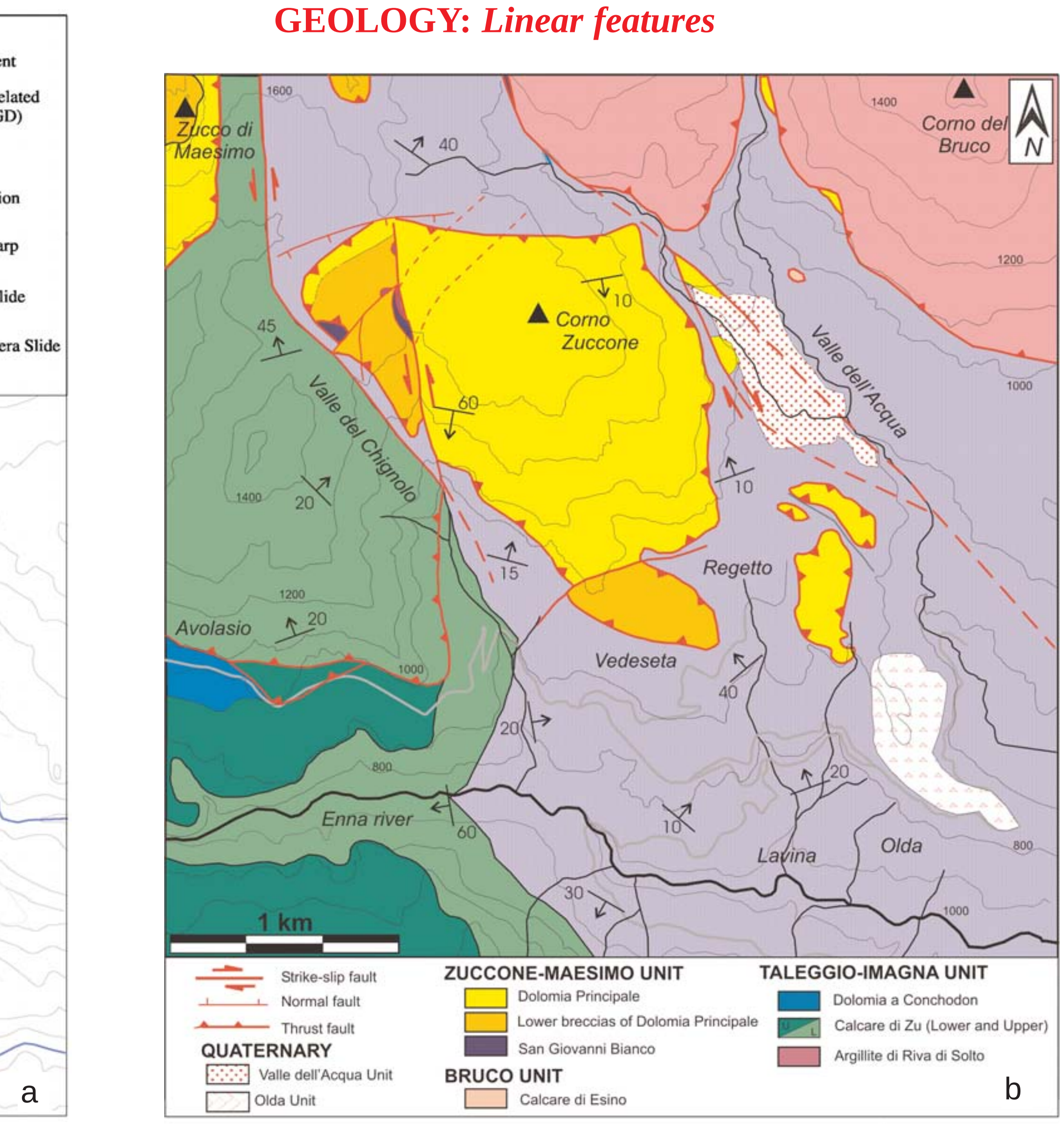
The whole slope of the Corno Zuccone shows impressive morphological features such as large down- and up-hill facing scarps and trenches (Fig 5a). The main morphostructures occur within the rigid mass of the Zuccone Klippe, which shows E-W to ESE-WNW striking south-dipping sliding planes. Three main parallel and continuous scarps cross the entire slope within the Argillite di Riva di Solto, suggesting that the DSSGD strongly affects also the plastic units lying below the rigid Zuccone Klippe.

A vertical down-throw of at least 100 m of the southern portion of the Zuccone Klippe has been observed along the main scarp. The lower part of the slope, entirely consisting of marls and shales (Argillite di Riva di Solto), is affected by deep landslides, possibly reaching the River Enna talweg.

Continuous movements in recent times are suggested by strong damages to roads and bridges. The sharp southward diversion of River

Fig. 8 - *View from south of the Corno Zuccone sackung. The main scarp of the DSSGD is clearly recognizable.*

GEOLOGY: *Linear features*



a) *morphostructural map;* b) *generalized geological map.*

STRUCTURAL DATA: *Attitudes and Cross-sections*

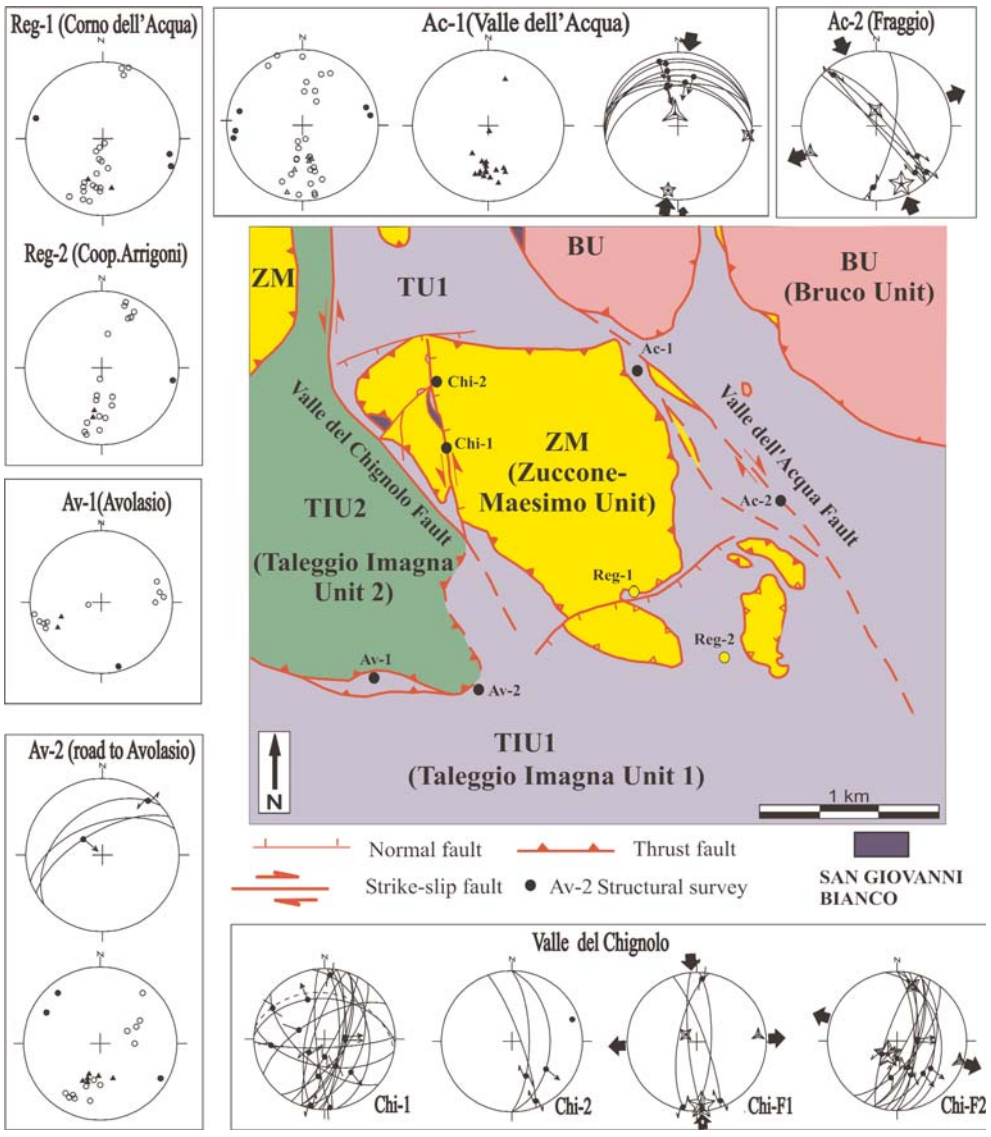
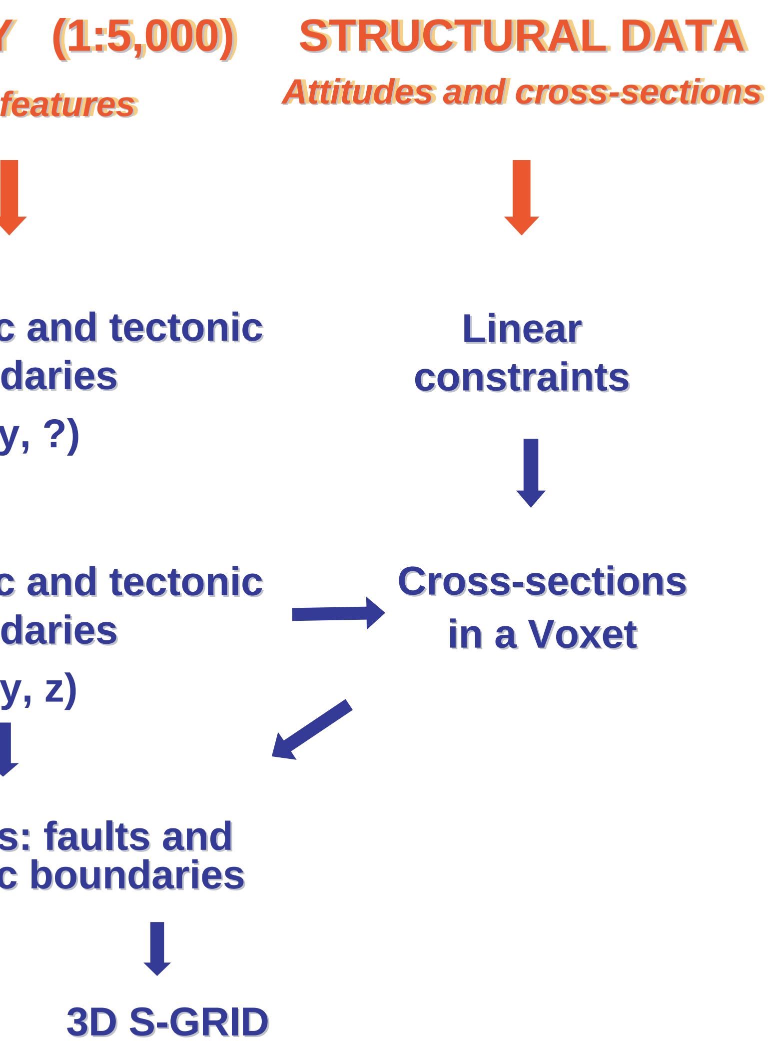


