Geological mapping and fold modeling using Terrestrial Laser Scanning point clouds: application to the Dents-du-Midi limestone massif (Switzerland)

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Abstract
Geological mapping in vertical rock faces is extremely challenging because of access difficulties and limited possibilities of recognition, localization and measurement of features at large distance with traditional tools. Moreover, vertical areas can be of primary interest since they often display good quality outcrops and relevant geological information. This study focuses on the detailed remote identification of rock types and fold structures using intensity values acquired by Terrestrial Laser Scanning. A correction of the intensity is proposed proportional to the square of the range and to the cosine of the incidence angle. Furthermore, two methods of remote lithological mapping in 3D have been developed using a manual and a semi-automatic approach. Both delivered good results that are consistent with the spatial distribution of rock-types and allowed us to generate an accurate 3D lithological map of Dents-du-Midi massif (Valais, Swiss Alps). The bedding orientation near the hinge of a Km scale fold was measured on LiDAR data in order to define the fold axis. Then, the result was used to build a model of the hinge in 3D.

Keywords: Remote geological mapping, fold modeling, Terrestrial Laser Scanning, intensity correction, 3D topography, vertical rock slopes.

Introduction
Geological mapping as well as characterizing structural features (faults, folds, bedding, joints, etc.) represent key issues for geological interpretations. Performing these tasks can be highly challenging in complex geological contexts and in steep, hazardous or very large slope areas. In particular, vertical and overhanging slopes are of primary interest as they often display good outcropping conditions and unique geological information. However these areas still remain poorly known when using only traditional field observations and classical two dimensional maps. The main advantages of remote geological mapping and remote structural measurement are:
- The possibility to define and accurately locate rock types at distance and to collect a large
number of measurements (layer thickness and extension, bedding plane orientation, etc.) in inaccessible vertical areas;
- The rapidity and accuracy of data collection over wide areas (discontinuities, faults, fold axis, stratigraphic layers, etc.). This allows building efficiently large 3D models of geological bodies;
- The possibilities of dynamic visualization in 3D of geological features.

For these reasons, remote sensing technologies are experiencing a rapid development and are being widely applied to enhance geological analysis of rock slopes. Aerial and Terrestrial Laser Scanning (ALS, TLS) are commonly used and constitute efficient remote sensing technologies for geological studies [Zanchi et al., 2009; Buckley et al., 2008, 2010; Jaboyedoff et al., 2012; Abellan et al., 2014]. The potential of LiDAR-derived topographic models has been demonstrated in different geological domains such as: structural characterization [Slob and Hack, 2004; Kemeny et al., 2006; Haneberg, 2007; Jaboyedoff et al., 2007; Sturzenegger and Stead, 2009; Sturzenegger et al., 2011; Gigli and Casagli, 2011; Lato et al., 2012], landslide monitoring [Rosser et al., 2007; Oppikofer et al., 2008; Stock et al., 2012] and 3D folds and layers reconstruction [Zanchi et al., 2009; Jones et al., 2009; De Donatis et al., 2009].

Classification of intensity derived from terrestrial LiDAR point clouds was achieved in several geomorphological contexts [Brodu and Lague, 2012] and rock type characterization was successfully performed [Bellian et al., 2005; Franceschi et al., 2009, 2011; Burton et al., 2011; Buckley et al., 2008, 2010; Campos Inocencio et al., 2014]. Very recently, Penasa et al. [2014] have greatly improved the capability to automatically discriminate different rock types with TLS intensity on close range 3D point clouds. Nevertheless, obtain a reliable intensity correction for long range acquisitions (>500m) remains a challenging task. Indeed, the footprint of the laser pulse increases with distance, which results to a loss of accuracy in the calculation of the normal vector. The atmospheric effect also becomes important with the increase in range, due to air humidity and temperature layering [Gross et al., 2008].

Structural and lithological field data have been used to obtain models of geological layers and folds in 3D [de Kemp, 2000; Husson and Mugnier, 2003; Maxelon and Mancktelow, 2005; de Kemp et al., 2006; Tonini et al., 2009] and several commercial softwares allow building models of geological structures [Wu et al., 2005; Zanchi et al., 2009; de Donatis et al., 2009]. Most of these studies are based on Digital Elevation Models from airborne photogrammetry or ALS and thus often do not perform well in vertical areas. Conversely, TLS point clouds are particularly accurate in steep and overhanging slopes.

This study aims to propose a remote lithological mapping at great distance (500-1200 m) of the limestone massif of Dents-du-Midi (Valais, Swiss Alps) based on Terrestrial Laser Scanning (TLS) intensity. The main objective is to accurately discriminate between the different outcropping rock types in order to build a detailed 3D geological map of the North-West face. We conducted signal treatment to achieve an appropriate correction of the LiDAR intensity according to range-to-target and incidence angle between the laser beam and the topographic surface. We coupled the LiDAR intensity data with high resolution photography, fieldwork, as well as existing geological maps and cross-sections form Collet [1943]. We present two different methods dedicated to remote lithological mapping according to LiDAR intensity: first a manual method using Coltop3D software [Jaboyedoff et al., 2007] and second a semi-automatic method, which is a supervised classification based
on different filtering and clustering techniques. Eventually, we used TLS point clouds in order to propose a 3D reconstruction of the fold geometry affecting the NW face of Dents-du-Midi.

