Reprint from Pflug, R. & Harbaugh, J.W. (Eds.) (1992): Computer graphics in geology: Three-dimensional modeling of geologic structures and simulating geologic processes.- Lecture Notes in Earth Sciences, v. **41**, xvii + 298 p., Berlin (Springer-Verlag).

COMPUTER MODELLING OF SURFACES: STRUCTURAL GEOLOGY APPLICATIONS

M.BARCHI[1], C. FEDERICO[1], F. GUZZETTI[2] and G. MINELLI[1]

1-Dipartimento di Scienze della Terra, Università degli
Studi, P.za dell'Università, 06100 Perugia, Italy
2-C.N.R. - Istituto di Ricerca per la Protezione
Idrogeologica nell'Italia centrale,
V. Madonna Alta 126, 06100 Perugia, Italy

ABSTRACT

Map analysis techniques are an important tool for a structural geologist. We explore the possibility of using these techniques to reconstruct the geometry of complex geological surfaces, such as thrust planes and deformed stratigraphic boundaries. We suggest that this procedure can be used to extract more information from existing geological maps, as well as to verify in three dimensions the geometry of structures during the map-making process.

INTRODUCTION

Geologists work every day in a three-dimensional world. Since it is difficult to visualize three dimensions graphically, the Earth scientists generally use two-dimensional tools, such as maps and cross-sections, to project three dimensional information onto a more manageable two-dimensional space (Jones and Leonard, 1990). Several different kinds of geological, geochemical, hydrological and geophysical data can be displayed in this way. A comprehensive review of the problem encountered in these fields can be found in Jones *et al.* (1986). In the last decade increasing computer advances have made it possible to develop applications that create, display and operate on databases which fully describe the three dimensional geometry and attributes of geological objects (Flynn, 1990). Different three-dimensional spatial representation models (*e.g.* voxels, G-octrees, isosurfaces, nurbs, etc.) have been proposed and tested (Fried and Leonard, 1990). Unfortunately most of these applications, developed chiefly for mining and petroleum explorations, are very expensive and still out of reach for 'the rest of us' in the geology and geography departments.

Our work is concerned with the application of standard, all-purpose map analysis techniques (Davis, 1986). We reconstruct and visualize the geometry of complex geological surfaces, from data easily derived from existing geological maps. We focus in particular on the solution of structural geology problems, attempting to reconstruct the geometry of thrusts and deformed stratigraphic horizons. In general our method requires the studied surface to have an extensive and articulated intersection with the topography. It is therefore applicable to any low-angle structure, stratigraphic or tectonic.

To carry out our experiment we used two software packages available at the C.N.R. Istituto di Geologia Marina in Bologna (Italy): DIGMAP-DATUM-PLOTMAP and SURFACE II. The first package is a series of programs that allow the digitization, transformation of coordinates, preparation and plotting of high quality topographic maps as well as simple geological maps (Bortoluzzi and Ligi, 1986; Ligi and

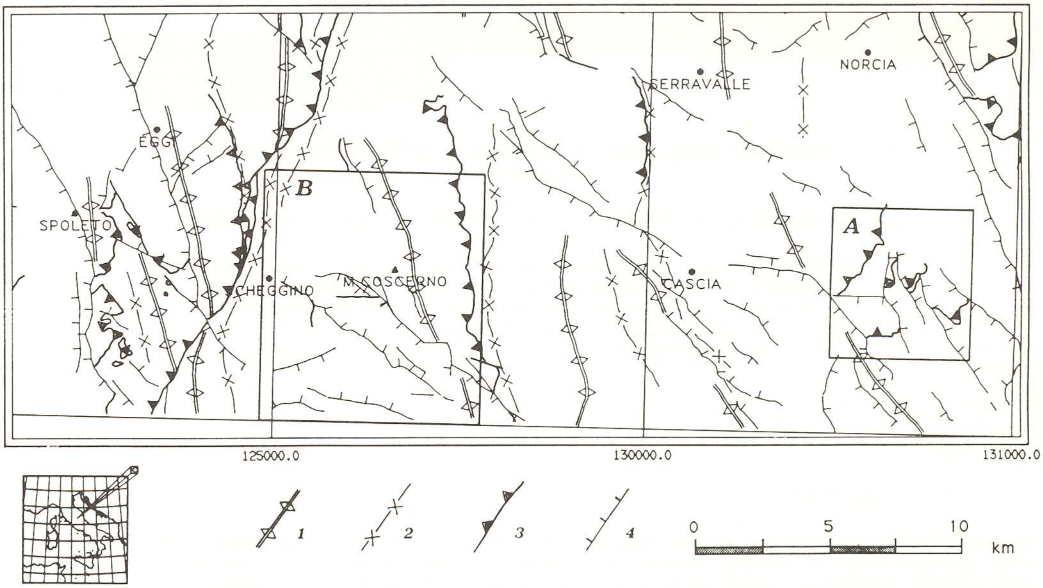

Fig.1. Location map showing the main structural features of the studied areas. A- Monte Pozzoni area; B - Monte Coscerno area; 1- anticline; 2- synclines; 3- thrusts; 4 - normal faults.

