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Cartographic Representation of Glacial Phenomena: Historical and Recent Developments

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Abstract

With the first systematic exploration of glacial phenomena in the middle of the nineteenth century, glaciology became an independent science. In parallel, glacial structures and processes needed to be visualized cartographically. Such representations always reflect the then-current states of the technology of glaciological data collection and of cartography. Already in the last century, well-designed and user-friendly glacier maps with a high information content were published with the help of precise geodetic measurements and well-developed cartographic techniques. The focus was upon statistical illustration of the changes in glacier geometry and by glacial-morphological forming. In the 1950s, glaciologists started to represent dynamic parameters such as glacier fluctuations, mass balance, and ice flow. Furthermore, the topographic information of the printed maps was supplemented by orthophotos and satellite images. Today, in the age of digital cartography, screen representations become more and more important. Using digital photogrammetry and remote sensing, new methods of geophysical sounding, or satellite-based global positioning systems (GPS), large quantities of data can be recorded. Using geographic information systems (GIS), these data can be manipulated, modelled, compiled as digital elevation models (DEM), analysed, and finally visualized interactively as high-quality maps or as perspective views. Future trends point towards comprehensive, interactive glacial information systems with integrated functions for database query, modelling, and visualization.

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Introduction

For centuries, people have been fascinated by glaciers. As an integral part of our physical environment, glaciers have been repeatedly depicted within landscapes and on maps. Beginning in the seventeenth century, glacier boundaries and surrounding terrain were included on the first large-scale topographic maps – initially as rough sketches, and later with more and more precision. Concurrent with these developments, glaciologists increasingly carried out scientific research on the structures and phenomena caused by glaciers. By the mid-nineteenth century, with the development of cartography as an independent discipline, large-scale mapping of Austrian and Swiss alpine glaciers was realized. Today, glacial cartography is an integral part of high-mountain cartography. Glaciers and surrounding phenomena substantially influence and shape mountain landscape, and ultimately, the mountain maps that represent these landscapes (Brunner 1989, Häberling 1998).

Cartographic representation of glacial and periglacial phenomena has always been determined by the general level of understanding of glaciology as a scientific discipline, the sophistication of available data acquisition and processing techniques, and the quality of available glaciological information. Last but not least, continually improving techniques for visualization are another determining factor.

This paper will discuss the presentation of glacial phenomena on maps during the past 200 years, in three sections. The first section provides an overview of the cartographic methods used for the presentation and visualization of glacial phenomena. In the second section, the fundamentals of glaciological data and the better-known data-handling methods are discussed. In the third section, an overview of the development of glaciothematic cartography is given, which is divided into cartographic time periods. Samples show the presentation styles that typified any given period, and evolutionary changes to these styles.

Glacial Phenomena

Glaciology is concerned with researching a multitude of glacial phenomena, including the resulting geomorphological structures, and those processes that influence structures. Some phenomena are macroscopic and can be observed in the landscape with the naked eye. On the other hand, many processes occur in a microscopic sphere, or in a sphere that isn't optical at all. Those processes can be observed and researched only by using scientific techniques. Over time, the scope of research has widened significantly. Earlier, its focus was on static quantities; today, more and more attention is paid to dynamic spatio-temporal processes (Kääb 1998, Haeberli and others 1999). The brief discussion that follows examines the most important phenomena to date that have been used to thematically visualize glacial cartography.

GEOMETRY MODIFICATION

The situation and modification of glacier-surface geometry, which has been thoroughly researched through the centuries, are the most distinguishable phenomena to be observed. The changing shape of glacier outlines as they advance and retreat has been a consistent theme of cartographic representation.

GLACIAL MORPHOLOGY

The forces exerted by glaciers gradually and substantially shape their environment. Wherever glaciated territory is freed from its icy burden, visible traces remain. A wide range of geomorphological processes are involved. In addition to the effects of ice, environments near or adjacent to glaciers are subject to periglacial processes, such as denudation or glacio-fluvial erosion (Maisch 1992). The resulting landscape elements are very diverse and widely varying in size and shape. Some are constant, while others are fashioned by additional forces. Besides various types of moraines, other dominant elements found in periglacial landscapes are glacial grindings, melt-water channels, sandy surfaces, and debris slopes, to name only the most important ones. Periglacial phenomena are well-suited for cartographic registration because of their readily identifiable appearance and simple delimitation.

MASS BALANCE OF THREE-DIMENSIONAL PROCESSES

Changes to the outlines of glacial structures as described above represent only one late link within the chain of glacial and periglacial processes. Mostly they are the result of spatial, three-dimensional processes, mirrored in the "mass balance." Indicated by changes in height, mass gains or losses, and shifts in mass, three-dimensional changes (kinematics) of glacial processes play an important role in glaciological research.

ICE FLUX

The most important kinematic process within a glacier is the flux of ice, which is responsible for all visible changes in a glacier's geometry and outline. The spatial distributions of ice velocity (velocity fields) or their spatial gradients (strain rate) are of interest. For example, strain rates are closely linked to crevasse formation. Frequent but temporary changes to flow velocity are examined as well. Glacio-thematic cartography is concerned with processes involving the complex variables of space and time (Kääb and Funk 1999, Kääb 2002).

PERMAFROST

Periglacial mass transport is another prominent process, one that has received less attention by researchers. Permanently frozen debris may creep slowly down slope if the inclination is sufficiently high, sometimes forming rock glaciers – conspicuous elements of the high alpine landscape. These "rock streams" are to be found in dry, cold, alpine regions and are defined essentially by their spatial kinematics. Knowledge and representation of kinematics provide important hints about the formation, evolution, and morphology of these landscape elements. In the case of rock glaciers, changes to their geometry are a function of material movement and climatic influences. Depending on their material properties, rock glaciers creep along at only a few centimetres or decimetres per year. Changes to the height typically occur in similarly small increments. These small rates of change present a challenge for cartographic visualization (Kääb 2002).

SLOPE INSTABILITIES AND LAKES

Slope instabilities and lakes are two more periglacial phenomena that tend to leave distinctive features upon a landscape. When valley flanks are relieved from the weight of retreating glaciers, destabilization of large slope sections may occur. The rate of change for these slope instabilities ranges from a few millimetres to several metres per year. As with the other cases described previously, change in surface geometry occurs as a result of spatial processes.

Glacial and periglacial lakes are situated on or near glaciers, or areas influenced by glaciers and permafrost. These lakes are impounded by advancing glaciers, fill tongue-basin depressions, or are dammed by moraine ramparts left behind by retreating glaciers. They are subject to constant exogenous fluctuation, because glaciers and permafrost conditions, upon which the existence of glacial and periglacial lakes depends, continually change. Lakes that are in contact with ice also experience thermally induced endogenous change (Haeberli and others 1999).

Basic Data and Recording Methods

Cartographic representation of glacial phenomena is concerned with a highly unstable space, which rarely behaves statically. The survey data to be represented have a space and time relationship. All structures and processes need to be referenced by a geographic coordinate system and a time axis.

TOPOGRAPHY

One of the most important basic issues is to ascertain a precise description of terrain surfaces. This includes quantitative topographic parameters, such as height, slope, or aspect, and qualitative terrain parameters as well. Historically, only classical terrestrial surveying was applied using levelling and plane-table techniques. Information about terrain geometry was stored using solitary spot elevations and contour lines. Today, terrain and glacial-surface phenomena are more often measured using air- or space-borne methods. Researchers work extensively with digital elevation models (DEMS), which are well-suited to automation. DEMs allow a multitude of digital functions to be applied for generating a wide range of products. The spatial resolution of DEMS tends to increase constantly. In addition to analytical and digital photogrammetry, DEMS nowadays can even be produced using laser scanning and microwave sensors (INSAR, for example).