**Dents-du-Midi**

*Geographical and geological settings*

Dents-du-Midi massif is located in southwest Valais (Swiss Alps) (Fig. 1). It is composed of a ridge of seven distinct summits with elevations above 3000 m a.s.l. and with 500 m high sub-vertical cliffs on the sides. This area has been affected by several rockfalls in the past [Marietan, 1926; Paget et al., 2013].

The Dents-du-Midi peaks are carved into lower Cretaceous to Oligocene limestone, marlstones and shale of the Helvetic realm. The area is affected by kilometric-scale recumbent folds which constitute second-order structures in the overturned limb of Morcles nappe [De Loys and Gagnebin, 1928; Gagnebin, 1934; Collet, 1943; Badoux, 1971; Steck et al., 1999] (Fig. 2). As a consequence, younger rocks are found at the base of the slope. These folds are related to the main deformation phase responsible for the emplacement of Helvetic nappes. In the study area, the orientation of fold axes is sub-horizontal with a strike oriented NE-SW [Steck et al., 1999].
Figure 2 - Folds at the base of the Morcles Nappe affecting the Dents-du-Midi massif. A) Three dimensional perspective (Google Earth™) showing the Km scale fold. B) Classical geological panorama of Dents-du-Midi modified from De Loys and Gagnebin [1928].

Terrestrial Laser Scanning (TLS)

Data acquisition

An Optech Ilris LR laser scanner was used to collect 3D point clouds with a mean point spacing of 5 cm. This scanner operates according to the time-of-flight of the laser pulse [Lichti et al., 2002; Petrie and Toth, 2008], is characterized by a wavelength of 1064 nm, a spot size of 27 mm at 100m and a maximum working range of 1500m for this type of material (Optech technical specifications). The final 3D point cloud is composed by six scans that have been acquired with a range comprised between 450m and 1200m.

LiDAR intensity correction

Method

The raw intensity is exported as integer in 16 bit format from the Optech parser along with xyz coordinates of the points (Fig. 3A and 4C). In order to perform lithological classification, the intensity value needs to be corrected according to the range-to-target and to the angle between the surface normal and the laser beam shot (i.e. incidence angle). The back-scattered intensity decreases inversely proportional to the square of range for a surface with a normal incidence angle [Kaasalainen et al., 2011; Rees, 2013]. Additionally, for a Lambertian scatterer, the back-scattered intensity decreases with the cosine of incidence angle as already observed by Pfeifer et al. [2008] and Vain and Kaasalainen [2011]. Then, the correction of intensity is computed with Equation 1 for each point of the six scans:

\[ I_{corr} = \frac{I_{raw} R^2}{\cos(k\alpha)} \]  

where \( I_{corr} \) is the corrected intensity, \( I_{raw} \) the raw intensity (integer), \( R \) the range between the scanner and the target, \( k \) is a constant (i.e. for Lambertian scatterer \( k=1 \)) and \( \alpha \) the incidence angle in degrees. The incidence angle was calculated using the normal vector, which was computed with Coltop3D software using the eigenvectors of the covariance matrix [Jaboyedoff et al., 2007]. Once the intensity was corrected, the six different scans were
merged to obtain a complete point cloud with corrected intensities that was subsequently georeferenced to the 1m cell size High Resolution Digital Elevation Model (HRDEM) (Swisstopo, Swiss coordinates CH1903). Both alignments were performed using a point-to-surface Iterative Closest Point (ICP) algorithm [Chen and Medioni, 1992].

Results

![Figure 3 - Steps of the intensity correction for scan number 6 of Dents-du-Midi (see also Fig. 4). The points represent the data and the red line is the mean value. A) Relationship between the Raw intensity (I_{raw}) and the distance-to-target. The raw intensity is composed of integer values. The inverse of the range (1/R²) is also plotted for comparison. B) Relationship between the distance-to-target and the intensity after correction of the range. The layering visible in the data is due to the fact that the raw intensity is composed of integer values. Then, one unit of raw data corresponds to a large difference of intensity after the correction of the range. C) Relationship between incidence angle and intensity after correction of the range-to-target and cosine of the incidence angle with k=1 (Eq. 1). D) Relationship between incidence angle and intensity after correction of the range-to-target and cosine of the incidence angle with k=0.75 (Eq. 1). Different values of k in equation 1 have been tested and the value of k=0.75 gives the best correction of the intensity at Dents-du-Midi.](image-url)
Figures 3 and 4 display the progressive reduction of intensity value with the range (3A and 4A) and with the incidence angle (4B). Figures 3B and 4D show our preliminary correction of intensity values with the square of the range. Our first attempt to correct the influence
of incidence angle on the intensity using $k=1$ is shown in Figure 3C. An overcorrection is observed for points with an incidence angle larger than 40°, which could be explained by the fact that rock outcrops do not behave as a perfect Lambertian Scatterer. Therefore, we iteratively varied the $k$ parameter and we found that the optimal value for this rock outcrop is $k=0.75$ (Fig. 3D). Figures 4C to 4F show the effect of the parameters of correction. The simple correction for the range ($R^2$) shows that the intensity remains largely influenced by the local orientation of the cliff (Fig. 4D). In fact the areas with a high intensity constitute the overhanging zones where the incidence angle is close to zero. A better result was obtained dividing the intensity by the cosine of the incidence angle, but edge effects are still present for incidence angles above 40° (Figs. 4E and 3C). These effects are particularly well visible in the lower part of the scan, where slope areas with a large incidence angle display the highest intensities (red areas). The final correction according to Equation 1 with $k=0.75$ delivers the best intensity values which are homogeneous and independent from the local variation of the topography (Figs. 4F and 3D). These are the intensity values that were used for the remote geological mapping. Eventually, the alignment of the six scans with the corrected intensity leads to a final TLS point cloud composed of 43 million points (Fig. 5).

