

## THE AVALANCHE MODELLING ATLAS – A FRAMEWORK FOR THE COLLECTION, ORGANISATION AND ANALYSIS OF AVALANCHE PATH AND EVENT DATA

Marc S. Adams<sup>1\*</sup>, Magdalena Fischer<sup>1</sup>, Laura Stephan<sup>2</sup>, Christian Demmler<sup>1</sup>, Anna Wirbel<sup>1</sup>, Felix Oesterle<sup>1</sup>, Christoph Hesselbach<sup>1</sup>, Christoph Mitterer<sup>2</sup> and Jan-Thomas Fischer<sup>1</sup>

<sup>1</sup> Austrian Research Centre for Forests (BFW), Innsbruck, Austria

<sup>2</sup> Avalanche Warning Service Tyrol, Austria

**ABSTRACT:** An extensive, detailed and reliable identification of avalanche paths and documentation of past avalanche events is the backbone of avalanche model development, calibration and validation, as well as avalanche hazard mapping and risk management. The Avalanche Modelling Atlas (AMA) constitutes a seamless framework to enter, store, edit and analyse an extensive dataset of avalanche paths and corresponding event records. As such, it includes two types of avalanche data: i) static data including the details on the avalanche path, such as name, thalweg, morphologically determined origin, transit and deposition points; ii) dynamic data with details on recorded past events, such as the geolocation of observed avalanche release and runout areas, as well as reports on damages, fatalities, affected infrastructure. Crucially, these two datasets are directly connected, thus each past event is attributed to an avalanche path with defined characteristics. This gives the AMA an advantage over cadastres, which only hold information on avalanche events, as it allows analysing the avalanches by their morphological characteristics, as well as calculating statistics on the avalanche's size or destructiveness, considering the maximum potential size in alignment with different international classification schemes. In this contribution, we present the AMA for the first time and show selected analyses with the datasets contained therein.

**KEYWORDS:** Avalanche modelling; past events cadastre; avalanche classification.

### 1. INTRODUCTION

Geospatial data on avalanches and their corresponding classification (genetic/morphological (De Quervain, 1981)), or size/destructiveness (CAA, 2016; AAA, 2022; EAWS, 2024), are the foundation of sophisticated process- and data-based avalanche models, their development, calibration and validation. Extensive and detailed documentation of past avalanche events is also the backbone of avalanche warning, hazard mapping and risk management (Rudolf-Miklau et al., 2014; Kapper et al., 2023). Major challenges when handling avalanche data, or in fact any data on natural hazards or gravitational mass flows, are their notoriously limited availability, uncertainty, and associated high variability in data quality. Additionally, such information content is often tailored to specific needs and is highly biased towards events that caused damages, but hardly usable for geospatial modelling or process simulation (Eckertorfer et al., 2017; Mayer et al., 2020).

In this contribution, we present the Avalanche Modelling Atlas (AMA), which was designed to provide a link between avalanche modelling and geospatial avalanche data.

The AMA was introduced in 2019 and has since been continuously developed, extended and furnished with data. The current version includes detailed recordings from >1,100 avalanche events and >560 avalanche paths. Future aims of the AMA include providing the possibility of adaptability for different functionalities (e.g. DEM time series, forest application extensions), the intersection/overlay with external raster and vector data, or other research / measurement data, and the spatial extension beyond the (current) national scope.

### 2. AMA STRUCTURE AND CONTENTS

The AMA constitutes a seamless framework to enter, store, edit and analyse detailed avalanche path and event cadastre data.

#### 2.1 Data structure

Studying and recording avalanches yields both static and dynamic data that allow their classification and analysis. Thus, the AMA structure accommodates for two types of avalanche records: i) details on the avalanche path (static data), and ii) information on recorded avalanche events (dynamic data). Crucially, these two datatypes are directly connected through a path ID, thus each past event is attributed to an avalanche path with defined characteristics. This gives the AMA a unique difference in the design approach compared to avalanche cadastres, which often focus on mixed information on avalanche events and the corresponding paths.

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\* Corresponding author address:

Marc S. Adams  
Austrian Research Centre for Forests (BFW),  
Rennweg 1, 6020 Innsbruck, Austria;  
tel: +43 1 87838 5100  
email: marc.adams@bfw.gv.at

It allows classifying the entered avalanches by their genetic or morphological characteristics, as well as calculating statistics on the avalanches' return periods or runout mobility, facilitating comparisons with international avalanche classification schemes (e.g. CAA, 2016; EAWS, 2024).

