TECHNISCHE UNIVERSITÄT DRESDEN

Faculty of Environmental Sciences Institute for Cartography

Master Thesis

Cross-Media 3D Cartography of 'Europe at the Last Ice Age' Based on Initial Data Compilations

submitted by Mara Jaunsproge

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Supervisors Prof. Dr. Manfred F. Buchroithner,
Dipl.-Geogr. Benjamin Schröter
Institute for Cartography

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The Last Ice Age in Europe was at its peak about 20 000 years ago. At that time in the Northern part of Europe, many areas were covered with ice as much as 3km thick. The mountainous regions of the Southern part of Europe, for example the Alps, Balkans, and Pyrenees, were covered with thick ice sheets. During the Last Glacial Maximum (LGM) the sea level was much lower than today indicating that there might have been a connection between England and mainland of Europe. The findings of the most recent research have so far never been combined to create a detailed Ice Age map of Europe. In school atlases and on wall maps one still finds more or less the state of knowledge from immediately after World War II. Thus, based on a collection of the most detailed data about the horizontal and vertical extent of the Last Ice Age in Europe (of which about 50 % currently exists) it is possible to generate a geodata base which can subsequently serve as a basis for cross-media cartographic presentations to be demonstrated by the examples listed below. The tasks comprise:

- Search and process missing information about the Last Ice age in Europe;
- Combine the information about ice coverage in Europe during the Last Ice Age and visualize it using different display media.

Output in the form of cartographic products are:

- a paper map of Europe at a scale of 1:5,000,000
- a map sheet of the Alps at a scale of 1:1,000,000 in the form of a classical hill-shaded paper map

The combined data might then be used as a source to develop other types of visual representation of the Last Ice Age in Europe.
The major findings have to be presented in the form of an A0 color poster.

Supervisors: Prof. Dr. Manfred Buchroithner, Dipl.-Geogr. Benjamin Schröter

Delivered: April 1, 2013

Date of submission: September 29, 2013

Prof. Dr. Manfred Buchroithner

Statement of Authorship

Herewith I declare that I am the sole author of the thesis named

„Cross-Media 3D Cartography of 'Europe at the Last Ice Age' Based on Initial Data Compilations"

which has been submitted to the study commission of geosciences today.
I have fully referenced the ideas and work of others, whether published or un-published. Literal or analogous citations are clearly marked as such.

Dresden, 29.09.2013 Mara Jaunsproge

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Abstract

During the Pleistocene (1.8 million years BP [before present] to 10 000 years BP) several glacial and interglacial periods occurred. The last glacial period of the Pleistocene, often referred to as the ‘last Ice Age’, reached its glacial maximum about 20 000 years ago. A data base containing detailed information about this time period in Europe has been created.

In the region of Europe, there are several maps and other data sources about the last Ice Age. Large ice sheets covered Scandinavia, the British Isles, Iceland, the Alps, Pyrenees and other smaller regions in Spain, Italy, Romania and the Balkans. The scale of the detail of the data varies from one source to another. All this information has been gathered, digitized and combined into one data set.

This thesis gives a theoretical overview of the ice distribution in Europe during the LGM (Last Glacial Maximum) and describes how the data was combined, digitized and the missing information modeled. An example of how to visualize this data for the whole of Europe and separately for the Alpine region are presented.

Kurzfassung

Während des Pleistozän (1,8 Million Jahre v.Chr. bis 10 000 Jahre v. Chr.) gab es mehrere eiszeitliche und zwischeneiszeitliche Perioden. Die letzte Periode, oft auch als letzte Eiszeit genannt, erreichte ihren Höchststand etwa vor 20 000 Jahren. Für Europa wurde eine geografische Datenbank erschaffen, die detaillierte geographische Informationen über diese Zeit enthält.

In Europa gibt es mehrere Karten sowie andere Informationsquellen über die letzte Eiszeit. Größte Eisdecken befanden sich über Skandinavien, den Britischen Inseln, Island, den Alpen, den Pyrenäen und weitere kleinere Bereiche über Spanien, Italien, Rumänien und dem Balkan. Es gibt Unterschiede in der Genauigkeit und Menge der Daten. Alle verfügbaren Daten wurden zusammen getragen, digitalisiert und in einen Datensatz zusammengefasst.

Diese Arbeit gibt einen theoretischen Überblick über die Verteilung des Eises während des letzten Gletscherhochstands, beschreibt wie die Daten zusammengefasst, digitalisiert und die fehlenden Informationen modelliert wurden. Ein Beispiel für die Visualisierung dieser Daten für ganz Europa sowie für die Alpenregion ist vorgestellt.

Content

Figures

All non-credited photos are by the author.

Index of Abbreviations

2D – Two Dimensional

3D – Three Dimensional

BIS - British Ice Sheet

DTM – Digital Terrain Model

FIS - Fennoscandian Ice Sheet

ka BP - Thousand years Before Present

LGM - Last Glacial Maximum

LGP – Last Glacial Period

SRTM - Shuttle Radar Topography Mission

Introduction

During the Pleistocene (1.8 mya to 10 000 yrs ago) several glacial and interglacial periods occurred. The last glacial period of it, or quite often referred to as the 'last Ice Age', reached its maximum about 20 000 years ago. Although the last glacial period has ended, its effects can still be felt today. For example, the moving ice carved out the landscape in Canada, Greenland, northern Eurasia and Antarctica.