Fig. 6 - *Mesoscopic structural data have been collected along the major tectonic structures to define their geometrical characters and kinematics. Schmidt's projection lower hemisphere. Great circle projections show faults with striations and sense of motion, small dots are poles to bedding, black triangles poles to axial plane of folds, and dots are fold axes. 5, 4 and 3-point stars show the main stress axes (σ1 > σ2 >σ3) obtained using* ANGELIER'S *(1984) inversion methods. Strike-slip motions* (CHI-F1) *occurred before the reactivation of the Valle del Chignolo Fault* (CHI-F2) *in an extensional regime.*



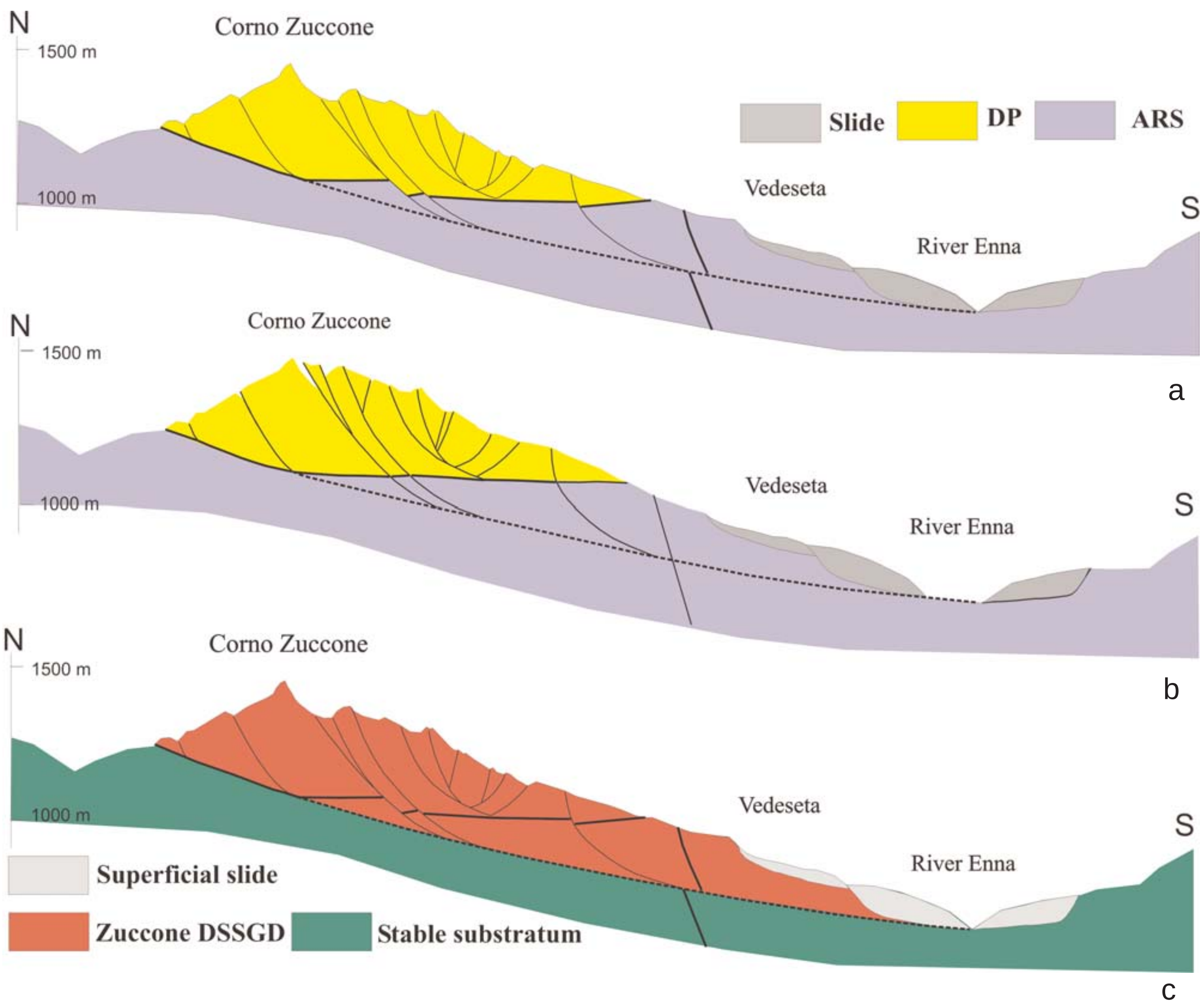
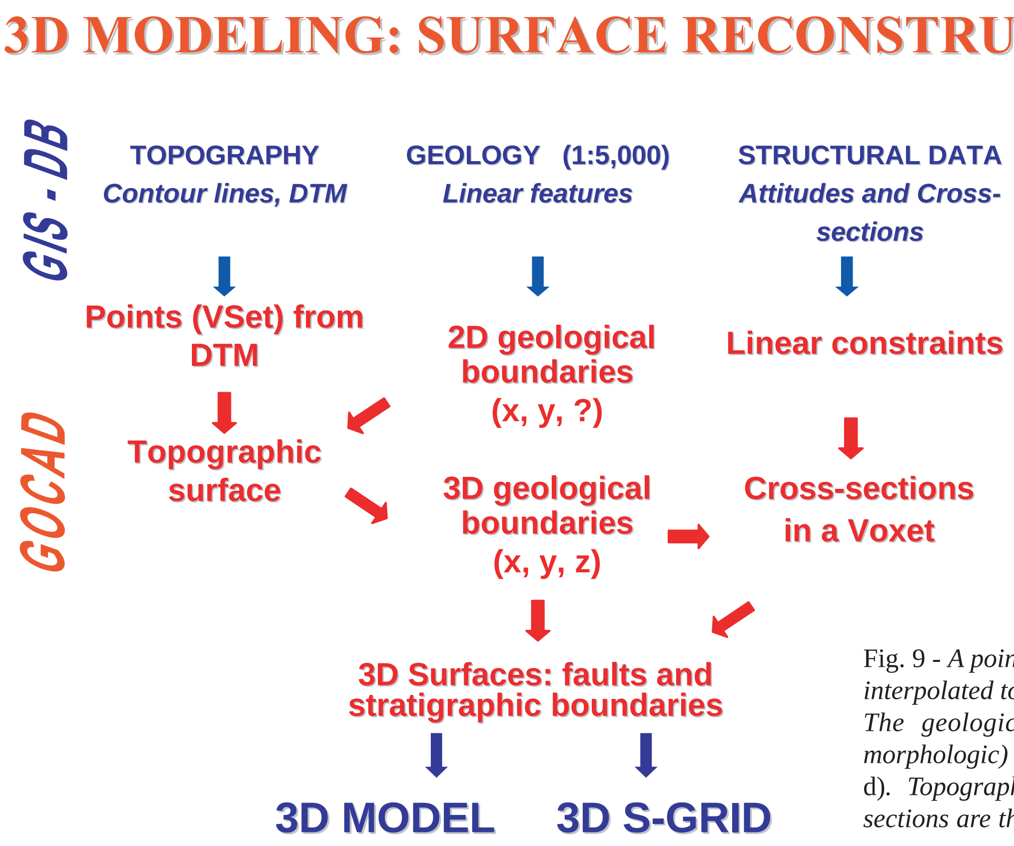