### Avalanche path data

The avalanche path data in the AMA includes the path's name and (internal) ID, an outline of the avalanche catchment, the thalweg, as well as key points along the thalweg: origin, transit and deposition (Figure 1, see De Quervain, 1981). Currently, this data is manually digitised by an interpreter and determined according to a set of specific criteria.

The thalweg is defined as the line representing the main flow direction of all potential avalanche events within a specific avalanche catchment. The thalweg is delineated according to the terrain characteristics and extends beyond the release area at the top, and the furthest assumed runout at the bottom of the avalanche path (Figure 1). Each thalweg in the AMA is classified based on the maximum avalanche size an event could potentially reach on this path, governed by its morphology. The corresponding maximum potential size  $D_{\max}$  is based on international size / destructiveness classifications, ranging from 1 (sluff) to 5 (extremely large avalanche) (CAA, 2016; EAWS, 2024). In other words,  $D_{\max}$  is the size of the maximum events in an infinite time series of avalanches on the terrain of a given avalanche path, corresponding to a relative size R5 (major or maximum, relative to path) on the relative avalanche size classification (American Avalanche Association, 2016). One must note that since size 1 events are limited to the release area, thalwegs with  $D_{\max} = 1$  are omitted from the AMA analysis.

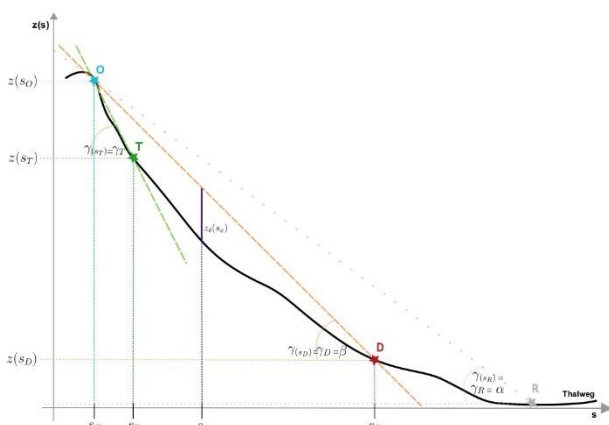


Figure 1: 2D-sketch of a thalweg with projected horizontal length ( $s$ ) vs. terrain altitude ( $z$ ) with origin (O), transit (T), deposition (D) and runout (R) point; travel angles and parameters for quantitative characteristic analysis are also shown (e.g.  $\alpha$ - and  $\beta$ -angles).

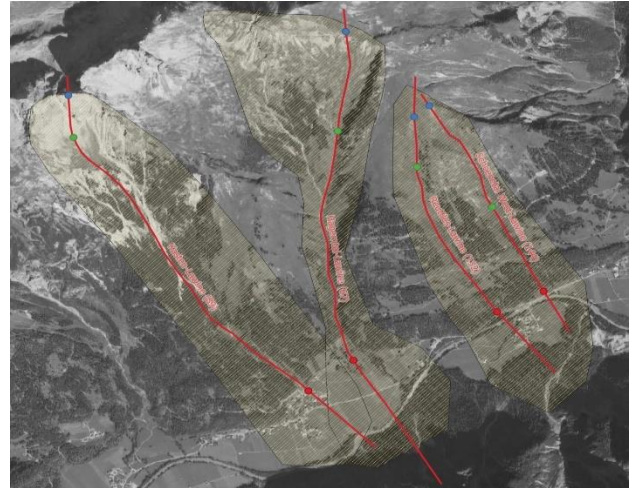


Figure 2: Example of avalanche path data in the AMA; avalanche catchment (yellow hashed polygon); thalweg (red line) labelled with name and ID; origin, transit and deposition points (blue, green and red points, respectively); current orthophoto set to b/w in background (image source: TIRIS, 2024).

The key points are defined for each thalweg and set according to morphological criteria: The origin point is set in the highest feasible point of the release area within the avalanche path. The transit point marks the transition from the end of the release zone to the beginning of the avalanche track and is typically located where the terrain reaches a steepness of  $<30^\circ$ . This is followed by the deposition point, which is characterised as the transition from the end of the avalanche track to the beginning of the deposition, which corresponds to the potential runout for the smallest events that reach relative size 5 or the related maximum potential size for this specific path.

