METHOD FOR AN AUTOMATIZED AVALANCHE TERRAIN CLASSIFICATION

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ABSTRACT: Avalanche terrain classification according to ATES (Avalanche Terrain Exposure Scale) has become a popular method to represent and disseminate avalanche relevant information. In the present paper a reproducible method for an automatized avalanche terrain classification is introduced. Even though the presented method expresses the avalanche exposure by the ATES scale, the underlying paradigm differs substantially from the one originally introduced by "Parks Canada". As skiers trigger 90% of the fatal avalanches themselves, the suggested approach explores the terrain from the skiers' perspective. The algorithm applies for each point in the terrain the following procedure:

1. Pre-processing of the Digital Elevation Model and Land Cover data.
2. Segmentation of a polygon describing the area relevant for the avalanche exposure at the current point.
3. Deduction of geomorphologic properties on the relevant slope area, representative for the hazard at the current point.
4. Calculation of a continuous ATES rating [0..100%] from the geomorphologic properties.

The procedure is repeated for each cell of a specified raster in order to create an ATES rated hazard map (see Fig. 5). The suggested approach emulates knowledge of "avalanche experts" planning a backcountry route and identifying avalanche hazard cruxes on the map.

KEYWORDS: ATES, Avalanche Terrain Exposure Scale, Avaluator

1. INTRODUCTION

1.1 ATES

Avalanches on backcountry recreation routes are the product of the three factors **terrain**, **snow conditions** and avalanche triggering **humans**. Since Munter (1997) introduced the first rule-based decision framework, **strategic methods** became popular among backcountry skiers. Strategic methods typically combine snow conditions with terrain characteristics to a **risk category** (low, elevated, high). Where the snow conditions are expressed by the danger level of the avalanche forecast, the terrain is described exclusively by the slope angle.

A creditable exception is the **Avaluator**, developed through the Canadian Avalanche Association (Haegeli et al. 2006). The terrain characteristics are based on the Avalanche Terrain Exposure Scale (ATES), introduced by Parks Canada (Statham et al. 2006). ATES provides a terrain analysis framework to comprehensively evaluate, describe and communicate the complexities of avalanche terrain exposure. It's not new. Basically an avalanche expert, planning a backcountry route and identifying avalanche hazard cruxes, performs an ATES rating. As ATES is based on 11 terrain criteria the Avaluator yields an important progress compared to strategic methods, that rely exclusively on the slope angle.

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1.2 Scope

Its important to understand, that ATES and Avaluator are primarily pre-trip planning tools. Rather then predicting exposure or risk to avalanches, they are intended to augment the avalanche awareness. ATES ratings can be used in a static or dynamic application context.

- Static application context: Even though ATES originally was designed to classify “trips”, its also possible rate individual pieces of terrain and establish ATES danger maps. These maps support an optimal route definition during the trip planning phase.
- Dynamic application context: A strategic method like the Avaluator combines the ATES rating and the snow conditions (ex-

pressed by a danger level) to a risk category. Analog to the static application, risk categories can be calculated for single "trips" as for individual pieces of terrain.

1.3 History

A few years after the presentation of ATES, the concept got introduced in several Parks of the US (Mcmanamy et al. 2008, King & Latosua 2012), Canada, New Zealand (Bogie & Davies 2010) and the Pyrenees (Martí et al. 2013, Gavaldà et al. 2013). Pielmeier et. al (2014) proposed an adapted model for the Jura hills, a low mountain range of Switzerland. Even though ATES is widely accepted in anglophone countries, it never really could gain ground in the Alps.

Down to the present date ATES rating is basically a manual process. A glance at the technical model of ATES (Statham et. al. 2006) reveal that most of the applied terrain criteria are of qualitative rather than quantitative nature. Nevertheless, Delparte (2008) presented a semi-automatized discrete decision tree to calculate ATES categories. In order to concretize the ATES model, Campbell et al. (2012) proposed some quantitative criteria. It's obvious, that the lack of sufficient quantitative description of the terrain criteria constitutes still a major obstacle for the development of a fully automatized ATES algorithm and for the further propagation of the ATES concept.