Fig. 7 - *Geological cross-sections are one of the best tools to define the 2D geometry of the studied object. Balanced sections have also been constructed to constrain the geometrical features of the slided mass. A rigid behaviour and limited block rotations (<10°) have been assumed. 2D balancing along a N-S cross-section passing through the summit of the Corno Zuccone* (a, b) *suggests that the River Enna diversion (about 120 m) is in agreement with the observed vertical displacement (about 100 m). A listric geometry of the sliding surfaces is suggested by their superficial traces* (c).



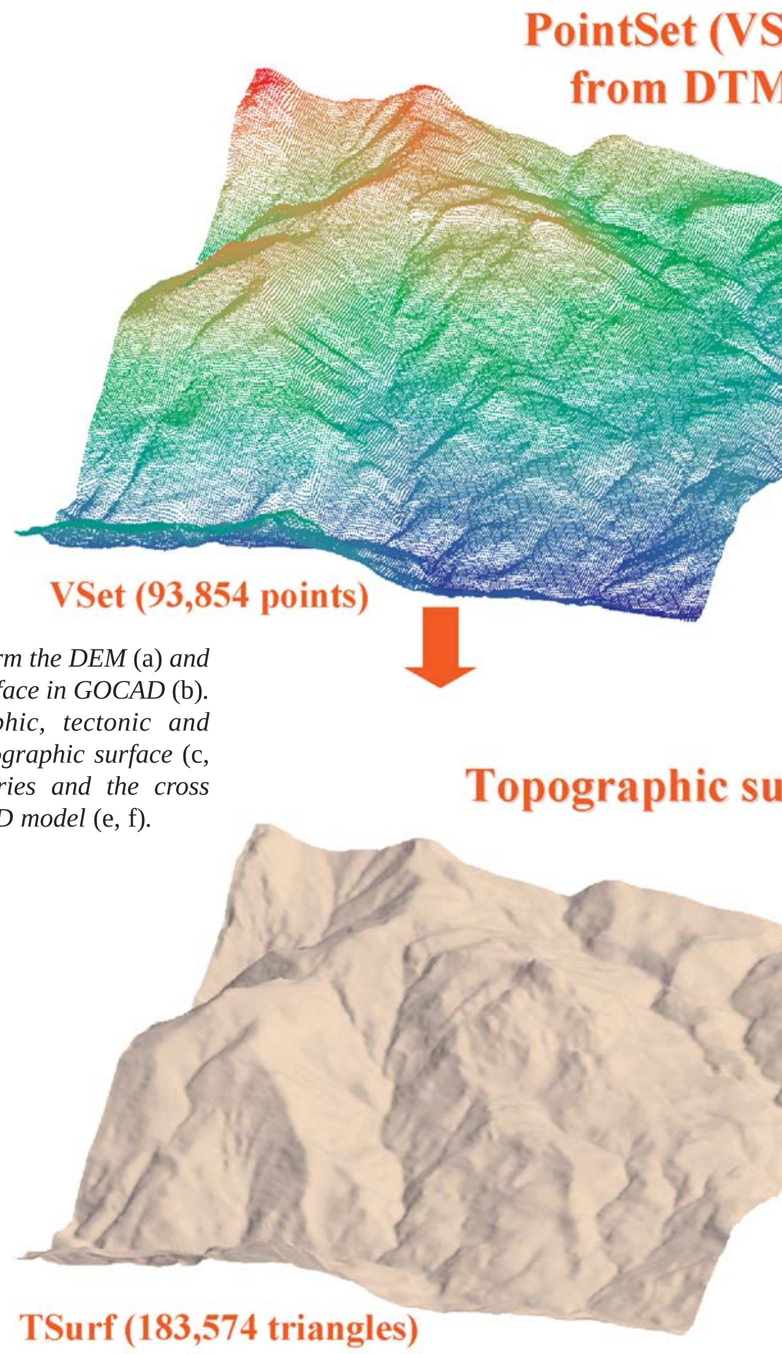


Fig. 9 - *A point set* (x, y, z) *is extracted form the DEM* (a) *and interpolated to create the topographic surface in GOCAD* (b). *The geological boundaries (stratigraphic, tectonic and morphologic) are projected onto the topographic surface* (c, d). *Topography, 3D geological boundaries and the cross sections are the main constrains for the 3D model* (e, f).

Enna along the toe of the DSSGD can be also related to the progressive movement of the Zuccone slide.

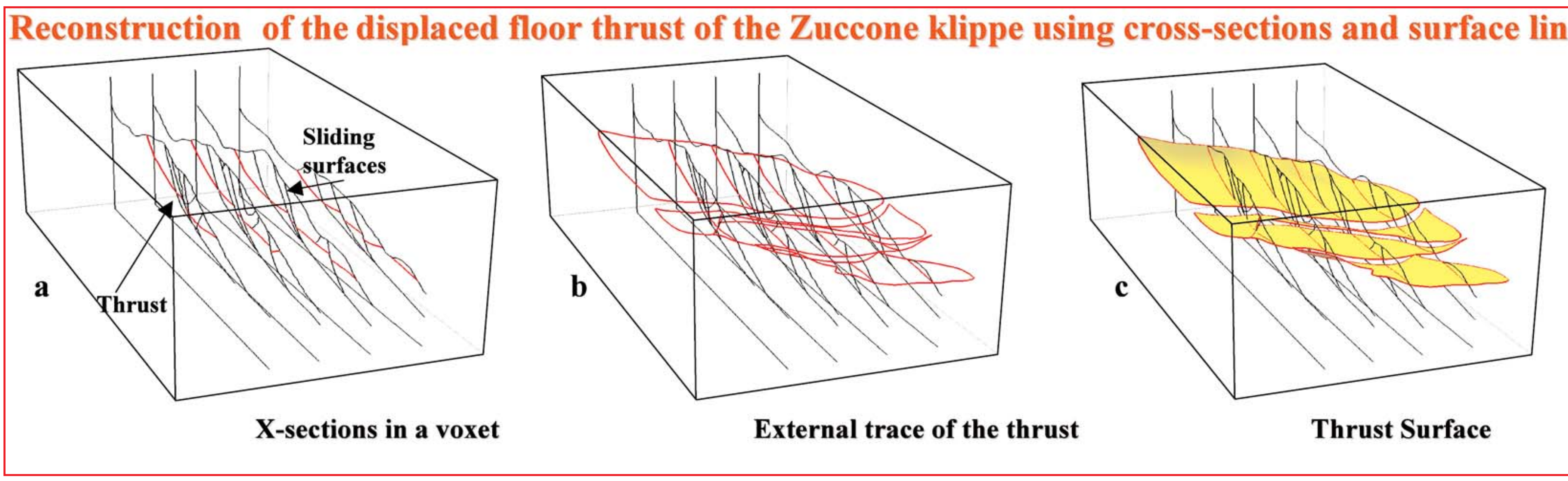
A simplified geological map has been obtained generalizing the original field data (Fig. 5b).

