

Vombat: An Open Source Tool for Creating Stratigraphic Logs from Virtual Outcrops

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Abstract

An open source tool, *Vombat*, is presented that is designed to operate on Virtual Outcrop Models of sedimentary rocks, with the specific aim of assisting the stratigraphic analysis and interpretation. *Vombat* makes it possible to estimate the average attitude of the bedding and to create one or more attitude-aligned stratigraphic reference frames. This allows *Vombat* to extract continuous stratigraphic logs of any property associated with the point clouds (e.g. the lidar intensity or RGB color). Stratigraphic logs produced by *Vombat* can be compared and correlated to typical outcrop logs and petrophysical logs obtained from boreholes (e.g. gamma ray logs) and can provide information about the lithological variations in a stratigraphic succession. Furthermore, *Vombat* stratigraphic reference frames can be used to associate a stratigraphic position (a depth in the stratigraphic column) to any observation made on the outcrop, allowing visualization in 3D (on the virtual outcrop model) and 1D (on a stratigraphic column) for any collected data. All the geological objects created in the virtual environment can then be saved. The tool has been developed to be user-friendly and is constituted by a dynamically loaded plugin for the open source software CloudCompare.

4.1 Introduction

Three-dimensional imaging techniques have increasingly been applied to the realization of Virtual Outcrop Models (VOMs), especially in the oil and gas industry, to be used as surface analogs for the investigation of buried reservoirs (Hartzell et al., 2014; Martinsen et al., 2011; Kurz et al., 2008; Rarity et al., 2014; Bellian et al., 2005; Marques et al., 2020). Terrestrial Laser Scanners (TLSs) and photogrammetry (see Wilkinson et al., 2016; Corradetti et al., 2021; Buckley et al., 2010) are often used to produce VOMs or DOMs: these two methods allow three-dimensional representations of an outcrop's surface to be obtained in the form of *point clouds* or *meshes*, thus providing a *virtual duplicate* of the outcrop, which can be visualized, navigated, and interpreted with appropriate tools (see Chapter 2 by Bistacchi et al., 2021; Tavani et al., 2011; Buckley et al., 2017; Caravaca et al., 2020).

The potential of laser scanner- and photogrammetry-generated VOMs was also explored in the perspective of quantifying lithological properties in a fast, semiautomated and geometrically accurate way. Franceschi et al. (2009) and Burton et al. (2011) investigated the relationship

between lithologies and the intensity recorded by laserscanners, Penasa et al. (2014) demonstrated a method for the automated detection of chert from TLS intensity, multi- and hyper-spectral data, fused with three-dimensional models, which gave promising results (Kurz et al., 2012a; Krupnik et al., 2016; Thiele et al., 2021), and hyperspectral lidars are currently being developed (Suomalainen et al., 2011; Malkamäki et al., 2019). A sound review of geologic applications of TLSs, which in some measure can be extended to photogrammetry, can be found in Telling et al. (2017).

Scalar properties associated to the VOM (e.g. lidar intensity, RGB) can be studied in the form of logs that display the variations of the property along a stratigraphic succession (Franceschi et al., 2011, 2015; Penasa et al., 2019). These logs can be considered a remote-sensing equivalent to stratigraphic logs obtained by sampling in the field and then measuring some properties (e.g. chemical or mineralogical composition) and reporting them on a stratigraphic column, or to petrophysical logs realized in boreholes (Ellis and Singer, 2007). These latter logs refer to a range of properties (e.g. gamma ray, resistivity, spontaneous potential, etc.) that are used to obtain information about the rocks crossed during core drilling, basically

describing how some measurable rock-property varies with the stratigraphic depth (Miall, 2016).

The logs obtained from VOMs could be used in a similar way and also provide means of correlating surface outcrop analogs and their buried counterparts. Despite this potential, however, there are no specific tools to construct property logs directly from 3D models, and their realization is complicated and limited by the fact that most software packages are not designed for this purpose. The development of a tool able to quickly and accurately provide such kind of logs from VOMs could be relevant both for stratigraphic investigations and for the industry.

In this contribution, we present Vombat, an open source software whose primary goal is to process lidar intensity, RGB data, or any scalar field associated with three-dimensional outcrop models, to create high-resolution and accurate stratigraphic logs of these properties. To reach this goal, we developed a simplified 3D modelling strategy, based on the identification of outcrop regions with constant attitude.

Vombat was developed as a dedicated toolbar within CloudCompare (Girardeau-Montaut, 2014), an open source software that makes it possible to visualize and modify point clouds. Far from being a complete toolbox, Vombat may set the stage for the development of a more complete data analysis and storage platform that could be used for exploiting the full potential of VOMs, whose applications range from the study of inaccessible outcrops to the mentioned correlation to boreholes, to the preservation of key outcrops in a virtual form, and may further expand in the broad field of geosciences.

4.2 Vombat

To provide a virtual counterpart to the operations commonly carried out by stratigraphers in the field, we first identified a suitable rendering engine for the visualization of point clouds. Point clouds are in fact the raw output of both lidar acquisitions and photogrammetric surveys. Many commercial software produced nowadays allow highly optimized point cloud visualization to be obtained, and are normally coupled with advanced editing tools. These tools are mainly closed-source proprietary solutions that leave little room for customization. We thus chose the open source software CloudCompare as a hosting application, which has been extended by means of a new plugin, Vombat.

CloudCompare (Girardeau-Montaut, 2014) is a software written in C++ and Qt libraries (e.g. Summerfield, 2011), dedicated to the editing, visualization, and comparison of point clouds. Being open source, its code can be freely

extended or modified by the user, thus making this tool the ideal candidate to host third-party plugins. Vombat (Virtual Outcrop Basic Analysis Tool) has been developed to provide a tool for operating stratigraphic tasks on Virtual Outcrop Models. CloudCompare also features several third-party plugins of geologic interests: the qCompass plugin (Thiele et al., 2017) allows for automatically tracing linear features on VOMs and takes fast and easy attitude measurements. The qFacet plugin (Dewez et al., 2016) allows the user to perform the automatic extraction of planar facets from point clouds that can be used for structural analysis. The qCanupo (Brodu and Lague, 2012) suite is a simple yet efficient way to automatically classify a point cloud on the basis of its geometric characteristics, through the use of Support Vector Machine classifiers (Mountrakis et al., 2011), in order to separate vegetation from exposed rock. Finally, qM3C2 makes it possible to estimate differences between point clouds in a robust way, with the aim of identifying changes in the outcrop through time (Lague et al., 2013). Vombat has been designed as a two-components tool:

- An underlying C++ library taking care of most of the computations, which can be also accessed by the user with programming skills by creating an executable linked to the library itself.
- A plugin for CloudCompare, which provides a toolbar for creating and editing the objects defined in the C++ library and allows any user to interact in a graphical way with the software through a Graphical User Interface (GUI).