**Remote geological mapping**

*Intensity interpretation*

![Image](image_url)

Figure 5 - TLS point cloud of the NW face of Dents-du-Midi colored in a greyscale according to the corrected intensity (Figures 3 and 4). The polygon A represents the area of the scan displayed in Figure 4. The yellow lines highlight the strong contrasts in the intensity value due to a lithological limit. The lighter differences are marked with dashed lines and display secondary limits. Weathered or humid surfaces are also reported, as well as fresh rockfall scars.
After the correction process, the intensity value is a function of rock type reflectance and of conditions of the outcrop surface, such as weathering or humidity [Franceschi et al., 2009; Penasa et al., 2014; Buckley et al., 2013; Hartzell et al., 2014]. Figure 5 displays the main features that have been highlighted on the corrected point cloud thanks to the contrast of intensity. The main alternations of higher and lower intensity correspond to lithological limits, as confirmed by field observations and comparison with high resolution photographs. Within these rock bodies we identified less marked contrasts that we interpreted as secondary lithological limits. Then, some areas of weathered rocks have been defined according to a darker color of the surface that is a consequence of persistent humidity, mostly on local north facing cliff areas. In addition we found that recent rockfall scars show high intensity contrasts due to the difference of weathering and color between long term and the freshly exposed rock.

**Manual mapping**

**Method**

The preliminary interpretation of intensity contrasts (Fig. 5) was confronted to the geological formations defined on existing geological maps and cross-sections [De Loys and Gagnebin, 1928; Gagnebin, 1934; Collet, 1943]. The limits between the main formations have been identified on the point cloud thanks to visual interpretation of the corrected intensity. Then, the points belonging to the same layer were selected manually by drawing polygons within Coltop3D software [Jaboyedoff et al., 2007] (Fig. 6).

![Figure 6 - Detail of the manual geological mapping at the North east side of Dents-du-Midi massif. A) Mapping performed on the TLS point cloud. B) Rock types recognition on the photograph.](image)

**Results**

We were able to precisely map the main formations reported on the Swiss geological atlas (Fig. 2B) [De Loys and Gagnebin, 1928; Gagnebin, 1934; Collet, 1943] namely Priabonian limestone and shales, Red marlstone (Eocene), TGA (Turonian, Gault and Aptian) limestone and marlstone, Urgonian massive limestone, Barremian marlstone, Hauterivian siliceous limestone and Valanginian limestone and shales (Fig. 7). A fold hinge is highlighted by the curved bedding plane inside the Valanginian formation and at the limit with the Hauterivian siliceous limestone (Figs. 2 and 8).
Figure 7 - 3D geological mapping. A) Panorama of the geological formations used as reference for the 3D mapping (modified from De Loys and Gagnebin 1928). B) Result of the manual 3D geologic mapping on the TLS point cloud. Each geological layer was manually classified using Coltop3D software according to the geological limits defined by De Loys and Gagnebin [1928].

Figure 8 - Fold hinge (see Figs 1 and 7 for location). A) Photograph of the fold hinge taken from the ground. The strike of the fold axis is approximately parallel to the slope surface and thus several layers are visible. B) Point cloud of the same area colored according to the geological formation.
Intensity distributions for the rock types

A representative sample of points has been selected for each rock type outcropping in the NW face of Dents-du-Midi and the statistical distribution of intensities is shown in Figure 9. Priabonian rocks are composed of shale and marly limestone with Nummulites and are characterized by a signal strength distribution situated in the middle of the whole Dents-du-Midi intensity values (Fig. 9). Lower Eocene “Red marlstone” is a thin (<10m) and discontinuous iron rich marly-limestone that displays an intensity signature very similar to the Priabonian. Turonian, Gault and Aptian formations are composed of intercalations of limestone and marlstone layers (TGA limestone, TGA marlstone) that are very different from each other, as displayed by their intensity distributions (Fig. 9). However, as they are thin and discontinuous, they are traditionally mapped together [De Loys and Gagnebin, 1928; Gagnebin, 1934]. The Urgonian layer is composed of massive white limestone and is the most characteristic formation of cretaceous Helvetic rocks. Its intensity is the highest of the Dents-du-Midi point cloud. Barremian dark marlstone is well recognizable at the top of the Urgonian limestone bar, due to its dark color and to the local concave profile of the cliff. The Hauterivian siliceous limestone has great intensity variability, displayed by a large standard deviation (Fig. 9). This is explained by lithological alternations and by the surface weathering associated to several wet areas where intensities result to be lower than the mean value for this rock type in proper outcropping conditions. Valanginian limestone and shales also are very weathered, often covered by lichens and water seepage. Then the composition and color of the surface is quite different from the freshly broken rock,
resulting in lower and more dispersed intensity values. These issues are responsible for the peaks of low intensity in the Valanginian histograms (Fig. 9). However the limit between the Valanginian limestone and the Hauterivian formation can be mapped quite well thanks to the exposure of the frontal part of an important fold (Fig. 8).