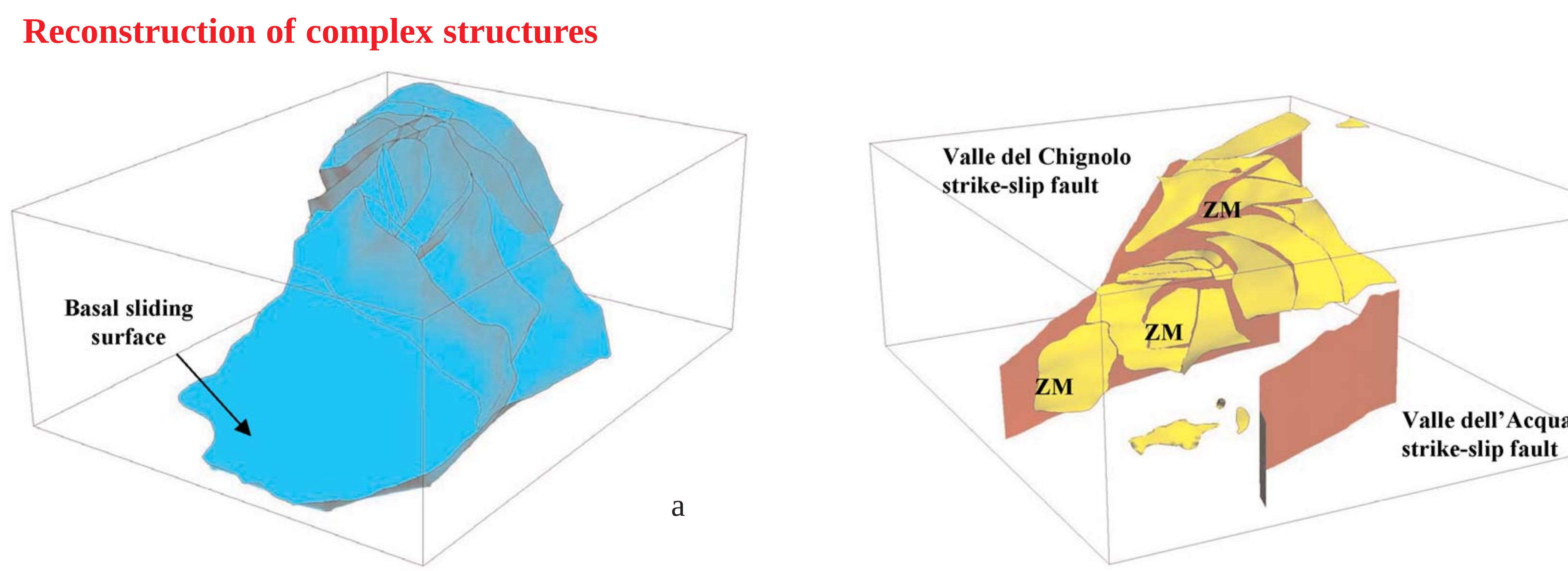
3D MODELLING: SURFACE RECONSTRUCTION

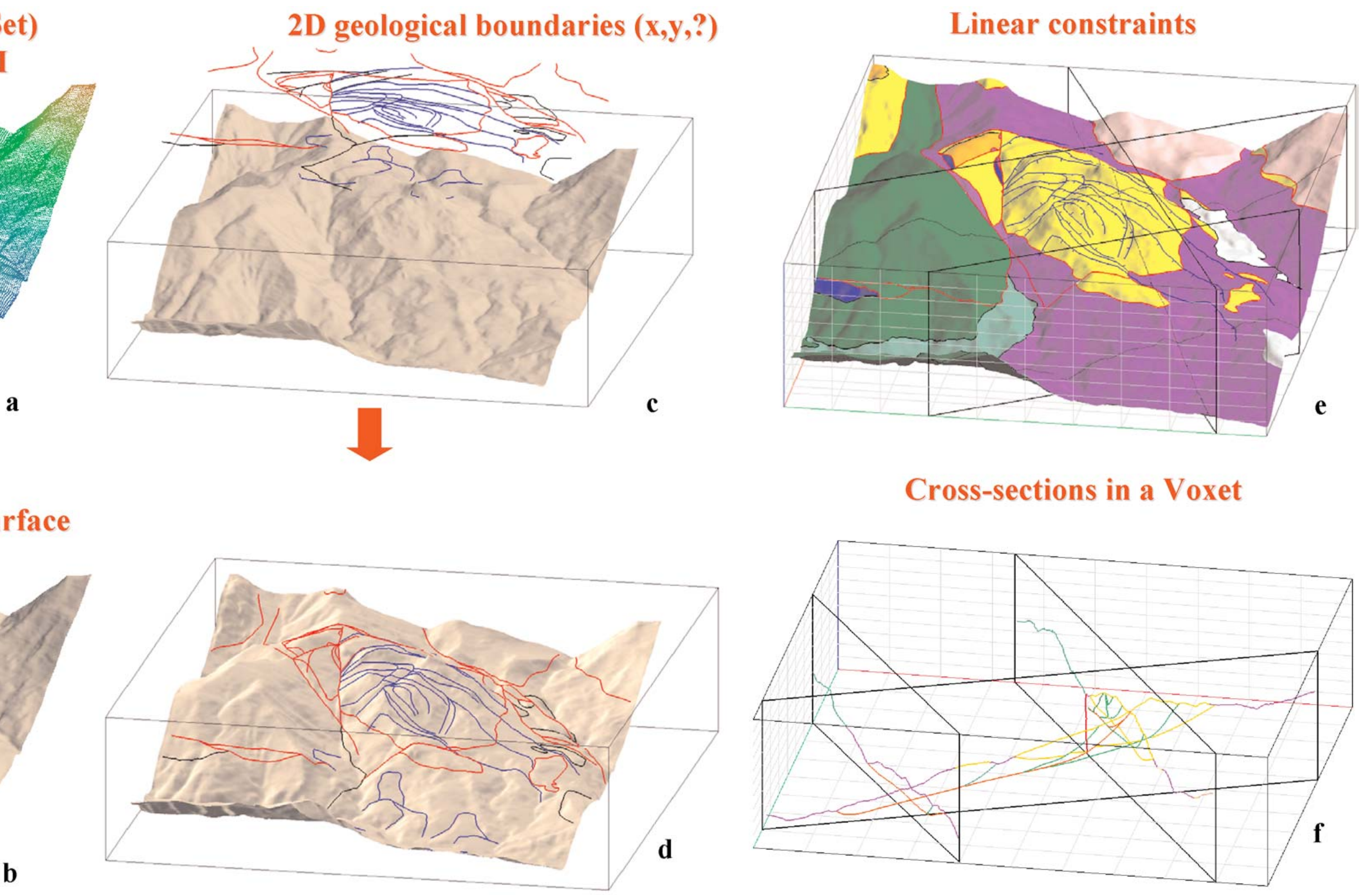
The procedure for 3D modelling (in red) starts with the construction of the topographic surface. Topographic data have been extracted from the DEM as points, which have been imported (VSet) and interpolated in GOCAD leading to the construction of a real 3D topographic surface (TSurf) (Fig. 9).

Lines have been directly imported in GOCAD and transformed into 3D linear features through projection on the topographic surface.

Starting from the topographic surface, a 3D grid has been built (Voxet), where geological cross-sections are digitized in GOCAD or directly imported from the geo-database (Fig. 10). Structural measurements are transformed into







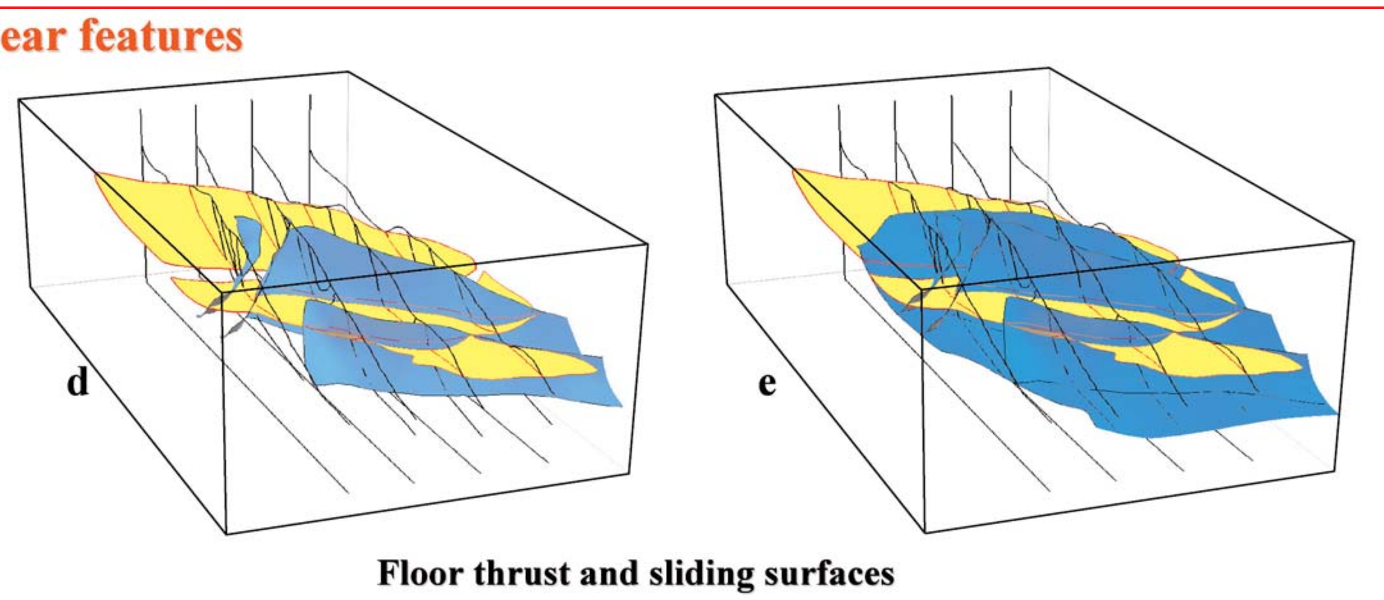


Fig. 10 - *The floor thrust of the Zuccone Klippe and the sliding surfaces of the sackung have been constructed following the steps defined in the previous scheme. Linear features from cross-sections* (a) *and superficial boundaries are combined to construct the external trace of the thrust surface* (b)*. Interpolation of the linear features through the DSI leads to the construction of the thrust plane which is shown in yellow* (c)*. The sliding surfaces (light blue:* d, e*) have been built following the same steps.*