Tbl. 1: Categorization of the original ATES criteria (v.1/04).

Terrain criteria	*Spontaneous avalanches*	*Human-triggered avalanches*	*Technical difficulty grade*	*Consequences of an eventual avalanche*
Slope angle	x	x		
Slope shape	x	x		
Forest density	x	x		
Terrain traps		x		x
Avalanche frequency	x			
Start zone density	x			
Runout zones	x			
Avalanche paths	x			
Route options			x	
Exposure time	x	x	x	
Glaciation			x	

2. TERRAIN CRITERIA

2.1 Original ATES criteria

Interestingly the available scientific publications don't reveal relevant questioning of the original ATES terrain criteria. Campbell et al. (2012) emphases the subjectivity and redundancy of the criteria. In addition, they suggested to introduce a class 0 (no avalanche terrain) into the ATES scale. Pielmeier et al. (2014) questioned the inclusion of criteria belonging to the technical difficulty degree and consequently proposed to rename the ATES class "challenging" to "variable". Martí (2013) added a new criterion, reflecting the wind drift exposure, thus the proximity to ridge.

An analysis of the original terrain criteria shows that they can be divided into four different categories (see Tbl. 1). Based on this assignment, the authors want to ask four questions:

1. Is it reasonable to refer to eventual **terrain traps**, suggesting that an avalanche can be survived? Among avalanche experts there is a broad agreement, we should focus on avalanche accident prevention rather than eventual avalanche consequences.
2. Is it useful to mix exposure to avalanches with criteria belonging to the **technical difficulty grade**? The SAC difficulty scale (Schweizer Alpen-Club 2012) proposes a comprehensive framework to describe technical difficulty grades of backcountry trips.

3. The remaining criteria can be split into criteria relevant for **spontaneous avalanches** and criteria relevant for **human-triggered avalanches**. The focus of ATES lies on spontaneous avalanches, hence ATES promotes the development of **dynamic avalanche models**. However more than 90% of avalanche fatalities in a backcountry context are due to human-triggered avalanches (Harvey et al. 2014). Shouldn't we develop models, that focus on human-triggered avalanches, rather than developing dynamic avalanche models, that follow a classical top-down approach?
4. Is the criteria catalog sufficient, if we want to focus on human-triggered avalanches?

Tbl. 2: Suggestion for a new catalog of terrain criteria.

Terrain Criteria	*Priority*	*Description*
Slope angle	high	There is no doubt, that the slope angle remains the primary terrain criteria to deduce exposure to avalanches.
Slope size	medium	In order to get a good terrain criterion, the slope angle must be linked to slope size.
Plan curvature	medium	Areas with convex plan curvature (e.g. ridges,) are less prone to promote avalanches, then areas with a concave plan curvature (e.g. gullies).
Forestation	medium	Closed forests provide a certain protection from avalanches. Furthermore, forests fall into a relatively low elevation zone, characterized by relatively few recorded avalanche accidents (Vontobel 2011).
Proximity to ridge	n.a.	Slopes close to ridges are more exposed to wind drift, hence more likely to promote critical snow layering.

2.2 <u>*Proposed ATES criteria*</u>

The authors of the present paper believe, that ATES is an extremely valuable tool, but they want to put up to discussion a slightly modified catalog of terrain criteria. The suggested catalog (see Tbl. 2) focuses on the question, whether a specific point in the terrain provides terrain characteristics, that enable human-triggered avalanches, if the skier disturbs the snow cover at that point.