Vombat is displayed as a new toolbar in CloudCompare (Figure 4.1), where each tool can be activated by clicking on the correspondent icon. Each tool in the toolbar (Figure 4.2) takes as input the objects that are selected within the database tree of CloudCompare and processes them, generating or modifying the entities. Vombat also provides a specific tool for plotting curves that can be used to obtain a visual feedback of the generated continuous stratigraphic logs. We will not discuss all the implementation details of the Vombat toolkit, but we will rather give a brief idea of the underlying computations; however, the code is open source and can be freely accessed and modified.

4.2.1 Example of Workflow

Vombat has been designed to be as generic as possible and the specific workflow is mostly dependent on the user needs. In Section 4.3 some examples with real data will be demonstrated, but a typical workflow including the use of our plugin can be depicted as follows:

1. The stratigrapher uses a TLS (or photogrammetric methods) to produce a virtual outcrop in the form of one or

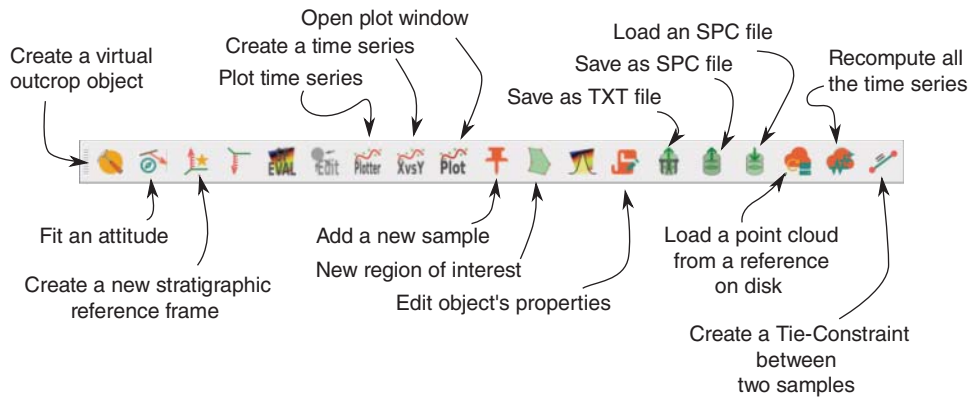


Figure 4.1 The Vombat toolbar as it appears in CloudCompare. Each icon corresponds to a specific operation that can be performed on the currently selected object.

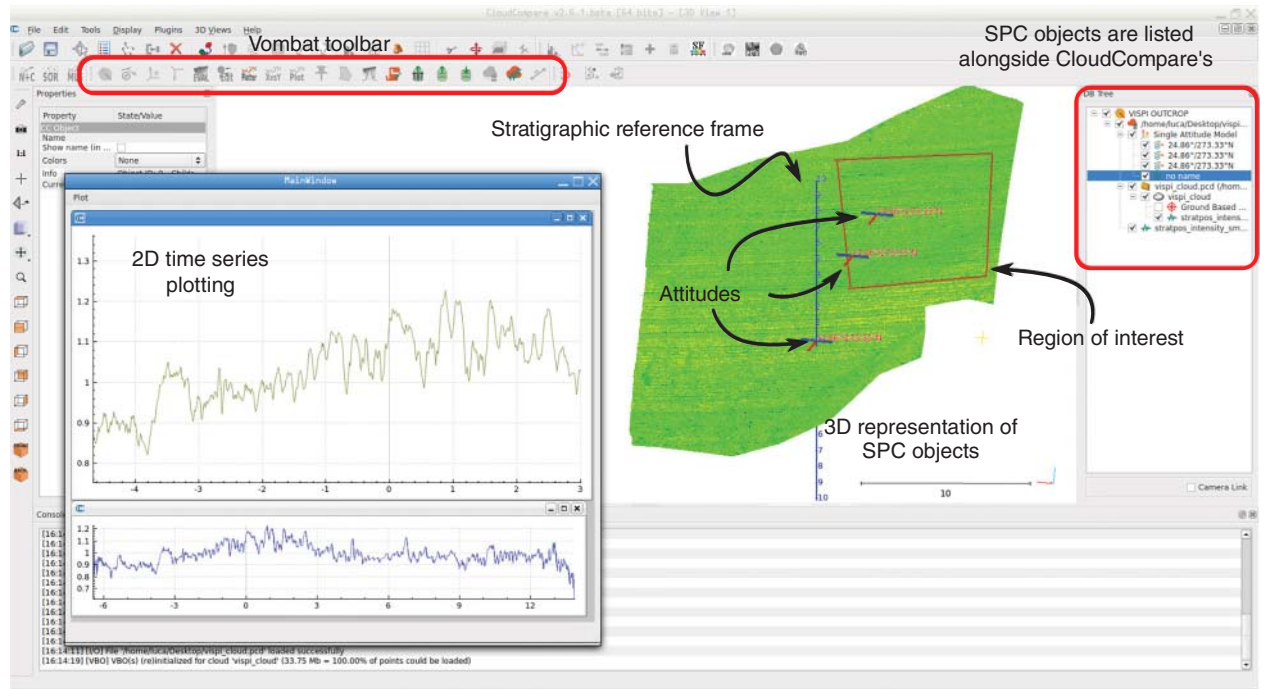


Figure 4.2 A screenshot of CloudCompare with the Vombat plugin. Basic tools for plotting logs are provided. Each Vombat object is represented as a hierarchical object, alongside those of CloudCompare in the DB Tree window (red square at right).

more point clouds. This data might be complemented by other investigations done in the field (e.g. rock samples that will undergo laboratory analysis and a stratigraphic column).

2. The point clouds are imported in CloudCompare, where geological linear or punctual features (important horizons and the location of collected samples) can be easily traced with the tools provided by CloudCompare itself.
3. The user then sets up one or more *Stratigraphic Reference Frames (SRF)*, which allows a *Stratigraphic Position (SP)* to be assigned to any linear or punctual feature that was identified. The setup of SRFs is very flexible: they

can be forced to respect various external constraints (e.g. placing the stratigraphic zero in correspondence with a particular horizon).

4. Thanks to the SRFs the user is now able to directly compare any new observation made on the virtual outcrop with the observations collected in the field. For example, he can measure the stratigraphic position of some cherty levels that were unreachable in the field, and place them in the stratigraphic column previously drawn.
5. The user then uses Vombat to produce a stratigraphic log of any remotely sensed scalar property, e.g. lidar intensity, which can be used as a proxy for clay content

(Franceschi et al., 2009). This log can then be compared with any other log obtained within the outcrop or nearby.