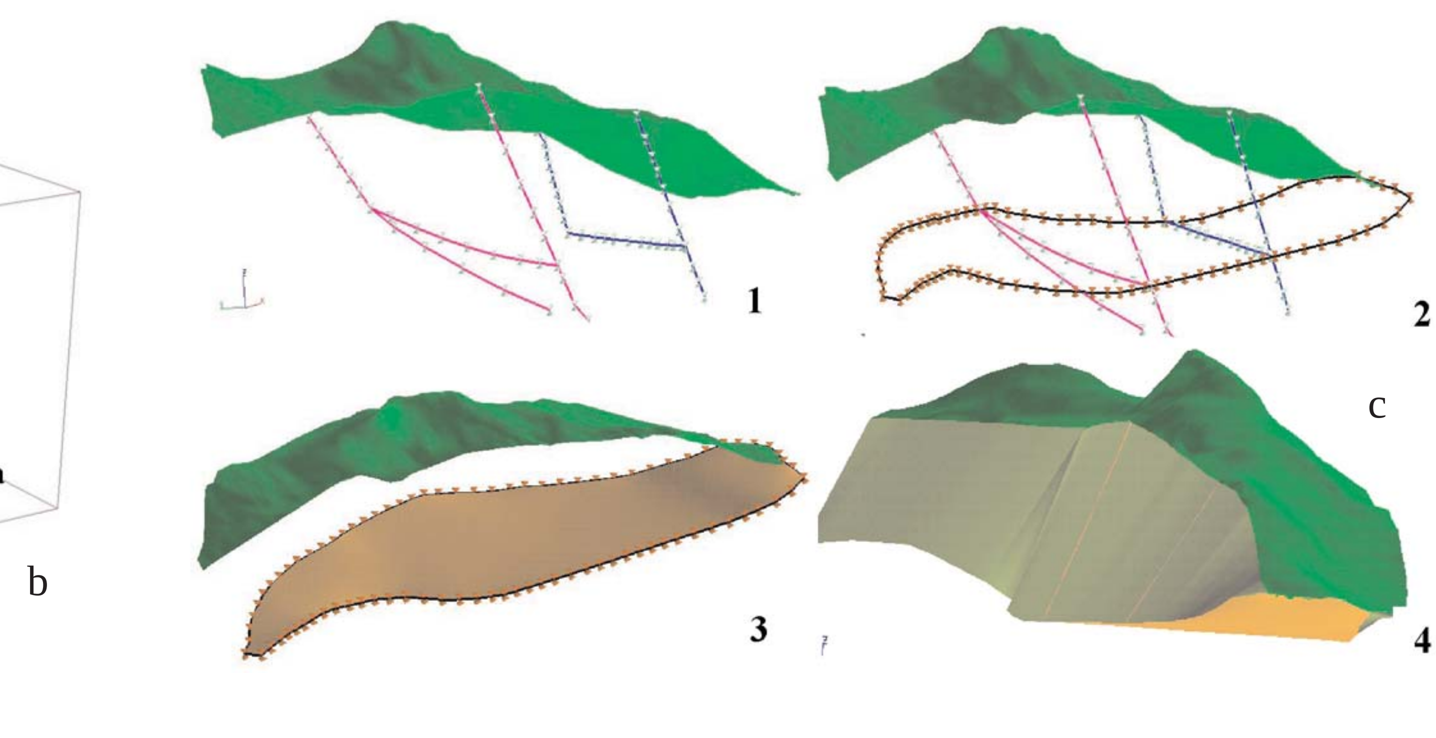
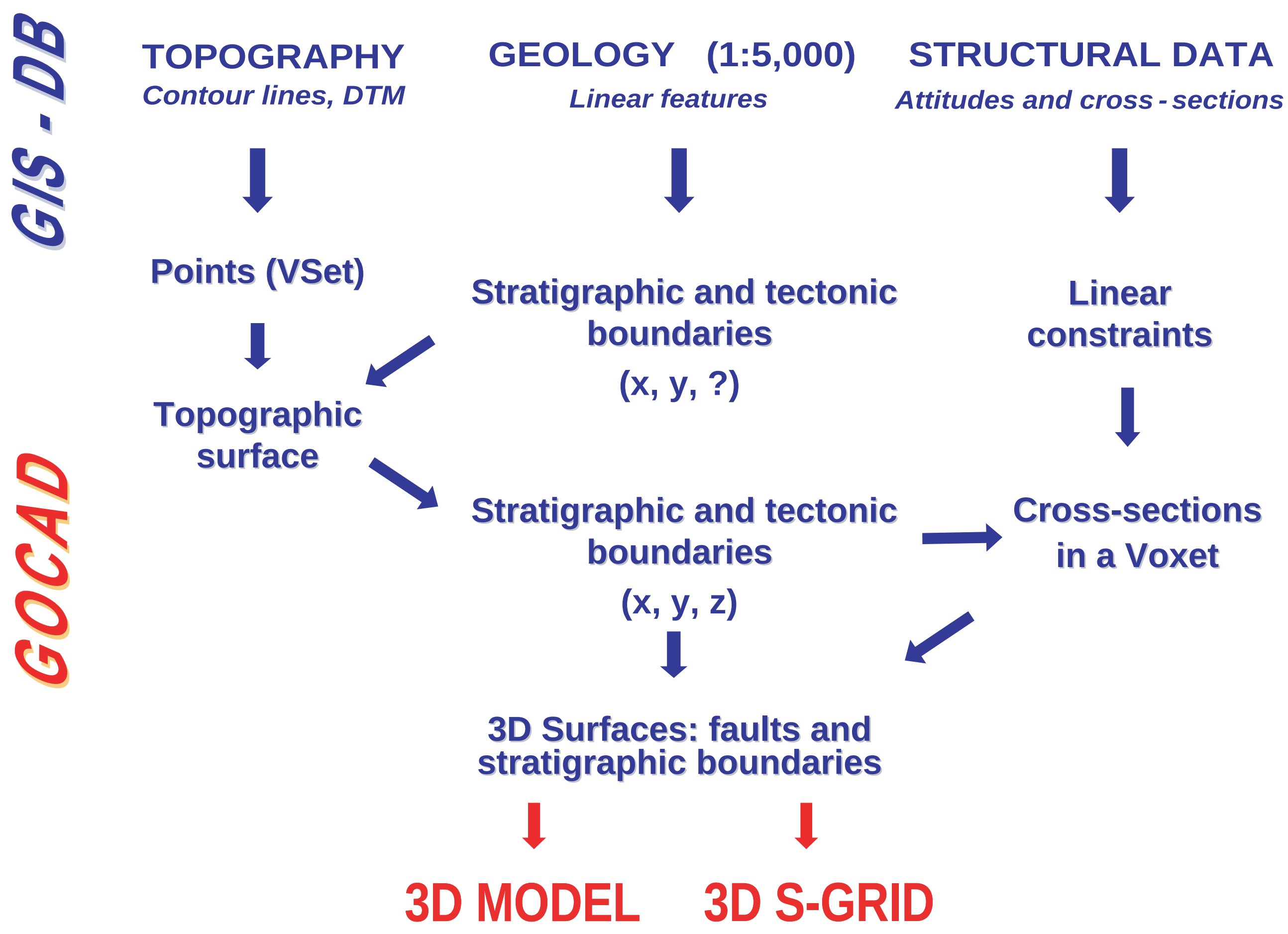


Fig. 11 - *The main tectonic and gravitational surfaces of the Corno Zuccone massif have been progressively built using the described procedure.*
a) *the basal sliding surface of the Corno Zuccone DSSGD is represented in light blue together with other minor gravitational structures. The floor thrust of the Klippe is in yellow;*
b) *the floor thrusts of the Zuccone-Maesimo Unit* (ZM) *and of the Bruco Unit* (BU) *are shown, with the main strike-slip fault systems bounding the Corno Zuccone Klippe;*
c) *closed surfaces can be created by merging different surfaces. Each single block of Dolomia Principale forming the Corno Zuccone Klippe has been constructed using the topographic surface and linear features obtained from the geological map and cross-sections.*
a: *main sliding surfaces of the Corno Zuccone DSSGD;*
b: buried thrust planes and strike-slip faults around Corno Zuccone;
c: construction of a closed surface forming the Corno Zuccone Klippe.

down-dip plunging lines to be used as constraints for the reconstruction of geological crosssections and structural surfaces. Each single surface is then created interpolating all the obtained 3D linear features (Figs. 10, 11a and 11b) .