When Munter (1997) presented the 3x3 method, he pointed already to three important terrain criteria not incorporated into the strategic methods: **Slope size**, **slope form** and **proximity to ridge**. Maggioni and Gruber (2002) suggested a model to define potential **release areas**. By comparing the geomorphologic properties of the release areas with well documented avalanches, they could show the relevance of the following geomorphologic parameters: **Mean slope angle**, **concave plan curvature** and **proximity to ridge**. Veitinger et al. (2014) developed a release area model accounting of the uncertainties by fuzzy logic. They focused on three parameters: **Slope angle**, **wind shelter** and **roughness.**

So far all research was focused on release areas as input data to dynamic avalanche models. Terrain characteristics of small to medium human-triggered avalanches have, however been the subject of limited attention. One of the few systematic geomorphologic analysis of human-triggered release areas, known to the authors, was performed by Vontobel (2011).

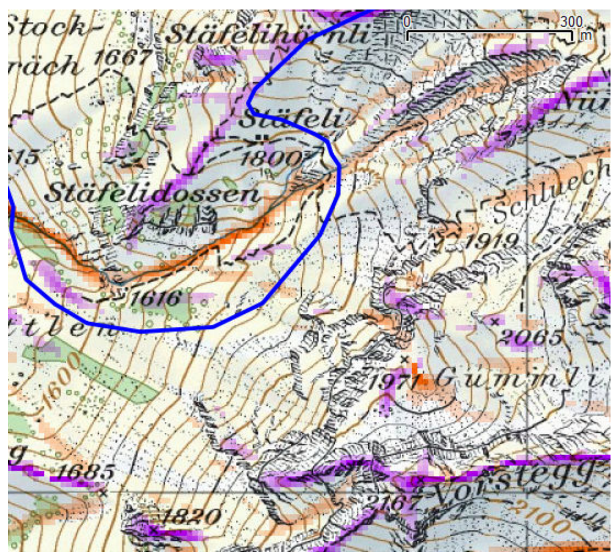

Fig. 1: Plan curvature (Base map: Swisstopo)

A statistical analysis of 142 release areas proved relevance for the following geomorphologic parameters: **Slope angle**, **proximity to ridge** and **concave plan curvature**. The pattern given by the profile curvature depended a lot on the location within the release area. Other criteria, like roughness or exposure showed less significance.

2.3 *Aspect and Elevation*

The relevance of **aspect** and **elevation** depend a lot on the climate zone. In the Alps they are highly significant (Munter 1997, Schweizer & Jamieson 2000, Harvey 2002, Vontobel 2011). Static ATES maps consumed by humans must take them into consideration. Most avalanche forecasting services of the world provide critical elevations and critical aspects. If ATES maps are further processed through strategic methods, it's recommendable to moderate the danger level depending on the current critical aspects and elevations. The corresponding danger level moderation procedure for the Swiss Alps is described in Schweizer (2015).

Tbl. 3: Pre-processed raster data.

Raster	*Data type*	*Data range*	*Value name*	*Description*
Slope	Real	[0..90°]	slope	Slope angle.
Aspect	Real	[0..360°]	aspect	Slope aspect.
Plan curvature	Real	[-∞..+∞]	planc	Ridges have a positive planc value (convex). Gullies have a negative planc value (concave).
Forestation	Boolean	[1, 0]	forest	1: closed forest; 0: open forest or no forest
Terrain fold	Real	[-180°..180°]	fold	Raster data, that describes the sharpness of terrain folds. The terrain fold value is expressed by the maximum angle between neighbouring slope normals.