Bortoluzzi, 1989). The second is a well known commercial package for the creation and display of spatially distributed data (Sampson, 1975).

DATA PREPARATION

The first step in the data preparation procedure consists in simplifying an existing geological map. For our experiments we use recent, detailed geological maps, at a scale of 1:25,000, that clearly portray all the structural features. These maps are to be simplified to produce schematic maps, specifically aimed for use in the study of the problem at hand. As an example, in the case of the reconstruction of a thrust surface, the schematic structural map shows only the trace of the major thrust and eventually of later faults that significantly affect its geometry. All the intermediate slices, eventually present between the hanging wall and the foot wall, are generally considered to be part of the overthrusted block. The formation boundaries and the minor faults, that are not essential for the reconstruction, do not appear on the schematic map.

During the second step of data preparation we intersect structure and topography, to obtain a population of scattered elevation points. By laying the schematic structural map on top of the topographic map, we determine the elevation of the studied structure at the intersection with each contour line. Scattered elevation points so obtained are then digitized, with the aid of a large format tablet.
It should be clear that the data preparation procedure is somewhat subjective and not at all automatic. To avoid the risk of introducing substantial biases, as well as to improve the quality and quantity of input data, the operation should be carried out by a geologist with a good knowledge of both the regional and local geology.

GRIDDING AND GRAPHICAL DISPLAY

Scattered elevation points are used to evaluate an elevation matrix (grid), i.e. a set of z-values arranged in a regular, rectangular or square, pattern. This grid will then be used to prepare conventional contour maps and perspective block diagrams of the surfaces under investigation. Several gridding algorithms are available to interpolate the value at each node of a regular grid from a variable number of scattered elevation points. The choice of the gridding algorithm is crucial to obtain correct results. In the choice of such an algorithm it is important to consider: the size of the grid matrix, *i.e.* the number of grid nodes or their spacing; the procedure to search for sample data points around each node; the interpolating algorithm and the weighting function to be used in the averaging process.

The size of the elevation matrix is to be kept consistent with the number of the original scattered elevation points. When graphically displayed, a grid that contains too many elements will give a misleading wiggling appearance of the studied surface. On the other hand a grid that is too coarse will produce a sharp and unrealistic image of the same surface.

The parameters that control the searching procedure specify the number, position and distance of the sample data points used to estimate the elements of the grid. It is advisable to adopt severe searching criteria to limit the unrealistic extrapolations in areas where only minimal information is available. We have generally preferred an octant search procedure, that divides the area around each grid node into eight equal sectors, forcing the estimating algorithm to use sample data points radially distributed around each grid node. Compared with other procedures, such as the nearest neighbour search, octants give a somewhat smoother surface.

Different interpolation algorithms may be applied to different geological problems. Some algorithms make use of the weighted average of data, with weights based on distance; others, more complex, calculate values through fitted, simple, low-order functions, commonly planes (Jones, 1989). We used an algorithm that estimates the elevation value at each grid node as the distance weighted average of the projection of the surface dip, computed at nearby scattered elevation points (Davis, 1986). The weighting function was assumed to be inversely proportional to the square of the distance. The choice of such an algorithm is consistent with the problem at hand, where the estimation of the dip of the geological surface is of particular interest in the reconstruction of its geometry.

It is worth pointing out that we have used all-purpose gridding algorithms, that don't have any built-in specific "knowledge" of the type of surface to be investigated (*e.g.* stratigraphic framework, geological history, style of deformation etc.). The elevation matrix obtained by gridding the sample elevation points can then be displayed in two dimensions by preparing contour maps (Figs. 2, 4). For a valid contour the density of elevation points must be sufficiently high, showing spatial persistence (Sharp, 1987). Contour lines are drawn using a simple spline interpolator, to avoid excessive and unrealistic angularity.