GEOMETRY OF THE GLACIER BODY

Measurement and representation of glacial fluctuation is largely determined by the sophistication of data-capturing technology. With the first historical methods, change was measured from single control points or control points arranged in lines. Typically, glacier height and speed were measured from a combination of longitudinal sections and cross-sections, or from single stakes. However, an accurate measurement of geometric changes, or even speed, can be captured only by using modern technology (Kääb and Funk 1999, Kääb 2002). Highly precise measurements are particularly necessary to determine speed fluctuations or spatial gradients within a velocity field. These measurements are obtained by analytical photogrammetry, differentiated GPS, or up-to-date terrestrial geodetic techniques.

INTERNAL ICE STRUCTURE

The techniques mentioned in the preceding paragraph yield mostly surface information. Geophysical methods, however, provide detailed information about the internal (subsurface) structure of glaciers and permafrost. Such data challenge glacial cartographers with how to represent hitherto unseen variables.

DATA MANAGEMENT

Data-management and data-processing developments within geographic information systems (GIS) also exert a significant influence upon the presentation of basic cartographic data. GIS has steadily increased in importance in glaciology. It provides ready-to-use cartographic tools, which greatly simplify the visualization of data. Thus, repetitive procedures may be completed more quickly than with analogue techniques.

MODEL CONSIDERATIONS

While spatial and temporal resolution and accuracy of terrain data are being improved, the importance of data modelling is also on the rise (Kääb and others 2002, Paul and others 2002). Physical-numerical models permit a three-dimensional simulation of dynamic or energetic processes, thus significantly enlarging the scope of basic cartographic data. These simulations typically produce three-dimensional results that also show temporal change. They are not strictly confined to visualizing collected data, however, since simulations even allow glimpses into the past and future.

Methods of Representation in Glacial Cartography

BEFORE 1950: PIONEERS OF GLACIER CARTOGRAPHY

Beginning in the first half of the sixteenth century, depictions of glaciers occur in topographic maps and landscape paintings from Europe's alpine countries and from Iceland (Brunner 1989). As would be expected, given the rudimentary cartographic techniques of the time, glaciers and periglacial phenomena were represented rather schematically, as were other elements of natural topography (Figure 1).

By the mid-1800s, the pioneers of European glacier research began carrying out the first systematic observations of alpine glacier coverage. A series of measurements on the Rhône Glacier, Switzerland, started in 1874, is probably the longest recording of its kind ever conducted (Figure 2). It wasn't until then that the need arose for exact scientific mapping of glacial phenomena.

Until the mid-twentieth century, glacial research contented itself with the simple mapping of glacial geometry, and with recording a very limited number of glacial phenomena. This mapping, often in the form of sketches, was primarily concerned with visible physical features, such as the delineation of glacial boundaries, crevasse areas, and debris fields. They are restricted mostly to purely static depictions of survey data. Representation of other measured glacial data was attempted only rarely. Interest was limited to the speeds of advancing glacier tongues, attained by geodetical stone row surveys, and to changing ice thickness in the terminus area, attained by stake measurements. These measurements were depicted in exemplary large-scale maps (1:5000 and larger) and could be contrasted with historical topographic base maps.

The measurements taken were generally quite precise. Unfortunately, revisions and updates were rarely undertaken, which means that mostly single research work exists. Map-manufacturing techniques were adequately sophisticated for scientific purposes. Copperplate engraving or lithography was commonly used, and together with the multiple-colour intaglio printing techniques of the day, these methods yielded very detailed paper products. We are able to deduct scientifically sound information about historical glacier extent from these large-scale records.

FROM 1950 TO 2000: MODERN GLACIAL CARTOGRAPHY

The last five decades have witnessed increased glaciological research in several countries. Since the 1950s, many

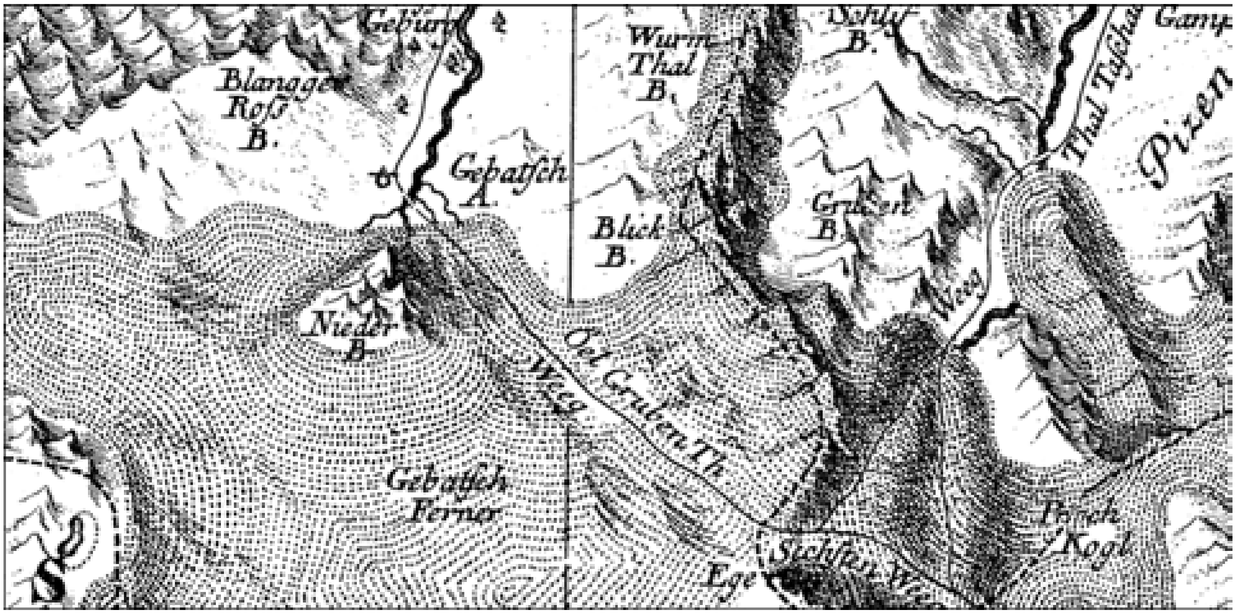

Figure 1. Reduced section of the "Atlas Tyrolensis," featuring the "Weisskamm" within the Ötztal Alps (Austria). Remarkable is the depiction of glacier surface with dotted lines and perspective depiction of mountain ranges ("mole-hills"). (Published by Peter Anich and Blasius Huber, 1774.)

Figure 2. Reduced section of the topographic-thematical map "The Rhône Glacier and Its Ice Movements 1874–1900" (Switzerland); scale 1:5000. With the help of marks on the ice, flux quantities were captured each year of observation, and they are represented by a colour scale. (Supplement to "Rhônegletschervermessung – Neue Denkschriften der Schweizer. Naturforschenden Gesellschaft." Vol. 52, plan #3. Bern: Federal Office of Topography, Wabern, Switzerland, 1916.)

