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Avalanche Cartography: Visualization of Dynamic-Temporal Phenomena in a Mountainous Environment

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Abstract

Avalanches represent a very short, local, dynamic event in snow-covered mountainous regions. They are not easy to predict and often can produce devastating results. Avalanche cartography deals with the causes and consequences of such incidents and attempts to depict them in a variety of ways. The most common cartographic representation within this field is the avalanche hazard map. It incorporates mainly large-scale topographic elements with thematic features. However, besides just visualizing what has happened and depicting locations of potential risk, it is now possible within modern cartography to experiment with different approaches and to visualize complex variables in a cartographically demanding way. This paper deals with the phenomena of avalanches from a cartographic perspective and shows the variety of possibilities cartography can offer today to understand and predict these complex natural hazards.

Introduction

On February 23, 1999, an avalanche struck the village of Galtür, Austria, killing 31 people. This tragedy, and a spate of other alpine disasters in recent years, has increased interest in the spatial analysis of avalanches in Austria. This trend could be seen during the state of emergency in the upper Paznaun Valley, Tyrol, also during February 1999, when more than 35 people lost their lives in several avalanches. The news media and officials in their briefing rooms noticeably relied on cartographic representations for explaining events and for evidence-based decision making. Despite the breaking news stories and attempts to explain the destructive and dynamic components of the catastrophe through traditional reporting, public interest was focused almost exclusively on three-dimensional cartographic representations. Portraying the avalanches in a spatial context allowed the concerned public to see complex correlations in a vivid and more conclusive way as the magnitude of the disaster began to unfold. Maps and map-related products provided an important public service throughout this ordeal.

Avalanches are common natural occurrences in mountainous regions during the snow season. They are terrifying spectacles, and remarkable – if watched from a remote and safe distance. Although an avalanche is usually only a short and localized event, the results can be disastrous if inhabited areas are involved. Besides temporarily closing off important transportation routes, such as passes, roads, and railroads, their track of destruction can destroy roads, protective forests, buildings, and all of one's personal effects. The ultimate tragedy is the loss of human life.

How does cartography deal with avalanches, their effects, and their three-dimensional representation? Avalanches develop primarily because of topographic and meteorological factors. Hardly predictable, avalanches are also difficult to pinpoint in the environment. Various dynamic processes have to be taken into consideration, which may in turn be influenced by many unpredictable factors. The following elements play an important role: snow properties; wind; temperature; sunlight exposure and intensity; slope; aspect; and terrain features. From the cartographer's point of view, all of these interrelated factors have to be portrayed in context on a map. Therein lies the challenge.

The art of simplifying real-world three-dimensional space into a spatial model without omitting essential features still remains an important, albeit tricky, task for cartographers. Thus a map can be considered as a model of reality. Large-scale topographic maps are well suited for showing terrain-specific parameters that influence and interact with avalanches. Slope and aspect, the major topographic features most often used to predict avalanche occurrence, can be derived easily from topographic maps. The features that characterize recurring avalanche events – catchment areas, avalanche tracks, areas of avalanches, and danger zones – can also be locally delineated on topographic maps. The representation of these features is strictly dependent on the map scale and the extent of generalization. All delimitations on maps, including areas of avalanche risk, are to a certain extent

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inexact and bear the burden of uncertainty, and therefore must be interpreted accordingly. The various meteorological factors are much more difficult for cartographers and avalanche researchers to comprehend. These complex, variable, and dynamic factors defy easy visualization. Moreover, meteorological factors lack unique spatial connectivity and, as a result of their variability and temporal character, can be only incompletely portrayed with conventional (static) cartographic tools.

The aim of this paper is to give a short overview of the task facing "avalanche cartography." Selected examples will show the cartographic products being made and the problems that arise with the spatial representation of avalanches – a most unpredictable, local, and dynamic phenomenon.

Properties of Avalanches

Avalanches are masses of snow and ice that abruptly slide down mountains. Although avalanches come in different sizes and exhibit different characteristics, they all have the potential to inflict great damage. Meteorological and topographic factors play a decisive role and are seen as important criteria for the discrimination and classification of avalanches. Many scientific research laboratories worldwide, such as the notable European research centre for avalanches, the Swiss Federal Institute for Snow and Avalanche Research, in Davos, Switzerland, are currently investigating in these areas.