**Semi-automatic approach**

This section describes the proposed methodology to semi-automatically classify the 3D point cloud of the NW face of Dents-du-Midi into different rock types. Preliminary fieldwork and intensity interpretation was necessary to ascertain the different rock types at specific locations (Fig. 5). Then, this knowledge was used to segment the dataset in consistent lithological layers, based on intensity values and on spatial relations between the points. A layer composed of a single material is considered as a patch of connected points, with homogeneous intensity values that fall within a specific interval (Fig. 9).

**Method**

The procedure is composed of a denoising and two filtering steps. A final clustering process completes the segmentation, which divides the 3D point cloud in several smaller point clouds depending on the rock type. The workflow was repeated to obtain a final point cloud for each rock type. We grouped TGA limestone, Red marlstone and Priabonian limestone as the overlapping of intensity distributions for these rocks was too large to achieve a differentiation with this approach (Fig. 10).

![Figure 10 - Distributions of corrected intensity for each rock type selected at Dents-du-Midi NW face.](image-url)
Denoising
To start, a denoising of the intensity values was carried out with a Nearest Neighbors algorithm (KNNsearch function of Matlab) in order to remove the points with an outlier intensity in respect to the average value of a given number of neighbors K (K=50). A mean intensity is re-attributed to the points according to the values of neighbors and so a point cloud with a smoothed distribution of intensities is obtained.

Filtering 1 (intensity values)
After a preliminary recognition of the spatial distribution of rock types, the user has to define the interval of corrected signal strength corresponding to the regarded rock type to map. This interval is defined as the average plus the standard deviation of the intensity distribution of a sample of points selected for the rock type (Fig. 9). At the end of this step, all the points with an intensity value external to the interval are excluded from the resulting dataset.

Filtering 2 (local density of points)
An overlapping between the distributions of intensities is displayed in Figure 10. Then, we applied an additional filtering procedure aiming at defining if a point with a given intensity is isolated or if it is surrounded by points with similar intensity values. In order to determine if a point has a sufficient number of close neighbors that fit inside the intensity limits established before (filtering 1) we calculated a local density of points: a first search radius R1 is defined for each point according to the needed distance to find K undifferentiated neighbors. A second radius R2 is obtained by searching the same number K of nearest points characterized by an intensity that fits in the interval already established (filtering 1). Then, the relative density of points defined as the ratio between the search radius (R1) and (R2), has been used as classification value. Only the points with a value above a user defined threshold of 0.95 are considered as being part of the regarded rock type and are retained for the next step of the procedure.

Clustering
Eventually, the clustering operation is needed to definitely decide if the remaining points have to be considered part of the regarded material or if they constitute groups of points with the same intensity but located outside the regarded rock type layer. The segmented point cloud, obtained at the end of the filtering procedure, is imported in the software CloudCompare and a clustering process is performed with the Label-Connected-Components tool [Girardeau-Montaut, 2006, 2014]. Two parameters must be defined to control the clustering: the search radius (octree level) and the minimum number of points per component. We performed several tests with this procedure to find the best parameters for each lithology in order to complete the discrimination of the different layers. A single connected cluster of points is obtained for each layer, except when a big gap in the dataset exists. Eventually, the final clusters of points that constitute a rock type layer are available for visualization in 3D and can be exported with xyz coordinates, intensity, a scalar lithological attribute and a scalar value related to the cluster number.
Results

With this semi-automatic procedure the main rock types of the lower part of the study area were classified (Fig. 11). The Urgonian limestone has intensity values significantly higher than other formations and thus could be isolated easily with this procedure (Fig. 10). The lowest intensity is associated with the TGA marlstone that is present in the right (SW) side of the cliff (Fig. 12). In this area, two layers of this rock type, about 10 m thick each, could be mapped taking advantage of the well-marked contrast in comparison to the surrounding rocks. TGA limestone is sufficiently different from the Urgonian to allow the discrimination (Fig. 10). However, the overlapping of the intensity distribution with the Red marlstone and the Priabonian layers is too important to obtain a satisfying classification of these three formations. No valid lithological discrimination could be achieved for the upper part of the face, as the overlapping of the intensity distribution for the Barremian, Hauterivian and Valanginian formations is too important (Figs. 10 and 11).

Figure 11 - Result of the semi-automatic 3D lithological mapping on the TLS point cloud. The limestone of the TGA formation, the red marlstone and the Priabonian limestone have very similar intensities and thus are not differentiated here. The undifferentiated rocks include the Hauterivian and the Valanginian formations. The white polygon represents the close-up shown in Figure 12.
Figure 12 - Close up of the right (South-West) part of the Dents-du-Midi NW face. A) Detail of the semi-automatic lithological mapping. B) Photography image of the same view as Figure 12A displaying the main rock types recognized on the TLS data with the semi-automatic method.
3D fold modeling

Method

Orientation of the fold axis

The fold affecting the NW face of Dent-du-Midi is well highlighted by the limit between the Valanginian and Hauterivian formations (Fig. 8). In order to collect structural measurement of the fold, we analyzed in detail the bedding orientation along this limit using Coltop3D software [Jaboyedoff et al., 2007]. We selected points corresponding to the bedding surface with the polygon tool all over the fold structure to cover the two limbs and hinge, in order to obtain a characterization of the geometry of the whole folded bedding plane (Fig. 13A). The local measurements of the bedding orientation extracted from the 3D point cloud were verified with high resolution photographs of the hinge zone. Subsequently, the dip and dip direction of the selected points were plotted in a stereographic projection. The fold axis was then deduced according to the Pi diagram technique [Ramsey, 1967]: the points of the folded bedding plane were linked by a best fit great circle. By definition, the orientation of the fold axis corresponds to the trend and plunge of the normal vector of the best-fitted great circle.