An alternative way of displaying the elevation matrix is to prepare perspective block diagrams (Figs. 3, 5). The ease with which the observation point (azimuth and elevation), the viewing distance and the vertical scale can be changed allows the production of several different synoptic views. These are very useful to gain a more effective and immediate understanding of the geometry of the studied surface. To obtain an overall view of the surface, eliminating short term variations, a smoothing algorithm may also be applied to the elevation matrix. We have successfully used an algorithm that re-evaluates the elevation value at each grid node as the distance-weighted average of the two nearby grid values (Barchi et al., 1989).

GEOLOGICAL EXAMPLES

We present the results of two experiments carried out in the Umbria-Marche Apennines of Central Italy, a thrust and fold belt, Upper Miocene-Lower Pliocene in age. In this area the deformed Mesozoic-Cenozoic sedimentary cover consists of two litho-structural units: a Lower Liassic carbonate platform, and a Middle Liassic-Lower

Miocene pelagic multilayer. The basal décollement is generally supposed to correspond to a thick sequence of Triassic Evaporites. Folds and thrusts are displaced by later normal faults, Upper Pliocene-Quaternary in age. A comprehensive overview and an extensive reference list of the Umbria-Marche geology has been recently published by Bally et al. (1986).

The two reported examples are located in the Southern part of the Umbria-Marche Apennines (Fig. 1). The first example, in the Monte Pozzoni area, concerns the reconstruction of the geometry of a low-angle thrust surface; whereas the second, in the Monte Coscerno area, regards the reconstruction of the geometry of a deformed stratigraphic boundary.

The Monte Pozzoni thrust

The Monte Pozzoni thrust consists of a series of small klippen of Liassic rocks, overthrusting a previously folded Mesozoic-Cenozoic multilayer, and displaced by a set of NW-SE trending normal faults. This structural setting produces a flat geometry of the thrust, and consequently an extensive intersection with the topographic surface.

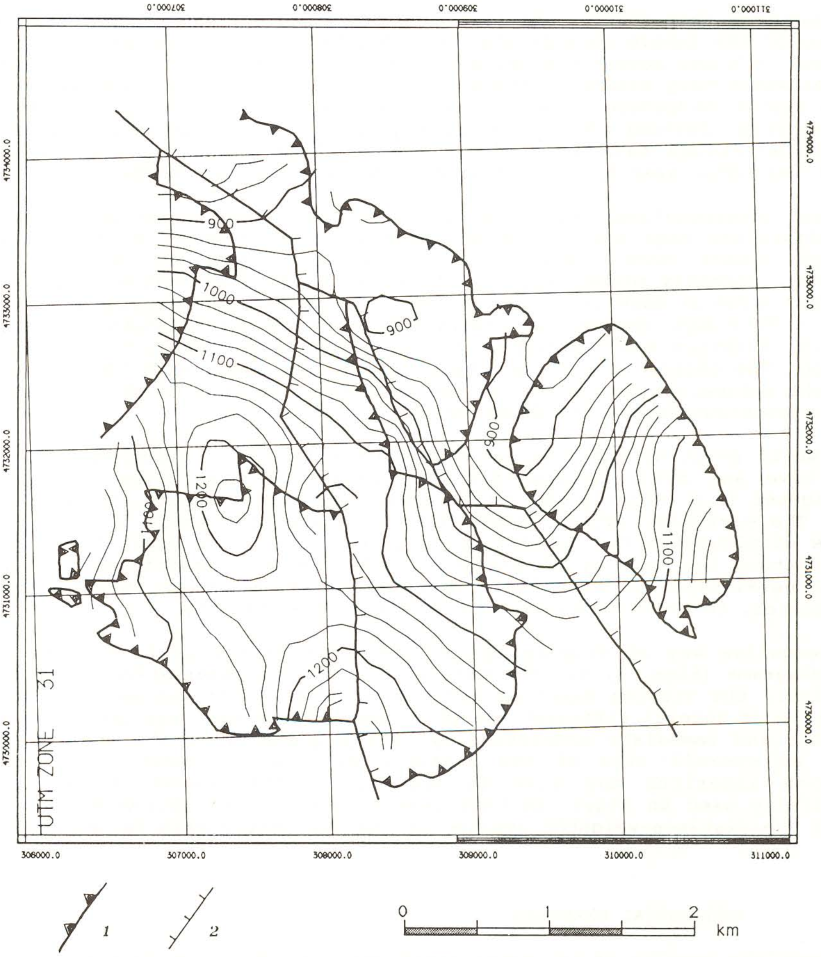

Fig.2. Contour map of the Monte Pozzoni thrust.
1 - thrust; 2- normal fault.