For detailed information, see http://www.slf.ch/welcome-en.html

Avalanche danger is defined by the probability of a downhill slide and the possible extent of destruction for a specific geographic area. The concept of risk – the potential for damage – requires the presence of real danger (slopes susceptible to avalanching) and people and property in potential harm's way. If an avalanche may occur in a remote mountain valley, without trees, settlements, or private property, then there is a danger of avalanches, but no risk. However, if a potential avalanche is within reach of settled areas, avalanche danger and high risk for destruction simultaneously exist (EISLF 2000).

Analyses of accidents in the European Alps show that most victims of avalanches on open terrain were engaged in leisure-time activities, such as skiing, snowboarding, or mountain climbing. In the past few decades, statistical comparisons of avalanche fatalities in the Austrian and Swiss Alps show that most of the victims were buried under snow, especially in buildings and on transportation routes. Nowadays winter sport activities on open terrain have the highest risk for lethal accidents involving avalanches (BUWAL 1999, EISLF 2000).

Although disasters like the one at Galtür are the exception, a significant trend is becoming clear. Alpinists cause more and more "skier avalanches," which are triggered by the victims themselves. Most skier avalanches are restricted to small local areas. The typical dimensions are: width 50 m, length 80 m, overall length 150 m, and rift height 45–50 cm. Accidents with a lethal outcome are relatively common. Comparing skier avalanches to other avalanches during the last 10 years reveals a percentage of death toll more than 90% (EISLF 2000).

Table 1. Slope and Avalanche Probability (DAV 1994)

Slope	Avalanche Probability
Below 10°	Practically no avalanches are triggered
10°–28°	Avalanches are scarce
28°–45°	Major danger zone for avalanche triggering
above 45°	High avalanche frequency; however, low snow accumulation due to steepness

Avalanches will never be completely avoidable, but a better understanding of the direct and indirect factors that cause avalanches is possible. Maps and map-related representations can be used to better understand or even in some cases prevent avalanches. This cartographic information is essential for the alpinist planning a backcountry excursion. However, before venturing into the mountains, another basic prerequisite is needed: proper knowledge about the genesis of avalanches.

According to avalanche experts around the world, a terrain's slope is one important factor in understanding and predicting potential avalanches (compare Table 1).

Cartography of Avalanches

METHODS OF REPRESENTATION

In order to depict avalanche-related phenomena accurately and meaningfully, it is essential to understand the various visualization methods as well as base-map information available to cartographers. A common form of presenting relevant avalanche information is the printed map, most often combining a large-scale topographic base with specific thematic information, such as avalanche paths, potential hazard areas, and event chronology. Terrain information on maps consists mainly of contour lines, hydrography, land cover (including, in some cases, rock depiction and hill shading), and infrastructure. The detail as well as accuracy of avalanche maps is dependent primarily on scale. Commonly used scales range from 1:1000–1:10,000 (cadastral maps), to 1:25,000–1:50,000 (classical topographic maps), down to 1:100,000 or smaller (regional overviews). Other common base maps used for mapping avalanches at large scales include orthophotos and satellite images, which show a high amount of detail but suffer from a lack of generalization.

Today, the focus of avalanche hazard mapping includes:

Table 2. Cartographic representation of avalanche phenomena and descriptions

Base	Usage and Map Scale	Advantage/Disadvantage
Cadastral map	Danger zoning, detailed delimitation ~ 1:1,000–1:5,000	[+] Exact surveying and mapping [–] Entire extent of hazard cannot be visualized, simple terrain representation
Aerial photomap (orthophotomap)	Avalanche flow, hazard areas, delimitation (scale dependent) ~ 1:5,000 – 1:25,000	[+] Up-to-date, high detail [–] Mainly summer representation, not generalized, insufficient additional cartographic information
Topographic map	Avalanche flow, coarse delimitation, event probability ~ 1:25,000–1:75,000	[+] Entire extent of hazard can be visualized, satisfactory terrain representation [–] Inaccuracy due to generalization, static, in detail frequently outdated
Satellite image map	Regional overview, coarse delimitation ~ 1:25,000–1:100,000 and smaller	[+] Up-to-date, seasonal availability [–] resolution restriction, static, not generalized, insufficient additional cartographic information
Middle- and small-scale overview map	Regional overview, representation of secondary information (meteorological factors, for example), potential hazard risk ~ 1:100,000 and smaller	[+] Regional overview [–] No detailed analysis possible
Static map-related representation	Photographic panorama, oblique aerial photograph, panoramic sketch, photographic documentation ~ mainly central perspective	[+] Occasionally up-to-date, high detail, realistic [–] No cartometric functionality, hidden areas, static
Dynamic map-related representation	Aavalanche flow, animation, virtual reality, 3-D analysis, GIS, interpretation, documentation ~ scale independent	[+] Representation of dynamic temporal processes, satisfactory terrain representation, interactive [–] Dependent on terrain information: DTM and thematic layer accuracy and quality

- Large-scale municipal and regional planning
- Hazard mapping for outdoor recreation
- Event chronology
- Probability of avalanche hazards
- Animation of occurrences
- Simulation modelling
- Hazard and risk management
- Small-scale regional overview

Table 2 categorizes cartographic representations that can be used for depicting avalanche-related topics. The table shows the type of cartographic base, relevant usage and range of map scale, and the major advantages and disadvantages of that base.