Erratic boulders, till, drumlins, eskers, fjords, kettle lakes, moraines, etc., are typical features left behind by glaciers which make it possible to reconstruct the ice coverage during the last Ice Age. Research of these features from different photographs, satellite pictures and numerous field works has been carried out for decades to produce maps showing the ice extents.

In the region of Europe there are several maps and other data sources about the last Ice Age. The most detailed data available covers the Alpine region. There are at least 3 maps that visualize different parts of the Alpine glaciers with isolines up to 100-200m. Also for the region of Scandinavia there are maps of the last Ice Age that show the absolute coverage of the land. Contrary to the Alps, here the snow didn't let through any peaks of the mountains as the snow thickness reached about 3km. Also the ongoing discussion of whether Scandinavia and the British Isles were connected with an ice sheet has to be examined.

Besides all the bigger ice sheets (in the Alps, Scandinavia, British Isles and Iceland) where there information not only about their horizontal extent but also the height information of the ice, there are several smaller ice sheets scattered across Europe that are provided only with their boundary information. From this 2D data and the terrain information underneath them (for example, a digital terrain model), approximate 3D ice coverage can be modeled.

All of this data about the last Ice Age in Europe has to be gathered and combined in one data set. It can then be used as a source to develop different types of visual representations of the last Ice Age in the whole of Europe or just portions of it. The data is appropriate for either 2D or 3D representation.

1 Last Glacial Period (LGP)

An Ice Age is "A period of the earth history with global cooling and vast extent of the glacier cover. An Ice Age Era is a period of time with alternating changes between cold glacial and warm interglacials, that is, rhythmic glaciations." (Singh, Singh, & Haritashya, 2011).

It is commonly thought that the Last Ice Age ended thousands of years ago, but to be precise, we are still living in it. During an Ice Age Era the overall air temperature is lower and the Poles are covered with ice. That is the situation today as well. But it has not been like this throughout all history of the Earth. Today's Ice Age Era began in Gelasian stage (2,588,000 to 1,806,000 years ago). Since then the Poles have been covered with ice. Ice Ages have different warm and cold periods. Since the beginning of the Last Ice Age there have been several of them (see Fig. 1). The cold periods (also called Glacials) are the actual "Ice Ages" and separate the warm periods (called Interglacials) of an Ice Age Era (Hamblin & Christiansen, 2004).

Approximate Ending (years ago)	**North American Stages**	**Northern European Stages**	**Central European Stages**
10,000	Late Wisconsin	Weichselian	Wurm
Interstadials	Mid Wisconsin	Eemian	R-W
45,000	Early Wisconsin	Saalian	Riss
Interglacial	Sangomonian	Holsteinian	M-R
125,000	Illinoian	Elsterian	Mindel
Interglacial	Yarmouth	Cromerian	G-M
690,000	Kansan	Menapian	Gunz
Interglacial	Aftonian	Waalian	D-G
1,600,000	Nebraskan	Eburonian	Danube

Figure 1 Division of today's Ice Age Era (Smart)

Thus, the end of the last glacial period is not the end of the last ice age. Currently, we are living in the warm period of an Ice Age Era. The indicators of an Ice Age are the volume rise of the glaciers, for example, in the Arctic and the Alps. The last 10000 years can be counted as the warm period of an Ice Age Era – the Poles are still covered with ice but the glaciers have decreased enormously.

In every glacial period there is a point of time when the glaciation reaches its maximum. The most recent maximum occurred about 20 000 years ago and is referred to as the Last Glacial Maximum (LGM). During this time the ice coverage reached its maximal extent, and from that moment on it started to shrink.

Today, about three quarters of all the world's freshwater (14,9 million km^2) is stored in glaciers, while during the last Ice Age it was about 3 times more (44,4 Million km^2) (Zepp, 2008). Only after the ice has melted it is possible to study the ice and melt water influence on the land masses.

Glaciation names

Because the glaciations during the last Ice Age covered many areas (mainly in the Northern Hemisphere and some parts in the Southern Hemisphere) they have acquired different names from different regions. The names have developed historically as well depending on their geographic distribution:

- Fraser in the Pacific Cordillera of North America
- Pinedale in the Central Rocky Mountains
- Wisconsinan or Wisconsin in central North America
- Devensian in the British Isles
- Midlandian in Ireland
- Würm in the Alps
- Mérida in Venezuela
- Weichselian or Vistulian in Northern Europe and northern Central Europe
- Valdai in Eastern Europe
- Zyryanka inSiberia
- Llanquihue in Chile
- Otira in New Zealand

During the LGM the earth's climate was colder and the sea levels globally stood lower than today. It is an interval in Earth climate history that is distinctly different from present conditions, yet it occurred sufficiently recently for reliable and measurable evidence of the climate to be preserved in sediment and ice records. An important element in understanding the LGM conditions is the timing of this event and of the ice distribution and ice volume.

1.1 Time period of the Last Glacial Maximum (LGM) in Europe

It is generally agreed among scientists that the LGM was 20 000 years ago. As the ice spread even to the very South of Europe, the glaciers in different regions reached their maximum extent during different time periods. Also, when talking about the LGM, it is important to know that the maximum volume does not coincide with the maximum extent. From different modeled simulations of the ice, it was noticed that the maximum extent has been reached near LGM and the maximum volume about one thousand years later (Forsstrom & Greve, 2004). According to Forsstrom &Greve (2004) the LGM in Europe varied vastly: in the western section, 25-22 ka BP; in the central section, 19-17 ka BP (ka-thousand years; BP – before present); in the eastern section 28-20 ka BP. According to Forsstrom & Greve (2004) the maximum position in the west was a late, short event at 25 ka BP, and the starting around 22-20 ka BP. The Scandinavian ice sheet grew to its maximum extent at 19-17 ka BP, then started to retreat.

