Common problems encountered in 3D mapping of geological contacts using high-resolution terrain and image data

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Abstract
An experiment has been carried out to find a reliable method to map 3D geological contacts using high-resolution Digital Elevation Models (DEMs) and pictures. Various airborne and ground-based photos, and a classical geological map, have been draped by several users on DEMs of the Scex Rouge Mountain (Vaud, Swiss Alps) producing several 3D textured models of the relief. On each of these photorealistic models, geological contacts were then drawn as polylines by hand. The locations of resulting polylines have been then compared. The draping procedure, actually the choice of pairs of control points used for the texturing step, appears to be the main source of discrepancies between the results of the different models. The subjectivity of users in drawing polylines is of lesser importance. We observed also that the widely accepted geological map of the area does not provide an accurate representation of the local geology in steep areas, especially near-vertical rock faces where this effect is marked. Even if high quality and high-resolution data are becoming increasingly more available, a robust way to map geological structures directly in 3D is still lacking. In addition, there is a crucial lack of tools, with editing capabilities able to handle large point cloud datasets and gigapixel images. Finally, the methodology described in this Technical Note is intended to be useful for modelling simple geological structures, such as cylindrical folds, in a complex environment comprising near-vertical rock faces.

Keywords: 3D geological mapping, digital outcrop, LiDAR, gigapixel photography.

Introduction
Numerous representations of geological information currently exist but most of them are in 2D (e.g., geological maps, geological panoramic sketch), and only a few are in 3D (e.g., block diagram). Current challenges in geological mapping consist in collecting more consistent 3D data, but also in harmonizing geological information to build better geological models. New remote sensing techniques such as LiDAR [e.g., Lim et al., 2010; Jaboyedoff et al., 2012; Abellán et al., 2014], Photogrammetry [e.g., Sturzenegger and
Stead, 2009; Firpo et al., 2011; Curtaz et al., 2014] and gigapixel photography [Stock et al., 2011; Lato et al., 2012; Kromer et al., 2014] have significantly improved the representation of three-dimensional surfaces during the last decade, especially for steep and inaccessible rock cliffs, allowing the development of high-resolution 2D geological maps [Putnam et al., 2014]. These techniques have also been used for the characterization of petroleum reservoir analogues and fracture systems at outcrop level [Olariu et al., 2008; Rotevatn, 2009; De Souza et al., 2013; Hodgetts, 2013; Penasa et al., 2014], texturing of high-resolution panoramas on digital outcrop models [Buckley et al., 2008, 2010; Minisini et al., 2014] and 3D geological/mineralogical mapping [Sima et al., 2012; Kurz et al., 2013; Murphy et al., 2013]. However, from a practical point of view, it is still very difficult to work in a fully 3D environment, drawing 3D lines or folded surfaces, because:

a) Common 3D geological modelling software packages (MOVE, GSI3D, PETREL, etc.) offer poor 3D feature editing capabilities (if available at all) and often poorly interpolate cross-sections. Usually, results are very far from the standard of 3D animation solutions proposed by BLENDER or MAYA software;

b) Common software packages are not able to correctly handle large datasets of tens of million points/triangles [Ferrari et al., 2012] and import several gigapixels of image data simultaneously;

c) Most available software packages are oriented towards basin analysis for oil industry and not suitable to alpine geology and the representation of complex geological structures, such as a stack of superimposed folds, stretched reversed limbs or non-cylindrical folds.

The aim of this Technical Note is to illustrate some problems encountered when trying to plot 3D geological objects, even if high-resolution data are available. Two sources of inaccuracies are considered here: (1) different images have been used, with various points of view (aerial and ground-based) and internal deformations; (2) different users have been asked to drape these images on Digital Elevation Models (DEMs) and/or to draw geological limits, producing also different results. For this purpose, the site of the Scex Rouge was selected because it presents interesting characteristics of Alpine geology: a steep rock wall, with a superimposition of folds and several thrust surfaces. Moreover, lithologies are clearly contrasted on the pictures, and a high quality geological map is available for this area.