Avalanche-related events possess static as well as dynamic components (compare Table 3). These again can have a spatial location with either a linear and/or areal dimension. If the map scale is too small or the avalanche-related information is below the minimal graphical size of depiction, then point or text representation is introduced.

Table 3. Examples of avalanche-related topics and their cartographic dimension

Cartographic Dimension	Example
Static-linear	Delimitation of an avalanche break-off line
Static-areal	Delimitation of an avalanche incident
Dynamic-linear	Avalanche path with flow direction
Dynamic-areal	Avalanche incident chronology

RANGE OF REPRESENTATION

Until now, avalanche hazard mapping has been mainly achieved using large-scale printed maps to represent static as well as dynamic features. The principal goal has

Table 4: Arrangement of avalanche-related cartographic products

Arrangement	Attribute	Description
Theme	Primary-reference	Direct causal connection with avalanches
	Secondary-reference	Involvement of avalanches indicated, indirect causal connection
Usage	Descriptive	Descriptive – based upon past events
	Prognostic	Predictive – based upon analysis and models
Scale	Local representation	Large-scale
	Regional representation	Medium-scale
	Super regional representation	Small-scale
	Variable representation	Variable scales – map-related expressions

been to depict potential areas of risk or areas subject to past hazard occurrences. Employing a broad spectrum of cartographic symbolization on these maps has made it possible to visualize the dynamic characteristics of avalanches and their causes. Qualitative and quantitative line symbols and arrows are the most common forms of representation. However, printed static maps very quickly reach their limits when temporal dynamic events need to be depicted. As an alternative, map-related representations, such as animation or virtual reality, can be used, provided that the topographic and thematic base information is of sufficiently high quality. Animations can show the temporal dynamic characteristics of avalanches from an optimal viewpoint selected by the cartographer. This can either be a map-like orthogonal viewpoint (from directly above) or the multifacets of an oblique view that yields a perspective three-dimensional scene. Adding interactivity to an animation allows the user to customize the cartographic presentation. In its most fully developed form, interactivity delivers an immersive virtual reality environment. No longer merely a detached observer, the user instead becomes an integral part of the representation and can interact with it from within.

THREE-DIMENSIONAL REPRESENTATION

Using the methods described above, it is now possible to depict avalanche information in a new dimension. Map-related representations can be either static, view-only illustrations (photo panoramas, 3-D perspective views, photographic documentations) or dynamic, interactive multimedia presentations (animations and simulations, 3-D GIS applications, virtual reality). In all of these cases the third dimension, as well as in some cases the temporal (time) factor, are present and can be utilized. High-quality digital terrain models (DTM) are required for these applications.

In order to produce 3-D perspective views or evaluate and use slope for avalanche classification, it is important to have a high-quality digital elevation model (DEM) as a base. DEMs can be derived from DTMs in numerous ways. Using contour lines from existing topographic maps in conjunction with breaklines and spot elevations to produce DTMs is very common. However, it is important to be aware of the quality issues that arise when using such methods. Resolutions of 5–10 metres are ideal for making the DEMs used for mapping avalanches. Although lower-resolution DEMs in the range of 25–50 metres are commonplace, they inadequately represent small but critically important terrain features. A good compromise for avalanche mapping is 1:25,000 scale with a DEM resolution of 10–15 metres.

GIS INCORPORATION

The major reason for using GIS (geographical information system) for avalanche-hazard management is to analyse and model scenarios that can help explain or even predict possible avalanche occurrences. For this to be possible, it is important to possess large-scale terrain and thematic information. Topographic maps (contours, hydrology, cultural infrastructure) and DTMs represent large-scale terrain information in an effective way. Available in digital form, they act as foundation for all subsequent GIS analysis and modelling.

GIS can be put to many practical uses. On the one hand it offers classic cartographic functionality for depicting singular classes of thematic information (slope, aspect, event chronology). On the other hand GIS can combine multifaceted attributes using various complex features to produce highly sophisticated results. One of the major input variables for most analysis and modelling is terrain slope information derived from a DEM.