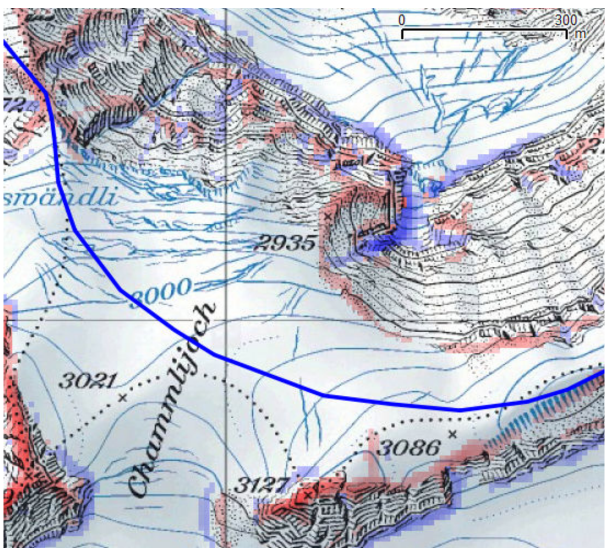

Fig. 2: Fold raster (Base map: Swisstopo).

3. METHODOLOGY

Accident statistics may shape an appropriate catalog of terrain criteria, but it's not possible to deduce an avalanche model directly from accident statistics. Accident statistics depend fundamentally on the movement pattern of the humans. Unfortunately, these patterns are still unknown. On the other hand, the physical knowledge of human-triggered avalanches is still not sufficient to shape models. So far all modeling must rely on the judgment of avalanche experts. When avalanche experts identify avalanche hazard cruxes on the map, they follow implicitly or explicitly a specific procedure. As far as possible, the algorithm presented in this article emulates such procedure. In order to keep the control on the output, fast iterative cycles, consisting of algorithm implementation, map generation, map evaluation and algorithm correction got realized.

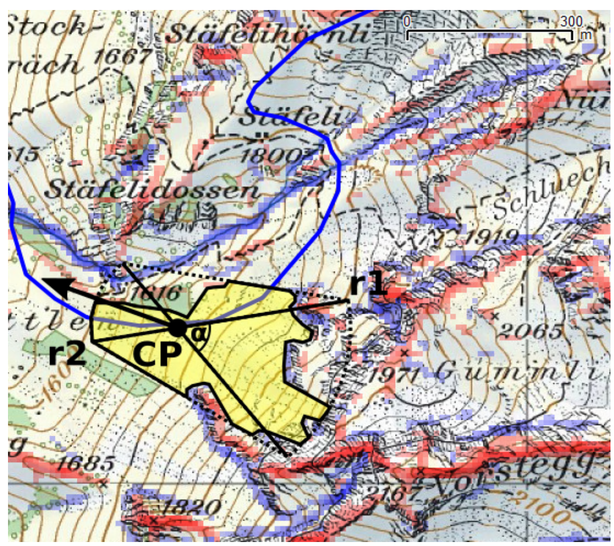

Fig 3: Delimited Relevant Slope Area (Base map: Swisstopo).

4. ALGORITHM

4.1 Overview

The algorithm performs for any Current Point (CP) in the terrain the following four steps (see as well Fig. 4):

1. Pre-processing of the Digital Elevation Model (DEM) and land cover data.
2. Definition of the Relevant Slope Area (RSA): Segmentation of a polygon describing the area relevant for the avalanche exposure at CP
3. Deduction of geomorphologic properties on the RSA, representative for the endangerment at CP.
4. Calculation of a continuous ATES rating [0..100%] from the geomorphologic properties.

4.2 Data pre-processing

Tbl. 3 shows the raster data deduced from the Digital Elevation Model (DEM) and land cover data.

Fig. 1 shows an example of the continuous **plan curvature**. Depending on the planc value convex locations (ridges) are marked with a variable transparent violet color, concave locations (gullies) are marked with a variable transparent orange color.

Fig. 2 shows an example of **terrain fold**. Depending on how sharp the folds are, convex folds are marked with a variable transparent red color, concave folds are marked with a variable transparent blue color.

Tbl. 4: Geomorphologic properties, calculated for the RSA.