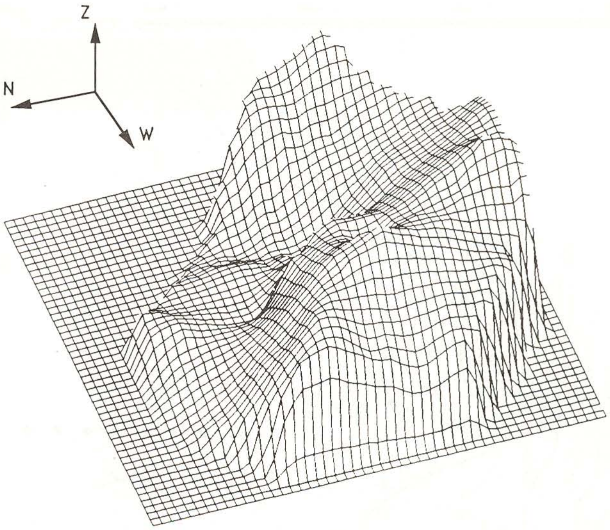

Fig.3. Perspective block diagram of the Monte Pozzoni thrust. The vertical exaggeration is 4, the azimuth of the observation point is N290°, the angle of the observation point is +45°.

The basis of our work was a detailed geological map published by Calamita *et al.* (1981), from which we derived a schematic structural map, portraying two major normal faults cutting the thrust surface. From the schematic map sample elevation points were collected along the trace of the thrust surface, to prepare a 30x30 elevation matrix, that was then visualized through a contour map (Fig. 2) and a perspective block diagram (Fig. 3). The modelled surface, according to the well known deformation history of the region, was interpreted as a W dipping thrust cut and displaced by a NE dipping normal fault. It is important to note that a similar geometry can be interpreted also as a thrust surface folded along a NW-SE axis. In this case the knowledge of the local geology is essential to discriminate in favour of one of the two different interpretations.

We have successfully applied the same methodology to the reconstruction of other low-angle thrusts in Central Italy. In particular we have analyzed the Spoleto thrust, also shown in Fig. 1, and the Gran Sasso thrust system, located further to the South. The obtained results and further discussion can be found in Barchi et al., 1989.

The Val Casana graben (Monte Coscerno)

The Val Casana graben is a narrow and relatively deep extensional structure, which cut across the N-S trending Monte Coscerno anticline. It is bounded by high-angle, NE-SW trending normal faults, whose vertical displacement exceeds 500 m in the central part of the graben, and quickly decreases along the strike. To understand this rather complex structure, starting out from a detailed geological map prepared by Barchi (1990), we reconstructed the top of the Maiolica Formation (Lower Cretaceous), an easily traced stratigraphic marker.
The reconstruction was carried out collecting sample points in three different ways. The elevation of the top boundary of the Maiolica Formation was measured directly on the map. The elevation of other formation boundaries was corrected, adding or subtracting the corresponding stratimetric distance from the studied horizon. This very simple criterion is sufficiently accurate if bedding planes are not too steep