**Study area**

The Scex Rouge Mountain (2,971 m) is located in the Diablerets Massif (Vaud, Swiss Alps) and comprises clearly visible folded structure on its South-West face (Fig. 1). This area belongs to the Helvetic zone of the Alps and is composed of four tectonic units: the Wildhorn nappe, the tectonic slice of Prapio-Audon, the Diablerets nappe and the Plaine-Morte Flysch [Badoux et al., 1990]. The South-West face of the Scex Rouge is mainly composed of sedimentary rocks belonging to Wildhorn nappe: the top-layer is composed of siliceous limestone, the fold layer is called “Pygurus layer” and consists of gritty limestone. Finally, the bottom-layer includes marly schist and clayey limestone [Badoux and Gabus, 1991].
Figure 1 - Location and visualization of the study area. Upper part: (Upper left image) Side view of the Oldenhorn West face from the Scex Rouge summit. (Lower left image) South-West face of the Scex Rouge Mountain - Extract of the gigapixel panorama taken in August 2013. (Right part) Extract of the geological cross-section of the Diablerets massif (modified after Badoux and Gabud, [1991]). Lower part: Topographic map at 1:25,000 (modified after SwissTopo - Federal Office of Topography - Swiss Confederation) showing the location of the study area (red frame) and the spot where the gigapixel panorama was taken (red cross). The average distance between this point and the Scex Rouge Mountain is five thousand meters.
Data types used
Different sources of information have been used to generate 3D photorealistic models of the Scex Rouge Mountain. Firstly, meshes of the topography were created from two DEMs of 25 m and 1 m cell size (Source: SwissTopo - Federal Office of Topography - Swiss Confederation). Then, pictures were wrapped as textures on these meshes. There are open access aerial pictures from Google Earth, Bing Maps and SwissTopo. The geological map of the area at 1:25,000 (Source: SwissTopo) was also draped on both DEMs. In addition, a terrestrial gigapixel panorama (Fig. 1) taken in August 2013 with a GigaPan EPIC PRO device was used to complete the aerial points of view with a high-resolution ground-based view of the South-West face. This panorama is accessible at full resolution online: http://www.gigapan.com/galleries/10989/gigapans/137754.

Methods and tools
This Technical Note presents a methodology for 3D mapping of geological contacts on DEMs textured with different kinds of images. The texturing procedure was done with 3DReshaper (MR1 version) software and the comparison of polylines was carried out with MATLAB (R2013b version). Note that 3DReshaper is a “non-geological” data processing software, especially developed for reverse engineering and surface construction using 3D point clouds.

Mesh building
In order to create photorealistic models, the first step was to transform the geo-referenced DEMs (point clouds of 25 m and 1 m spacing) in triangular meshes (Fig. 2). Two parameters play important roles for the quality of the meshing: the average distance between points (spacing) and the maximum size of the triangles that control the holes occurrence in the meshes (zone masked by the relief). For information, both DEMs have respectively 84,000 and 1.3 million of points, and all the points have been kept for the creation of meshes.

Texturing procedure
The second step consisted loading the different pictures in the 3DReshaper interface. It is important to highlight that the current limits of 3DReshaper and many 3D visualization software packages do not allow loading images larger than 16,384*16,384 pixels (typically 0.25 gigapixels). Therefore, a GigaPan panorama (typically 5 to 15 gigapixels) is presently too heavy to be draped at full resolution on a 3D mesh. To overcome this limit, the panorama of the Scex Rouge has been reduced by a factor 16.