At this point along the thalweg, the avalanche decelerates, and friction increases enough to allow stopping and deposition. For  $D_{\max} = 5$  thalwegs, this typically is where the terrain gradient reaches  $<10^\circ$  (Lied & Bakkehøi, 1980). Figure 1 gives a schematic overview of these key points along the thalweg and the corresponding angles and length scales that can be calculated for a morphological avalanche classification.

Figure 2 shows an example of avalanche path data available in the AMA from the Lechtal in Western Austria, including Thalweg with AMA-ID, origin, transit and deposition points, as well as the outline of the avalanche catchment.

### Avalanche event data

Figure 3 shows an example for event data available in the AMA within the same extent of Figure 2. It includes the geolocation (lines and points) of the observed avalanche events' release (yellow), as well as dense (white/grey) and powder (blue) runout locations.

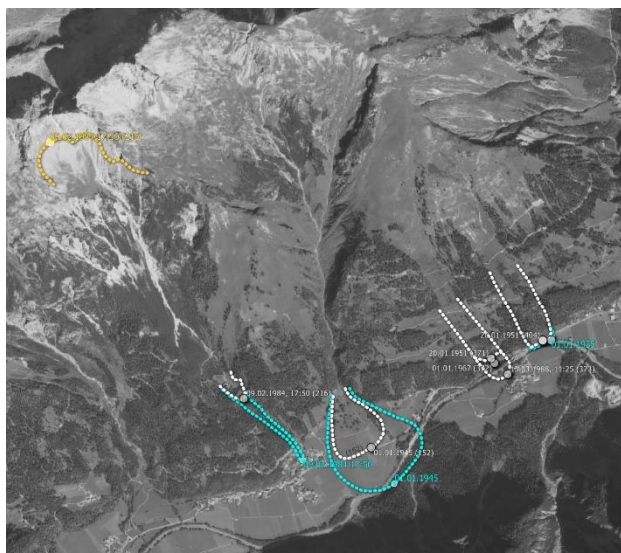


Figure 3: Example of avalanche past event data, recorded in the AMA within same region as shown in Figure 2; the extent (lines) or approximate location (points) of an event's release, dense or powder snow runout, are highlighted in yellow, white and blue, respectively; current orthophoto set to b/w in background (image source: TIRIS, 2024).

As far as spatially explicit data on the avalanche extent was available, this was transferred from the original sources to the AMA. The events within this portion of the AMA occurred between 1935, where a large powder snow avalanche reached the river Lech, and 1988, where a loose snow avalanche buried 100 m of state road and damaged a forest stand. Additional to geolocation data, date and time of the event, reports on avalanche type, release mechanism, debris type, damages, fatalities, affected infrastructure or other ancillary information is retrievable from the AMA. Key variables (e.g. time, date, location of deposition) are amended with an accuracy metric to indicate whether the provided information was measured, estimated, not available or void.

## 2.2 Interfaces, Input, Output

The AMA combines different open-source tools. It builds on a geodatabase (PostgreSQL/PostGIS) to store and organise all data, which can be accessed through GIS interfaces (QGIS or WebGIS) for entering and visualising content. Script-based search, export, and analysis functions are available through the open avalanche simulation framework AvaFrame (Tonnel et al., 2023; AvaFrame, 2024) and the AmaConnector therein. This directly interfaces with the AMA to supply model and simulation inputs or to evaluate their outputs. Furthermore, tools provided within AvaFrame and the AmaConnector can be used to perform geodata / statistical analysis on the avalanche path or event data.

### 2.3 AMA data

Currently (as of August 2024), the AMA holds 1,144 avalanche events, which occurred between the years 1668 and 2023, and have been attributed to 568 avalanche paths, all of which are located in the Austrian Alps. The event and corresponding path data was mainly compiled from the following two large, but conceptually rather different sources.

**AUT80+**

This portion of the AMA is based on sources, which mostly encompass large-scale or catastrophic events. It is based on a seminal Austrian avalanche cadastre published in 1994, containing events recorded throughout Austria on 80 different avalanche paths (AUT80).