Figure 13 - Structural analysis of the fold hinge affecting the Dents-du-Midi NW face. A) Coltop3D visualization of the 3D point cloud. The white lines highlight the bedding plane. B) Stereographic projection (lower hemisphere, equal area) of the poles of the bedding and their density (black and gray lines). The fold axis orientation is deduced by best fitting a plane (white great circle) through the poles. The axis of the fold is defined as the normal vector to the best fit plane, which has a trend and plunge of 064° / 02°.

Modeling of the fold surface

The surface of the fold was then reconstructed according to 1) the previously defined fold axis and 2) the stratigraphic limit between the Valanginian and Hauterivian formations (Fig.
About 40 points have been selected along the bedding plane at this limit. The selected points are then linked by a b-spline function in a Bezier curve that was subsequently reproduced laterally along a vector with the orientation of the fold axis [Fischer et al., 1991; de Kemp, 1999, 2000; de Kemp and Sprague, 2003; Jones et al., 2009]. A mesh was then built by triangulation to connect the nodes of the curves and draw the surface of the folded bedding plane in 3D.

**Results**

An axis with a trend of 064° and a plunge angle of 02° is obtained with the Pi diagram technique (Fig. 13B). Figure 14 illustrates the proposed modeling of the fold structure, which corresponds to an overturned isoclinal anticline of secondary order, with a NW direction. This fold is considered as cylindrical at the scale of the investigated outcrop.

![3D fold model of the hinge surface at the limit between the Hauterivian and the Valanginian formations.](image)

**Discussion**

**Correction of the LiDAR intensity values**

The intensity of the back-scattered laser beam decreases proportional to the incidence angle and inversely proportional to the range-to-target, as already demonstrated by Kaasalainen et al. [2011] (Fig. 4). Moreover we observed that rock outcrops do not behave as Lambertian scatterer, probably because the size of the laser footprint leads to a back-scattered signal that is reflected by multiple rock-facets with different orientations [Rees, 2013] (Fig. 3).
The correction equation (1) with $k=0.75$ is optimized for the rock mass properties at Dents-du-Midi and the corrective factor $k$ needs to be adapted at every case study according to the material. Eventually it is important to point out that the correction realized with Equation 1 leads to a relative value of intensity. To obtain an absolute reflectance value of the material, the intensity should be calibrated with a standard reference, which could be made after displaying several targets with a-priori known reflectivity in the scan area. Due to the size of the face and to the access difficulties at Dents-du-Midi, it was not possible to place targets on the outcrop to realize this kind of calibration.

**The potential of remote geological mapping**

**Manual method**

The visual interpretation of the corrected LiDAR intensity allowed to define the main lithological limits even without a prior geological knowledge (Fig. 5). To associate these limits with lithological classes, it was necessary to compare the point cloud with traditional geological maps [De Loys and Gagnebin, 1928; Gagnebin, 1934] and cross sections [Collet, 1943]. The manual approach with Coltop3D leads to a 3D geological map where every feature is precisely located with georeferenced coordinates and where accurate measurements can be performed (Fig. 7). The high resolution of TLS point clouds allows mapping lithology limits with greater detail than using classical 2D maps. The stratigraphy can be improved with the detailed characterization of fine intensity contrasts, in particular for vertical and inaccessible cliffs. The accuracy of the classification is tributary to the point spacing of the point cloud and to the preliminary rock types identification performed in the field. In addition, this method is largely manual and thus it can be applied only to relatively simple geological settings. Especially, it is hard to render very small ($<2 \text{ m}^2$) geological bodies, like enclaves in plutonic rocks. The main advantage of the manual method is that the user can overcome potential issues related to the variability or the continuity of intensity values within a given layer. For instance the effect of surface weathering or covering as well as rockfall scars can be taken into account during the classification of lithological contacts (Fig. 5). The main limitations are the subjectivity of the user’s choices as well as the needed preliminary geological knowledge.

**Semi-automatic method**

In the NW face of Dents-du-Midi it was possible to classify the main lithological layers on the base of the corrected TLS intensity value (Figs. 11 and 12). The semi-automatic approach is data driven and thus theoretically more rigorous than the visual discrimination of intensity contrasts. However, not all the layers could be classified and the upper part of the face remains undifferentiated. This kind of semi-automatic mapping technique can be successfully applied to entirely map large and complex geological structures if the LiDAR intensity value is sufficiently contrasted [Franceschi et al., 2009]. An important limitation of this method is the overlapping of intensity distributions, as was shown in Figure 10. When two rock types have the same intensity signature but are not contiguous, this issue can be solved quite easily with some additional expertise of the user, which has to discriminate the two clusters. Conversely, if two contiguous rock types have a large intensity overlapping, it will be very complex to differentiate these two layers according to a single channel. Then our approach can be coupled to other data such as RGB or hyperspectral [Kurz et al., 2011;
Buckley et al., 2013; Penasa et al., 2014; Hartzell et al., 2014]. Other difficulties can arise as a consequence of the non-continuity of the LiDAR data that can be linked to the surface weathering or to the lack of points in the occluded areas. When the point cloud does not present large gaps, it is possible to obtain a single cluster of points for each layer. Structural features, such as faults or folds can also be responsible for a displacement or duplication of the same material in two or more unconnected parts. Addressing these issues also requires additional field investigations or remote sensing techniques. Eventually, a potential limit to this approach is the necessity of a sample of intensity values for each lithology to direct the classification algorithm. This is a typical issue of supervised methods and requires a preliminary knowledge of the spatial distribution of rock types.