6. The virtual outcrop, together with the collected geological data, can then be shared to unambiguously identify key stratigraphic features on the outcrop, e.g. to plan a field campaign on the same outcrop.

In this work, we present the basic issues that must be faced when creating stratigraphic logs from Virtual Outcrops, exposing some of the functions that have been implemented in Vombat to deal with these specific problems. Later sections are dedicated to the discussion and conclusion of the presented toolkit.

4.2.2 Estimation of the Average Bedding Attitude

Vombat provides an improved method for computing attitudes of bedding planes of an outcrop. A common approach for estimating the normal of a stratigraphic feature is to obtain a subset of points which *lay* on the plane of interest and then compute the best fitting plane for these points (see, for example, Fernández, 2005; Woodcock, 1977). In a similar way, a trace of the bedding plane can be digitized and then used in the best-fitting procedure to obtain an attitude.

When considering point clouds representing outcrops exposed on vertical cliffs, the approach to selecting points on a bedding plane does not perform well, because the bedding planes can be poorly exposed. Instead, using the digitized trace of a bedding plane, the estimated attitude will be representative of that specific trace and, depending on the distribution of its nodes in space, can led to unreliable results (Fernández, 2005). In order to be representative of the whole outcrop the attitude must be computed by taking into account the geometry of the layers on the whole outcrop.

Vombat tries to solve this issue by providing a tool for normal estimation that takes into account as many digitized bedding traces as possible. This may prove particularly useful in defining a more representative average attitude computed by taking into account many layers. Figure 4.3 shows an example of a point cloud for which an attitude should be estimated. The user identifies the bedding by using polylines, providing sets of points, each representing a specific horizon. Vombat then computes a best-fitting attitude using the information provided by all these point sets: in this way the estimated attitude will be representative of a larger portion of the outcrop.

The problem of estimating a unique attitude by using several bedding traces at once (instead than just one) is solved in Vombat as a minimization problem. The user defines two or more sets of points, each set representing a

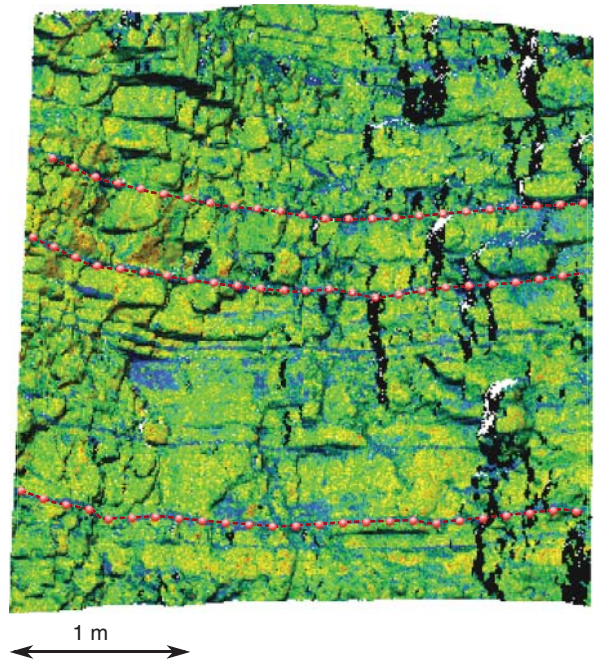


Figure 4.3 Example of a TLS point cloud representing an undeformed stratigraphic sequence for which an attitude should be estimated. Colours depend on intensity values retrieved by a TLS. The user creates one or more sets of hand-picked points, each representing a bedding plane, and then a dedicated algorithm computes the best fitting attitude for the outcrop. Attitudes can be computed for each bedding separately or a unique normal can be fitted to ensure representativeness of the attitude for the whole outcrop or outcrop region.

different bedding plane, parallel to the others, as depicted in Figures 4.3 and 4.4. For simplicity, we will consider just two sets of points in the following, but the extension to more sets is straightforward and can be found in Shakarji and Srinivasan (2013). Two sets of points, $\{\mathbf{p}_1, \dots, \mathbf{p}_n\}$ and $\{\mathbf{p}_{n+1}, \dots, \mathbf{p}_{n+m}\}$, represent two linear features traced by the user. Consider two equations representing two planes:

$$\hat{\mathbf{n}} \cdot \mathbf{p}_A - d_1 = 0$$

$$\hat{\mathbf{n}} \cdot \mathbf{p}_B - d_2 = 0$$

where \mathbf{p}_A and \mathbf{p}_B are points of their respective planes, $\hat{\mathbf{n}}$ is the unit normal defining the orientation of the planes and d_1 and d_2 are the distances of these planes from the origin. The problem is thus to find $\hat{\mathbf{n}}$, d_1 , and d_2 minimizing the distance of the points from their respective plane by means of a least squares solution:

$$\sum_{i=1}^{n+m} r_i^2 = \min \quad (4.1)$$

where r_i is the distance of the point to the first plane for $1 \leq i \leq n$ or to the second plane for $n + 1 \leq i \leq n + m$.

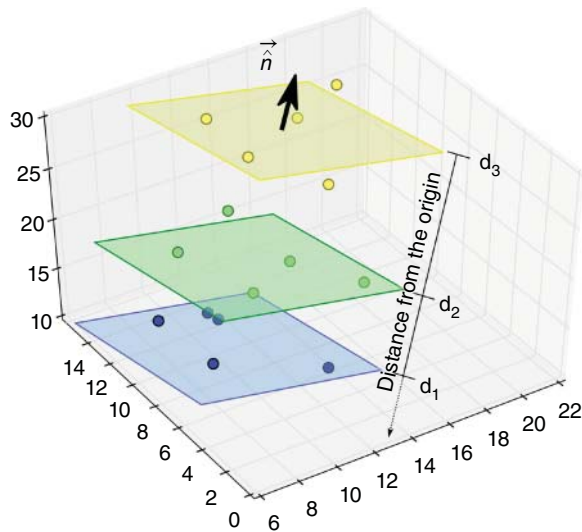


Figure 4.4 Vombat can compute the attitude of a layered sequence by using a multiple set of points lying on parallel planes. The normal \hat{n} and multiple d parameters, one for each set of points to be fitted, are determined by means of a least squares solution.

This problem has a simple linear solution (see, for example, Shakarji and Srinivasan, 2013), which can be extended to any number of parallel planes to be fitted at once.

Vombat can solve this problem for any number of point sets, providing a reliable estimate of the average attitude of an outcrop. Estimated attitudes are then shown in the 3D window of CloudCompare as a dip vector and a direction line. Figure 4.2 shows three attitudes that were estimated on the point cloud. These are treated as generic CloudCompare's objects and listed in the DB Tree window.