This core dataset was amended by researching and collecting additional large-scale events from various sources and related research projects (from the cadastres of the Austrian Torrent and Avalanche Control Service, technical reports, chronicles, airborne campaigns, surveys, historical photographs, etc.). In total, 586 avalanche events were compiled and attributed to 180 avalanche paths.

**SPOT6**

At the beginning of February 2023, a large avalanche cycle occurred in Western Austria. Between 3 and 5 February, 64 avalanches were reported, claiming the lives of eight backcountry skiers. In all cases, a persistent weak layer in the old snowpack was the relevant cause of the accidents.

Based on previous experience on area-wide mapping of avalanches found in the current literature (e.g. Bühler et al., 2019; Hafner et al., 2021), the Austrian Research Centre for Forests and the Tyrolean Avalanche Warning Service jointly commissioned a commercial satellite (SPOT-6) data acquisition over a 700 km<sup>2</sup> large region in Western Austria, covering crucial parts of one of the most affected areas, the Stubai Alps (Figure 4, inset). The image was recorded on 13 February 2023, after an interim period of very calm and clear weather. The 4-channel (red, green, blue, NIR), 16-bit imagery was orthorectified, georeferenced and pan-sharpened to 1.5 m ground sampling distance (Figure 4).

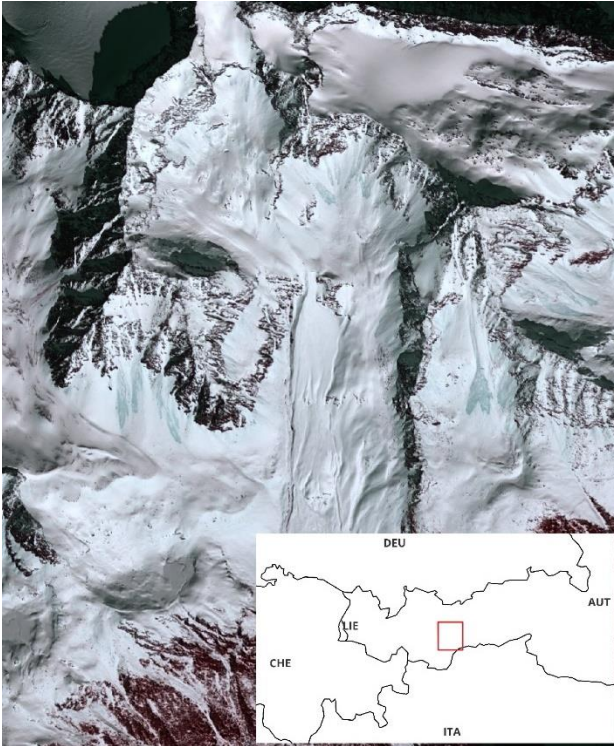


Figure 4: Excerpt from the SPOT6-scene acquired over the study site on 13 February 2023 at 10:03 AM; false colour image showing avalanche debris in blueish colours (© Airbus DS, 2023); insert shows extent of the mapped area in Western Austria (red polygon).

The whole image was manually interpreted, and avalanche release, track and deposition areas mapped and entered in the AMA. Additionally, the above-described avalanche path data was added for unsigned catchments. In total, 558 avalanche outlines were mapped from the imagery on 388 avalanche paths. With very few exceptions, the avalanches were mapped on sunlit areas of the imagery, while shaded areas remained very difficult to map and are thus highly underrepresented in this dataset.

### 3. ANALYSES

In the following, we present selected analyses of avalanche spatial and intensity characteristics derived from the AMA thalweg data, categorised by their  $D_{\max}$  value. A full analysis and detailed discussion of the results can be found in Fischer (2024).

For all 558 thalwegs in the AMA, first order geometric and second order energy conservation-based avalanche characteristics were calculated, including travel length, altitude difference, travel angles, maximum velocity, destructiveness and travel time. These characteristics were determined using the spatial extent of the thalwegs, combined with elevation data and additional calculations. The results were categorised by  $D_{\max}$  and statistically evaluated.