**Fold modeling**

On the stereoplot of Figure 13B some areas are more represented than others because of exposition differences in the outcrop and occlusions in the point cloud. For instance, in horizontal areas we could measure only few orientations of the bedding plane because only a limited number of points could be collected in these areas. Conversely, some points were accidentally measured on the side of the bedding plane, but their number is so small compared to the total that no impact is observed on the final result. In fact, the fitting of the great circle on the global amount of measurements is good, ultimately leading to an accurate measurement of the axis. Furthermore, this measurement is consistent with the regional ENE-WSW sub-horizontal axis orientation established in this sector of the Morcles nappe [Collet, 1943; Steck et al., 1999]. The folded structure presented here is quite simple because only one hinge is reported in our 3D point cloud, but the methodology can be applied to more complex cases. More extended TLS data would allow mapping several fold hinges that could be linked to form a series of anticlinal and synclinal structures [de Kemp and Sprague, 2003; Tonini et al., 2009]. Moreover the fold axis can be projected at several kilometers of distance to link in 3D several hinges located at the same structural level. At the moment this procedure is efficient for cylindrical folds and could be modified to reproduce more complex structures and to take into account the lateral changes of the axis orientation.

**Conclusions**

The present study demonstrates the potential of remote geological mapping based on the ground-based LiDAR intensity that allowed building a 3D geological map of the NW face of Dents-du-Midi. The LiDAR intensity values have been successfully corrected to remove topographic effects and then the point cloud has been differentiated in 9 rock types. Two remote mapping methods have been developed and compared to demonstrate the potential of supervised material classification based on LiDAR intensity. TLS point clouds prove to be particularly suitable to perform structural measurements needed to build fold models in 3D. Thus, we achieved the goal of modeling both the normal and the overturned limb of a kilometric scale fold. This procedure of fold modeling based on TLS point clouds opens interesting perspectives for structural geology applications and tectonic interpretations. The 3D representation of geological structures is also a major contribution to study natural hazards or planning engineering projects such as tunnels, mines or reservoirs. The remote mapping performed in this work is based on a single channel and is therefore limited, in
particular when contiguous materials display very similar intensity values. Therefore, the results could be enhanced by coupling several bands. Other functions could be implemented in the fold modeling to allow dealing with variable axis orientations or with complex non-cylindrical folded structures.

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References
Abellan A., Oppikofer T., Jaboyedoff M., Rosser J., Lim M., Lato M. (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. (1971) - Atlas géologique de la Suisse 1:25000, Feuille 58 Dent de Morcles, Notice explicative. Commission Géologique de la Société Helvétique des Sciences Naturelles.
Bellian J.A., Kerans C., Jennette D.C. (2005) - Digital outcrop models: applications of terrestrial scanning lidar technology in stratigraphic modelling. Journal of Sedimentary Research, 75 (2): 166-176. doi: http://dx.doi.org/10.2110/jsr.2005.013.
Brodu N., Lague D. (2012) - 3D terrestrial lidar data classification of complex natural scenes using a multi-scale dimensionality criterion: Applications in geomorphology. ISPRS Journal of Photogrammetry and Remote Sensing, 68: 121-134. doi: http://dx.doi.org/10.1016/j.isprsjprs.2012.01.006.
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., Kurz T.H., Howell J.A., Schneider D. (2013) - Terrestrial lidar and hyperspectral data fusion products for geological outcrop analysis. Computers & Geosciences, 54: 249-258. doi: http://dx.doi.org/10.1016/j.cageo.2013.01.018.
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.
Burton D., Dunlap D.B., Wood L.J., Flagg P.P. (2011) - Lidar intensity as a remote sensor of rock properties. Journal of Sedimentary Research, 81: 339-347. doi: http://dx.doi.org/10.2110/jsr.2011.31.
Campos Inocencio L., Veronez M.R., Wohrnath Tognoli F.M., de Souza M.K., da Silva R.M., Blum Silveira C.L. (2014) - Spectral Pattern Classification in Lidar Data for Rock Identification in Outcrops. The Scientific World Journal. doi: http://dx.doi.org/10.1155/2014/539029.
Chen Y., Medioni G. (1992) - Object modelling by registration of multiple range images.
Image Vision Computing, 10 (3): 145-155. doi: http://dx.doi.org/10.1016/0262-8856(92)90066-C.

Collet L.W. (1943) - La Nappe de Morcles entre Arve et Rhône, Materiaux pour la carte géologique de la Suisse. Commission Géologique de la Société Helvétique des Sciences Naturelles.

De Donatis M., Borraccini F., Susini S. (2009) - Sheet 280-Fossombrone 3D: A study project for a new geological map of Italy in three dimensions. Computers & Geosciences, 35 (1): 19-32. doi: http://dx.doi.org/10.1016/j.cageo.2007.09.004.

De Kemp E.A. (1999) - Visualization of complex geological structures using 3-D Bezier construction tools. Computer & Geosciences, 25 (5): 581-597. doi: http://dx.doi.org/10.1016/S098-3004(98)00159-9.

De Kemp E.A. (2000) - 3D visualization of structural field data: examples from the Archean Caopatina Formation, Abitibi greenstone belt, Quebec, Canada. Computer & Geosciences, 26 (5): 509-530. doi: http://dx.doi.org/10.1016/S009-3004(99)00142-9.