Even a single large ice sheet can have different glacial maximums in different smaller regions of it. A good example how a glacier's maximum extent can differ in time and location is shown in research on the British Isles ice sheet by Clark et al. (2010). They marked the youngest advance date and the oldest deglacial date to attach a range of dates to each margin segment. After that it was clearly visible that the ice sheet reached its maximum extent at different times in different regions (see Fig. 2). The difference between the maximum extents in various regions was about 10 thousand years. Retreat from the continental shelf edge is taken to be from 26 ka BP and from the southern limit at 23-20 ka BP in the Scilly Isles, 25-21 ka BP in South Wales and the Cheshire Plain, 23-21 ka BP in the Vale of York and 19-15 ka BP along the eastern English coastline. The black contour denotes the position of an estimated coastline at about 27 thousand years ago.

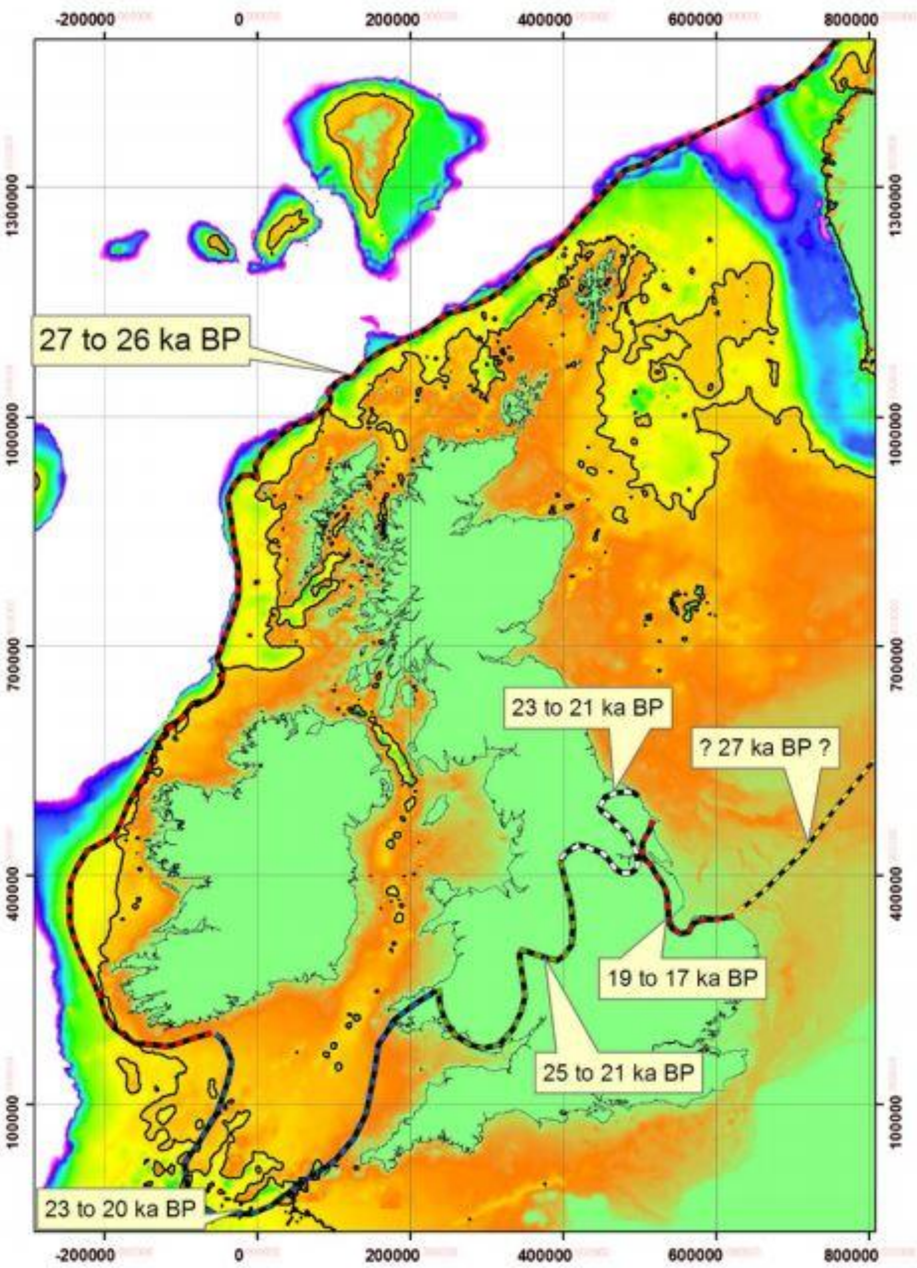


Figure 2 Ice sheet maximum limits annotated according to when they were attained (Clark, Hughes, Greenwood, Jordan, & Sejrup, 2010)

1.2 Ice extent in Europe

During the LGM, ice covered large parts of Europe. The northern part of Europe had the most coverage while less significant ice sheet distributions were found all around the continent. Figure 3 shows the horizontal extent of ice during the LGM. Altough the actual east border of Europe is determined by the Ural mountains in Russia, they were not included for the reason that they did not contain more ice during the LGM than they have today (Mangerud, Gosse, Matiouchkov, & Dolvik, 2008), (Hubberten, et al., 2004) and were not of a significant size. If these small ice patches were to be included then the final map would contain a large ice free zone across the entire eastern part of it.