CLASSIFICATION OF AVALANCHE-RELATED CARTOGRAPHIC PRODUCTS

An analysis of numerous avalanche-related cartographic products shows that three major classification criteria can be distinguished (compare Table 4):

- Arrangement by theme
- Arrangement by usage
- Arrangement by scale

The arrangement by theme distinguishes two categories of attributes: "primary-reference" and "secondary-reference." The classification differentiates between a direct causal connection with avalanches (for example, avalanche flow map, avalanche animation) and an indirect causal connection that indicates only an involvement of avalanches (for example, hazard map, snow accumulation map).

The arrangement by usage differentiates between past and future outcomes. Occurrences based upon past events (for example, event chronology) are classified as "descriptive." Occurrences based upon analysis and models for example, avalanche simulation) are classified as "predictive."

Classification by scale is very common in cartography; however, it becomes somewhat tricky when including map-related representations that do not usually have a defined unified scale (for example, 3-D perspective view, photographic document, sketch). Therefore the three classical distinctions have been made (large, medium and small-scale), with the addition of a variable scale for map-related representations.

Examples

The following examples show a small cross-section of the many avalanche cartography representations that have been produced recently. Some of the examples were downloaded from the Internet, some were scanned at high-resolution from analog sources, and others were made available directly by the authors. It is important to note that the excerpted examples show only a small area of characteristic detail. The original source may be obtained from the provided references or Internet links.

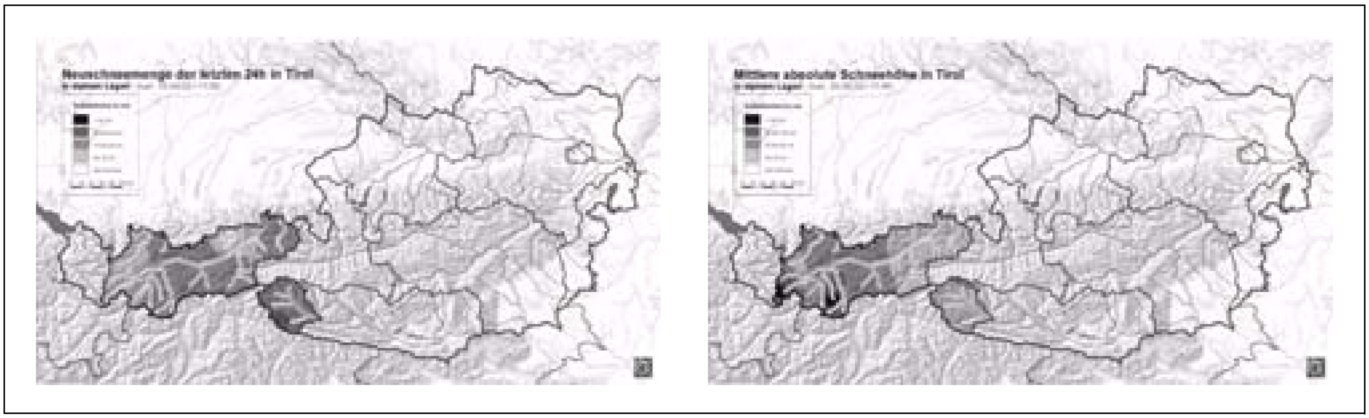

Figure 1. "Secondary-referenced, descriptive, super regional representation." Small-scale, topographic overview map of the current regional snow situation in the Tyrolean Alps. Left: Snow accumulation within the past 24 hours in Tyrol, Austria. Right: Mean snow depth in Tyrol, Austria. See more at http://www.lawine.at

Figure 2. "Secondary-referenced, descriptive, super regional representation." Small-scale, administrative overview of North American and International Avalanche Centers. North American Avalanche Centers (2002). See more at http://www.avalanche.org/

Figure 3. "Primary-referenced, descriptive, local representation." Map-related representation and large-scale thematic, topographic map with potential avalanche risk. Left: Photographic panorama, Silvretta. Right: Potential avalanche risk map, Silvretta (Kriz and Galanda 1998).

