From photo-geology to 3D geological models. An open source approach

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ABSTRACT

Three-dimensional modeling of geological bodies is a useful tool for multiple applications. Such tasks are usually accomplished starting from field-collected data, which typically suffer from intrinsic limitations such as accessibility constraints and punctuality of data collected. In this work, we explore the reliability of photo-geological mapping from interpretation of aerial photographs in providing data useful to build up 3D geological models. The test was conducted in a 15 km^2 in Umbria, central Italy. The three-steps open source GIS procedure that outputs 3D models from photo-geological data was developed using python in GRASS GIS environment and GNU-Linux OS. We maintain that this procedure can have potential broad applications in Earth Sciences, including geological and structural analyses, up to the preliminary evaluation of potential reservoirs.

Keywords: Photo-geology, Aerial photographs, Bedding, GRASS GIS, 3D geological model, Quaternary deposits.

INTRODUCTION

Three-dimensional geological characterization is a useful tool for multiple purposes, from mining exploration (Perrin et al., 2005) to slope stability analyses (Günter et al., 2002), from tectonic (Wu et al., 2015) to sedimentary studies (Do Couto et al., 2014). Such studies usually rely on field-collected data, even on large areas (Do Couto et al., 2014). The application of remote sensing data and techniques to geological data collection (i.e. photo-geological mapping) has recently proven a valuable tool to support high-detail geological field mapping, overcoming its main limitations: (i) local accessibility constraints, (ii) poor outcrop availability, and (iii) punctual

measurements vs spatially distributed observations (Santangelo et al., 2014, Bucci et al., 2016).

The intersection between the sedimentary and the topographic surfaces is a "bedding trace", BT (Santangelo et al., 2014). Aerial photo-interpretation (API) criteria to both detect and map bedding traces (BTs) are mainly based on the morpho-selection principle. The morphological and photographic signature of sequences of rock layers reflects their lithological and mechanical characteristics. In particular, bedding traces can be identified by typical texture features, such as: (i) sub-parallel bands of different tone/color in unvegetated areas, (ii) sub-parallel vegetation bands, (iii) stepped profile slopes, and (iv) considerations on reliefs asymmetry.

Marchesini et al. (2013), and Santangelo et al., (2014) have shown that photo-geological mapping can successfully highlight geological structures even in areas characterized by poor outcrops and high anthropic pressure. In this paper, we show an open source processing chain that, starting from aerial photo-interpreted data and a proper resolution DEM, (i) obtains a vector map of bedding attitudes, (ii) produces an interpolated bedding attitude raster map, and (iii) generates a 3D geological model given a set of input bedding traces. The modelled geological layers are then compared to a geological section produced by an independent geologist starting from the same dataset integrated by field data and sub-surface (well) data. This work represent an attempt of conjugating unprecedented quality data extracted through rigorous interpretation of stereoscopic aerial images to existing rigorous modeling techniques. The open source approach represents an alternative to proprietary 3D modeling software tailored to photo-geological data.