Figure 3 Horizontal ice extent during the LGM

Many of today's countries were entirely covered by thick ice sheets for thousands of years. These countries include Iceland, Ireland, Norway, Sweden, Finland, Estonia, Latvia and Lithuania. The big Scandinavian and British ice sheet extended south as far as northern Poland and Germany while also covering almost all of Denmark. At the same time in the eastern regions, the ice spread into the territory of Russia (about 300km west from Moscow) and some northern parts of Belarus. In the west, ice covered almost the entire British Isles, leaving just a relatively small ice free zone in the south of the United Kingdom.

Besides the Icelandic, Scandinavian and the British Isles ice sheets, there were many other glaciated regions. In figure 4 is shown what regions were covered by the Alpine glacier. In the north the ice was as far as the region of Munich, and in the southwest it almost reached the Ligurian Sea. Some part of the ice even extended in northwest of Slovenia. Overall, the Alpine ice mass covered most of the Alpine mountain region, leaving only the highest mountain peaks (nunataks) exposed.

Figure 4 Horizontal ice extent on the Alpine region (visualized on Google Earth)

Another rather large ice sheet (about 300km long from NW to SE) laid over the Pyrenees, stretching almost from the Bay of Biscay to the Balearic Sea (see Fig. 5). The snowline in the Pyrenees during the glacial maximum varied from region to region. However, the most marked asymmetry occurred between the north- and south-facing slopes, with glaciers on the southern Spanish slopes located at much higher elevations than on the French slopes to the north (Calvet, 2004).

Figure 5 Horizontal ice extent on the Pyrenees Mountains (visualized on Google Earth)

During the LGM snow reached south as far as the highest points in the Iberian Peninsula. Even though the ice mass was not as significant as in the alps or Pyrenees, it still had a large number of glaciers around the Cordillera Cantabrica, Sistema Iberico, Sierra de Gredos, Sierra de Guadarrama and Sierra Nevada (see Fig. 6).

Figure 6 Horizontal ice extent in NW of Spain (visualized on Google Earth)

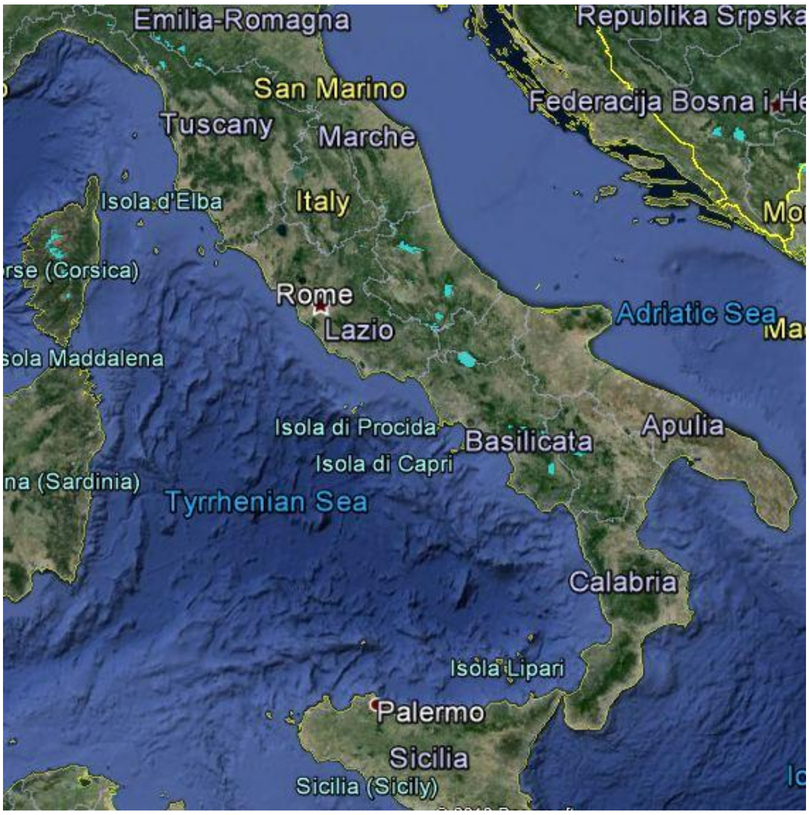


Figure 7 Horizontal ice extent in the Apennine peninsula (visualized on Google Earth)

Also, in the Apennine peninsula there were many glaciers on the highest mountains: Appno Tesco-Emilliano, Apno Abruzzese, Appno Napoletano and Apno Lucano. Some researches have proven that there has been some ice on the top of Mount Etna. It was not very large, but still managed to cover about 40 km^2 (Carveni, Benfatto, Imposa, & Mele, 2012). The ice extent on the Apennine peninsula and Corsica can be seen in figure 7.

Even in Balkan region it was possible to find larger and smaller glaciated areas. They covered the tops of Dinaric Mountains (some peaks in Bosnia and Herzegovina, Montenegro and Albania), big parts of the Rila and Pirin mountains (Bulgaria, south of Sofia) as well as some peaks of the Pindus Mountains (Albania and Greece) (see Fig. 8).