De Kemp E.A., Sprague K. (2003) - Interpretive tools for 3-D structural geological modelling. Part I: Be’zier-based curves, ribbons and grip frames. GeoInformatica, 7 (1): 55-71. doi: http://dx.doi.org/10.1023/A:102282227691.

De Kemp E.A., Schetselaar E.M., Sprague K. (2006) - 3-D symbolization of L-S fabrics as an aid to the analysis of geological structures. Computers & Geosciences, 32 (1): 52-63. doi: http://dx.doi.org/10.1016/j.cageo.2005.04.006.

De Loys F., Gagnebin E. (1928) - Monographie géologique de la Dent du Midi, Matériaux pour la carte géologie de la Suisse. Commission géologique de la Société Helvétique des Sciences naturelles.

Fischer T., Wales R.Q. (1991) - 3-D solid modeling of geological objects using non-uniform rational B-splines (NURBS). In: Turner A.K. (Ed.), Three Dimensional Modelling with Geoscienti®c Information Systems. Kluwer, Dordrecht, pp. 85-105.

Franceschi M., Teza G., Preto N., Pesci A., Galgaro A., Girardi S. (2009) - Discrimination between marls and limestones using intensity data from terrestrial laser scanner. ISPRS Journal of Photogrammetry and Remote Sensing, 64: 522-528. doi: http://dx.doi.org/10.1016/j.isprsjprs.2009.03.003.

Franceschi M., Preto N., Hinnov L., Huang C., Rusciadelli G. (2011) - Terrestrial laser scanner imaging reveals astronomical forcing in the early cretaceous of the tethys realm. Earth and Planetary Science Letters, 305: 359-370. doi: http://dx.doi.org/10.1016/j.epsl.2011.03.017.

Gagnebin E. (1934) - Atlas géologique de la Suisse 1:25000, Feuille 483 St-Maurice, Notice explicative. Commission géologique de la Société Helvétique des Sciences naturelles.

Gigli G, Casagli N. (2011) - Semi-automatic extraction of rock mass structural data from high resolution LiDAR point clouds. International Journal of Rock Mechanics and Mining Sciences, 48 (2): 187-198. doi: http://dx.doi.org/10.1016/j.ijrmms.2010.11.009.

Girardeau-Montaut D. (2006) - Détection de Changement sur des Données Géométriques Tridimensionnelles. PhD thesis, Telecom Paris. Available on line at: http://www. danielgm.net/cc/.

Girardeau-Montaut, D. (2014) - Cloudcompare, a 3D Point Cloud and Mesh Processing Free Software. EDF R&D, Telecom ParisTech. Available online at: www.danielgm.net/ cc (last accessed 08.02.14).
Gross H., Jutzi B., Thoennessen U. (2008) - *Intensity normalization by incidence angle and range of full-waveform lidar data*. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXVII (B4).

Haneberg W.C. (2007) - *Directional roughness profiles from three dimensional photogrammetric or laser scanner point clouds*. In: Landslides and Engineered Slopes: Protecting Society through Improved Understanding. Eberhardt E., Froese C., Turner K. (Eds). CRC Press-Taylor and Francis: Canada, pp. 101-106. doi: http://dx.doi.org/10.1201/noe0415444019-c13.

Hartzell P., Glennie C., Biber K., Khan S. (2014) - *Application of multispectral LiDAR to automated virtual outcrop geology*. International Journal of Photogrammetry and Remote Sensing, 88: 147-155. doi: http://dx.doi.org/10.1016/j.isprsjprs.2013.12.004.

Husson L., Mugnier J.L. (2003) - *Three-dimensional horizon reconstruction from outcrop structural data, restoration, and strain filed of the Baisahi anticline, Western Nepal*. Journal of Structural Geology, 25 (1): 79-90. doi: http://dx.doi.org/10.1016/S0191-8141(02)00044-5.

Jaboyedoff M., Metzger R., Oppikofer T., Couture R., Derron M.-H., Locat J., Durmel D. (2007) - *New insight techniques to analyze rock-slope relief using DEM and 3D-imaging clouds points: COLTOP-3D software*. In: Eberhardt E., Stead D., Morrison T. (Eds) Rock mechanics: meeting society’s challenges and demands. Taylor & Francis, London, pp. 61-68. doi: http://dx.doi.org/10.1201/noe0415444019-c8.

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: 5-28. doi: http://dx.doi.org/10.1007/s11069-010-9634-2.

Jones R.R., Mccaffrey K.J.W., Clegg P., Wilson R.W., Holliman, N.S., Holdsworth R.E., Imber J., Waggotts, S. (2009) - *Integration of region-al to outcrop digital data: 3D visualisation of multi-scale geological models*. Computers & Geosciences, 35 (1): 4-18. doi: http://dx.doi.org/10.1016/j.cageo.2007.09.007.

Kaasalainen S., Jaakkola A., Kaasalainen M., Krooks A., Kukko A. (2011) - *Analysis of incidence angle and distance effects on terrestrial laser scanner intensity: search for correction methods*. Remote Sensing, 3: 2207-2221. doi: http://dx.doi.org/10.3390/rs3102207.

Kemeny J., Turner K., Norton B. (2006) - *LIDAR for rock mass characterization: hardware software accuracy and best-practices*. In: Tonon F., Kottenstette J. (Eds.), Laser and Photogrammetric Methods for Rock Face Characterization ARMA, American Rock Mechanics Association (ARMA): Golden, Colorado, 49-62.