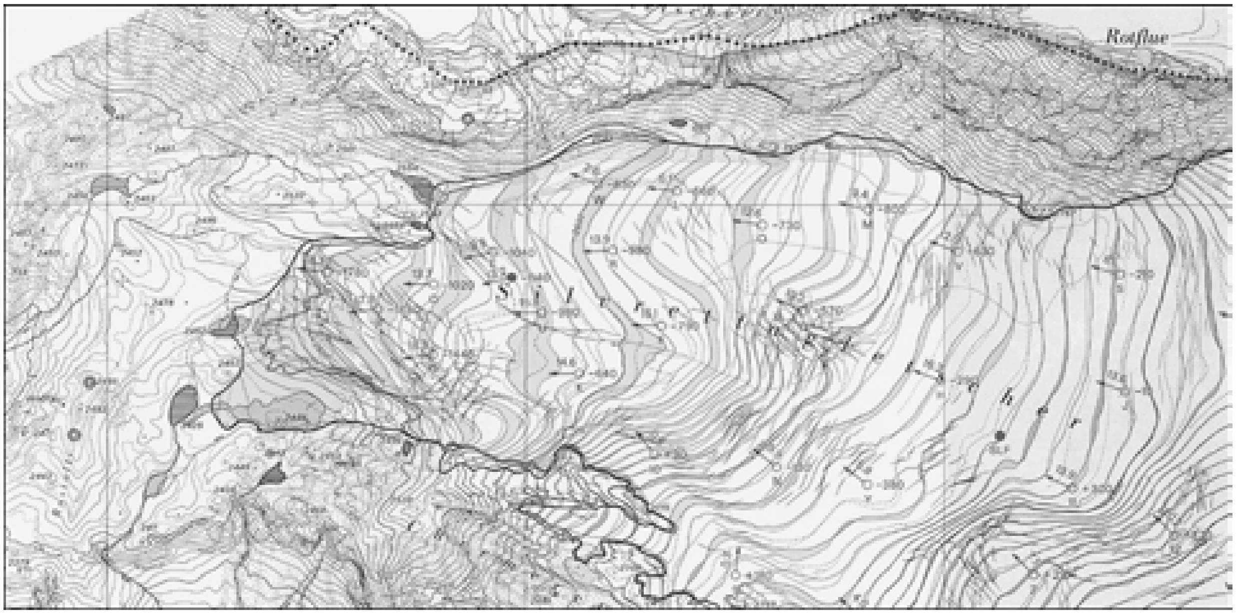

Figure 3. Reduced section of the topographic-thematical glacier map "Silvretta, Verstancla and Chamm Glaciers" (Switzerland), state of 1959 and 1973; scale 1:10,000. Primarily change in glacier depth, quantities of ice movements, and situation of glacier and snowfield borders are visualized for each year of observation. (Published by Federal Office of Topography, Wabern/Berne; by the Department for Hydrology, Hydraulic Engineering, and Glaciology at the Swiss Federal Institute of Technology, Zurich; and by the Glacier Commission of the Swiss Natural Research Society Zurich, 1976; reproduced by permission of the Federal Office of Topography, Wabern, Switzerland (BA035538).)

colleges, universities, and state institutions have collected a large number of glaciological data, which have found their expression in a multitude of scientific glaciological representations. Today we are able to refer to systematic records on the current state and historical evolution of numerous high-mountain and inland ice sheets. Public awareness of global glacier decline from the middle of the past century has contributed to increased global glaciological research (WGMS 1998). National glacier inventories, of varying scope, have been published. Also during this time, several methods of representation were developed and widely implemented. Many are still reproduced and valued for their outstanding quality.

Topographic–Thematic Glacier Maps

Perhaps the best-known map type – topographic-thematic maps – are well suited for depicting glacial structures and processes. Official topographic maps are generally suitable as base maps. These are still revised periodically by national surveying agencies using aerial photography or – more and more rarely – terrestrial photography. Thus, map series can be produced on the basis of corresponding spatial references, which at the same time contain up-to-date thematic glaciological information. Thus traditional orthogonal perspective is used consistently. Scale may vary between 1:5000 and 1:10,000. Finished maps are usually printed on paper.

Topographic-thematic maps frequently describe change in glacier geometry by showing the surface overlap of corresponding glacier extents at a given time. Additionally, all localized glacio-historical traces can be included. These include moraines and objects released by melting ice – trees, rocks, soil, and synthetic relics, such as water-conduits and buildings. Flow velocity or direction may be integrated using extra vectors within surface representations of glacial bodies. Measured changes of ice depth are visually represented by comparing contour lines. Consistently recorded geometrical and other measured data are integrated into and processed into this type of map. Only the background base map depicts topography. These maps are published mostly as single sheets; their representations present glaciologists with a means to visualize research data. They are also suited for educational purposes (Figure 3).

Glaciological Orthophoto Maps

Beginning with the early 1970s, the use of orthophotos as base images has become more widespread in glacier mapping (Brunner 1988). Basic data are obtained from optical or radar images, rectified differentially, and regenerated as geo-referenced images in orthogonal projection. Those colour or greyscale images are often large-scale and depict the terrain surface in a photo-realistic way. With orthophotos, glacial information can be kept

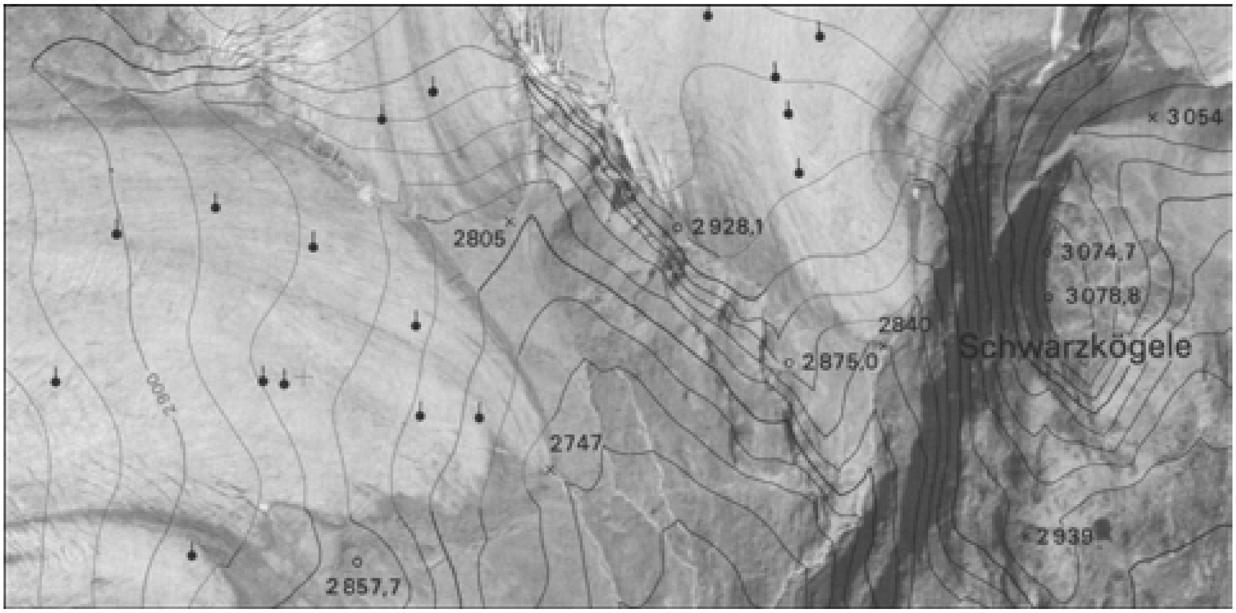

Figure 4. Section of the orthophoto map "Vernagtferner 1990"; scale 1:10,000. Topography is transmitted by the coloured orthophoto, as well as by deducted contour lines and altitude data. As additional glaciological information, stake positions are symbolized cartographically. (Published by the Commission for Glaciology, Bavarian Academy of Science, Munich, 1992.)

in precise registration with the surface of the glacier and surrounding terrain. Before the digital era, orthophoto creation was a sophisticated and difficult undertaking, which explains why early orthophoto maps tend to be single representations. Most orthophoto maps are printed on paper (Figure 4).

By using orthophotos as base images (at scales ranging from 1:2000 to 1:200,000), visible macroscopic glacial structures, such as boundaries, crevasse systems, debris, and firn cover, and melt water channels may be easily delineated on glacier maps. Adding topographic information, such as contours or altitude tints, completes these maps. Additional data, or qualitatively homogenous terrain, may be symbolized by point, line, or area map symbology. This abstract thematic imprint is simply compared to naturalistic surface information. Introduced elements, however, need to contrast well with the base image. Placing two or more orthophotos taken at different times upon one another can be done technically, but usually results in dense, illegible information.