As an example for spatial, first order characteristics that can be derived from the AMA thalweg data, the travel angle was calculated from the tangent of travel length and altitude difference. This angle, also known as the  $\beta$ -angle ( $\gamma_D$ ), represents the overall inclination of the terrain between the origin and the deposition points (Figure 1). **Error! Reference source not found.** illustrates the  $\beta$ -angles of all AMA thalwegs (grey plot on the left) and the  $\beta$ -angles binned by  $D_{\max}$  (coloured plots). The analysis resulted in a median of  $35^\circ$ , with the 25<sup>th</sup> and 75<sup>th</sup> quantiles at  $31^\circ$  and  $38^\circ$ , respectively. Since the median of the whole dataset is skewed by the relatively large sample sizes of class 3 and 4 ( $n=278$  and  $n=168$ , respectively), compared to the other classes, the analysis of the single class results is more relevant.

Overall, the analysis shows higher  $\beta$ -angles for smaller  $D_{\max}$  thalwegs (e.g.  $38.0^\circ$  and  $26.9^\circ$  for  $D_{\max} = 2$  and  $D_{\max} = 5$ , respectively). Thus, the median for each  $D_{\max}$  bin suggests a rule-of-thumb to classify thalwegs based on their  $\beta$ -angle. However, the violinplots also show that there is considerable overlap of  $\beta$ -angles between the different  $D_{\max}$  classes.

As an example for intensity or second order avalanche characteristics, the maximum velocity ( $V_{\max}$ ) between the origin and the deposition points was determined. This calculation is based on the velocity altitude ( $z^s(s)$  in Figure 1), also known as the kinetic energy height (Lied & Bakkehøi, 1980, Körner, 1980). Figure 6 shows the maximum velocity median of all thalwegs and the medians of the maximum velocity per  $D_{\max}$  class. The violin plots suggest a steady increase in maximum velocity through the  $D_{\max}$  classes (e.g. from 14.6 m/s to 55.5 m/s for  $D_{\max} = 2$  and  $D_{\max} = 5$ , respectively) and a considerable overlap between the single classes. The fastest speed calculated for events on a  $D_{\max}$  class 5 thalweg was 88 m/s, conversely, the slowest speed for events on a thalweg only reached a velocity of 4 m/s.

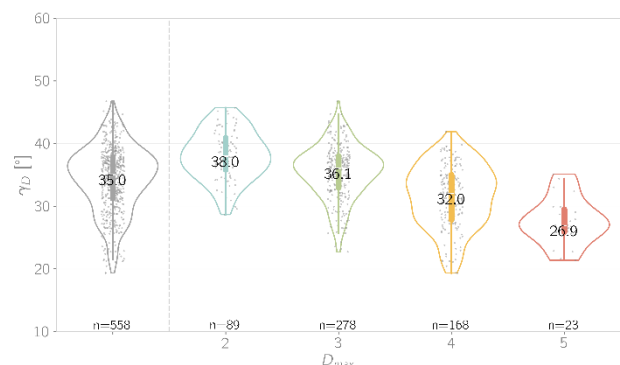


Figure 5: Violinplots in combination with boxplots and scatterplots, illustrating the  $\beta$ -angle of each thalweg between the origin and the deposition point. The plots are categorised by their  $D_{\max}$ , showing the median and quantiles of each bin and the sample size used for the analysis.

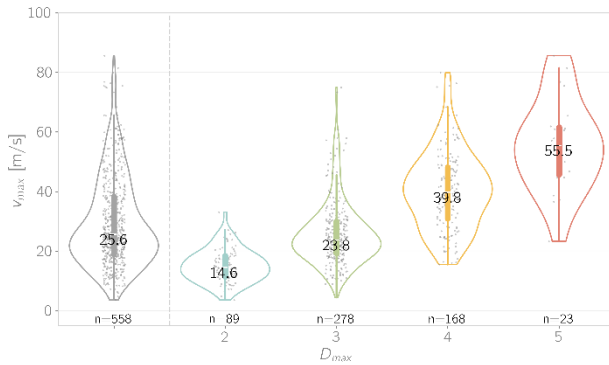


Figure 6: Violinplots in combination with boxplots and scatterplots, illustrating the maximum velocity of each thalweg between the origin and the deposition point. The plots are categorised by their  $D_{max}$ , showing the median and quantiles of each bin and the sample size used for the analysis.

Some of the retrieved characteristics were further put into the context with the international and widely used avalanche classification schemes of the Canadian Avalanche Association (CAA, 2016) and the European Avalanche Warning Services (EAWS, 2024). Comparing the travel lengths retrieved from the AMA thalweg analysis with the CAA destructiveness scale and EAWS avalanche size scale shows good agreement between the three values, with the CAA mostly representing the upper thresholds of each class and a large overlap between the EAWS scale and the typical travel lengths of the AMA thalwegs (Figure 7).