STUDY AREA

The study area extends for about 20 km² in central Umbria, Italy, within the fault-bounded, intramontane Montefalco Basin (Figure 1A-B). In the area, Quaternary continental sediments unconformably overlay marine sediments pertaining to the Umbria-Marche stratigraphic sequence (Cresta et al., 1989), and to the Marnoso Arenacea Formation (Ricci Lucchi and Pialli, 1973). The continental sediments of the Montefalco Basin consist of, from bottom (older) to top (younger), fine-grained (clay, silt, find sand) lake and fluvial sediments, overlaid by coarse-grained (gravel, sand) fluvial and alluvial fan sediments. #In our study area, lignite layers are interbedded within sand, silt and clay layers. These lignite layers were explored and mined up to the 1990s for thermo-electric power production (Ge.Mi.Na. 1962)#. In the study area, the identification of the BTs was facilitated by the colour contrast between the dark (black) lignite layers and the light (light grey, light brown, ochre) sand,
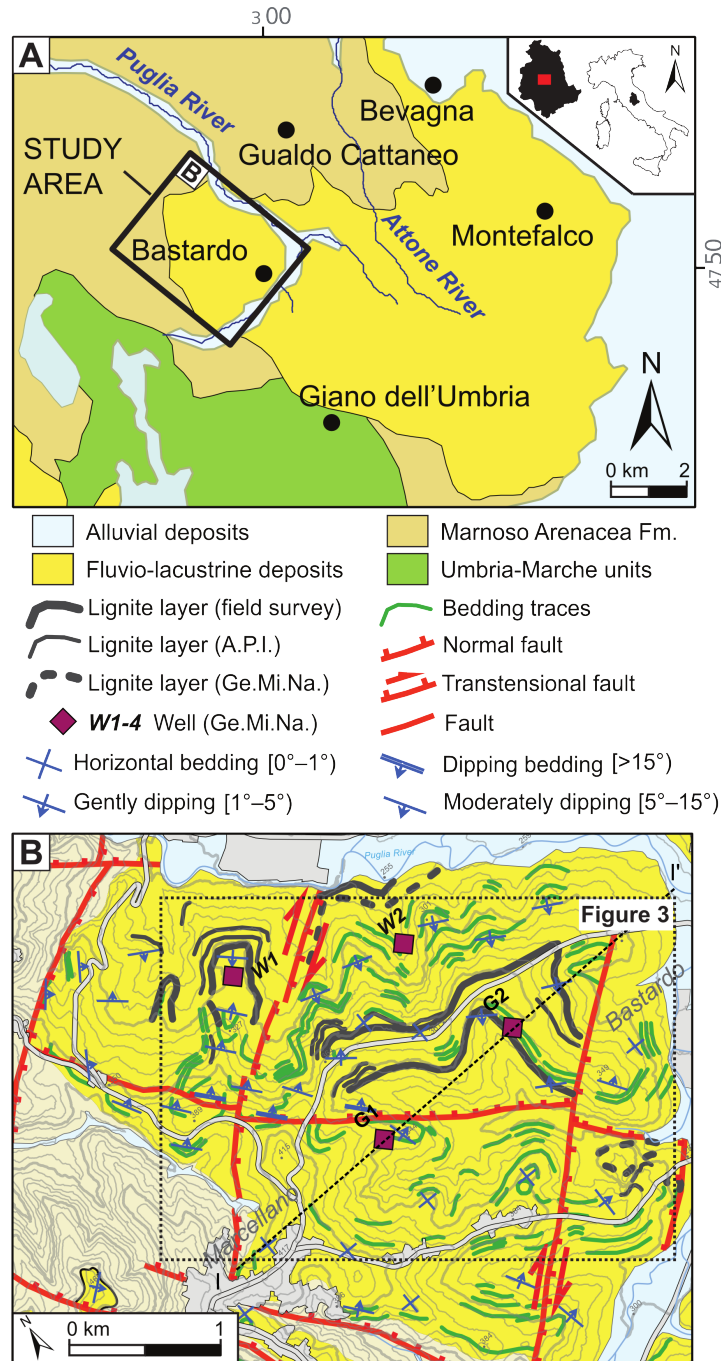
silt and clay layers (Figure 2A-B).

Figure 1. (A)Location map. (B) Photo-geological map.