3D MODELLING: VOLUMES AND GRIDS

The last step consists in the definition of closed surfaces (volumes) and in the construction of 3D grids. As previously mentioned, single surfaces can be combined in order to generate "closed" elements defining volumes (Figs. 11c, 12 and 13). These objects can be translated along selected directions, e.g. for 3D retro-deformation. A comparison between the results of 3D reconstruction and previous 2D balancing is thus possible. Moreover, in the latter case, 3D grids with regular (Voxet) or deformable cells (S-Grid) can be obtained and fitted to structural or stratigraphic surfaces. One or more properties can then be associated to each surface and interpolated across the grid.



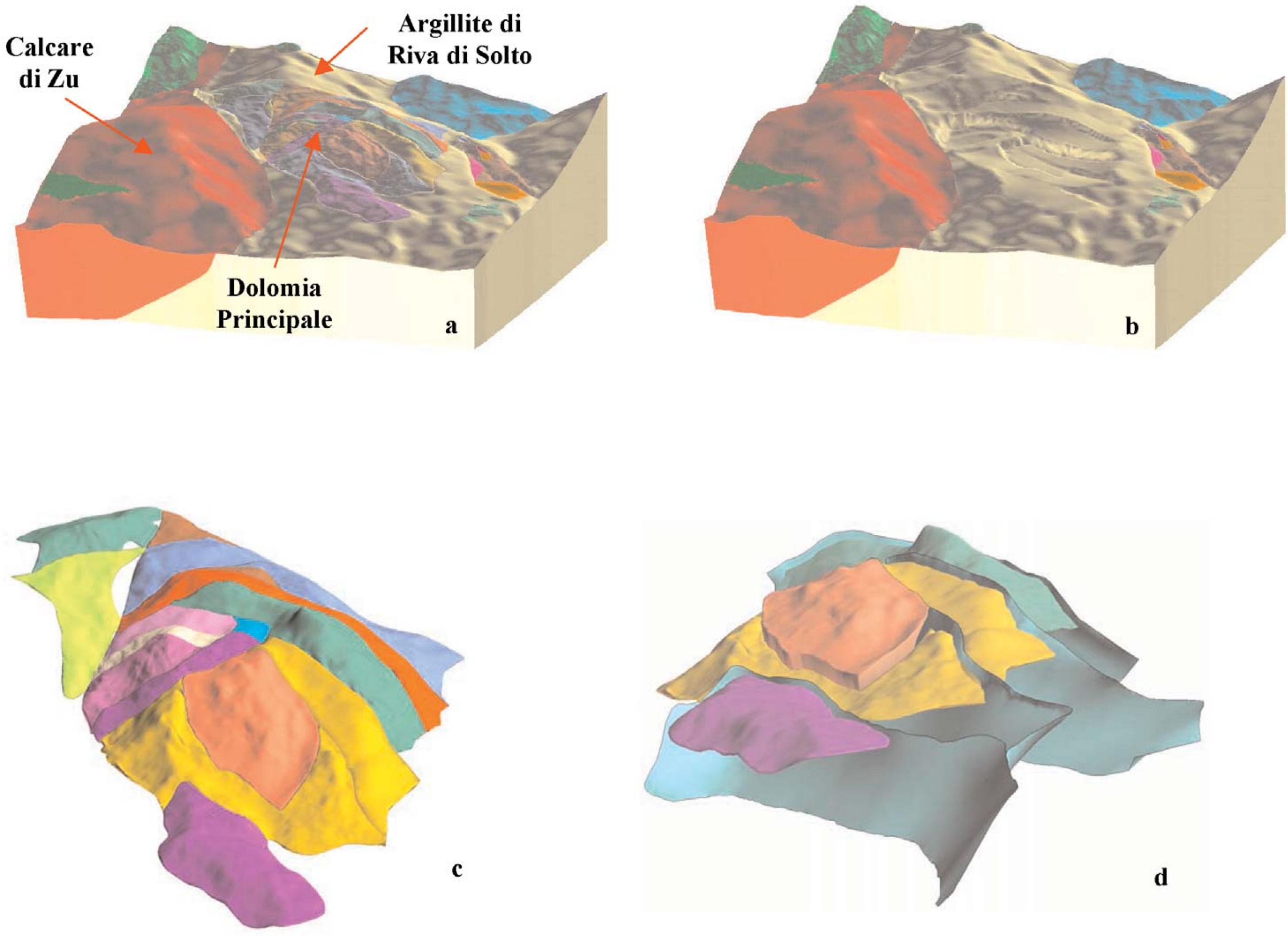


Fig. 12 - a) *3D geological map of the Corno Zuccone area.* b) *Top of the Argillite di Riva di Solto after removing the Corno Zuccone klippe.* c) *The blocks forming the Corno Zuccone klippe have been reconstructed as closed surfaces. The total volume of the klippe (222,372,800 m³) has been computed.* d) *Main sliding surfaces of the Corno Zuccone DSSGD with displaced blocks of the klippe.*

THICKNESS EVALUATION

Starting form the topographic and basal sliding surfaces obtained, the thickness of the main slide can be easily evaluated (Fig. 14).

GRIDS AND GEOMECHANICAL PROPERTIES

Starting from the above surfaces, properties can be directly computed and introduced into a special 3D deformable grid (S-grid) which will be adapted to the shape of the basal sliding surface (Fig. 15). An S-grid with 4 different layers has been created for the Zuccone DSSGD. Different cohesion values (Crosta *et alii*, 1999) have been assigned to each layer and interpolated across the grid. Very low cohesion values (0.1-0.2 MPa, yellow) have been assigned to the Argillite di Riva di Solto close to the thrust plane and to the basal sliding surface, and higher values to the core of the slided mass