Kurz T., Buckley S., Howell J., Schneider D. (2011) - *Integration of panoramic hyperspectral imaging with terrestrial lidar*, Photogrammetric Record, 26 (134): 212-228. doi: http://dx.doi.org/10.1111/j.1477-9730.2011.00632.x.

Lato M., Vöge M. (2012) - *Automated mapping of rock discontinuities in 3D LiDAR*. International Journal of Rock Mechanics and Mining Sciences, 53: 150-158. doi: http://dx.doi.org/10.1016/j.ijrmms.2012.06.003.

Lichti D.D., Gordon S.J., Stewart M.P. (2002) - *Ground-based laser scanner: Operation, systems and applications*. Geomatica, 56: 21-33.

Marietan I. (1926) - *Les éboulements de la Cime de l’Est des Dents du Midi en 1926 et le Bois-Noir*. Bulletin de la Murithienne, 44: 67-93.
Maxelon M., Mancktelow N.S. (2005) - Three-dimensional geometry and tectonostratigraphy of the Pennine zone, Central Alps, Switzerland and Northern Italy. Earth-Science Reviews, 71: 171-227. doi: http://dx.doi.org/10.1016/j.earscirev.2005.01.003.

Oppikofer T., Jaboyedoff M., Keusen H.R. (2008) - Collapse of the eastern Eiger flank in the Swiss Alps. Nature Geosciences, 1(8): 531-535. doi: http://dx.doi.org/10.1038/ngeo258.

Paget J., Ravanel L., Deline P. (2013) - Les écroulements rocheux dans les massif des Dents du Midi (3257 m, Valais, Suisse): documentation et analyse. Master Thesis, Edytem, University of Savoie, France.

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.

Petrie G., Toth C.K. (2008) - Introduction to laser ranging, profiling, and scanning, II. Airbone and spaceborne laser profiles and scanners, III. Terrestrial laser scanners. In: Shan J., Toth C.K. (Eds.), Topographic laser ranging and scanning: principles and processing, CRC Press, Taylor & Francis.

Pfeifer N., Höfle B., Briese C., Rutzinger M., Haring A. (2008) - Analysis of the backscattered energy in terrestrial laser scanning data. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences; 37:1045-1052.

Ramsey J.G. (1967) - Folding and Fracturing of Rocks. Mc Gray-Hill, New York.

Rees W.G. (2013) - Physical principles of remote sensing. 3rd edition, Cambridge University Press.

Rosser N., Lim M., Petley D., Dunning S., Allison R. (2007) - Patterns of precursory rockfall prior to slope failure. Journal of Geophysical Research, 112 (F4014). doi: http://dx.doi.org/10.1029/2006JF000642.

Slob S., Hack R. (2004) - 3D terrestrial laser scanning as a new field measurement and monitoring technique. Engineering geology for infrastructure planning in Europe: a European perspective. Lectures Notes in Earth Sciences, Springer, 104: 179-189. doi: http://dx.doi.org/10.1007/978-3-540-39918-6_22.

Steck A., Bigioggero B., Dal Piaz G.V., Escher A., Martinotti G., Masson H. (1999) - Carte tectonique des Alpes de Suisse occidentale (1:100000) Feuille 41 Col du Pillon. Service hydrologique et géologique national, Bern, Switzerland.

Stock G.M., Martel S.J., Collins B.D., Harp E.L. (2012) - Progressive failure of sheeted rock slopes: the 2009-2010 Rhombus Wall rock falls in Yosemite Valley, California, USA. Earth Surface Processes and Landforms, 37: 546-561. doi: http://dx.doi.org/10.1002/esp.3192.

Sturzenegger M., Stead D. (2009) - Close-range terrestrial digital photogrammetry and terrestrial laser scanning for discontinuity characterization on rock cuts. Engineering Geology, 106 (3-4): 163-182. doi: http://dx.doi.org/10.1016/j.enggeo.2009.03.004.

Sturzenegger M., Stead D., Elmo D. (2011) - Terrestrial remote sensing based estimation of mean trace length trace intensity and block size/shape. Engineering Geology, 119 (3-4): 96-111. doi: http://dx.doi.org/10.1016/j.enggeo.2011.02.005.

Tomini A., Guastaldi E., Meccheri M. (2009) - Three-dimensional reconstruction of the Carrara Syncline (Apuane Alps, Italy): An approach to reconstruct and control a geological model using field survey data. Computers & Geosciences, 35 (1): 33-48. doi:
http://dx.doi.org/10.1016/j.cageo.2007.09.010.

Vain A., Kaasalainen S. (2011) - Correcting Airborne Laser Scanning Intensity Data. In: Wang C.C. (Ed.), Laser Scanning, Theory and Applications. doi: http://dx.doi.org/10.5772/15026.

Zanchi A., Salvi F., Zanchetta S., Sterlacchini S., Guerra G. (2009) - 3D reconstruction of complex geological bodies: Examples from the Alps. Computers & Geosciences, 35 (1): 49-69. doi: http://dx.doi.org/10.1016/j.cageo.2007.09.003.

Wu Q., Xu H., Zou X. (2005) - An effective method for 3D geological modeling with multi-source data integration. Computers & Geosciences, 31 (1): 35-43. doi: http://dx.doi.org/10.1016/j.cageo.2004.09.005.

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