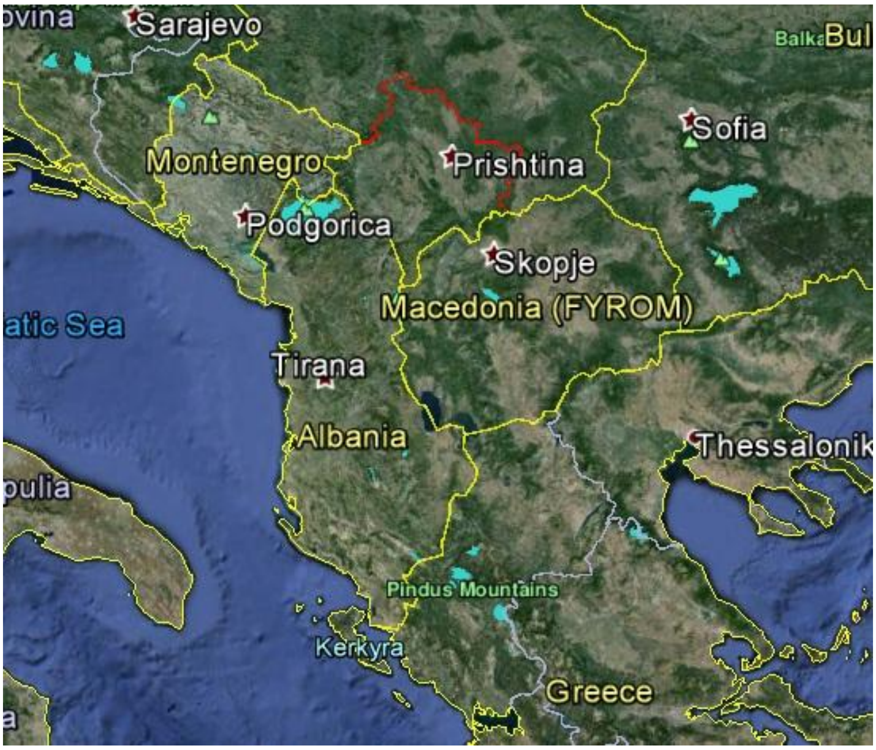


Figure 8 Horizontal ice extent in the Balkan region (visualized on Google Earth)

In what is today Romania, in the southern and eastern Carpathians it was also possible to find some glacial masses on the mountain tops. The largest ice masses (two of them stretching more than 30km long) were to be found in the Transilvanian Alps (see Fig. 9).

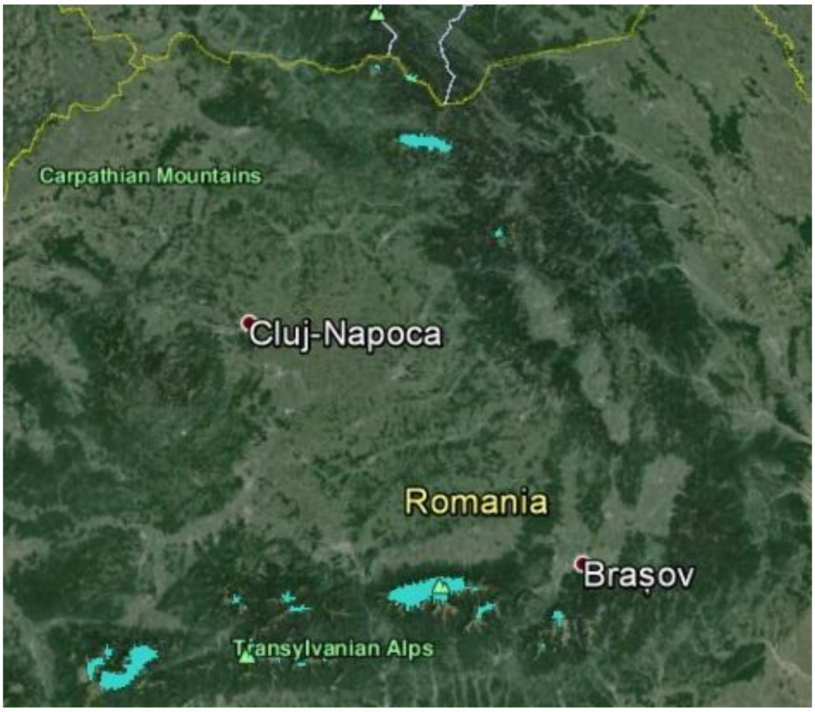
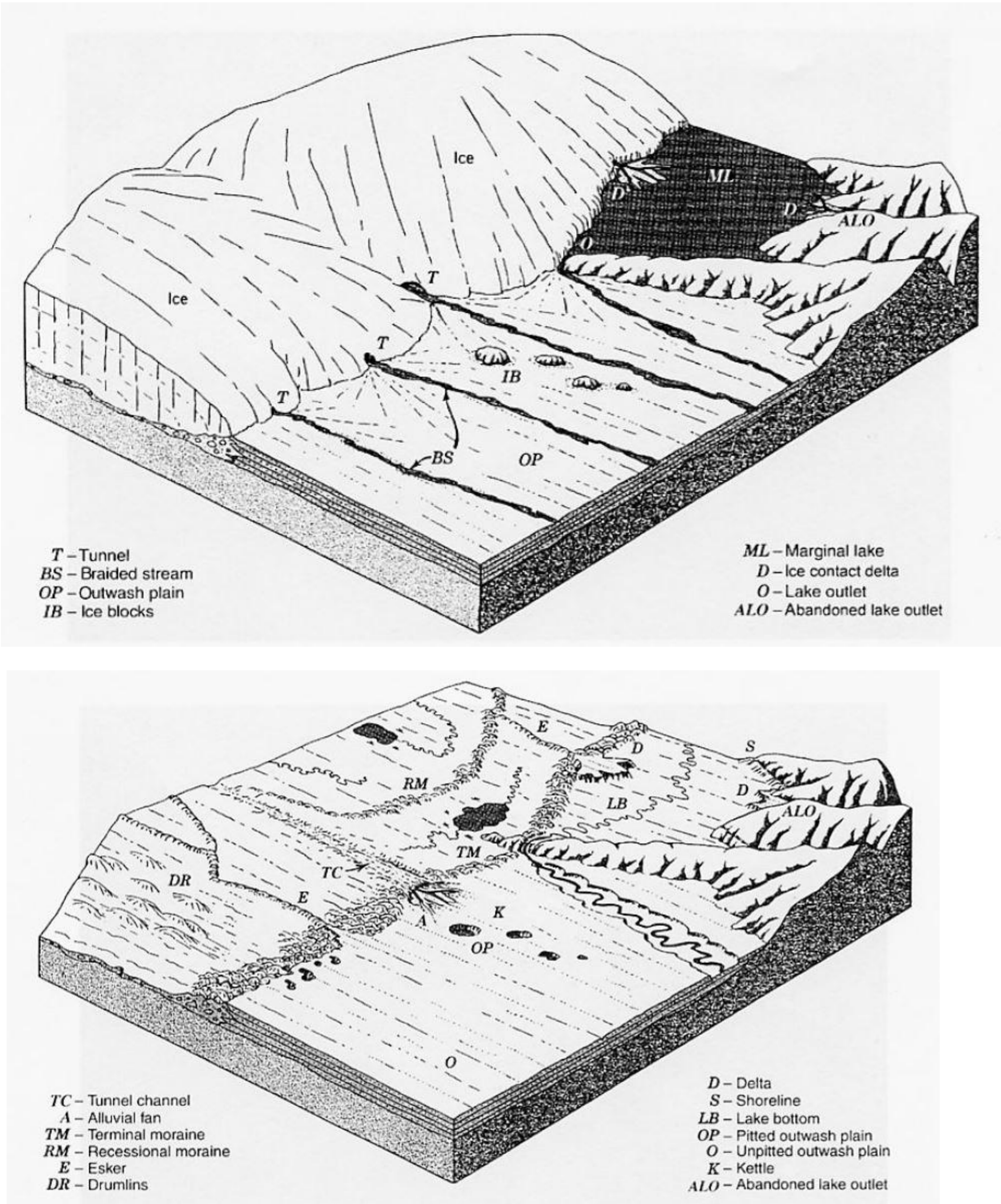