In order to texture the meshes, it was necessary to define several pairs (at least 5) of control points in the pictures and on the meshes. The couples of control points have to be spread over the entire picture to map correctly the texture. This part of the methodology is the most critical since the choice of the control points may vary a lot from one user to another. Finally, camera parameters, such as position (geo-referenced coordinates of the shooting point), orientation as well as lens distortion or focal length can be added to adjust the texturing.
Three-Dimensional geological contacts/limits mapping

Once the texturing done, polylines (3D lines) have been drawn manually and then orthogonally projected (shortest distance) on the triangular meshes in order to follow the exact shape of the triangles (Fig. 2). For each draped image, a polyline was drawn (10 polylines in total). A reference polyline (ground truth) was also drawn directly on the hillshade of the 1 m resolution DEM (mesh without texture). This polyline is used as reference since no extra error is added by the picture draping method (choice of control points). Figure 3 shows all drawn polylines by a single user, superimposed to the 2D geological map at 1:25,000 (Fig. 3a) and superimposed to the same geological map, but vectorized (Fig. 3b). Moreover, in order to quantify the influence of the user, the whole procedure (draping + polylines) was redone by six different users and three other users did only the drawing of the polylines, on the same textured 3D reliefs.
Figure 3 - Superimposition of the drawn polylines by a single user over the geological map at 1:25,000. (a) 2D visualization of the drawn polylines over the raster geological map (modified after Badoux et al. [1990]). The black arrow located just below the spot elevation 2,940 m (ski lifts) indicates the direction and the plunging angle (10°) of the fold; (b) 3D visualization of the drawn polylines over the vectorized geological map (modified after SwissTopo, [2014a, 2014b]).

**Deviation calculation**

To evaluate the deviation between a polyline and the reference, the distance from a spline to another spline has been measured. Insofar as polylines are defined by a set of points (small point clouds) characterized by geo-referenced coordinates, 3D splines have been
fitted along the coordinates in order to represent all polylines by curves piecewise-defined by polynomial functions. Then, for each vertex of a spline, the function “distance2curve” [D’Errico, 2012] calculates the nearest distance of the vertex to the function given by the reference 3D spline. Finally, in order to compare the spatial distribution of polylines, a density plot of all splines has been done from the same function (Fig. 5).

**Results**

**Comparison of drawn polylines by a single user**

Figure 3 shows that polylines are drawn in three areas: in the first one located in the summit part of the Scex Rouge (above 2,700 m), the 10 polylines are present and close from each other while in the lower part (below 2,700 m), polylines are spaced and some of them are missing (Figs. 3 and 5a). The lower part is also divided into two areas: the left sector consists only of polylines drawn in the gigapixel panorama whereas the right sector contains only polylines drawn on aerial images. These differences are explained by the fact that the upper part of the South-West face shows a strong contrast of color in all images, whereas the lower part characterized by a steeper slope, is more difficult to analyze on aerial images. Moreover, due to the terrestrial point of view in low-angle shot of the GigaPan panorama, the right part is not visible (zone masked by the relief) and polylines cannot be drawn in this area. Figure 4a shows that the median (second quartile of boxplots) of the deviations with the reference polyline vary between 3 m (using an image SwissTopo draped on the 1 m resolution DEM) and 25 m (using the geological map draped on the 25 m resolution DEM), with a mean value from all deviations of 11 m. The comparison of boxplots shows also that the texturing made from aerial pictures is characterized by the smallest deviations (3-5 m).

![Figure 4 - Boxplots of deviations between all drawn polylines and the reference polyline (drawn on the 1 m resolution DEM). (a) Deviations for all images used; (b) Deviations for the 6 users redoing the whole method (from texturing to geological limits drawing); (c) Deviations for the 3 users performing the geological limits drawing only.](image)

The difference observed with the GigaPan panorama unmodified (deviation of about 12 m) is related to the shooting point location since the point of view of aerial pictures was practically the same as the one of DEMs (airborne LiDAR); in addition all aerial images have been
easier to drape on the meshes than ground-based ones. As said above, the zones masked by the relief are larger in the case of the GigaPan panorama (ground-based point of view) whereas for aerial images, these effects are only observed in vertical and overhanging areas. The accuracy of polylines also depends on the color contrast applied to photographs since the deviation associated with modified gigapixel picture (the brightness and contrast has been strengthen to highlight the folds) approximates the one of aerial images, especially for the 1 m resolution DEM. Due to the lower resolution of the 25 m resolution DEM, the improvement is less noticeable and all the texturing made on this dataset are less accurate, except for the geological map where deviations are the same. Finally, the inverse method has also been tested: the polyline has been firstly drawn over the modified GigaPan panorama, and then textured (projected) on the 1 m resolution DEM but this method does not improve the result.