Property	*Name*	*Relevance*	*Description*
Slope angle maximum	SAM	Medium	Highest slope angle found on the RSA.
Slope angle fractile 20	SAF20	High	The slope angle SAF20, that splits all slope angles of the RSA into two classes, 80% are smaller and 20 % are bigger then SAF20. SAF20 can be understood as a typical slope angle, representative for the steepest zones on the RSA.
Distance weighted slope angle	DWSA	Medium	Steep slopes receive a higher weight, if near to CP.
Summed slope angles	SSA	High	Slopes are dangerous if they combine high slope angles with big slope size. By summing all slope angles over the RSA, we get a measure for the slope size.

Tbl. 5: Further possible features powered by ATES maps.

Geometry	*Static Output*	*Dynamic Output*
Raster	ATES danger map: Used to optimize the route design during the planning phase.	Risk map: Used to optimize the route design during the planning phase.
Route segments	ATES rating along a route: Used to create awareness about hazard cruxes on the route.	Risk rating along a route: Used to create awareness about risk cruxes on the route.
Trip target rating	ATES rating for single trips: Used to choose a target trip.	ATES rating for single trips: Used to choose a target trip.

4.3 Relevant Slope Area

The avalanche exposure at any point (CP) in the terrain depends on the terrain characteristics of the near environment. The relevant near environment will now be called **Relevant Slope Area** (RSA). Avalanche experts typically refer to the next sequence of "terrain folds", when asked about the delimitation of the RSA. A terrain fold can be a ridge, the bottom line of a gully, a hillside toe or a slope edge. Fig. 3 shows the example of a delimited RSA, valid for CP. In order to define the RSA, a **base form**, consisting of two linked circle segments is aligned parallel to the gradient at CP. The RSA gets delimited by the **next fold**, by the **next forest** or by the **base form**. As shown in Fig. 3, the base form can be fully described with the radius r1, r2 and the opening angle α:

r1 = f1(planc, fold, slope, MRSAR)
r2 = f2(r1)
α = f3(planc, fold, slope, MRSAR)
MRSAR = Maximal RSA Radius

We could say, the base form gets modulated by the form of the slope. As the functions are complex, its beyond the scope of this paper to describe the details. The formula follows a logic, that can be described by four principles:

1. On terrain with high absolute planc value (ridges and gullies) the base form becomes a perfect circle (r1=r2 and α=180°). On terrain with low absolute planc value (uniform slopes) the base form becomes more narrow and longish.
2. The steeper the terrain, the smaller becomes α: On steep slopes we look more upwards and downwards, on less steep slopes we look more to the side.
3. The steeper the terrain, the bigger becomes r1 and r2: On steep slopes more terrain is considered to be relevant.
4. The smaller the planc value, the bigger the size of r1 and r2. The bigger, the planc value, the smaller r1 and r2. This means in gullies the base form becomes big, on ridges the base form becomes small.

All four principles are combined. Its fundamental to understand, that not only the model functions f1, f2 and f3 are continuous, but also the input values to these functions (planc, fold, slope). Therefore, the model is not subject to high sensitivity, like it's typical for discrete modeling.

4.4 Geomorphologic properties

So far we can assign an RSA polygon to any CP of the terrain. Tbl. 4 specifies the geomorphologic properties to be calculated for the RSA polygon.

There is an enormous potential to propose further relevant geomorphologic properties, like **curvature**, **wind shelter**, **roughness** or **proximity to ridge**.