METHODS

We implemented a GIS tool (geobed.py, Marchesini et al., 2013) using python in GRASS GIS environment (GRASS development Team 2015) and GNU-Linux OS. The geobed.py tool requires a bedding traces map and a DEM to be executed. The script iterates five steps for each BT, and returns a point vector map containing information on dip angle, dip direction, and associated uncertainty. In the first step, the bedding trace is transformed into a 3D linear feature using the DEM. Secondly, the BT is closed into a 3D polygon. Thirdly, a sequence of regularly spaced points is generated on the polygon boundary. A 3D Delaunay triangulation (Davis 1973) is then performed which outputs a nearly flat surface corresponding to the bedding surface - BS. The slope and aspect raster maps of the bedding surface are then computed (step four). Lastly, the mean values of slope (dip angle) and aspect (dip direction) of the BS are estimated. The uncertainties of dip angle and dip direction are computed as (i) the standard deviation of the BS slope map and (ii) as the circular variance (Davis 1973) and angular standard deviation (Butler 1992) of the BS aspect map.
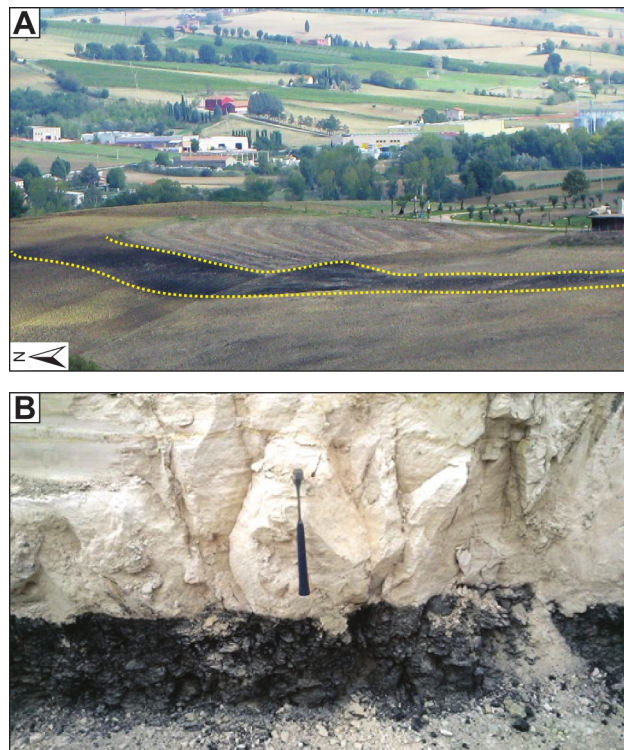

Figure 2. Examples of lignite rich layers in a (A) cultivated field; (B) sub-vertical slope.

A second GIS tool (r.surf.ba.py, Santangelo et al., 2014) was developed using python in GRASS GIS environment (GRASS development Team 2015) and GNU-Linux OS to interpolate the bedding attitude (BA) data output by geobed.py. Care was taken since the dip direction is an angular value ranging between 0° and 360°, being the extremes the same value (N). Therefore, problems arise when (i) opposite beddings are interpolated and/or (ii) polarity of bedding is considered. To overcome these limitations, the dip direction and the dip angle were interpolated simultaneously, considering the single bedding measurements as unit vectors and combining them using analytic geometry. In particular, our approach builds on directional cosines, i.e. the cosines of the angles between the unit vector n perpendicular to the bedding plane and the three coordinate axes (de Kemp 1998; Günther 2003) pointing to the E (x), to the N (y) and upward (z). The three components of the unit vector perpendicular to the bedding plane are then interpolated using the regularized spline with tension and smoothing (RST) method (Mitášová et al. 2005; Neteler and Mitášová 2008). Marchesini et al., (2015) have shown that the tension parameter can influence the final results. According to their work, we chose a tension value of 40. The interpolation outputs three raster GIS layers of the components of the unit vector computed for each grid cell in the modelling domain. The interpolated BA is then obtained re-combining these three raster maps.

Finally, a code was developed to build up the 3D geologic model of the bedding attitude. The code is developed in the GRASS GIS software (GRASS Development Team, 2015) and exploits the pygrass API (Zambelli et al., 2013). The tool generates a DEM of a given bedding layer (BL) starting from a bedding traces layer and a map of the interpolated bedding attitude. The procedure computes the elevation of all the pixels that share at least one side with the bedding trace pixels, and is performed only for the underground side of the input bedding trace (i.e., where the BL "enters" the terrain). The first run of the code grows the bedding layer of a one-cell "buffer" according to the derived elevation of the grid cells, given the bedding attitude. The output of each run is used as input of the subsequent one, in place of the bedding trace layer. Therefore, the BL grows in a stepwise fashion of one pixel line per run. The number of runs is user-defined, and influences the final BL size.