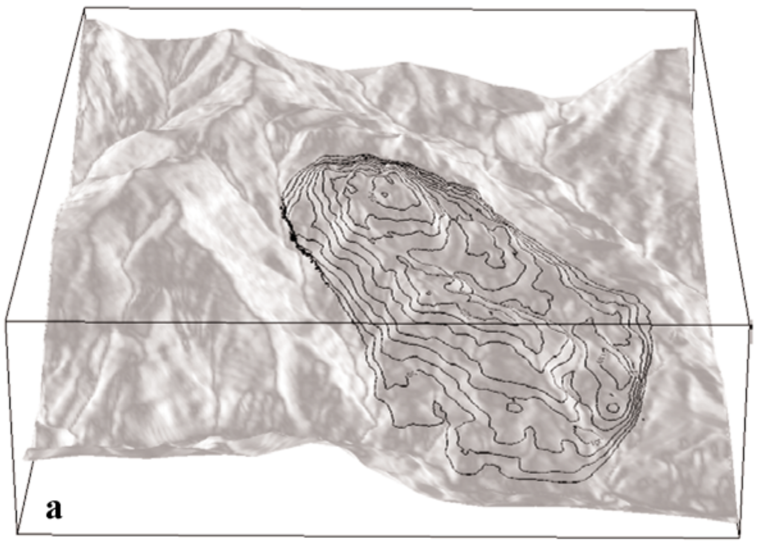
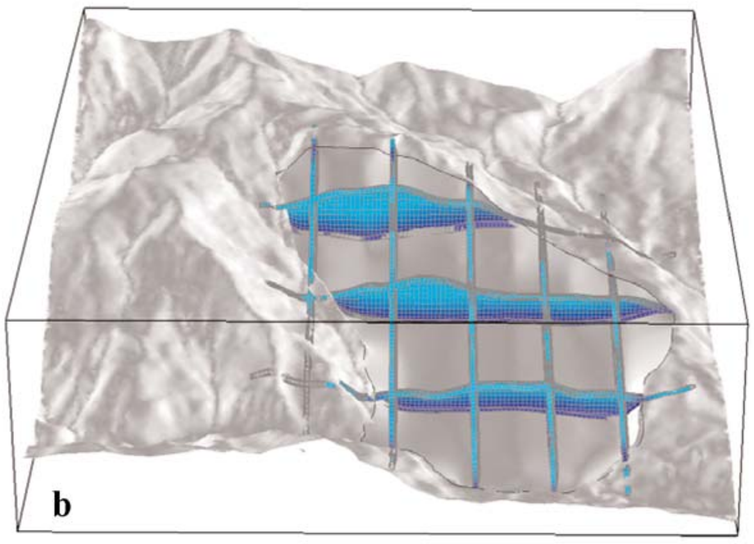
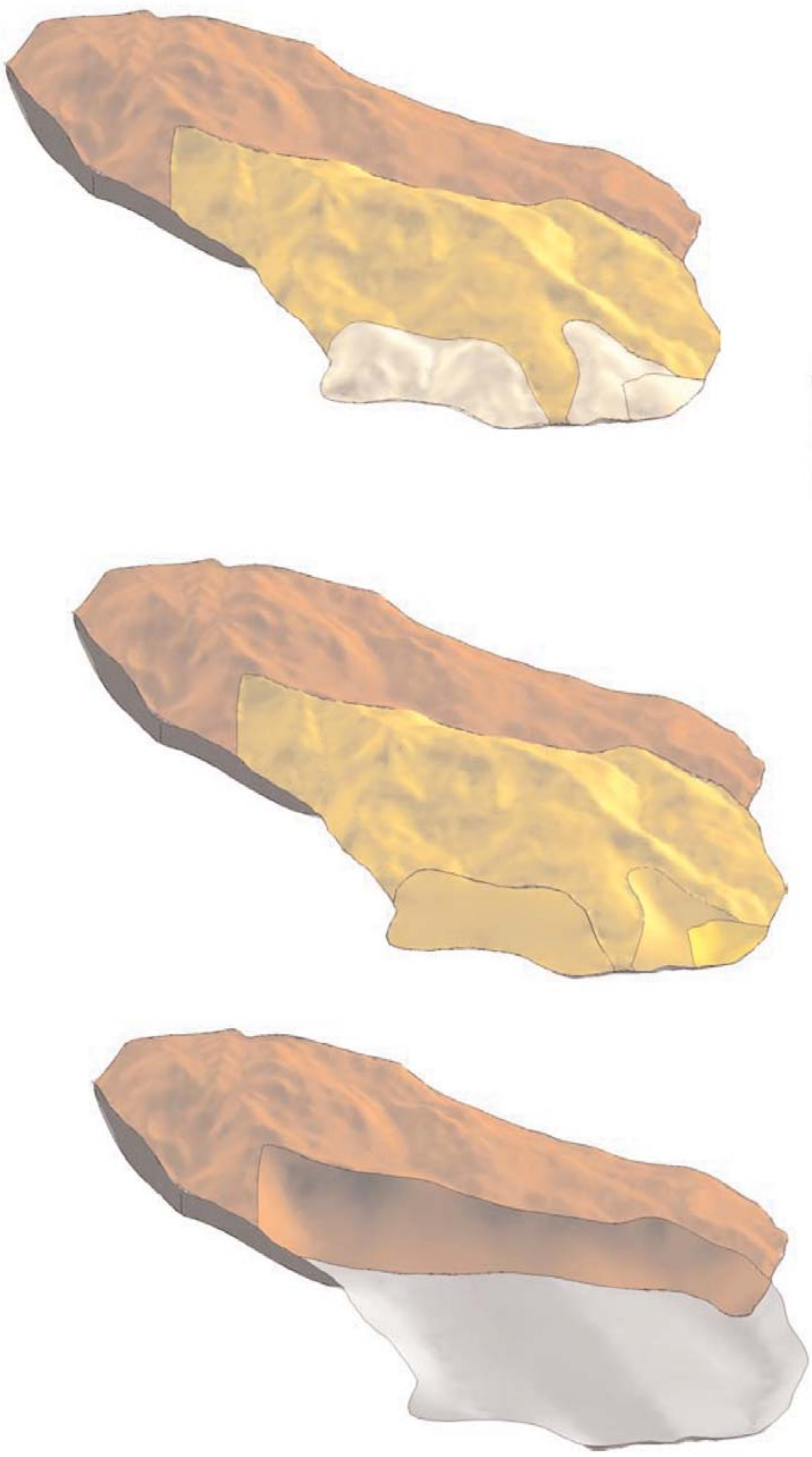


Fig. 14 - a) *Isopachytes of the Corno Zuccone DSSGD (contour interval 25 m);* b) *S-grid of the Corno Zuccone DSSGD (cells in dark blue represent the thickest parts of the slide).*