The great advantage of this static map type is visualization that is closer to nature, which helps make the interpretation of surface information easier for readers. Orthophoto maps are a valued information source for glacier inventories.

Satellite Image Maps

Similar to orthophotos, satellite images are used in glacier cartography as orthogonal base images (Figure 5). Although modern satellite technology has been raised to an astonishing level in the last years (IKONOS satellite images have a ground resolution of one metre), the low resolution of most of the former space-borne sensors (for example, SPOT, Landsat) compared to orthophotos (one pixel will often represent more than 100 square metres in nature, which obscures delicate structures) render them unsuitable for detailed representation of glacial phenomena. Recognizing interrelationships with topographic microforms is close to impossible. Nevertheless, small-scale satellite images offer a great advantage for depicting and mapping large and difficult-to-enter glacier surfaces. Thanks to repeated imaging of the same area over time, satellite images are particularly suitable for continuous monitoring programs.

Manually Produced Map-Related Representations

In addition to standard orthogonal maps, more exotic map-related representations have been used sporadically for several decades to visualize glaciological phenomena. In glaciology visualization, specialized perspective representations have been used, such as block diagrams and panoramic views (Figure 6). Three-dimensional depictions, most often showing a small portion of a landscape, provide a simple way to explain complex glaciological information to readers, if the depiction direction and distance are favourable. On 3-D representations, topographic information is not only transmitted numerically and graphically, by means of altitudes and contour lines, but an intuitive feeling of space is provided by perspective and shading. As for content, these static depictions

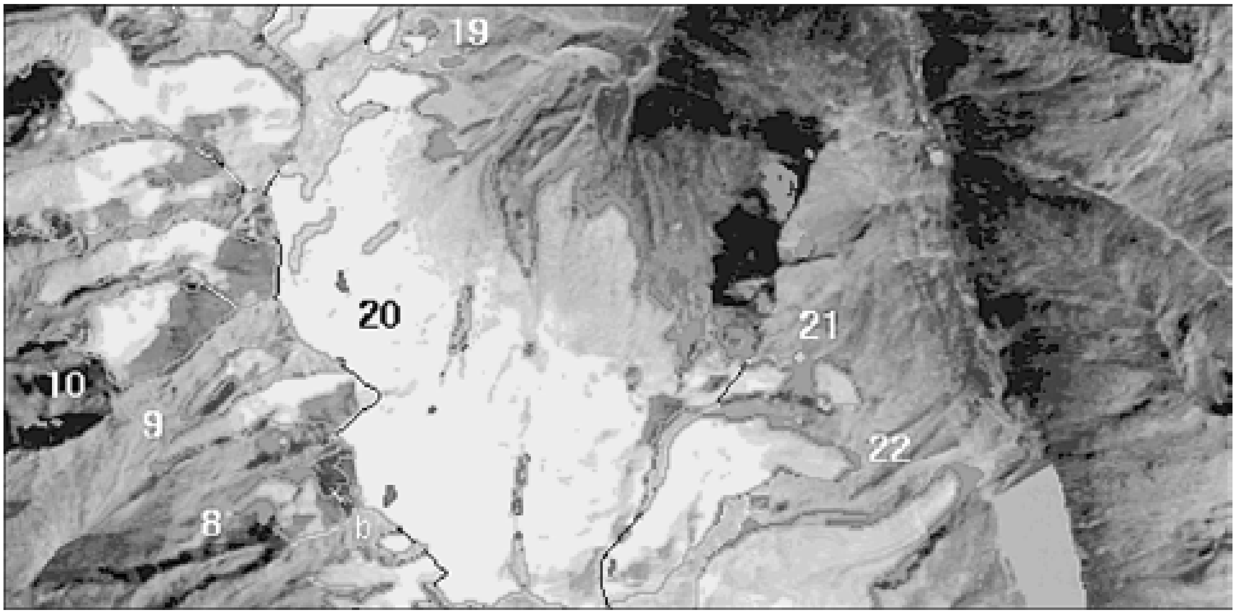

Figure 5. Glacier map based on a Landsat satellite image with automatically classified glacier surfaces from the Mischabel mountains (Switzerland). (Paul and others 2002.)

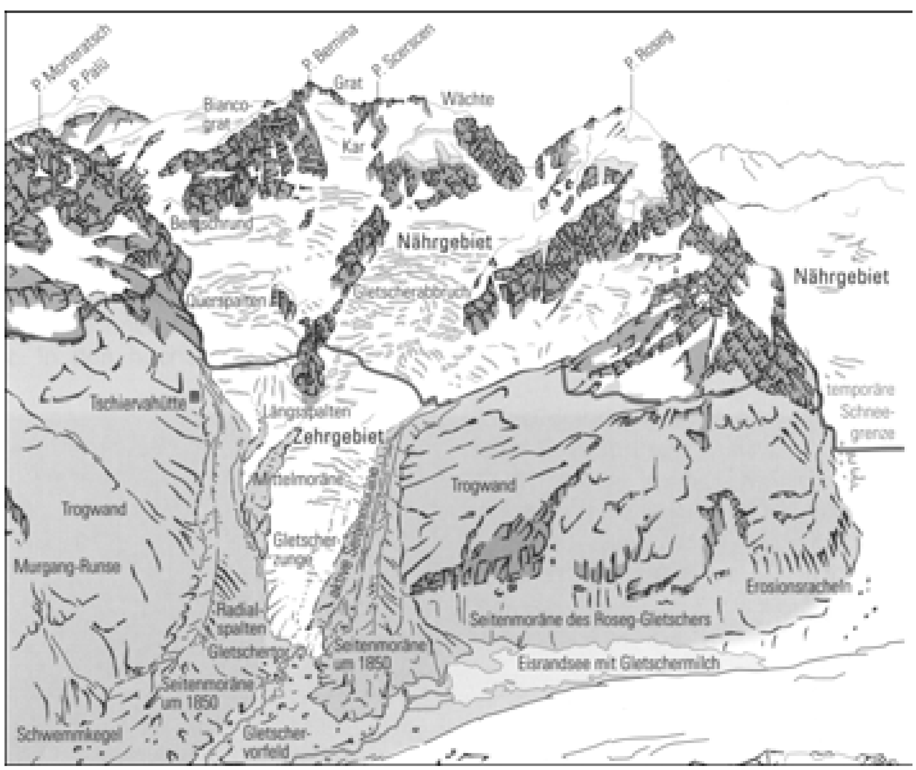

Figure 6. Perspective sketch of the Tschierva Glacier's landscape (Switzerland), with inserts of glacial phenomena and elements of topography and locations for orientation purposes. (Burri 1995.)