**Comparison of drawn polylines by several users**

![Figure 5 - Density plots of polylines. The deviations between splines are represented in [m]; the blue color indicates the areas where there is a high density of polylines. (a) Density of the polylines resulting from all the textured mapping (scale: min=1.3, max=23.6); (b) Density of the polylines drawn by 6 users and for the whole method (scale: min=2.1, max=16.8); (c) Density of the polylines drawn by 3 users and for the geological limit drawing only (scale: min=0.1, max=5.2).](image)
The involvement of the user also plays a significant role since his judgment and his experience influence the texturing procedure and the drawing of polylines. Figure 4b and 4c show that median deviations are larger and more variable when the users applied the whole method (between 8 m and 45 m). The median deviations associated with only the drawing of polylines are lower and vary between 7 and 11 m. This indicates that most of the errors result from the texturing procedure, especially on the choice of the reference vertices. This observation is enhanced by Figure 5b and 5c which clearly indicate that the density of polylines is higher (polylines closer) in the case where users have only drawn polylines.

**3D fold modelling**

Figure 6 shows an attempt of a 3D fold modelling of the Scex Rouge South-West face and the Oldenhorn Mountain (3,123 m) from the function “extrusion” of 3DReshaper. A second polyline (in red in Fig. 6) was drawn on the West face of the Oldenhorn Mountain where the same rocks are present (Fig. 1). Then, a normal vector has been defined in the same direction as the fold axis (axis plunging of 10° in the North-East direction after the geological map at 1:25,000 from SwissTopo; see also the black arrow in Fig. 3a). The folds of the Scex Rouge were then extruded along this vector. Both polylines, the one of the Scex Rouge and the one of the Oldenhorn, connect without shifts, that means that the upper part of the fold can be considered as locally cylindrical and that one can predict its behavior in depth [Pollard and Fletcher, 2005].

![Figure 6 - 3D Modelling of the cylindrical fold (blue and brown surface) of the Scex Rouge and Oldenhorn Mountains. The reference polylines drawn on the 1 m resolution DEM are in blue in and red (upper left image) and the normal vector defined in the same direction as the fold axis is represented in white (axis plunging of 10° in the North-East direction after the geological map at 1:25,000 from SwissTopo, see also the black arrow in Fig. 3a).](image)
Discussion
The results show that the 2D geological map (1:25,000) of the area does not provide an accurate representation of the local geology on steep areas, this effect is obviously more notable in sub-vertical rock walls. In complex topographical and geological context, the 3D drawn lines representing a geological limit may vary from 3 to 25 m depending on the data types used (geological map, aerial pictures, gigapixel panorama) even if the quality of these datasets is high. For example, all polylines drawn on the GigaPan picture are characterized by significant deviations (about 12 m), mainly visible in the lower part (areas masked by the relief), which results from distortions induced by the 2D-3D transition.
The comparison between different users showed that the texturing (draping) procedure is by far the biggest source of errors. The choice of the control points and the location of the shooting point also play a significant role in the final result. In this method, the main challenge has been to properly fit the texture when the shooting point was on the ground and not from an aircraft, since we used only DEMs from airborne data. The other problems encountered are related to the fact that due to the current limits of 3D visualization software packages, it is not yet possible to drape a GigaPan panorama at full resolution. To overcome this limit, the gigapixel image has been resized and this operation is accompanied by a loss of resolution. However, some tests have shown that it is not better to draw the folds or limits first on the 2D picture, even at full resolution, and to drape afterwards. Finally, the methodology described in this Technical Note can be useful for modelling simple geological structures, as cylindrical folds, in a complex environment of vertical rock walls.

Conclusion
Many tests have been carried out and they indicate that for sub-vertical rock walls, the classical horizontally-projected geological maps do not provide an accurate representation of the local geology on steep areas. Thus, in Alpine areas there is a strong interest in mapping the limits between the different geological units directly on DEMs, high-resolution point clouds or 3D photorealistic models. The coupling of GigaPan and new remote sensing techniques opens new opportunities to improve geological mapping over inaccessible vertical cliffs and it is therefore necessary to develop this kind of methodology to better characterize complex geological bodies as stratigraphic series, magmatic intrusions or fractured reservoirs.