Figure 4. "Secondary-referenced, prognostic, super regional representation." Small-scale, administrative overview thematic map of current regional avalanche risk levels . Map of Avalanche Risk Levels, Tyrol, Austria (2000) See http://www.lawine.at

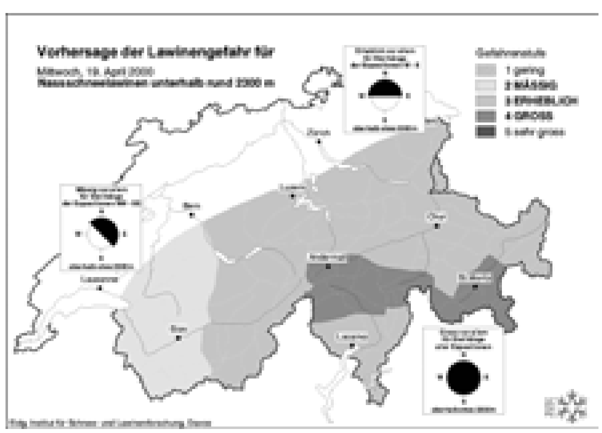

Figure 5. "Secondary-referenced, prognostic, super regional representation." Small-scale, administrative overview thematic map of current regional avalanche risk levels. Avalanche risk forecast, Switzerland. See http://www.wsl.ch/slf/avalanche/avalanche-en.html

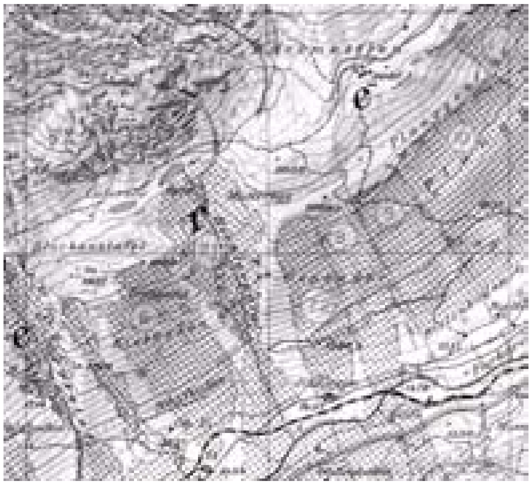

Figure 6. "Primary-referenced, descriptive, local representation." Large-scale thematic, topographic map. Avalanche Atlas Uri 1:25,000, Switzerland (Frutiger 1980)

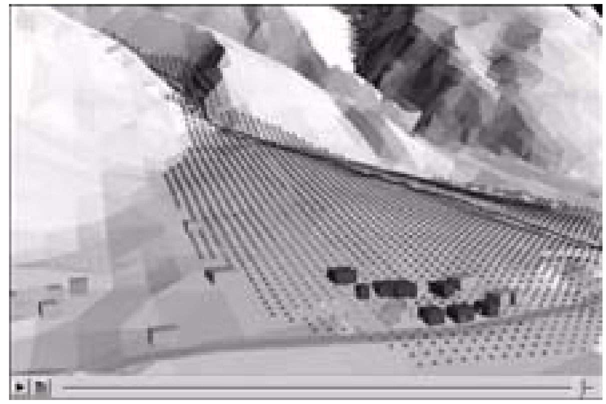

Figure 7. "Primary-referenced, descriptive, variable representation." Animation of flowheight, Avalanche Disaster in Valzur, Austria (Volk and Kleemayr 2000)