RESULTS AND CONCLUSIONS

For a portion of the Montefalco basin, we produced a detailed photo-geological map, delineating bedding traces, the main faults and lithological domains. When delineating bedding traces, care was taken to distinguish lignite beds from other lithologies (Figure 1). Data were transformed in

appropriate GIS vector layers. We produced a bedding attitude map starting from 148 bedding traces mapped in the study area (Figure 3). The BA map was then used to derive a map of the interpolated bedding attitude, obtaining two raster maps, one for the bedding dip and one for the dip direction. Our preliminary results indicate a good correspondence between field/photo-geological data and the computed bedding attitudes.
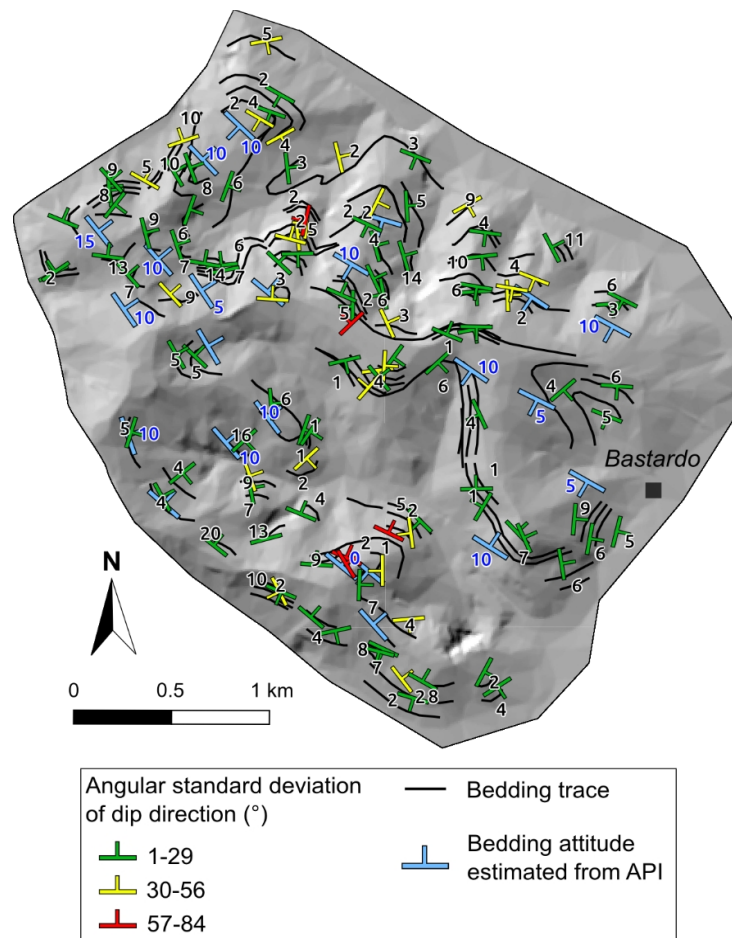

Figure 3. Bedding attitude map. Beddings evaluated from Aerial Photo-Interpretation (API, light blue) are compared to the beddings modelled by the tool geobed.py.

Comparison of the 3D model with a geological section prepared by a geologist starting from the same input data integrated by field surveys and sub-surface data (Figure 4), show a good agreement between the two models. In particular, the shape of a gentle South-East plonging asymmetrical

syncline having the south-western flank more inclined is well portrayed in the model. Furthermore, a disturb in the lateral continuity of the syncline geometry is well portrayed where the structure is dislocated by a NE-SW trending fault system.