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References
Abellán A., Oppikofer T., Jaboyedoff M., Rosser N.J., Lim M., Lato M.J. (2014) - Terrestrial laser scanning of rock slope instabilities. Earth surface processes and landforms, 39 (1): 80-97. doi: http://dx.doi.org/10.1002/esp.3493.
Badoux H., Gabus J.-H., Mercanton C.-H. (1990) - Atlas géologique de la Suisse 1:25,000. SwissTopo, Feuille 1285, les Diablerets.
Badoux H., Gabus J. (1991) - Les Diablerets, feuille n° 88 de l'Atlas géologique de la Suisse 1:25,000. SwissTopo.

Buckley S.J., Howell J.A., Enge H.D., Kurz T.H. (2008) - Terrestrial laser scanning in geology: data acquisition, processing and accuracy considerations. Journal of the Geological Society, 165: 625-638. doi: http://dx.doi.org/10.1144/0016-76492007-100.

Buckley S.J., Enge H.D., Carlsson C., Howell J.A. (2010) - Terrestrial laser scanning for use in virtual outcrop geology. Photogrammetric Record, 25 (131): 225-239. doi: http://dx.doi.org/10.1111/j.1477-9730.2010.00585.x.

Curtaz M., Ferrero A.M., Roncella R., Segaliní A., Umili G. (2014) - Terrestrial photogrammetry and numerical modelling for the stability analysis of rock slopes in high mountain areas: Aiguilles Marbrées case. Rock mechanics and rock engineering, 47 (2): 605-620. doi: http://dx.doi.org/10.1007/s00603-013-0446-z.

D’Errico J. (2012) - Distance2curve, MATLAB. Central File Exchange. Available online at: http://www.mathworks.ch/matlabcentral/fileexchange/34869-distance2curve. (Retrieved October 27, 2014).

De Souza M.K., Veronez M.R., Tognoli F.M., da Silveira Jr. L.G., Inocencio L.C., da Silva R.M., Modena R.C.C. (2013) - Terrestrial Laser Scanning: Application for Measuring of Structures Information in Geological Outcrops. International Journal of Advanced Remote Sensing and GIS, 2 (1): 260.

Ferrari F., Veronez M.R., Tognoli F.M.W., Inocencio L.C., Paim P.S.G., da Silva R.M. (2012) - Visualização e interpretação de modelos digitais de afloramentos utilizando laser scanner terrestre. Geociências, UNESP, 31 (1): 79-91.

Firpo G., Salvini R., Francioni M., Ranjith P.G. (2011) - Use of digital terrestrial photogrammetry in rocky slope stability analysis by distinct elements numerical methods. International Journal of Rock Mechanics and Mining Sciences, 48 (7): 1045-1054. doi: http://dx.doi.org/10.1016/j.ijrmms.2011.07.007.

Hodgetts D. (2013) - Laser scanning and digital outcrop geology in the petroleum industry: A review. Marine and Petroleum Geology. doi: http://dx.doi.org/10.1016/j.marpetgeo.2013.02.014.

Jaboyedoff M., Oppikofer T., Abellán A., Derron M.-H., Loye A., Metzger R., Pedrazzini A. (2012) - Use of LIDAR in landslide investigations: a review. Natural hazards, 61 (1): 5-28. doi: http://dx.doi.org/10.1007/s11069-010-9634-2.

Kromer R., Hutchinson J., Gauthier D., Lato M., Ondercin M., MacGowan T. (2014) - Characterization and monitoring of talus in rock slope gullies using high temporal resolution terrestrial LiDAR and Gigapixel photography. In: Humair F., Matasci B., et al (Eds.), Vertical Geology, from remote sensing to 3D geological modelling. Proceedings of the first Vertical Geology Conference, 5-7 February 2014, University of Lausanne, Switzerland, pp. 167-171.