4.2.3 Stratigraphic Reference Frames

We implemented in Vombat a specific object, called a *Stratigraphic Reference Frame* (SRF), which can be used to project any 3D point in the one-dimensional stratigraphic domain. Figure 4.2 shows how an SRF is represented in the three-dimensional window of CloudCompare. An SRF is basically a ruler that can be used to project any observation in a direction orthogonal to the bedding. In its simpler formulation, an SRF in Vombat is fully defined by a plane in space: when the plane is oriented as the bedding, the distance from the plane itself is a scalar value that can be used as a metric in the stratigraphic domain. The stratigraphic position of a point is thus computed as:

$$SP(\mathbf{p}) = \alpha \cdot \hat{n} \cdot \mathbf{p} - d \quad (4.2)$$

where \hat{n} is the (unit) normal to the bedding plane, \mathbf{p} is any 3D point and SP is the estimated Stratigraphic Position for

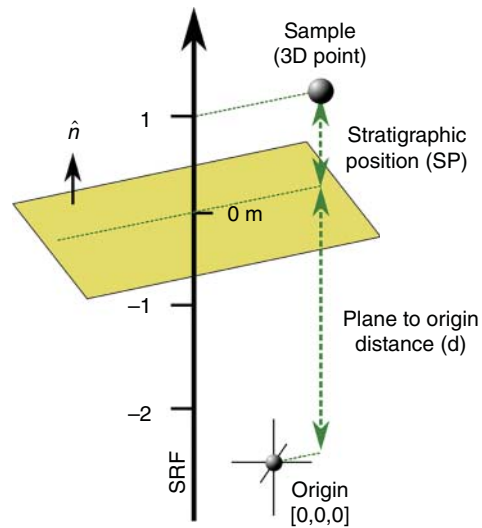


Figure 4.5 An SRF can be viewed as a plane in space: its orientation is determined by a unit normal \hat{n} and the parameter d corresponds to the distance of the plane from the origin of the three-dimensional reference system. Any 3D point (e.g. the location of a sample) can be projected in the stratigraphic domain by computing its SP as the distance of the point from the plane.

that point. The parameter d is needed to define a plane in space and corresponds to the distance of the plane from the origin. Adding or subtracting any value from it corresponds to shifting the whole reference frame, while preserving the overall orientation. This simplified model is illustrated in Figure 4.5. The parameter α of Equation (4.2) is a scale factor that is normally equal to 1, but can also be modified, with the effect of *stretching* (>1) or *compressing* (<1) the reference frame, to accommodate specific needs.

Being defined by a plane, an SRF can be created in Vombat by using any *Attitude* object previously created by the user. The user selects the *Attitude* of interest in the DB Tree of CloudCompare, then activates the corresponding tool, which will initialize a new SRF accordingly oriented. Any newly created SRF is represented as a sort of ruler in the 3D window and is listed in the DB Tree of CloudCompare.

4.2.4 Vombat Objects and Their Stratigraphic Positions

The Stratigraphic Reference Frame introduced in the previous section allows a specific Stratigraphic Position (SP) to be associated with any point in space through Equation (4.2): for example, a stratigrapher might be interested in determining where a specific point on the three-dimensional model is positioned on the stratigraphic column. For this task, Vombat provides two different

kinds of objects for which a Stratigraphic Position can be evaluated. The first one is the *Sample* object, as a generalization of a *rock sample*, which materializes any 3D point that might be of interest. An example of Samples on the outcrop can be seen later in Figure 4.9: each Sample is rendered in 3D as a small sphere, each with its SP value. The second one is the *Linear Geological Feature* object, which can be used to materialize a specific layer on the outcrop, for which the SP will be computed.

Each Sample object can also be used to represent a user-provided stratigraphic position, for example, because it was previously used as stratigraphic zero in former campaigns. In such a case the user can use the properties dialog provided by Vombat to force the specific Sample to have a fixed SP, which Vombat will maintain constant.

4.2.5 Stratigraphic Constraints to Build Composite Reference Frames

When dealing with large outcrops, it is desirable to deal with deformations and faulting in a consistent way. This can be done in many high-end 3D geological modelling software packages through the interpretation and the modelling of the depositional and tectonic geometries. Although this approach would produce the most exhaustive representation of the underlying geometries, it is often a highly time-consuming and specialized task, not within everyone's grasp.

Vombat implements a simpler way to deal with faulted or deformed sequences by permitting the creation of as many SRF as needed, each representing a locally undeformed portion of a larger outcrop. For example, a faulted sequence can be modelled by using two different SRFs, one valid in the footwall block and another one to be used in the hanging wall block. These two SRFs must then be aligned by changing their d parameter, so that the corresponding layers in the two regions will be at the same SP (Figure 4.6).

To do so, Vombat allows the user to impose specific *Stratigraphic Constraints*, which can thus be used to produce a composite stratigraphic reference frame. This concept is illustrated in Figure 4.6. Two types of constraints can be defined:

- A *Tie Constraint* can be created between two Sample objects, and correspond to providing the software with the information that those two points lie on the same stratigraphic horizon. This kind of constraint is used to establish a direct and known stratigraphic correlation between samples on separated parts of an outcrop.
- The known stratigraphic position of a Sample object can also be used as a constraint. This operation corresponds to fixing the position of that Sample in the stratigraphic column to a specific stratigraphic position. This feature is useful, for example, to define on which horizon the stratigraphic zero must be located.