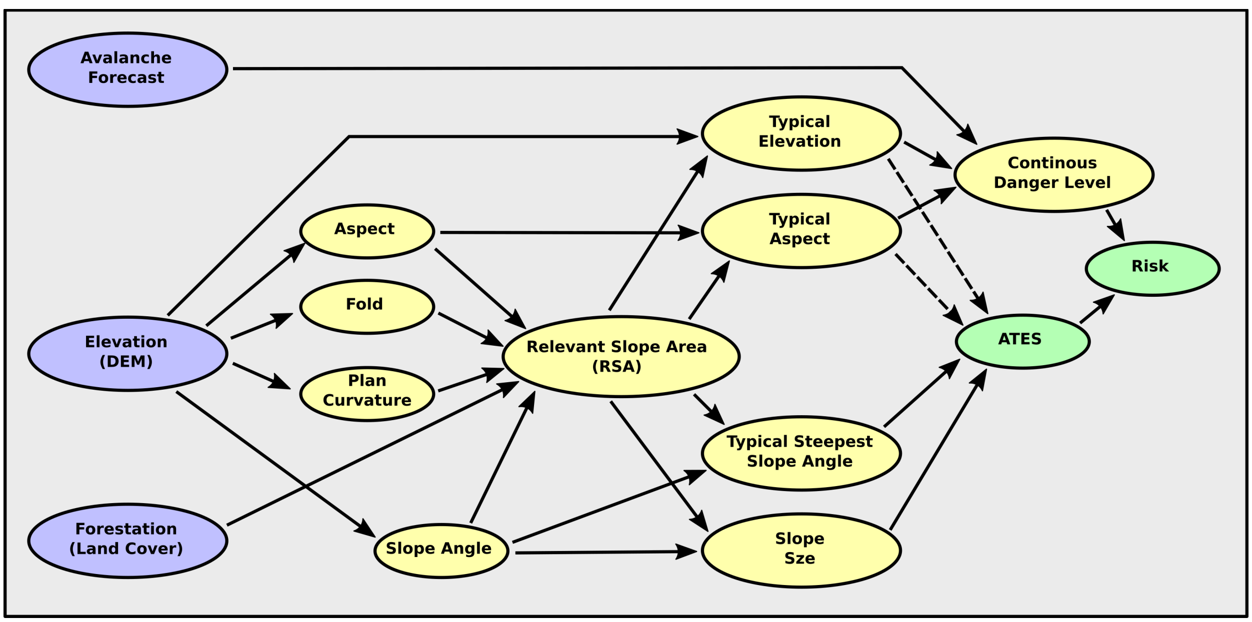

Fig. 4: Data-flow diagram of the algorithm.

4.5 ATES

In the last step the ATES value can be calculated out of the geomorphologic properties. The according formula gives specific weights to the relevant geomorphologic properties and rescales the resulting value to generate an ATES value in the range [0..100%].

If ATES is directed to end user, it makes sense to moderate the ATES values depending on elevation and aspect. The moderation procedure depends a lot on the respective climate conditions.

5. RESULTS

If the algorithm is repeatedly applied for all points within a raster (e.g. 10 m x 10 m), it's possible to generate a continuous ATES danger map. Fig. 5 shows a sample of the Oberalppass in Switzerland. Further samples can be found under the following link:

http://www.skitourenguru.ch/index.php/ATES2

Under the same link a video is available, showing the ascent to the "Gross Chärpf", a well known backcountry trip in Switzerland. The Video visualizes on a topographic map the respective RSA (yellow) and the resulting ATES value (white to red color gradient).

If the ATES danger map is combined to realtime data available from the avalanche forecasting service, it's possible to calculate **dynamic risk maps**. These maps can be used to generate further output, as shown in Tbl. 5.

6. CONCLUSIONS

The paper introduces a new ATES criteria catalog, that targets a model describing exposure to human-triggered avalanches. As backcountry skiers are the subject of human-triggered avalanches, the approach departs from dynamic avalanche modeling of spontaneous avalanches. The applied criteria result from statistical release area analysis. The model design is based on expert judgment. The approach reveals a huge need for further research, particularly the refinement of further relevant geomorphologic parameters.