The presented procedure can further be implemented to become a processing chain that produces 3D geological models starting from surface
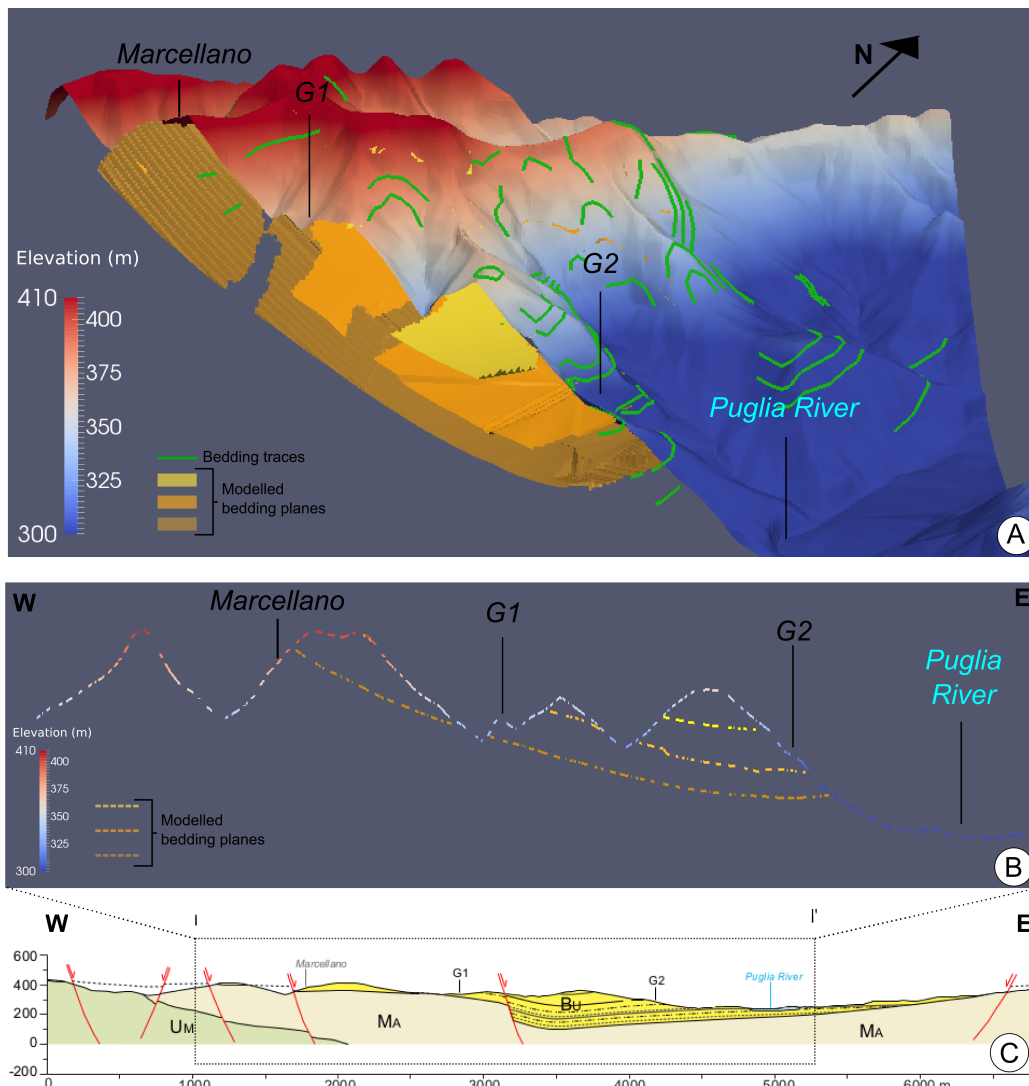

Figure 4. (A) 3D geological model of a set of layers in the study area ; (B) profile showing the same set of layers modelled in 3D ; (C) geological section (trace I-I' in Figure 1B). MA, Marnoso-Arenacea Fm. ; UM, Umbro-marchigiana sequence ; BU, Bevagna Unit ; G1, G2, exploration data points.

(photo-geological) data. We see it useful for multiple purposes: (i) preliminary analyses of potential reservoirs, (ii) physically-based slope stability analyses, (iii) validation of the throw of Quaternary faults, (iv) analysis of the lateral continuity of beds in lacustrine basins, (v) hydrogeological studies.

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