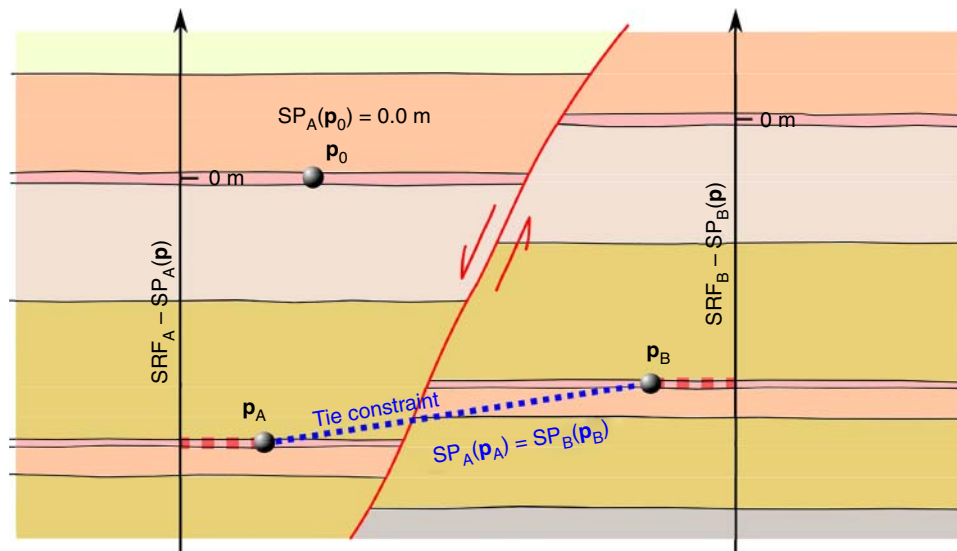


Figure 4.6 Representation of a faulted sequence for which two different SRFs are considered. To constrain the two SRFs, the user imposes the stratigraphic position of the Sample at p_0 to be equal to 0.0 m. Such a constraint will suffice to fully determine the d parameter of SRF_A . To align SRF_B , the user instead establishes a *Tie Constraint* between two Samples, each associated with a different SRF (p_A and p_B). Vombat will thus take care of aligning all the SRFs to match the constrained Stratigraphic Positions. Any number of constraints can be added: in such a case, the solution is provided by means of non-linear least squares. The two SRF, here represented as vertical lines, can be freely oriented in space in order to accommodate any geometry that can be locally approximated with a plane-parallel bedding.

Once the user has defined the Stratigraphic Constraints, Vombat recomputes the d parameters of the two SRFs, in order to accommodate the required shift between the two. The software takes care of any number of stratigraphic constraints that the operator might want to impose and will try to honor them in a least squares sense.

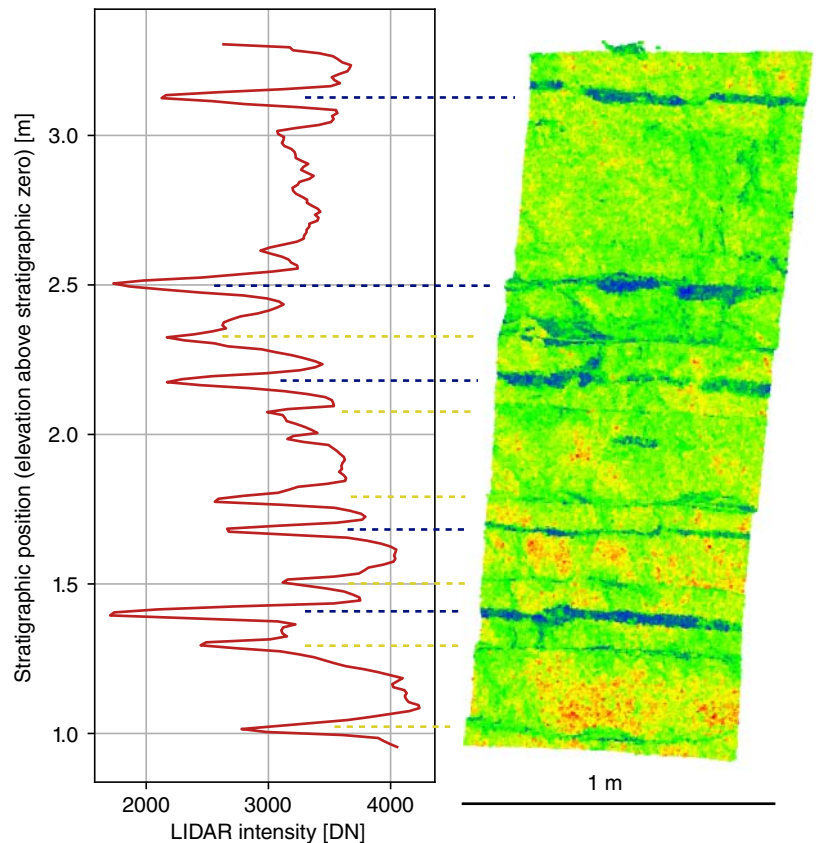
4.2.6 Creation of Continuous Stratigraphic Logs

The three-dimensional models obtained from TLS or photogrammetry often come associated with additional properties. TLSs normally provide intensity data that represent the recorded power of the back-scattered laser beam, while in the case of photogrammetry the models are often equipped with per-vertex Red-Green-Blue (RGB) color. Furthermore, the output of hyperspectral cameras can be mapped on the three-dimensional representation of the outcrop (see Sterzai et al., 2010; Kurz et al., 2012a, 2012b). These additional properties are normally in the form of scalar values associated with the vertices of the 3D model and can be used to create pleasant visualizations of the model by mapping the values to a color scale, but they can also provide insights about the lithologies.

Provided a point cloud with an associated scalar field, for example the intensity, was derived from the TLS, the user first estimates the average attitude of the outcrop with the method described in Section 4.2.2. This attitude will then be used to define a Stratigraphic Reference Frame, orthogonal to the bedding plane, that will be used to estimate the stratigraphic positions for each point of the cloud. From these two fields (the stratigraphic position and the intensity), it is then possible to estimate how the lidar intensity varies at varying stratigraphic positions: an example is shown in Figure 4.7.

To create continuous stratigraphic logs of a scalar field, Vombat uses a *Kernel Smoother* (Hastie et al., 2009), which makes it possible to estimate a continuous scalar function (the intensity log) from scattered observations of its value (the points of the cloud). For simplicity, we will consider the creation of a TLS intensity log, but the same method can be applied to any other scalar field. Let $X : \{x_1, \dots, x_N\}$ be the set of computed stratigraphic positions for each vertex of the model and $Y : \{y_1, \dots, y_N\}$ be the corresponding intensity value at the same location. Kernel smoothing can be seen as a weighted running average of the two scalar fields: the function $\hat{Y}(x_0)$ predicts the value of the lidar intensity at the

Figure 4.7 At right, a small extract of a TLS point cloud, colored by the intensity values obtained from the scanner, representing an outcrop composed of limestone (green and red colors) with some horizons and nodules of chert (blue color). The complete point cloud is also shown in Figure 4.9. Chert is characterized by a typical low-intensity response at the wavelength of this TLS. At left, the intensity has been extracted to a stratigraphic log. The log was computed along a direction orthogonal to the bedding by using Vombat. Chert nodules are clearly visible as local minimums in the log (blue dotted lines). Also notice that bedding planes, which are not easily identifiable in the point cloud, are characterized by a low-intensity response, probably due to a higher clay content (yellow dotted lines).



stratigraphic positions x_0 :

$$\hat{Y}(x_0) = \frac{\sum_{i=1}^N K_\lambda(x_0, x_i) y_i}{\sum_{i=1}^N K_\lambda(x_0, x_i)} \quad (4.3)$$

where N is the total number of observations and y_i is the observation at x_i . The weights are provided by the kernel function $K_\lambda(x_0, x)$, centred in x_0 :

$$K_\lambda(x_0, x) = D\left(\frac{|x_0 - x|}{\lambda}\right) \quad (4.4)$$

The size of the kernel (the averaging window) is controlled by the λ parameter (kernel radius), which thus determines the smoothness of the kernel smoother. $D(t)$ is a real-valued function, usually decreasing with increasing distance between x and x_0 , which determines the shape of the weighting function. Different kernels $D(t)$ can be used, for example the Epanechnikov kernel:

$$D(t) = \frac{3}{4}(1 - t^2) \mathbf{1}_{\{|t| \leq 1\}} \quad (4.5)$$

Note that the notation $\mathbf{1}_A$ is a short form for the indicator function (1 for $t \in A$ and 0 otherwise).