Besides the travel length, the destructiveness derived from the AMA velocity data (assuming the impact pressure  $P_{max} = \rho \cdot v_{max}^2$  with  $\rho = 200 \text{ kg/m}^3$ ) is compared with the CAA classification and data published by Rudolf-Miklau et al (2011).

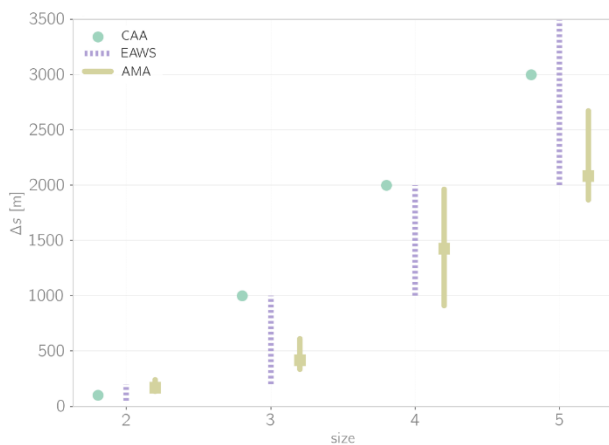


Figure 7: Comparison of travel lengths between the Canadian Avalanche Association destructiveness scale, the European Avalanche Warning Services avalanche size scale and the retrieved data from the AMA thalweg analysis.

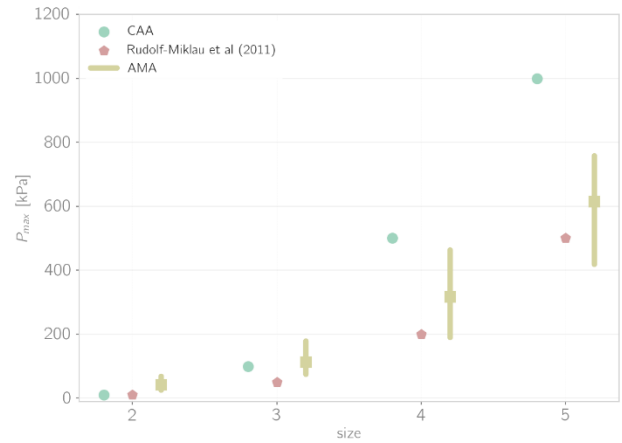


Figure 8: Comparison of destructiveness between the values retrieved from the AMA thalweg analysis, the Canadian Avalanche Association classification scheme (CAA, 2016), and the values published by Rudolf-Miklau et al. (2011).

As shown in Figure 8, the CAA destructiveness values are slightly smaller for  $D_{max}$  thalwegs 2 and 3, while being considerably larger for  $D_{max}$  4 and 5. Furthermore, the values suggested by Rudolf-Miklau et al (2011), are closer to the results retrieved from the AMA thalweg analysis but also indicate smaller values for smaller  $D_{max}$  thalwegs. Overall, the three scales show reasonable alignment, but suggest that a definition of concrete values per avalanche size class is not quite straightforward and additional research is necessary to validate and further develop a consistent, quantitative avalanche classification scheme.

#### 4. CONCLUSION & OUTLOOK

In this contribution, we presented the status of the Avalanche Modelling Atlas, an open-source initiative for avalanche documentation, modelling and analysis. The AMA currently holds a total of 1,144 avalanche events, which are directly linked to the 568 avalanche paths they occurred on. Key data, including the thalweg and its morphologically determined destructiveness potential ( $D_{max}$ ), as well as origin, transit and deposition points are available for each avalanche path. The presented analysis of the path data by  $D_{max}$ , shows the AMA's potential for an area-wide calculation and comparison of first- (e.g.  $\beta$ -angle) and second-order (e.g.  $v_{max}$ ) avalanche characteristics. Furthermore, it allows evaluating size and destructiveness values from established international classification schemes (e.g. CAA, 2016; EAWS, 2024).

Next steps in the development and extension of the AMA will include making the data contained therein publicly available and continuously adding high-quality datasets from other cadastres, projects or mapping campaigns from Austria and beyond.

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