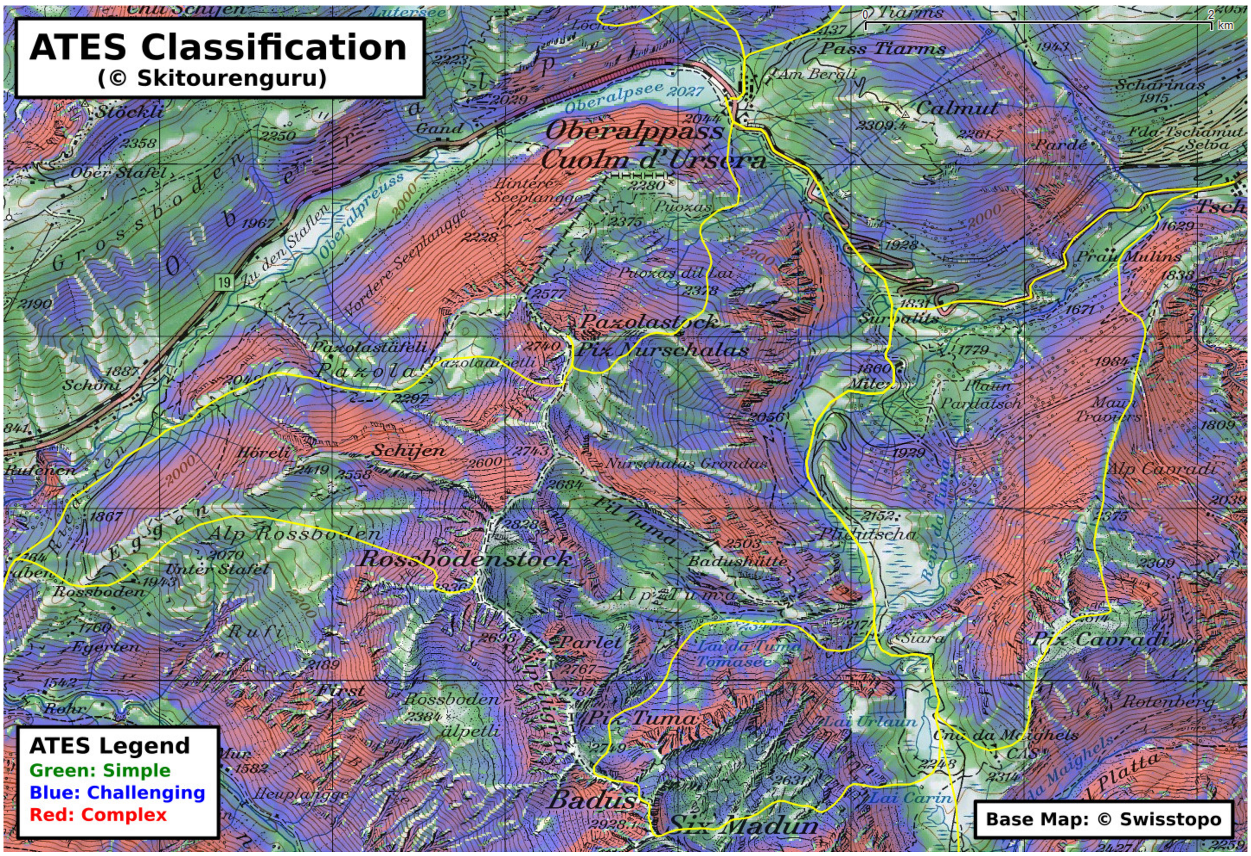

Fig 5: ATES danger map of the Oberalppass (Switzerland).

A difficult topic is the model validation. As long as the movement pattern of backcountry skiers is unknown, it's not possible to validate the model with accident data. To this date a validation procedure can only be designed by consulting the knowledge of avalanche experts.

In many regions of the world, particularly in the Alps, ATES never could gain ground. Further propagation of ATES depend on two issues:

1. A broad discussion of the applied terrain criteria.
2. The development of a fully automatized algorithm, able to calculate reproducible and standardized ATES danger maps from DEM and land cover data.

If ATES finds answers to these two challenges, it can provide a valuable decision-making tool for backcountry skiers and hence make an important contribution to avalanche accident prevention.

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