4.2.7 Regions of Interest

A *Region of Interest* (ROI) is a Vombat object that provides repeatable selections of a portion of a point cloud. It is created by the user as a closed polyline, which is then extruded at a specific depth to create a volume. Figure 4.8 illustrates this concept. This object allows regions of the outcrop to be unequivocally identified that might be of interest, e.g. undeformed regions bounded by faults on which stratigraphic computations will be performed. Being independent of the specific cloud, an ROI can be used to extract the same portions of the 3D model from different point clouds. This feature is especially useful when a VOM is updated, for example when a model at higher resolution becomes available: a ROI will make it possible to replicate on the new dataset the same operations of data selection that were previously done on the lower-resolution model.

4.2.8 Input/Output and Log Plotting

Vombat objects can be serialized (i.e. saved to disk files) as JSON, XML, and binary files. Some of the objects (e.g. the continuous stratigraphic logs) can also be exported as an ASCII text file for facilitating the use of the data in other software packages. A specific object, called Virtual Outcrop, represents a container for all data and objects related to a single outcrop. It is a hierarchical object that can be used to group together all the elements the user creates (Samples, ROIs, SRFs, stratigraphic logs, etc.). This object can

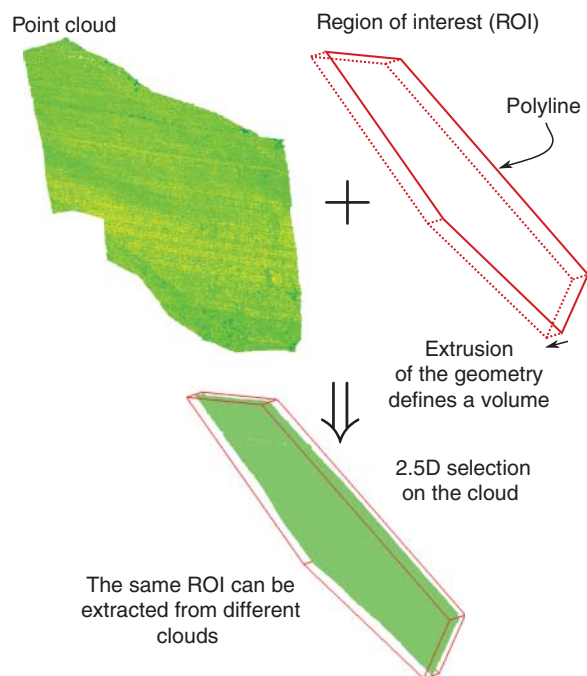


Figure 4.8 An ROI in the case of point clouds can be defined as a 2D polyline, extruded to define a volume. This kind of ROI, being halfway between a real *volume of interest* and an *area of interest* may be regarded as a 2.5D ROI. This approach allows replication in a consistent way of any operation of data selection on different models.

be saved to disk and then reloaded on a different machine granting cross-platform exchange of the dataset. Basic log plotting functions have also been implemented in Vombat to provide immediate visual feedback of the obtained stratigraphic logs, as illustrated in Figure 4.2.

4.3 Examples

Vombat has been successfully used to prepare and to process several datasets that have been at the basis of cyclostratigraphical analyses, for example in Franceschi et al. (2015), while CloudCompare was also employed in the preparation and the analysis of the dataset presented in Penasa et al. (2014). In that work, use was made of intensity information to automatically classify a point cloud, with the goal of extracting chert layers in a limestone series in Central Italy. We show here how the same datasets can be further interpreted with Vombat.

In the next sections we will first show how Vombat can be used to extract stratigraphic logs of the intensity, in a case in which there is a demonstrated correlation between the TLS intensity and the lithology. In a second case we will show how a continuous log of TLS intensities can be easily correlated with a dataset that was collected in the

field. As an example, we will use the total carbonate content curve of a pelagic succession exposed in the Smirra section (northeastern Apennines of Italy), previously published in Franceschi et al. (2015).

4.3.1 Locating Samples on a TLS Intensity Log

Figure 4.9a shows a TLS point cloud representing a sedimentary sequence at outcropping near Gubbio in Central Italy (see Penasa et al., 2014). The colors represent the measured TLS intensities: higher values of intensity (green to yellow) correspond to limestone while cherty and marly layers are characterized by lower values (blue). We used CloudCompare and Vombat to provide a simple interpretation of the geometries directly on the VOM. We started by tracing some bedding planes by using polylines that were then employed to estimate the average attitude of the outcrop, which is needed to initialize a Stratigraphic Reference Frame aligned with the direction perpendicular to the layering.

In the upper part of the point cloud, an iron protection net was also captured during the scanning operations. To exclude the net, we created a specific ROI that has

been used to extract a subset of the point cloud. We then used this portion of the virtual outcrop to reconstruct a continuous log, with a sampling step of 1 cm, representing how the intensity varies at varying stratigraphic positions. The result of this operation is shown in Figure 4.9c, where the continuous stratigraphic log of the intensity is plotted together with the collected Samples at the right stratigraphic positions. No additional stratigraphic constraints were used in this example.