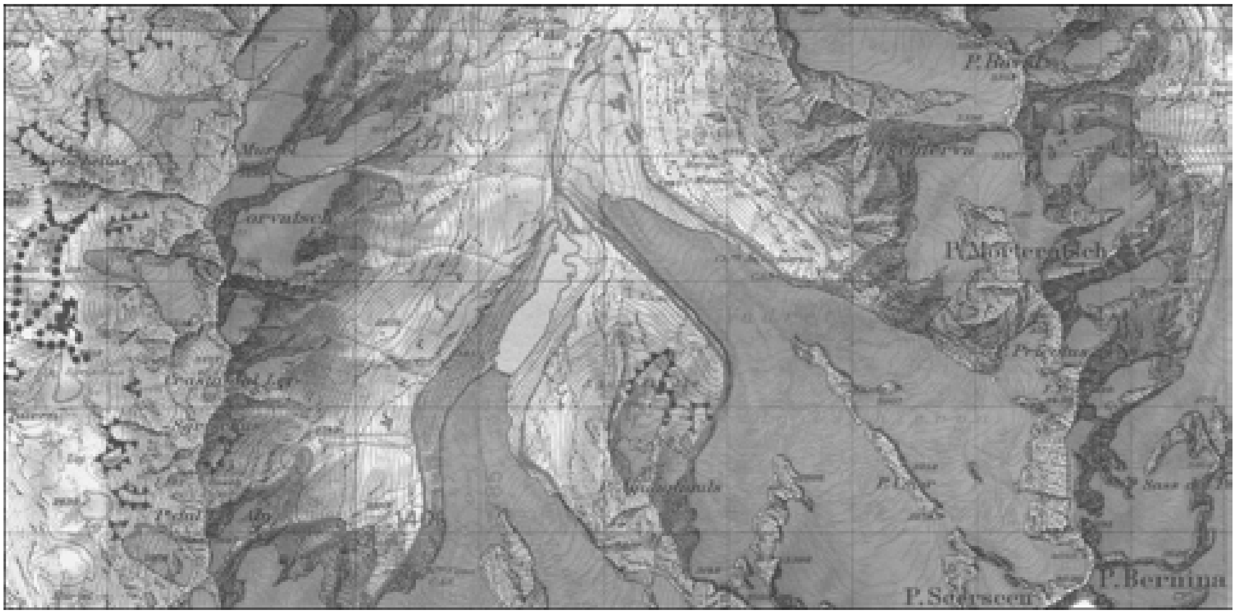

Figure 7. Section of the glaciological synthesis map "Julier-Bernina" (Switzerland); scale 1:60,000. Glacier positions of 1850 and 1973, as well as periglacial phenomena, were drawn from a GIS database. The probability of permafrost occurrence was obtained with DEM analysis. (Base map: © Federal Office of Topography, Wabern, Switzerland (BA035538). Published within the Swiss National Research Program NRP 31, Climate Changes and Natural Disasters, *1998.)*

are limited to naming and structuring a local situation, modifying glacial extent, depicting glacio-morphoAs a result of perspective distortions, variable scale, and hidden areas of the terrain that cannot be seen from a particular viewpoint, these representations do not allow for thorough analysis involving measurement. They are used primarily as illustrations in scientific publications, or as a learning aid in textbooks. For the period under discussion, most 3-D representations were produced manually. Often a photograph was used simply as a reference for a hand painting of a landscape. In a next step, glaciological information was introduced to the picture. Cartographic revision was limited to conventional illustration and reproductive methods.

RECENT DEVELOPMENT: RISE OF COMPUTER-BASED REPRESENTATIONS

The rapid development in recent years in computer measuring and communication technology has pointed glaciology towards new horizons in the areas of data acquisition (density and accuracy), data management, and visualization. In spatial data processing, GIS has gradually become the dominant technology. With the help of these systems, glaciologists may efficiently and lucidly manage researched glacial phenomena upon a large, clearly defined, and geo-referenced terrain. Besides orderly data management, these systems present the researcher with extensive possibilities for the assessment of existing data, for modelling new concepts in glaciology, and for combined analysis with DEMs. Today, a wide spectrum of continually up-to-date basic data is at our disposal, ready for cartographic visualization. Progress in computer graphics and hardware enables cartographers to deduct complex visual products from processed glaciological and geodetic data files. Thus, not only are we able to use developed, computer-based printing techniques for producing high-quality paper maps, we may, enabled by digital technology, also visualize data on a screen, or use it within new information media, such as digital multimedia atlases or animated computer presentations adapted for a multitude of communication channels.

The following two map types exemplify the state of the art in modern, computer-generated representation of glacial phenomena.

GIS Maps

The glaciological-thematic content of so-called synthesis maps is deducted from GIS data files and other databases. In addition to the glacial and periglacial structures mentioned earlier – glacial stages, snow-lines, and geomorphological structures – synthesis maps also include dynamic flux data in defined situations, or virtual data calculated analytically, such as the glacier's equilibrium lines or potential occurrences of permafrost. They are also called GIS maps, in order to stress the source of visualized basic data. Official topographic maps, or aerial photographs and satellite images, serve as a base image for these two-dimensional representations. Using GIS, image bases may be geo-referenced with stored glaciology data. With the help of integrated cartographic tools

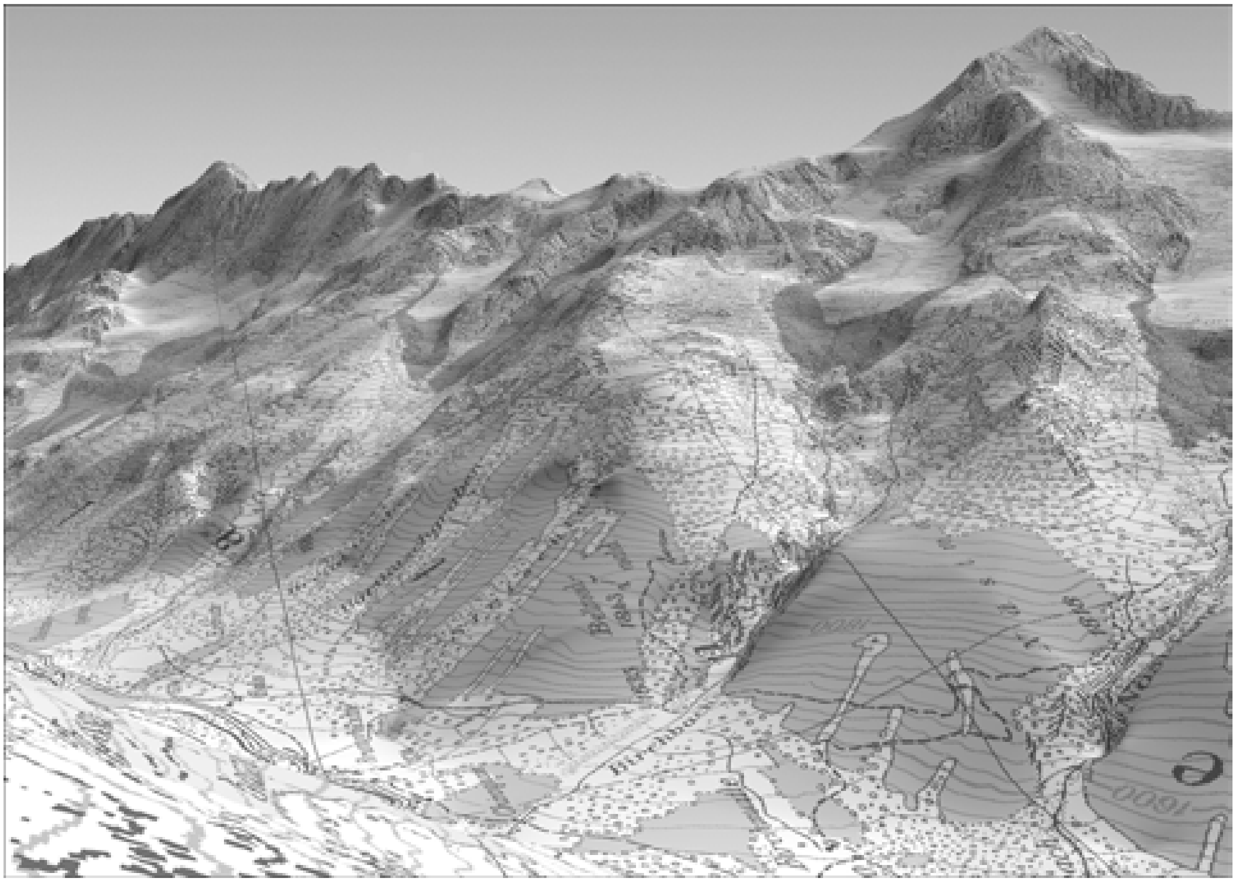

Figure 8. Perspective view of glaciated Bietschhorn area (Switzerland). Presented is the glacier surface cover of 1850 and 1973, computed with DEM data, topographic raster map and glacier geometry data out of a GIS database. (Data source: ©Federal Office of Topography, Wabern, Switzerland (BA035538).)

and auxiliary graphical or CAD software, GIS data can be portrayed with cartographic symbols, edited digitally, displayed on screen, or printed on paper (Figure 7).