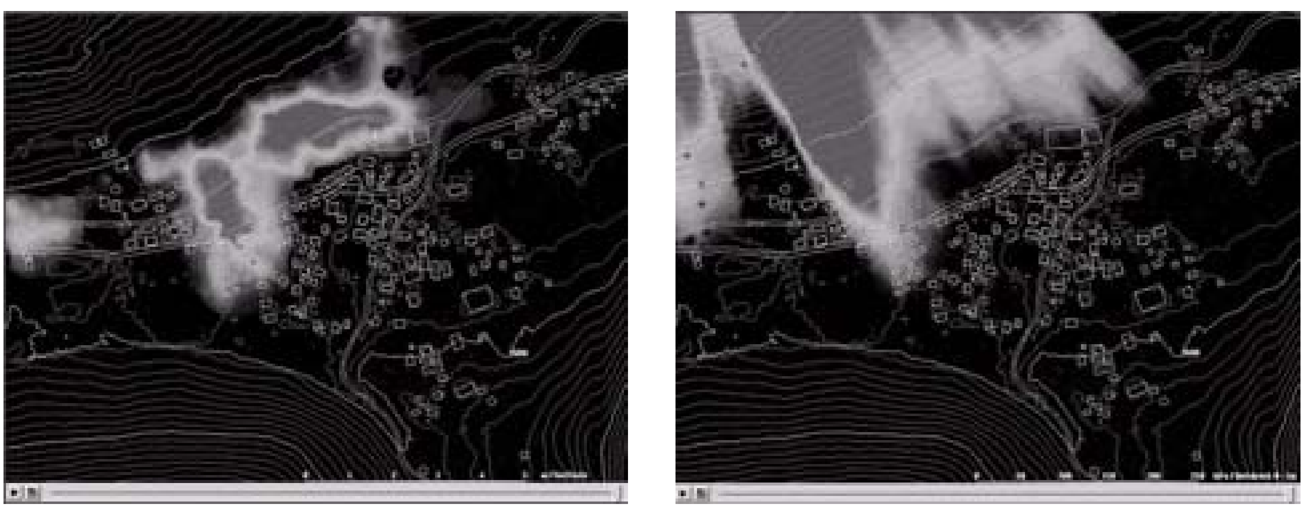

Figure 8. "Primary-referenced, descriptive, variable representation." Animation of flowdepth (left) and flowpressure (right) of the Avalanche Disaster in Galtür, Austria (2000). See http://www.lebensministerium.at

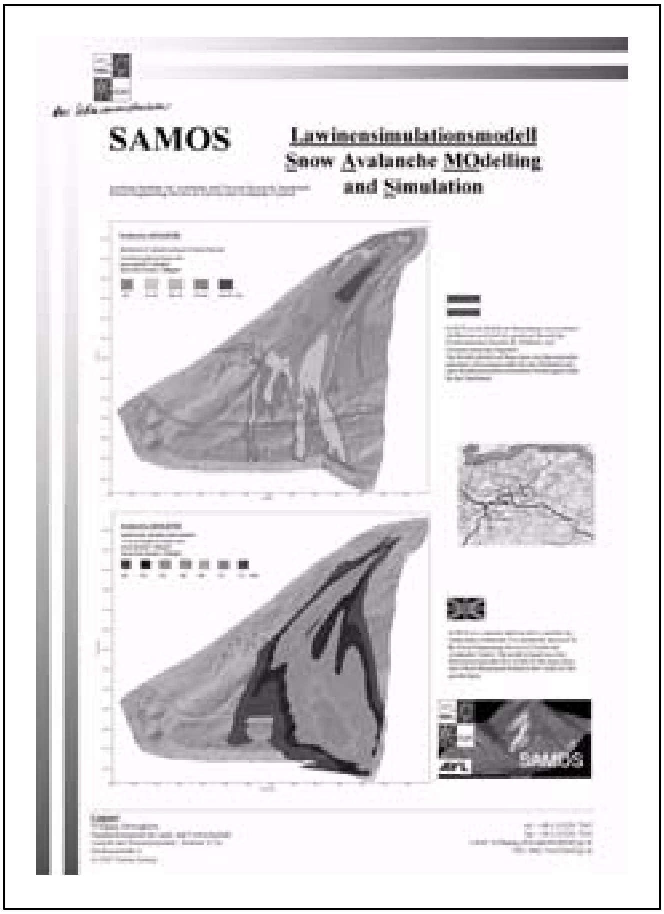

Figure 9. "Primary-referenced, descriptive, variable representation." Simulation of the Lechleiten Avalanche, Austria (2000). See http://www.bmlf.gv.at/ge/forst/wlv.html

Figure 10. "Primary-referenced, descriptive, local representation." Avalanche Disaster Galtür, aerophoto map, Austria (2000).
See http://www.tirol.gv.at/applikationen/tiris/index.shtml

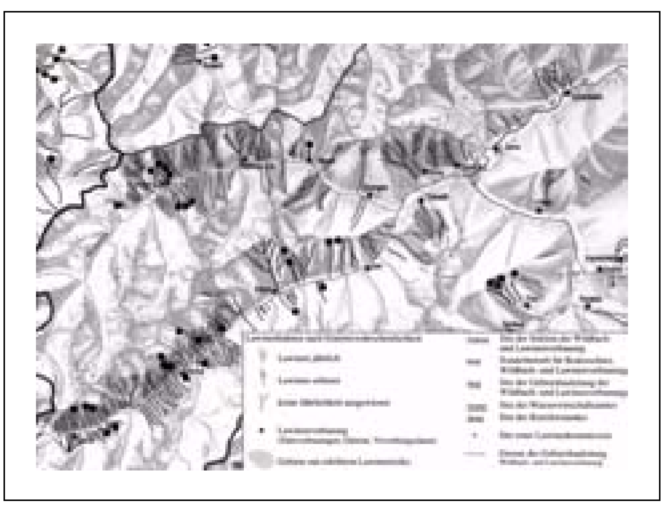

Figure 11. "Primary-referenced, descriptive, regional representation." Torrent and avalanches, Tirol Atlas, Austria (2000). See http://geowww.uibk.ac.at/land/atlas/e-lawine.html