By using Vombat it is possible to identify specific locations on the outcrop by using Sample objects (purple spheres in Figure 4.9a), which are automatically projected in the stratigraphic column (dotted lines in Figure 4.9c), providing a geometrically accurate way of describing stratigraphic features both in the 3D and in the corresponding stratigraphic domain (1D). In this example, we placed a Sample in correspondence with some cherty horizons, which can be easily recognized on the colored TLS point cloud. Vombat automatically computes a stratigraphic position for each, using the created SRF. In a more general case, Sample objects could represent any punctual information that needs to be reported on a stratigraphic

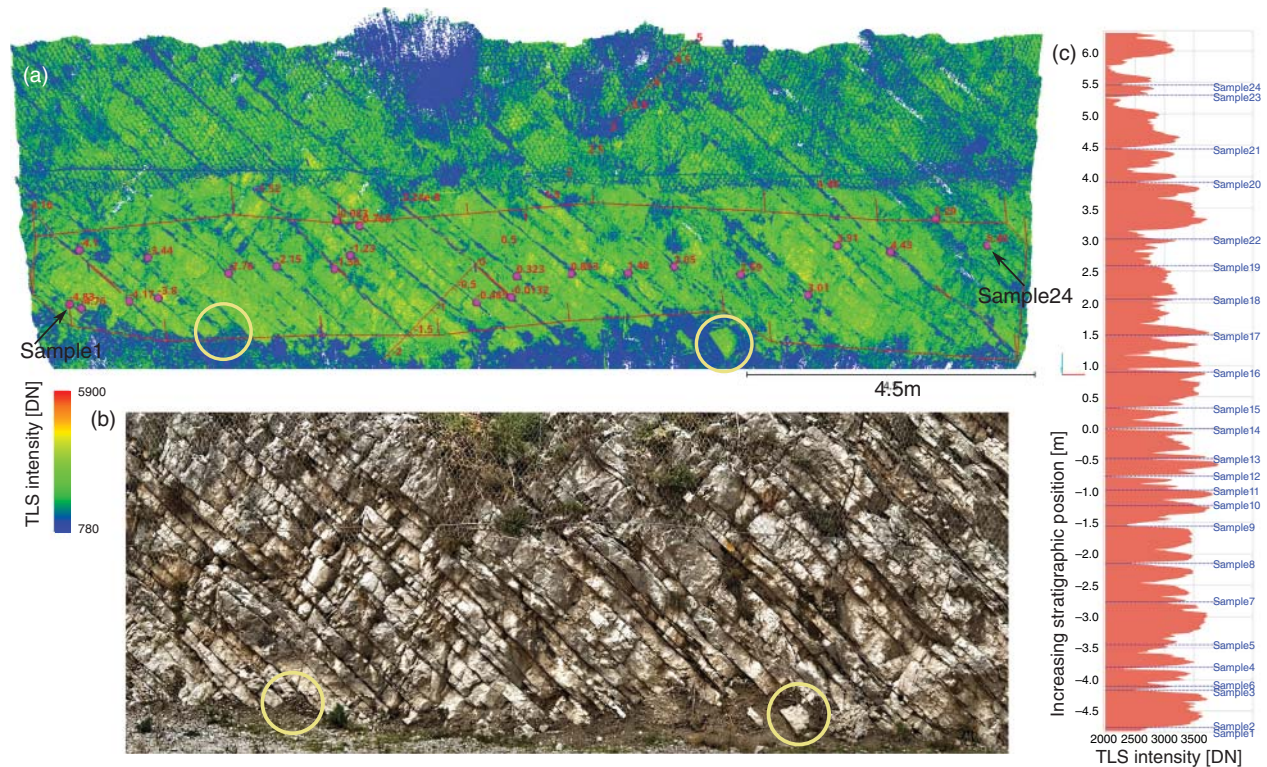


Figure 4.9 (a) TLS scan of an outcrop of cherty limestone (Lower Cretaceous Maiolica Formation) in Central Italy, nearby Gubbio, showing some of the objects that can be defined in Vombat. This same dataset was used in Penasa et al. (2014). Chert is characterized by lower intensity values in the infrared. (b) The same outcrop in the color domain; chert is mostly undetectable. As a reference, the yellow circles highlight corresponding points in the two views. (c) The continuous stratigraphic log of TLS intensities for the region defined with an ROI object.

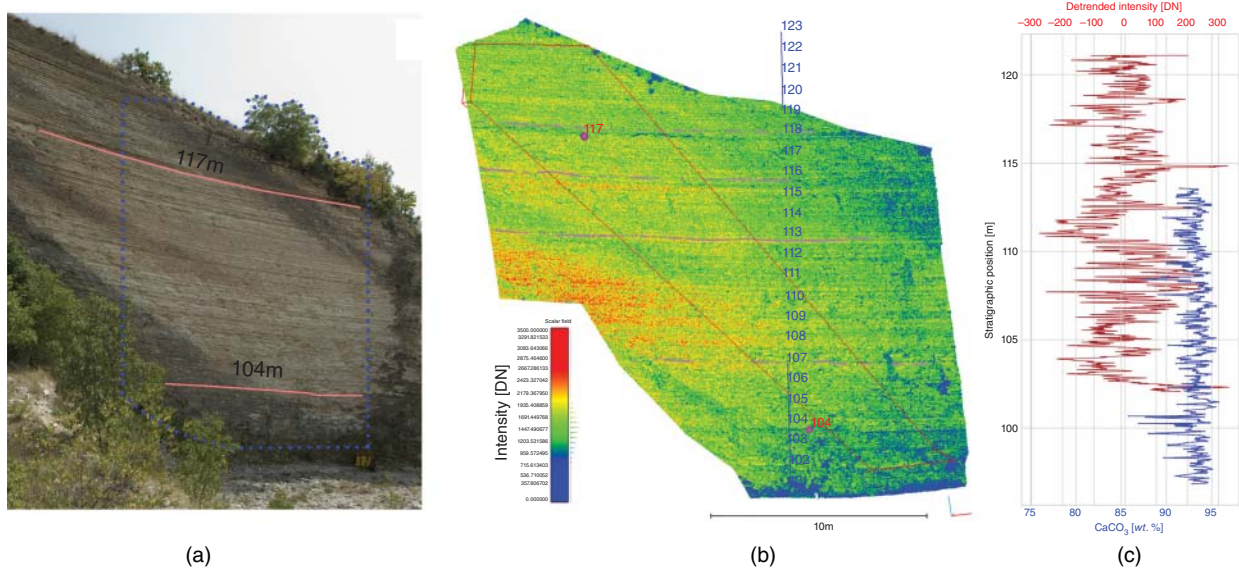


Figure 4.10 (a) The pelagic succession at the Smirra quarry, which comprises the Ypresian–Lutetian boundary (see also Franceschi et al., 2015, for additional details). The region highlighted by the dashed lines was acquired with TLS. The red lines are two horizons where the stratigraphic position was measured in the field during the collection of CaCO_3 rock samples. (b) A screenshot from CloudCompare with the Vombat objects that were created for processing the data. (c) The resulting intensity log, in alignment with the in-field measured CaCO_3 log.

scale (e.g. an annotation about a notable punctual feature observed in the field).

4.3.2 Using Stratigraphic Constraints to Match Field Data

With a second example, we illustrate how stratigraphic constraints can be used to align a stratigraphic reference frame to data that were previously collected in the field. We will use the dataset described in Franceschi et al. (2015) to show how an SRF can be forced to obey external stratigraphic constraints. In this specific case, a detailed log of the calcium carbonate content was previously obtained from the chemical analysis of samples collected in the field. At the same time, it was known that in a limestone-marl alternation, TLS intensity values should correlate to carbonate content (Franceschi et al., 2009). We thus wanted to compare how the calcium carbonate log correlates with a log of TLS intensities.