Computer-Generated Map-Related Representations

Computer technology, used in conjunction with DEMS and large glacial GIS data files, facilitates a wealth of analytical visualization possibilities. Sophisticated visualization software offers extensive possibilities for the purely digital generation of entire landscapes, with interactive control of the viewing angle. Such glacial information may be represented on DEMS by combining two methods. It can be transformed into a raster file and superimposed upon the topographic surface (Figure 8). Or glaciological data may be retained as vector data, which can be used directly for model computing. Computer-generated perspective representation is particularly suited for a deeper understanding of relationships between a glacial theme and its associated topography. This method of representation is used mostly for illustrating spatially limited phenomena (Figure 9).

With software applications from the field of scientific visualization, analytical representations are specifically used to single out interesting phenomena, which in earlier times were difficult to measure and depict cartographically (Figure 10). Long-duration time series can be generated from animation software in order to model and visualize entire process sequences (Figure 11).

Depending on the presentation's purpose, the rendering medium is chosen. If a paper map or illustration is needed, perhaps for a scientific publication, a print-ready representation may be obtained by editing the image graphically. However, computer-generated visualizations can be used in virtually any digital application, particularly as static images, or as dynamic animations in electronic media (for instance information systems on CD-ROM, video sequences).

THE FUTURE: DEVELOPING INTEGRATED REPRESENTATION SYSTEMS

The global trend towards ever more extensive use of computer technology applies to glaciology as well. Computers will be applied to every stage of research. The capture of glaciological data will occur in even greater

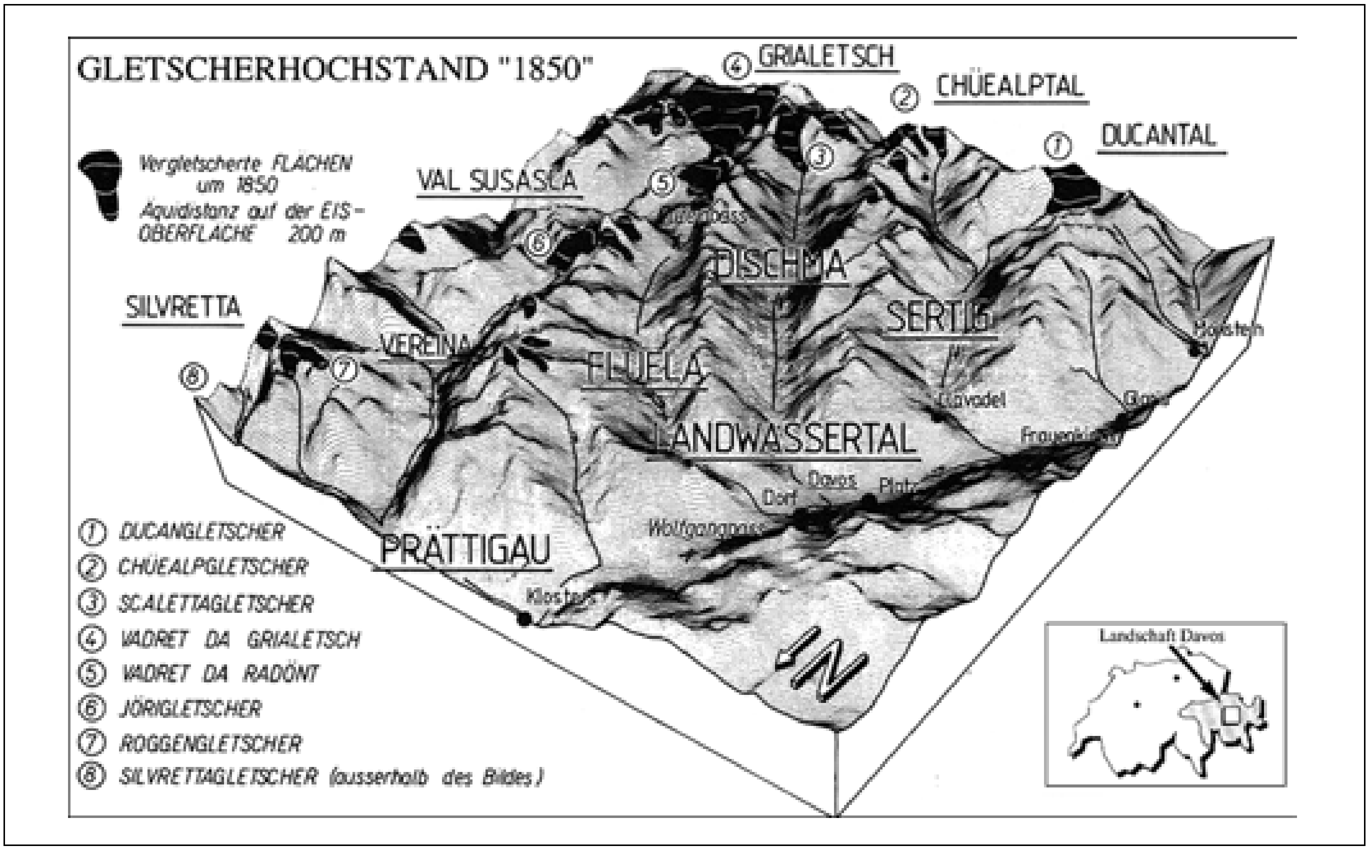

Figure 9. Computed block diagram of the Davos landscape (Switzerland) featuring glaciers at the time of maximum position 1850; published 1992. Terrain is represented by diagonal cross-section lines. (Maisch 1992.)

density, with greater accuracy, and more frequency. Information will be integrated, managed, analysed, and modelled in more powerful GIS applications and databases. Last, but not least, elegant yet powerful on-line computers offering visualization tools will become more functional and user-friendly. In an era of visual communication, glaciologists will increasingly present the results of their research using customized techniques of representation, which also facilitate widespread publication. Two emerging methods of representation give us a hint of the future: interactive atlas information systems, and integrated glacial information systems, which are discussed next.

Interactive Atlas Information Systems

The significance of glaciological atlas information systems will continue to grow. Interactive atlas information systems will integrate edited GIS data databases that are accessed and processed by a number of multimedia functions. Additionally, up-to-date alphanumerical data and supplementary information on studied glacial phenomena contain the geo-referenced geometry as vector data. DEMs and raster maps or images serve as a topographic base maps. On the basis of these map models, individual orthogonal and perspective views can be generated as desired, and may be combined with thematic features and other data. Standard functionality will focus on the simple qualitative and quantitative analysis of map content, and on displaying the findings. From these data files, even animations can be generated to show dynamic glacial processes, such as modification of glacier extent, or the intensity of change to stationary measured data. Interactive control over the data will be limited, at least at first, to give the software a user-friendly graphic user interface and compact architecture. Finally, limited Internet functionality will be possible.