Figure 9 Horizontal ice extent in the Carpathian Mountains (visualized on Google Earth)

1.3 Determination of former ice location

Although the outlines of most of the major ice sheets are now reasonably well known, in some regions the geological record of ice sheet extent is difficult to interpret. Because the ice sheets left little direct evidence of their height, estimates of the LGM ice volume have come mainly from indirect evidence or from glaciological modeling (Clark & Mix, 2000). Even though the last glacial period has ended, its effects can still be felt today. For example, the moving ice carved out the landscape in Canada, Greenland, northern Eurasia and Antarctica. When an ice sheet retreats it leaves some 'footprints' behind itself (see Fig. 10). These footprints can be different signs found in the landscape of a former ice sheet region. The erratic boulders, till, drumlins, eskers, fjords, kettle lakes, moraines, etc. are typical features left behind by glaciers. Knowing them and being able to distinguish them in the nature as well as in satellite images or other photographs gives an opportunity to reconstruct horizontal and vertical ice sheet extents for different time periods.



A

B

Figure 10 Lowland landform assemblage: (A) during glaciation; (B) after deglaciation. (Mickelson & Winguth, 2007)

1.3.1 Horizontal extent

After glacier meltings there have been many landmarks left behind that help to determine the horizontal extent of the ice. Some are more obvious and can be used as a reliable data source, and some just indicate the possible location of it. To reconstruct the form and flow of former ice sheets geological evidence is needed. As such evidence drumlins, striations and till fabrics which reflect the direction of the ice sheet movement can be used. A way to detect these geological forms is by using satellite images. They provide unique means of identifying large scale flow generated lineations produced by former ice sheets. They can be interpreted to reconstruct the major elements which make up the integrated, large scale structure of ice sheets. Although for the final reconstruction satellite images are not enough; field work is still needed.

Moraines

A good way to detect the location of former ice margins is by moraines found in the regions which were covered with ice. When the ice starts to melt, at a glacier margin it causes the ice to thin. In this way the ground-up rock debris carried in the base of the ice or dragged along beneath the glacier is deposited. When the ice margin remains in the same place for a relatively long time (tens to hundreds of years), enough debris flows to the glacier's leading edge and piles up to form a large end moraine on the landscape.

Lateral meltwater channels

Another sign left behind a glacier is lateral meltwater channels. Meltwater flows down to topographically lower regions, following the gravitational forces. There they merge into receiving streams. The meltwater coming out of the glacier combines at the ice-marginal channels, thereafter flowing together in a sandur (an outwash plain formed by meltwater from glaciers). They record actual margin positions and are often found as a flight of channels documenting ice thinning down the flank of a hill (Greenwood, Clark, & Hughes, 2007). Subglacial meltwater channels, which are similar to eskers, mostly record the direction of ice surface slope close to the margin and therefore the direction and orientation of retreat. This presumes that most preserved subglacial meltwater channels are cut close behind the deglaciating margin.

Eskers

Also Eskers (long winding ridges of stratified sand and gravel) can also be used for gathering information about former glaciers. From eskers it is possible to infer the orientation of the backstepping palaeo-margin and thus a retreat pattern. This is based on the knowledge that water drainage is driven primarily by ice surface slope and should therefore exit the ice sheet roughly orthogonal to the margin.