The data collected in the field are constituted by a log of the carbonate content in wt.%. Each sample that was collected in the field was positioned on the stratigraphic column by measuring its stratigraphic distance from a specific horizon with a ruler. In Figure 10a we reported the position of two stratigraphic horizons, as measured in the field, that were identified both on the field log and on the virtual outcrop.

We used this information to create a “virtual counterpart” to the metric framework that was used in the field

to measure sample positions. This can be easily done in Vombat, as depicted in Figure 4.10b. A Stratigraphic Reference Frame was set up using some traces of the bedding planes to obtain the average attitude. Then the same horizons of Figure 4.10a were recognized on the scan and marked using two Sample objects. We then imposed these Sample objects to have a fixed Stratigraphic Position of 104 and 117 meters, respectively. Vombat then automatically aligned the Stratigraphic Reference Frame to these constraints. Additionally, to compensate for the measurement errors that cumulate when taking thickness measures in the field, we also computed the α parameter of Equation (4.2), which resulted in 1.02, meaning that the error introduced by the operator in the field must have been in the order of a couple of meters for 100 m of section measured.

Finally, we reconstructed the continuous log of the intensities, as shown in Figure 4.10c, which can now be plotted in the same stratigraphic frame of the CaCO_3 samples, thus providing a real bridge between the intensity log from the 3D model and the samples collected in the field.

4.4 Discussion

In stratigraphy, outcrops often represent the primary source of information for geoscientists. Classical methods of investigation based on the realization of stratigraphic columns require the compression of the information collected on

an outcrop, which is obviously three-dimensional, into a one-dimensional log where each observation (lithology, lateral bedding geometry, presence of fossils, etc.) is annotated by assigning it a stratigraphic position.

This procedure makes it difficult to maintain the original relationship between observations and the real outcrop. Furthermore, each research team or scientist produces its own log, so that the integration of stratigraphic logs of the same outcrop made by different researchers can be difficult. This problem has been normally solved by producing annotated photographic documentation of the outcrop: in this sense the use of three-dimensional imaging could be viewed as the natural evolution of this established practice in sedimentary geology. One of the key features of VOMs is that they provide a permanent and accurate geometric representation of the outcrop that can be preserved through time, even when an outcrop is degraded (Lozar et al., 2015; Dumitriu, 2013). This might be particularly relevant to some specific outcrops that represent the physical expression of key geologic boundaries or events and become of worldwide reference (GSSP; Salvador, 2013).

The model used in Vombat to define a Stratigraphic Reference Frame can be seen as an extremely simplified version of the modelling tools that are available in many commercial 3D geological modelling software. Although our tool does not allow complex deformed geometries to be modelled, it can be used to create fairly complex setups. For example, it is possible to produce composite sections by linking multiple reference systems. The simplicity of this tool permits stratigraphic measurements to be easily carried out, without the need to produce an exhaustive modelling of the underlying geometry, which is normally a highly specialized and time-consuming task. Furthermore, the implementation is made with the aim of being as generic as possible, thus allowing, in the future, to extend its capabilities to account for more complex outcrop geometries.

Due to the simplified geological modelling technique used in the definition of SRFs, this system is expected to perform better when applied to undeformed plane-parallel bedding. In the case of sediments that were not originally deposited as plane-parallel layers (e.g. carbonate platform slope deposits), it might still be possible to define smaller portions of the outcrop that can be approximated by a parallel bedding, by considering one or more narrow ROIs on the outcrop. The generated stratigraphic logs suffer from the same problems that might be present in petrophysical logs obtained from well data: e.g. faults and hiatuses/unconformities that might be present are not directly taken into account by the software. On the other hand, they can be more easily identified thanks to the VOM

itself. Being open source, Vombat could be implemented to account for some of the listed problems.

Vombat was originally designed for obtaining long TLS intensity logs to be used for cyclostratigraphical analysis, for which long and continuous stratigraphic logs are needed to perform time-series analysis (Hinnov, 2013). In fact, three-dimensional models, possibly associated with other remotely sensed data, are also a potential source of high-resolution lithological information that can complement classical methods of investigation. When dealing with inaccessible outcrops, remote sensing methods might be the only chance to obtain information on a valuable stratigraphic record. The continuous stratigraphic logs that can be obtained using Vombat allow the variations of specific properties to be quantified at varying stratigraphic depths directly from outcrop data, mimicking the information obtained by means of petrophysical logs, which can be normally obtained only from a well log. TLS intensity logs in the infrared domain, for example, have been demonstrated to be a valid proxy for lithological variations in some instances (Franceschi et al., 2011, 2015; Burton et al., 2011).

4.5 Conclusions

The open source Vombat toolkit allows some of the most common operations to be performed in a simple way that might be needed by a stratigrapher dealing with Virtual Outcrop Models. The source code is made freely available to the community on the project page <https://github.com/luca-penasa/vombat>, where a precompiled version of CloudCompare with Vombat can be found. Vombat has been developed for the purpose of providing a user friendly and easily extensible 3D environment for the analysis of VOMs by making it possible to:

- Estimate attitudes by means of bestfitting planes on multiple coplanar set of points.
- Create stratigraphic reference frames, and merge multiple stratigraphic sections into a single and continuous measurement framework.
- Automatically compute stratigraphic positions for samples and for bedding traces.
- Generate continuous stratigraphic logs of the properties attached to the point clouds, as the intensity or RGB values.
- Create an exchangeable database of geological features directly on the outcrop.

Commercially available point cloud processing software is generally designed for engineering and architecture applications. Although some dedicated solutions have

been recently developed, they are difficult to extend due to their closed-source nature. Vombat is open source and also provides a simple C++ programming interface that can be used to perform geological-related operations by the researcher with programming practice. Although still being a simple tool, Vombat is novel in its approach to the extraction and storage of stratigraphic logs that may display high-resolution 3D-property logs or any observation linked to a VOM.

Being able to compute a stratigraphic position for any three-dimensional stratigraphic feature that might be reported on the VOM, Vombat makes it possible to produce a highly accurate dataset of observations, with real thickness measures, while still maintaining the three-dimensional nature of the data itself. Relevant data and observations can then be preserved on the VOM as they

were collected directly on the outcrop and visualized as a stratigraphic log. This aspect might be of particular relevance when dealing with outcrops of special chronostratigraphic value, as the ones selected to represent specific time boundaries (GSSP) by the International Commission of Stratigraphy. These outcrops might be made more accessible thanks to tools similar to Vombat, which allows the stratigraphic data to be merged with their original, three-dimensional context.

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