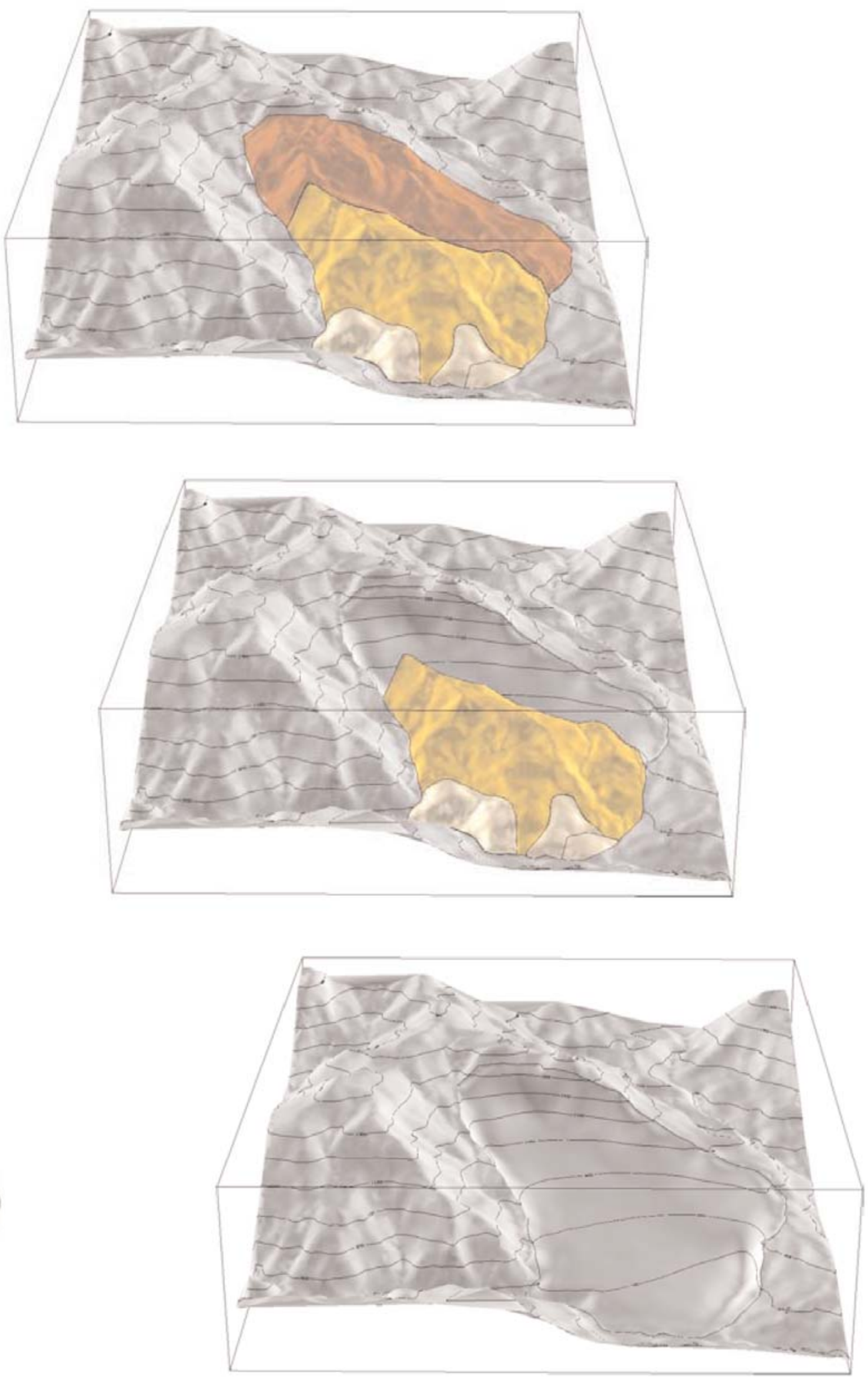


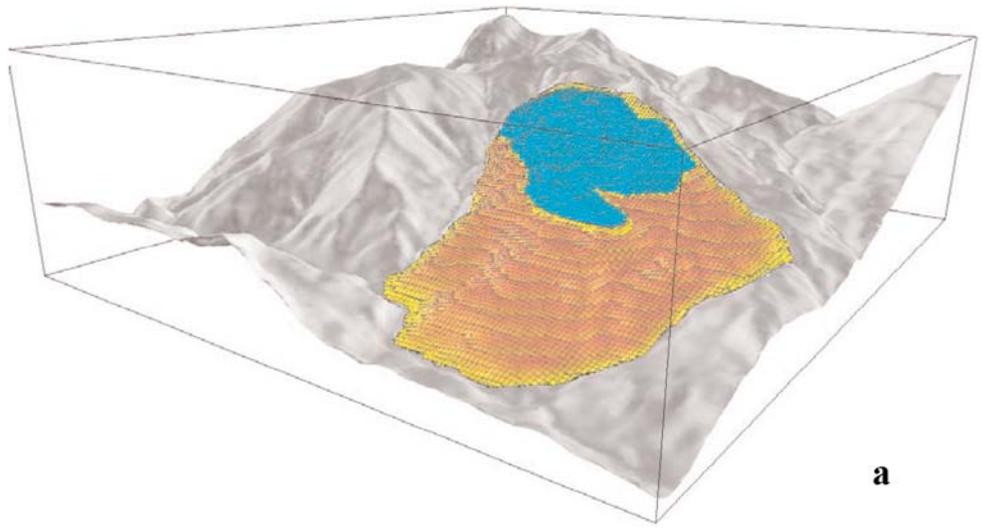
Fig. 13 - *The Corno Zuccone sackung has been subdivided into 3 main bodies. After removing each body, the basal sliding surface can be directly observed.*

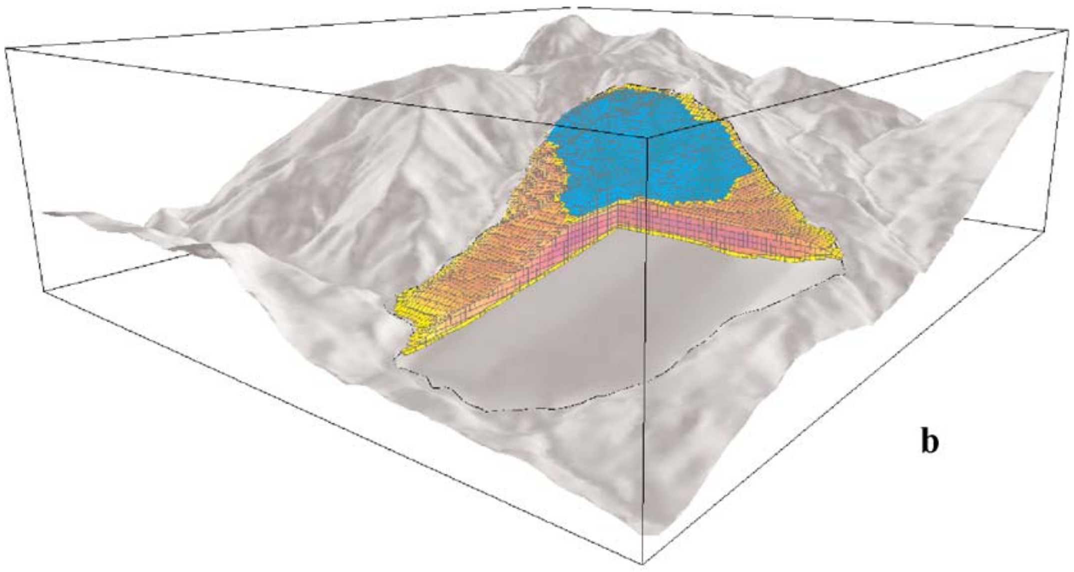
(0.3-0.4 MPa, violet). The dolomitic Klippe (light blue) has been considered as a homogenous mass with higher mechanical properties. The 3D geometry obtained for the DSSGD and the 3D distribution of the mechanical properties can be used, e.g., in the construction of 2D sections along preferred orientations for slope stability analyses.

CONCLUSIONS

3D geological modelling offers several advantages for the comprehension of analysed structures.

- A rigorous check of the consistency of surface geology and 2D interpretative sections was made possible, leading generally to an improved geometrical interpretation of the Zuccone DSSGD.
- 2 and 3D balancing suggests that the finite strain cannot be accommodated by plastic deformation of the lower unit and that a basal detachment must have been active, as also suggested by numerical modelling (CROSTA *et alii*, 1999).
- A preliminary evaluation of the 3D geometric features of the slided mass can be very useful with a view to establishing preliminary monitoring plans or subsurface investigations.
- Finally, GOCAD makes possible the construction of 3D grids where geomechanical properties can be interpolated taking into account the whole geometrical complexity of the geological bodies. This could be considered to be a new kind of approach for future 3D geomechanical numerical modelling.





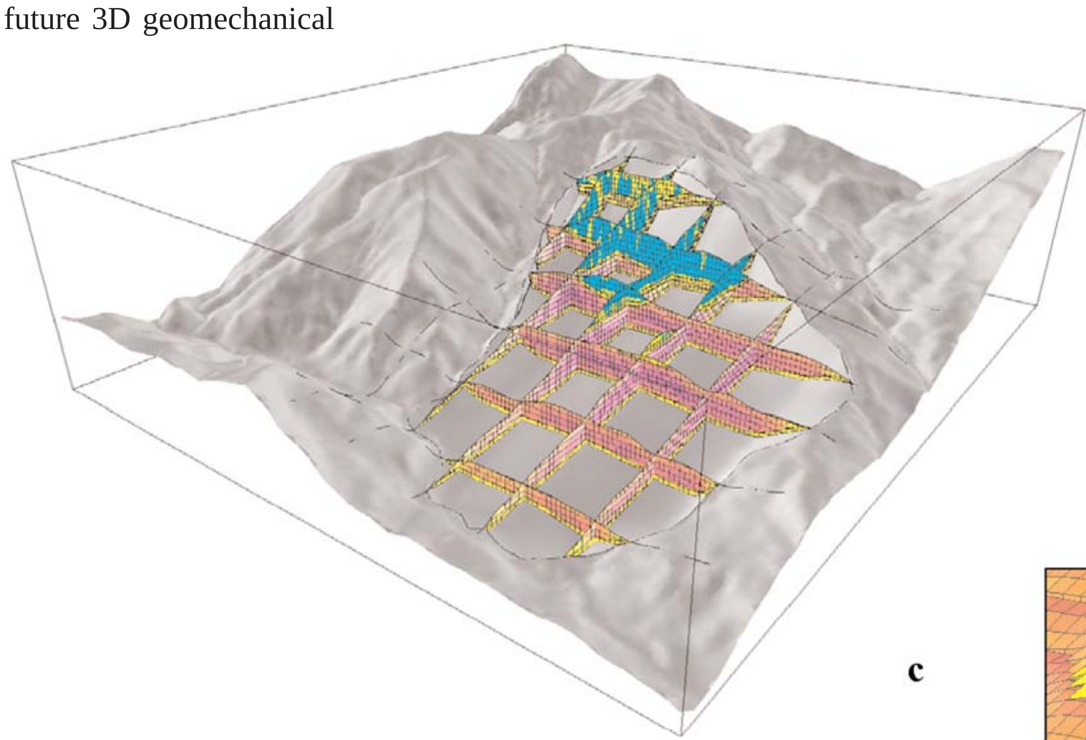
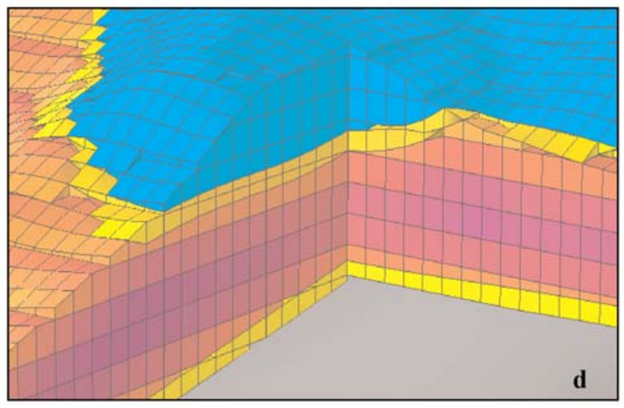


Fig. 15 - a) *S-grid of the Zuccone DSSGD with 4 different layers; each colour corresponds to a different cohesion value (0.1-0.2 Mpa in yellow, 0.3-0.4 Mpa in violet; the dolomitic klippe with a much higher cohesion value is in light blue;* b) *and* c) *cross sections of the S-grid;* d) *zoom of the S-grid.*



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