Drumlins

Drumlins (enclosed hills in the shape of an inverted spoon or half buried egg) incorporate information about the ice flow and by careful analysis of their pattern and context. Some drumlin fields can confidently be inferred to have been generated during retreat (Greenwood & Clark, 2009).

These are only a few of the marks that can be found after a glacier has melted. Besides the four previously mentioned land marks other signs left behind a glacier can be seen in figure 10.

1.3.2 Vertical extent

More uncertain than the horizontal extent of a glacier is the ice thickness. In a few instances, this has been measured directly from trimlines on ‘nunataks’, mountain peaks that stood above the ice. But this has not been possible for the major northern European ice sheets. The estimates of ice thickness are dependent on assumptions about snow supply and ablation and about the nature of the rock-ice-interface (Lambeck & Chappell, Sea Level Change Through the Last Glacial Cycle, 2001).

The vertical extent of former glaciers and ice sheets is much more difficult to determine than the areal extent and involves more uncertainties. Most of the time there is no geological evidence to be found that would indicate the height of the ice, but there are some methods that are commonly applied in order to indicate the vertical extent of ice masses. These include the isostatic rebound, global sea level change and landmarks.

Isostatic rebound

It is easy to think of the Earth as solid, but in fact it is elastic. It moves very slowly, but it does move. So when the land under the ice was depressed, the crust in other parts of the world rose. When the ice melted, the situation reversed. The land that was previously ice covered is now rising relatively rapidly and the land in other parts of the world is falling on average at a slower rate. This process then is called isostatic rebound. Present rates of uplift in former glaciated areas can be used to infer former ice thickness (Lambeck, Yokoyama, Johnston, & Purcell, 2000). It is worth noting that the data is more suitable for coastal regions and provides little constraint on ice thickness in interior regions. Furthermore, in these calculations only the ice melting, no possible tectonic components are considered (Mickelson & Winguth, 2007).

Global sea level change

It has been proven that the growth of continental ice lowers the global sea level. This means that records of sea-level change can be used to reconstruct changes in ice volume. Records of past sea levels provide the most direct means of determining changes in ice volume, but many of these records are incomplete or poorly dated. Drilling tropical coral reefs offers the best opportunity to develop a well-dated and relatively continuous sea-level record (Lambeck, Yokoyama, Johnston, & Purcell, 2000).

Landmarks

Another way to recognize the upper limit of former ice sheets is with the help of geomorphic indicators like trimlines. A sharp line on a hillside marking the boundary between well-vegetated terrain that has remained ice-free for a considerable time and poorly vegetated terrain that until relatively recently lay under glacier ice. These trimlines separate an upper zone of weathered bedrock and a lower zone of glacial erosion; in this way indicating the upper limit of glaciation in mountainous areas (Mickelson & Winguth, 2007). However, these landmarks are often controversial for several reasons. For example, they indicate a border where a glacier had re-advanced rather than the maximum vertical ice limit. They could also mislead because they might represent the boundary between frozen and temperate conditions at the ice base. It is also possible that periglacial weathering may have taken place after deglaciation. All these factors have to be kept in mind when researching the former glaciated area.

2 Ice sheets in Europe

It might seem that there should be already a good map from the last Ice Age because of the vast amount of information about this time period. But this information seems to be divided into smaller parts like Scandinavia, British Isles, Alps, etc. So the challenge here is to find ‘the true’ information and combine it into one data set. The term ‘true information’ refers to different indicators like the most recent research, the information source of the data, the particularity of the data, etc.

2.1 The Alps

The most detailed information about ice coverage in Europe was found for the Alpine region. Three main information sources, besides numerous additional less important sources, were used to create the representation of the ice sheet on the Alps. These information sources include:

- Die Ostalpen in den Eiszeiten by D. van Husan (1987) (see Fig.11);
- Western Alps at the Last Glacial Maximum by S. Coutterand et.al (2011) (see Fig.12);
- Die Schweiz während des letzteiszeitlichen Maximums by P. Schoeneich et.al (2009) (see Fig.13).

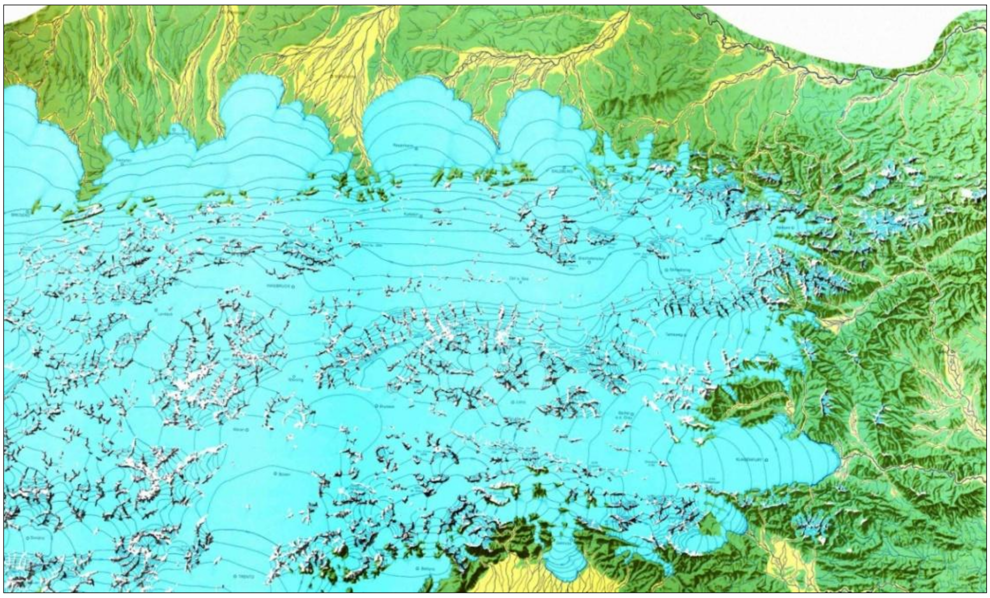


Figure 11 Eastern Alps during the LGM (van Husen, 1987)