Glacial Information System with Functions for Analysis and Simulation

A long-term vision and goal for the representation of glacial phenomena is the development of a comprehensive glacial information system (Häberling 1998). It would feature elaborate multimedia tools for interactive graphical visualization of measured glaciological data displayed in combination with DEMs. Such a system would allow glacial stages, glacier bodies, and dynamic glacial processes (for example, glacier fluctuation, ice flux, and snow melt) to be animated (Figure 12). Another partial goal would be to predict change in glacial phenomena based on climate modelling, analysis of the resulting representations, and reintegrating the final analytical results into the database. Networking different glaciological GIS

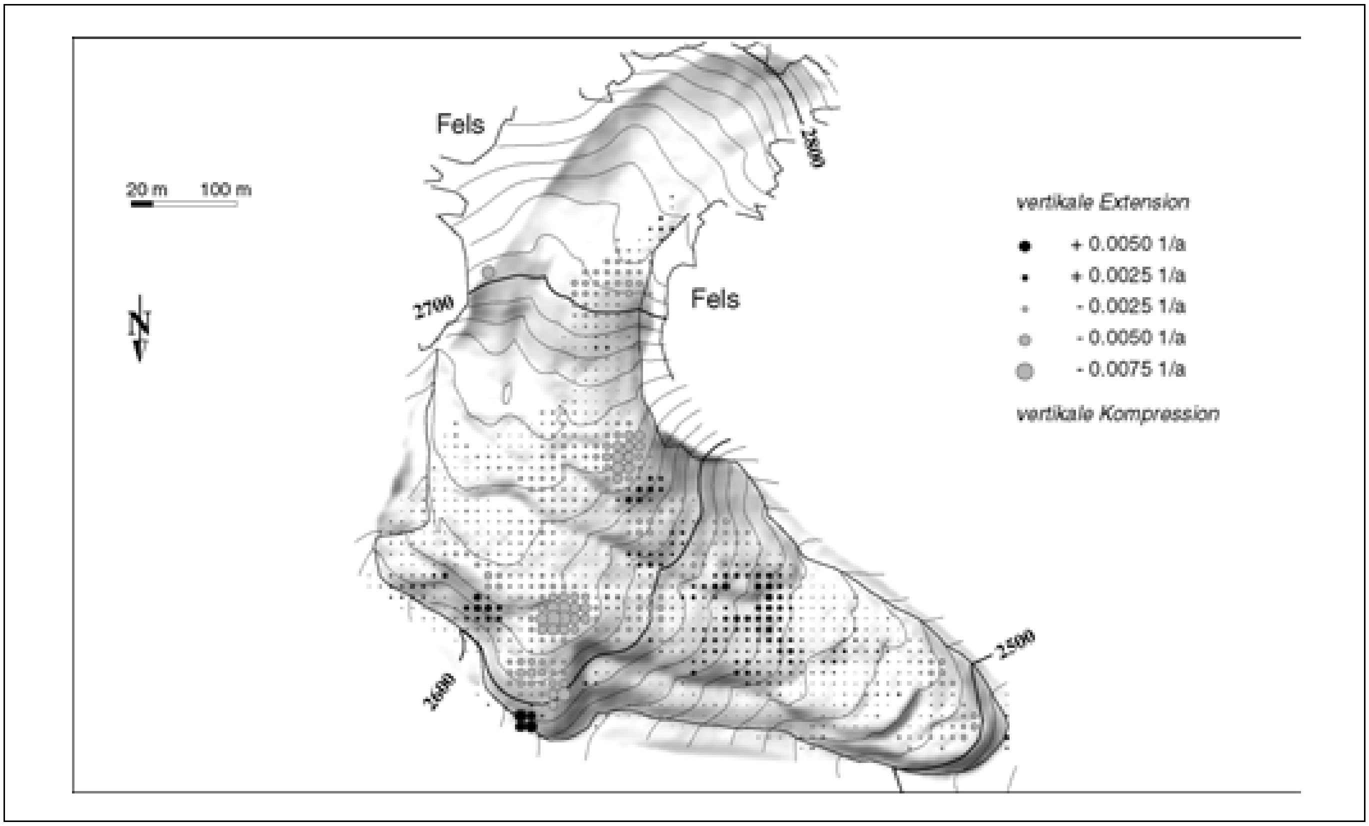

Figure 10. Analytical representation of longitudinal strain rate of Muragl rock glacier (Switzerland). Rates indicate extensive or compressive flux of permafrost, which in turn suggests where the creeping mass is dilating and where it is compressing. Spatial deductions have been calculated from the two-dimensional flux field. (Kääb 1998.)

databases is an important prerequisite to achieving a sufficiently large database. Another important condition for developing a glacial information system is an open system environment, so that further development can take place at any time.

Conclusions and Outlook

Glaciology today is chiefly concerned with multi-dimensional ways of looking at issues – be they two-dimensional spatial structures, three-dimensional models, or even four-dimensional spatio-temporal processes. Technological progress in data capturing and data modelling has led to larger and more complex data sets. New geophysical methods are being tested to facilitate regular measurement of three-dimensional data, such as temperature distribution, flow velocity, water pressure within glaciers, and ice deformation and force.

As a result of this development, glaciologists will experience a pressing need for the adequate representation of multi-dimensional data. However, new techniques and forms of cartographic depiction can be developed only after the limitations of current visualization methods are acknowledged, and after the system requirements for a solution are formulated (Häberling 1998). It would be helpful to forge digital data and representative functions into one universal system, which would recognize both aspects as supplementary. In the future, time-tested methods of traditional two-dimensional representation of glacial phenomena (on topographic-thematic glacier or orthophoto maps) will remain useful, and therefore will be further developed. New approaches in glaciological representation, using three or more dimensions, are likely to be discovered, since emerging technology will undoubtedly be even better suited for dynamic and animated representations, as well as for analysis and simulation of structural glaciological data and spatio-temporal processes.

As a crucial player in the endeavour of visualizing space-related data, cartography – together with glaciology – faces the challenge to offer informed and intelligent solutions for representing glacial phenomena.

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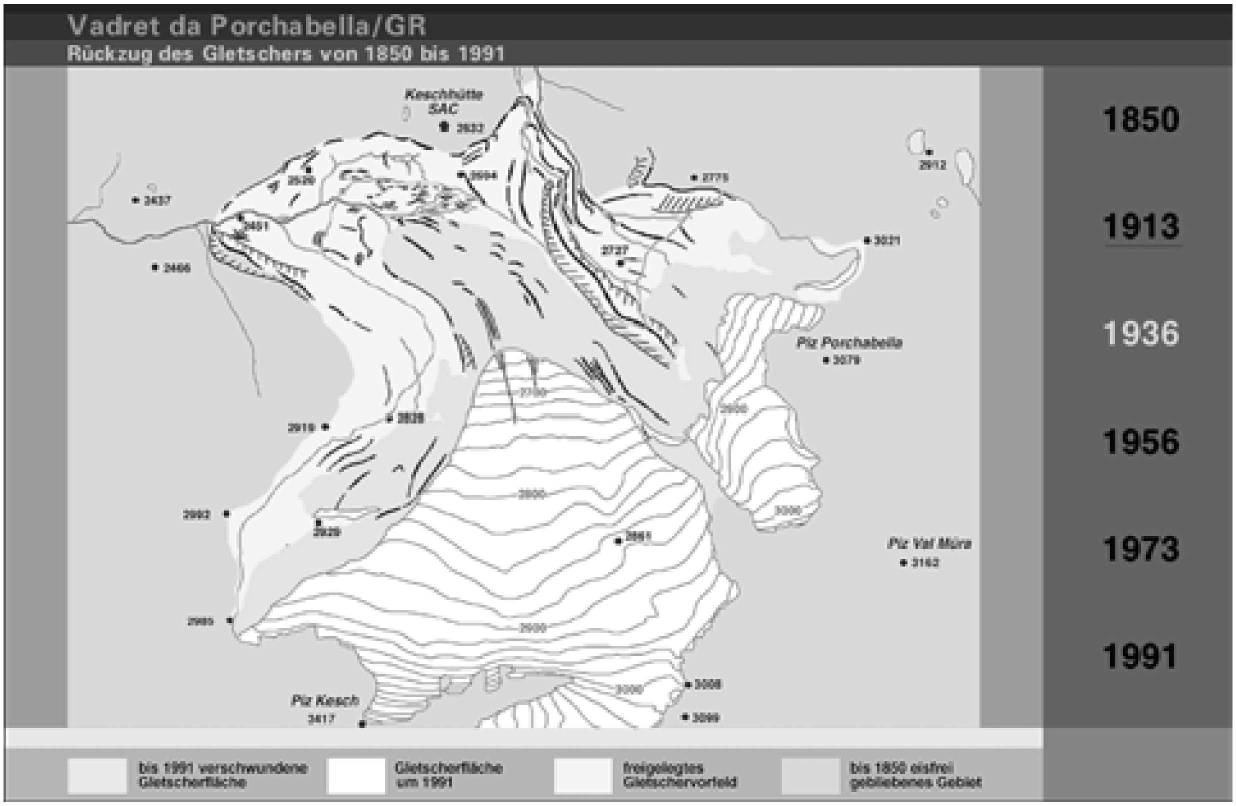

Figure 11. Screen shot from a computer animation on the retreat of Vadret da Porchabella (Switzerland) from 1850 up to 1991.