Figure 12. "Primary-referenced, descriptive, local representation." Example from the Sign Construction Set for Natural Hazards, Switzerland. See http://www.tydac.ch/english/index.php

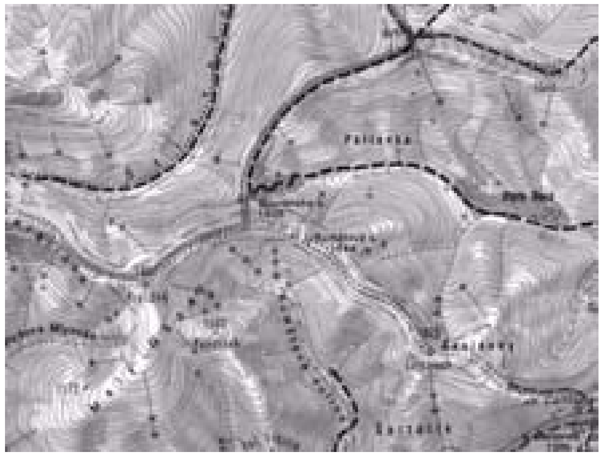

Figure 13. "Primary-referenced, descriptive, local representation." Touristic Winter Map, Nízke Tatry – zimne strediska, Slowakei, Slowenska kartografia, Bratislava 1990.

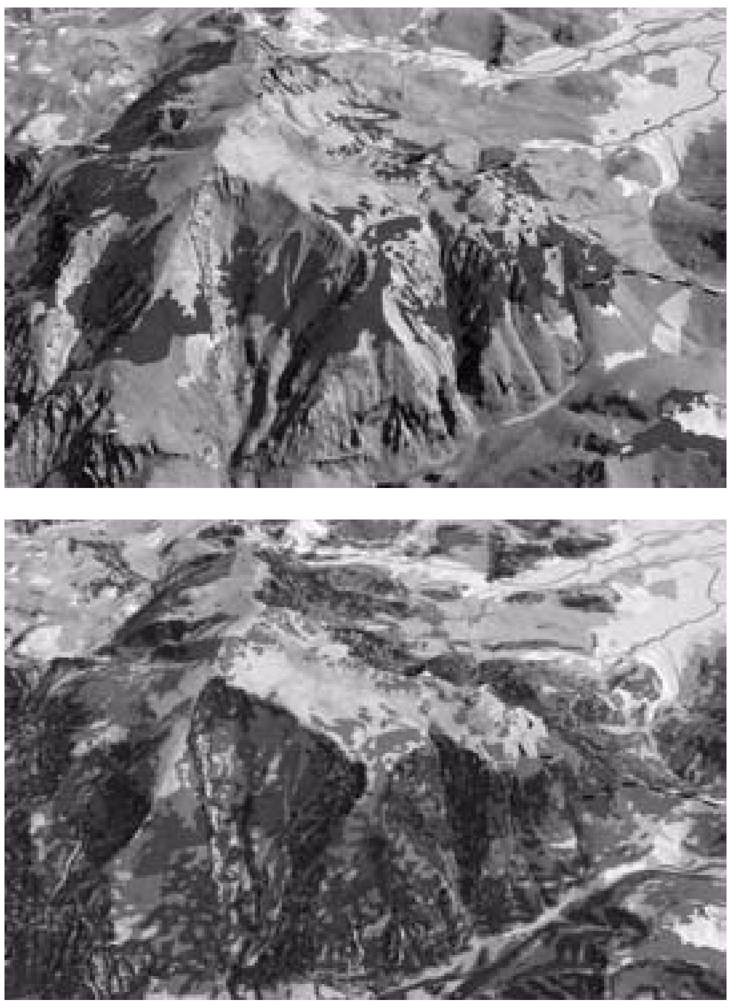

Figure 14. "Secondary-referenced, prognostic, variable representation." Top: 3-D panoramic view of Schneeberg with thematic depiction. Bottom: 3-D panoramic view of Schneeberg with avalanche relevant information – slope depiction (green 25°–35°, red 35°–45°, violet 45°–50°). See http://www.gis.univie.ac.at/karto

Outlook

The cartography of avalanches has evolved from traditionally printed maps containing static information to modern flexible presentations. The aim for the near future will be creating fully interactive and dynamic systems to represent avalanche-related phenomena. Topics like interactivity, virtual reality, GIS, and database connectivity, as well as the application of fuzzy logic to support cartographic communication, dominate current research.