Kurz T.H., Buckley S.J., Howell J.A. (2013) - Close-range hyperspectral imaging for geological field studies: workflow and methods. International Journal of Remote Sensing, 34 (5): 1798-1822. doi: http://dx.doi.org/10.1080/01431161.2012.727039.

Lim M., Rosser N.J., Allison R.J., Petley D.N. (2010) - Erosional processes in the hard rock coastal cliffs at Staithes, North Yorkshire. Geomorphology, 114 (1): 12-21. doi: http://dx.doi.org/10.1016/j.geomorph.2009.02.011.

Lato M.J., Bevan G., Fergusson M. (2012) - Gigapixel imaging and photogrammetry:
development of a new long range remote imaging technique. Remote Sensing, 4 (10): 3006-3021. doi: http://dx.doi.org/10.3390/rs4103006.

Minisini D., Wang M., Bergman S.C., Aiken C. (2014) - Geological data extraction from lidar 3-D photorealistic models: A case study in an organic-rich mudstone, Eagle Ford Formation, Texas. Geosphere, 10 (3): 610-626. doi: http://dx.doi.org/10.1130/GES00937.1.

Murphy R.J., Monteiro S.T. (2013) - Mapping the distribution of ferric iron minerals on a vertical mine face using derivative analysis of hyperspectral imagery (430–970nm). ISPRS Journal of Photogrammetry and Remote Sensing, 75: 29-39. doi: http://dx.doi.org/10.1016/j.isprsjprs.2012.09.014.

Olariu M.I., Ferguson J.F., Aiken C.L., Xu X. (2008) - Outcrop fracture characterization using terrestrial laser scanners: Deep-water Jackfork sandstone at Big Rock Quarry, Arkansas. Geosphere, 4 (1): 247-259. doi: http://dx.doi.org/10.1130/GES00139.1.

Penasa L., Franceschi M., Preto N., Teza G., Polito V. (2014) - Integration of intensity textures and local geometry descriptors from Terrestrial Laser Scanning to map chert in outcrops. ISPRS Journal of Photogrammetry and Remote Sensing, 93: 88-97. doi: http://dx.doi.org/10.1016/j.isprsjprs.2014.04.003.

Pollard D.D., Fletcher R.C. (2005) - Fundamentals of Structural Geology. Cambridge University Press, pp. 92.

Rotevatn A., Buckley S.J., Howell J.A., Fossen H. (2009) - Overlapping faults and their effect on fluid flow in different reservoir types: A LIDAR-based outcrop modeling and flow simulation study. American Association of Petroleum Geologists Bulletin, 93 (3): 407-427. doi: http://dx.doi.org/10.1306/09300807092.

Sima A., Buckley S.J., Kurz T.H., Schneider D. (2012) - Semi-automatic integration of panoramic hyperspectral imagery with photorealistic lidar models. Photogrammetrie-Fernerkundung-Geoinformation, 4: 443-454. doi: http://dx.doi.org/10.1127/1432-8364/2012/0130.

Stock G.M., Bawden G.W., Green J.K., Hanson E., Downing G., Collins B.D., Leslar M. (2011) - High-resolution three-dimensional imaging and analysis of rock falls in Yosemite Valley, California. Geosphere, 7 (2): 573-581. doi: http://dx.doi.org/10.1130/GES00617.1.

Sturzenegger M., Stead D. (2009) - Close-range terrestrial digital photogrammetry and terrestrial laser scanning for discontinuity characterization on rock cuts. Engineering Geology, 106 (3): 163-182. doi: http://dx.doi.org/10.1016/j.enggeo.2009.03.004.

SwissTopo (2014a) - Géologie en 3D. Available online at: http://www.swisstopo.admin.ch/internet/swisstopo/fr/home/topics/geology/3D-Geology.html (Last accessed 22.01.2014).

SwissTopo (2014b) - Données vectorielles des cartes géologiques de la Suisse au 1:25,000. Feuille 1285, les Diablerets.

Technodigit (2013) - 3DReshaper 2013 - Beginner’s Guide. Hexagon, Metrology.

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