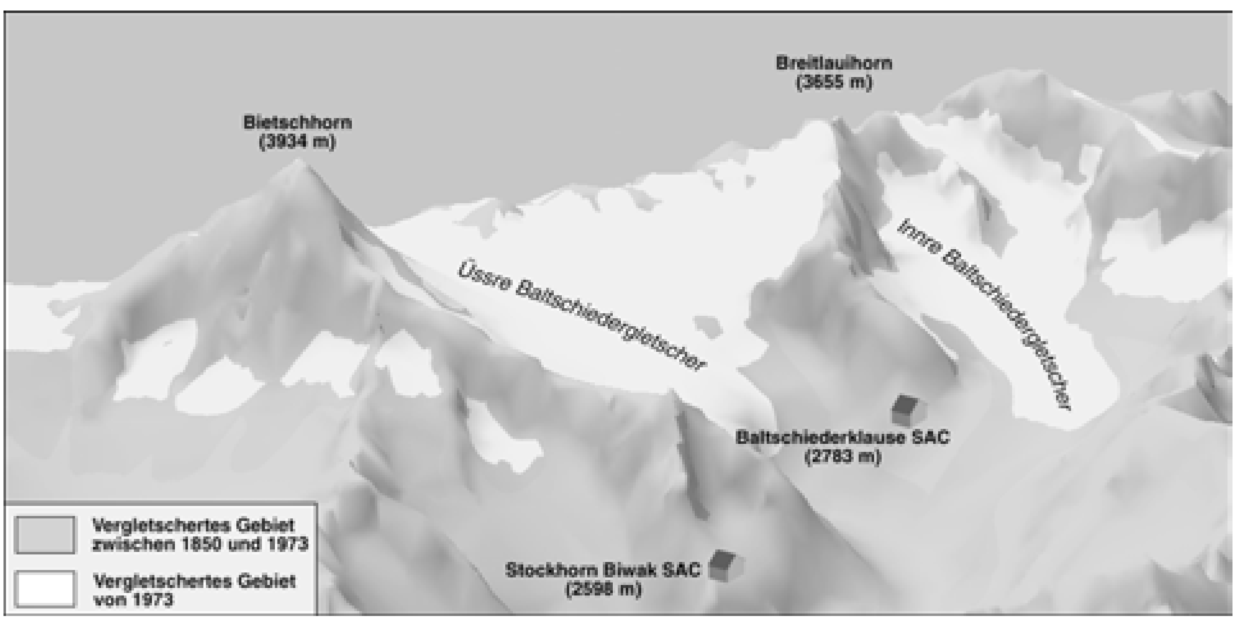

Figure 12. Screen shot of a potential interactive glacial information system. The sample, a perspective view of the glacier area around Bietschhorn (Switzerland), depicts glacier retreat between 1850 and 1973, completed with a few topographic details. In the future, screen representations should be generated directly from calculations of GIS data by DEM visualization software and other graphic tools. (Data source: © Federal Office of Topography, Wabern, Switzerland (BA035538), and Department of Geography, University of Zurich.)

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Résumé La glaciologie est devenue une science indépendante au milieu du 19e siècle avec la première exploration systématique de phénomènes glaciaires. Parallèlement, il a fallu visualiser cartographiquement les processus et structures glaciaires. De telles représentations nous montrent aujourd'hui la technologie utilisée alors pour la collecte de données glaciaires et pour la cartographie. Déjà au siècle dernier, grâce à des mesures géodésiques précises et des techniques cartographiques de pointe, des cartes de glaciers bien conçues, simples à utiliser, et avec un contenu relativement complet, ont été publiées. L'attention était alors portée sur les modifications géométriques des glaciers et les formations glaciomorphologiques. A partir des années cinquante, les glaciologues commencèrent a y représenter des paramètres dynamiques, telles les fluctuations des glaces, le bilan des masses, ou encore la circulation de la glace. En outre, l'information topographique a été complétée par des orthophotoplans et des images satellites. Aujourd'hui, avec l'avènement de la cartographie digitale, les visualisations à l'écran sont de plus en plus fréquentes. L'utilisation de la photogrammétrie digitale, de la télédétection, des nouvelles techniques sonores de géophysique, ou encore des GPS (Global Positioning Systems), ont par ailleurs permis l'acquisition d'un grand nombre de données. Avec un SIG (Système d'Information Géographique), ces données peuvent être manipulées, modelées, compilées sous forme de MNE (Modèle Numérique d'Elévation), analysées, et finalement visualisées interactivement sous forme de carte de haute qualité ou de vue en perspective. La glaciologie va probablement évoluer vers le développement d'un Système d'Information Glaciaire interactif incluant des fonctions d'interrogation de base de données, de modélisation, et de visualisation.

Zusammenfassung Mit Aufkommen von systematischen Studien an glazialen Phänomenen in der Mitte des 19. Jahrhunderts entwickelte sich die Glaziologie zu einer eigenständigen Wissenschaftsdisziplin. Zudem verlangten die intensiveren Untersuchungen an Gletschern nach entsprechender kartographischer Visualisierung. Die Darstellungen widerspiegeln somit auch eindrücklich den damaligen Technologiestand bezüglich der Datengewinnung und der Kartographie. Bereits im letzten Jahrhundert wurden benutzergerecht gestaltete klassische Gletscherkarten mit komplexem Informationsgehalt und hochstehender graphischer Gestaltung veröffentlicht. Diese Entwicklung wurde ermöglicht durch immer präzisere Methoden der Geodäsie und verfeinerten Techniken bei der analogen Kartenherstellung. Der Schwerpunkt der wissenschaftlichen Betrachtung in der Glaziologie lag seit jeher auf der Vermessung von Gletscherausdehnungen und beim glazio-morphologischen Formenschatz. Ab den Fünfzigerjahren des letzten Jahrhunderts wurden zusätzlich auch dynamische Größen wie Gletscherschwankungen, Massenbilanzen und Eisbewegungen Gegenstand der glaziologischen Forschung. Zusätzlich ergänzten Orthophotos und Satellitenbildaufnahmen die topographische Basisinformation in Gletscherkarten. Mit Beginn des digitalen Zeitalters wurden mehr und mehr auch Bildschirmdarstellungen verlangt und erstellt. Mit der Entwicklung in der digitalen Photogrammetrie und Fernerkundung, mit feineren geophysikalischen Sondierverfahren und mittels modernster satelliten-gestützten Standortbestimmung (Global Positioning System GPS) werden enorme Mengen an Geodaten generiert. Durch Einsatz von Geoinformationssystemen (GIS) können diese Datensätze effizient gespeichert, verwaltet, analysiert und zur Weiterverarbeitung vorbereitet werden. Zudem lassen sich damit genaue digitale Höhenmodelle berechnen. Dies alles führt zu einer Vielzahl von qualitativ hochstehenden Kartenprodukten für unterschiedlichste Visualisierungszwecke. Der zukünftige Trend geht hin zu komplexen interaktiven Gletscherinformationssystemen mit integrierten Funktionalitäten zur Datenanalyse, Datenmodellierung und anschließender Visualisierung.

Resumen Con la primera exploración sistemática de los fenómenos glaciales a mediados del siglo XIX, la glaci-