Interactivity and virtual reality are the new areas of interest for cartography. The user may interact with the new artificial environment by analysing, simulating, and interpreting processes in detail. Unrestricted positions and viewpoints enable an immersive, holistic, three-dimensional insight. Thematic and dynamic-temporal contents may be freely combined and manipulated. Opportunities not previously possible, for cartography in general as well as for avalanche cartography, are unlocked by this outstanding new technology.

The importance of GIS and databases in the geoscience and geovisualization fields is constantly growing. Access to – and the processing and cartographic presentation of – recent experimental data has made rational and target-specific evaluation and analysis of avalanches possible. Decision makers at emergency operations centres and avalanche centres can access relevant data, which are presented three-dimensionally in real time. This method of data presentation will undoubtedly accelerate decision making and shorten response times in emergencies. Reliable and fast online communication and access to GIS-databases and a network of data-recording stations are major prerequisites for achieving this goal.

In the domain of avalanche investigation and cartography, uncertain knowledge is an unfortunate fact of life for making many decisions and solving problems. Fuzzy logic, used in addition to the available tools for processing data, can help manage uncertain knowledge. Sets of linguistic terms, such as “slope,” “danger,” and “avalanches” – terms that taken alone have limited meaning – can be interpreted together using fuzzy logic to represent a “slope in danger of avalanches” (Benedikt and others 2000). This approach holds much promise. Cartographers, by combining graphic multimedia variables with temporal, dynamic, and interactive components, can create completely new and informative avalanche representations. If successful, tragedies such as Galtür, 1999, will, we hope, be minimized.

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Résumé Situées dans les régions montagneuses couvertes de neige, les avalanches représentent un événement local dynamique très court. Elles ne sont pas facilement prévisibles, et ont assez fréquemment des effets dévastateurs. La cartographie d’avalanche tient compte des causes et conséquences de ces événements, et essaye de les représenter sous différentes formes. La représentation la plus classique est la carte des risques d’avalanche. Celle-ci incorpore essentiellement des éléments topographiques à grande échelle et des caractéristiques thématiques. Cependant, en plus de permettre la visualisation de ce qui s’est déjà déroulé ou de déterminer des risques potentiels, il est maintenant possible, à l’aide de la cartographie moderne, d’expérimenter des approches différentes et de visualiser des variables complexes. Cet article traite des phénomènes d’avalanche d’un point de vue cartographique, et présente le vaste choix de possibilité qu’offre la cartographie actuelle pour comprendre et prévenir ces phénomènes naturels complexes.

Zusammenfassung Lawinen stellen ein sehr kurzes, lokales, dynamisches Ereignis im schneebedeckten Hochgebirge dar. Sie sind schwer vorhersagbar und können des öfteren verheerende Folgen haben. Die Lawinen-Kartographie beschäftigt sich mit den Ursachen und Konsequenzen von solchen Ereignissen und versucht sie auf vielfältiger Weise zu repräsentieren. Die gebräuchlichste Darstellungsform ist die Gefahrenkarte. Sie umfasst primär großmaßstäbige topographische Informationen mit thematischen Merkmalen. Neben dieser gebräuchlichen Form der Visualisierung von potentiellen Gefahren ist es nun möglich mit Hilfe der modernen Kartographie neue anspruchsvolle sowie komplexe Darstellungsmethoden umzusetzen. Dieser Beitrag beschäftigt sich mit dem Phänomen der Lawinen aus einem kartographischen Blickwinkel und zeigt wie die Kartographie heute dieses komplexe Thema behandelt.

Resumen Los aludes representan un fenómeno breve, local y dinámico específico de las regiones de montaña cubiertas de nieve. No son fáciles de predecir y con mucha frecuencia pueden producir resultados devastadores. La cartografía de aludes versa sobre las causas y las consecuencias de tales incidentes e intenta representarlos de diversas formas. La representación cartográfica más común en este campo es el mapa de riesgo de aludes, que incorpora principalmente información topográfica de gran escala con elementos temáticos. Además de visualizar los sucesos y de representar localizaciones de riesgo potencial, actualmente es posible experimentar diferentes enfoques y visualizar variables complejas desde un punto de vista cartográfico. El artículo trata del fenómeno de los aludes desde una perspectiva cartográfica y muestra la variedad de posibilidades que la cartografía puede ofrecer actualmente para entender y predecir estos fenómenos naturales tan complejos.