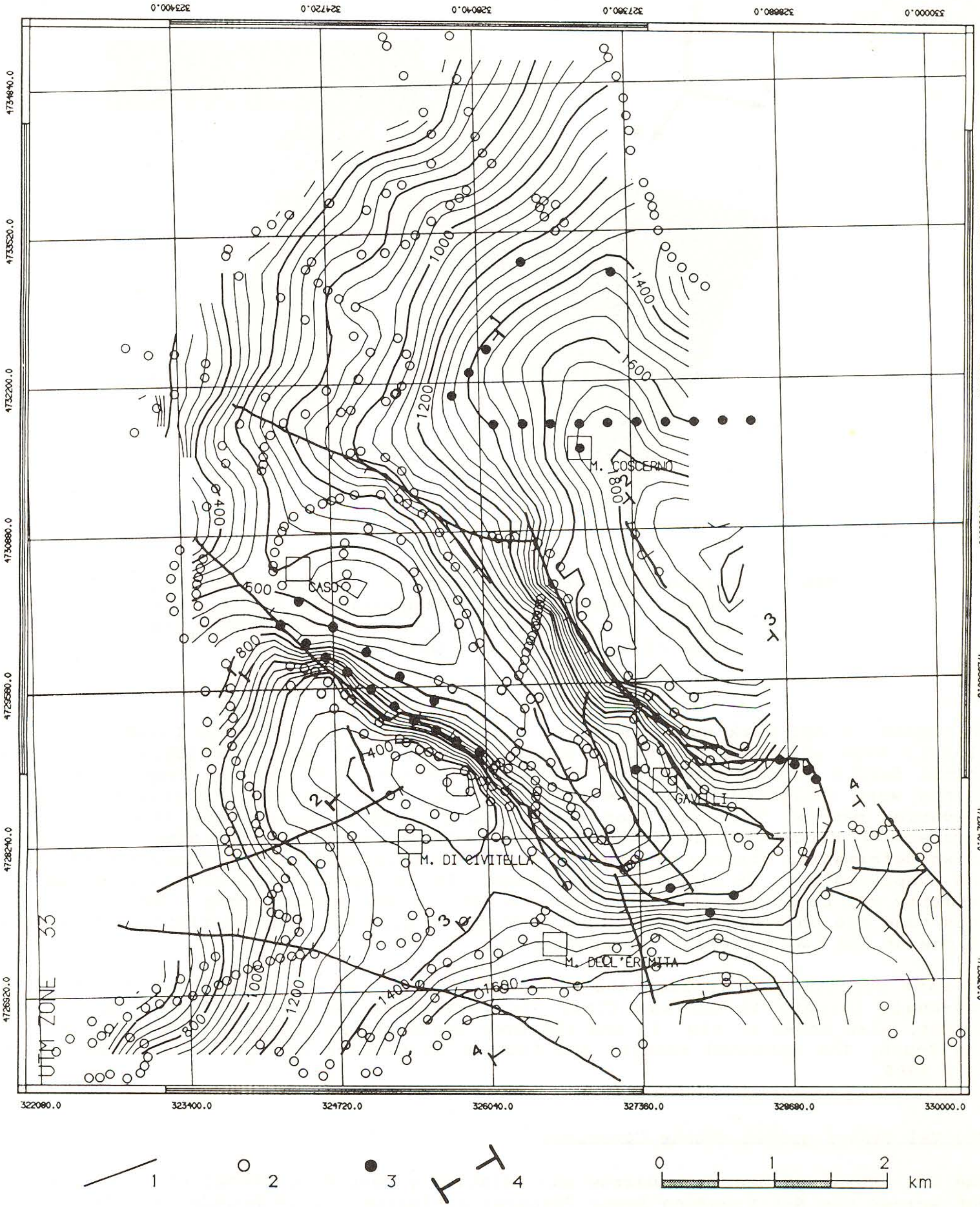

Fig.4. Contour map of the top of the Maiolica Formation in the Monte Coscerno area. 1- normal fault; 2 - sample elevation point obtained from formation boundaries; 3- sample elevation points obtained from geological cross-sections; 4 traces of the sections of Fig. 6.

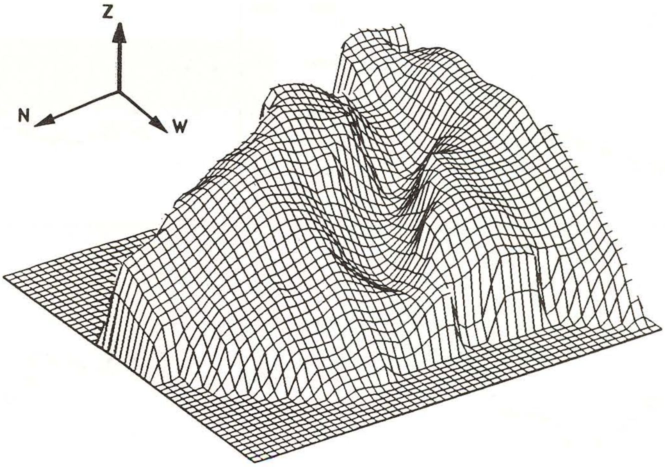

Fig.5. Perspective block diagram of the Val Casana graben in the Monte Coscerno area. The vertical exaggeration is 3, the azimuth of the observation point is N305°, the angle of the observation point is +30°.

(if the dip is < 30° the error is < 15%). Finally, in the areas with a poor distribution of elevation data, points were obtained from expressly prepared short geological profiles.

The reconstructed surface is shown as a contour map in Fig. 4 and as a perspective block diagram in Fig. 5. Both representations clearly show the Monte Coscerno anticline, striking N-S, cut by the deep and narrow Val Casana graben. Note in Fig. 4 the good correspondence between the closely spaced contour lines and the location of major normal faults. To check the accuracy of the results we also prepared four profiles across the contour map and we compared them with the corresponding geological cross-sections. The results, summarized in Fig. 6, show a good fit. The somewhat smoother appearance of the estimated surface, in comparison with the geological data, is due to the type of gridding algorithm and, locally, to the distribution of sample elevation points.

In the Monte Pozzoni and Monte Coscerno areas the geological surfaces were reconstructed using the entire set of available elevation data, not taking into account the presence of any fault. To study the effects of these faults, a simple method is to divide the elevation points into several sub-groups, one for each faulted block, and treat them separately. The resulting contour maps indicate that the extrapolation across major faults can produce local, unrealistic features that do not relate to the actual geometry of the studied surface (Barchi et al., 1989, Fig. 9). In the presented examples we were most interested in the reconstruction of the overall geometry of the surfaces, and therefore we have disregarded all local effects.

CONCLUDING REMARKS

The starting point of this work was the observation that the information content of a geological map is not readily and completely available. To analyze and fully represent the geometry of complex structures, geologists usually build up two orthogonal sets of balanced cross-sections, checking their reciprocal consistency. This is a time consuming and rather difficult procedure. The method that we propose is based on the possibility of rapidly extracting, from a geological map, elevation data relative to structural surfaces such as thrusts and deformed stratigraphic

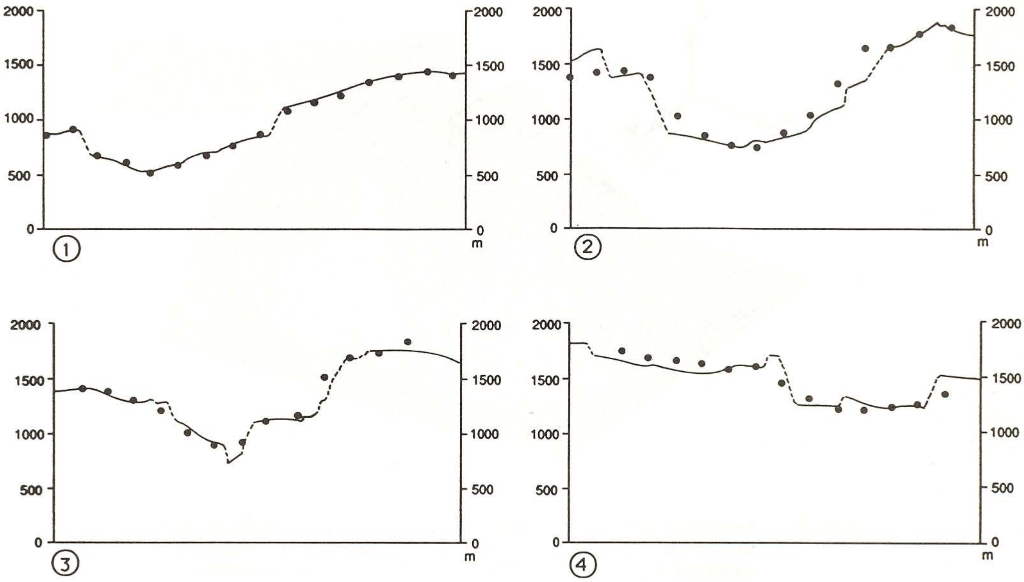

Fig.6. Schematic profiles across di Val Casana graben. Solid line shows the trend of the top of the Maiolica Formation derived from geological cross-sections. Closed dots show the elevation of the same horizon as obtained from the contour map of Fig. 4. Horizontal scale equal to vertical scale.

boundaries. The geometry of these surfaces can then be reconstructed using simple, standard map analysis techniques.

With these techniques it is not possible to investigate surfaces that have more than one z value for any x-y location, such us recunbent folds. 3-D technology is rapidly evolving, and approaching towards the solution of these problems, but it requires laborious procedures for data acquisition, and hardware/software resources which are not widely available.

Finally, it must be stressed that modelling geological surfaces by computer should not become an automatic procedure. A good knowledge of the local and regional geology is essential to obtain realistic results.

Acknowledgements - We are particularly grateful to G. Bortoluzzi and M. Ligi of the C.N.R. Istituto per la Geologia Marina (Bologna) who supplied us with the graphical software. We also wish to thank P. Reichenbach for helping in various stages of the work. This work was supported by grants from the CNR-IRPI and CNR-GNDCI as well as from MURST (40% and 60%: U.O. Perugia, Responsabile G. Pialli) grants.

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