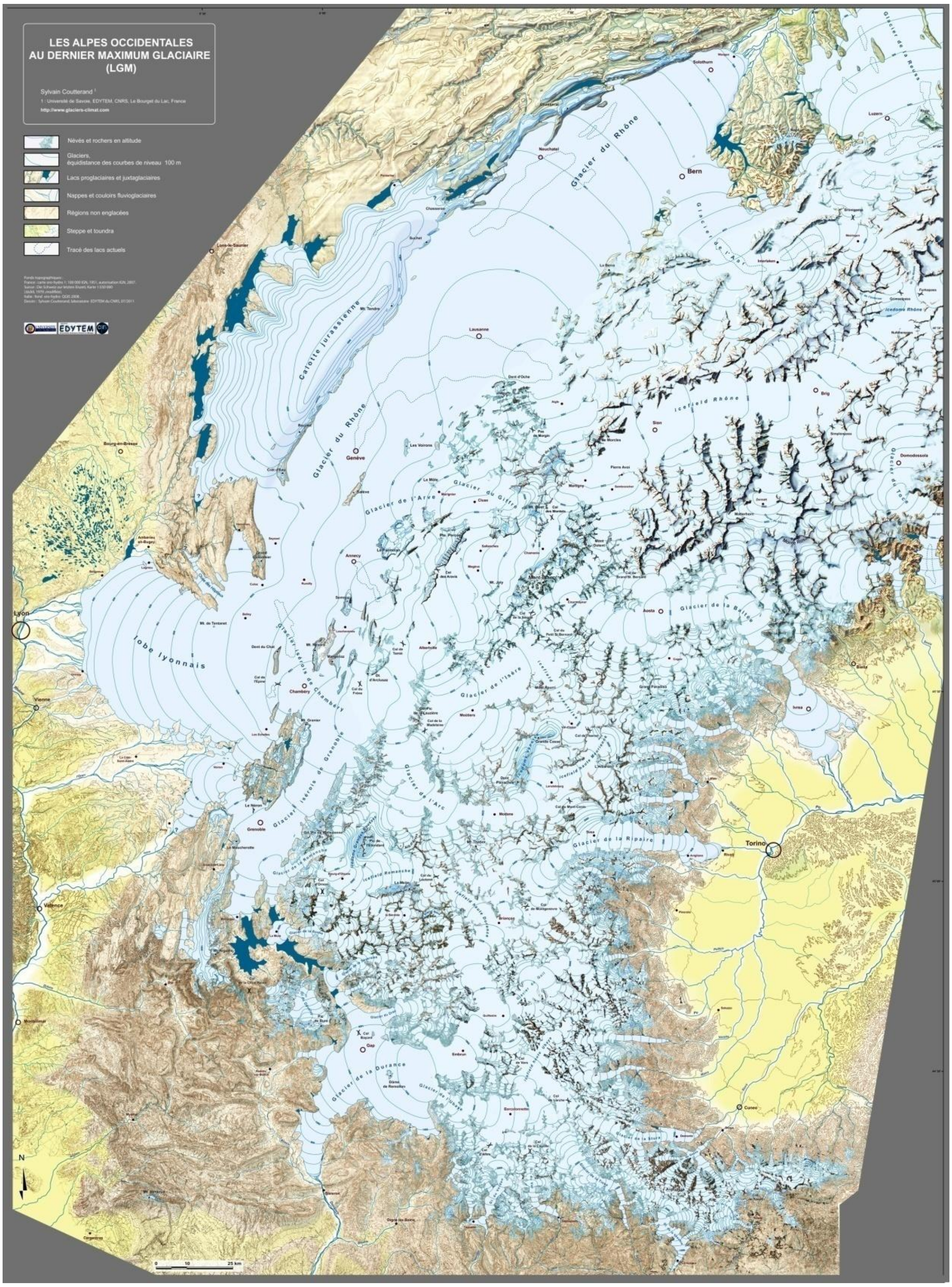


Figure 12 Western Alps at the Last Glacial Maximum (Coutterand, Schoeneich, & Nicould, 2011)

Figure 13 Switzerland during the LGM (Schoeneich et.al 2009)

The ice visualization in all three maps differs from each other. For example, in the East Alps map, mountain peaks are clearly standing out from the ice while in the Central Alps map many of them have ice coverage. Also the different shading of the ice and contour lines are results of different cartographers who worked on each map.

All information sources were combined to create a digital dataset for the entire Alpine region (see Fig.14 and Fig.15). Figure 14 shows how the maps look when they are combined and georeferenced. Figure 15 illustrates the Alpine ice shield digitized with ice contours that have intervals of 200m. To be able to make one dataset from 3 maps, special attention had to be paid to the regions where the maps intersect. The alpine ice mass covers almost the entire Alpine mountain region and the ice height difference stretches from 200m up to 4600m above sea level.

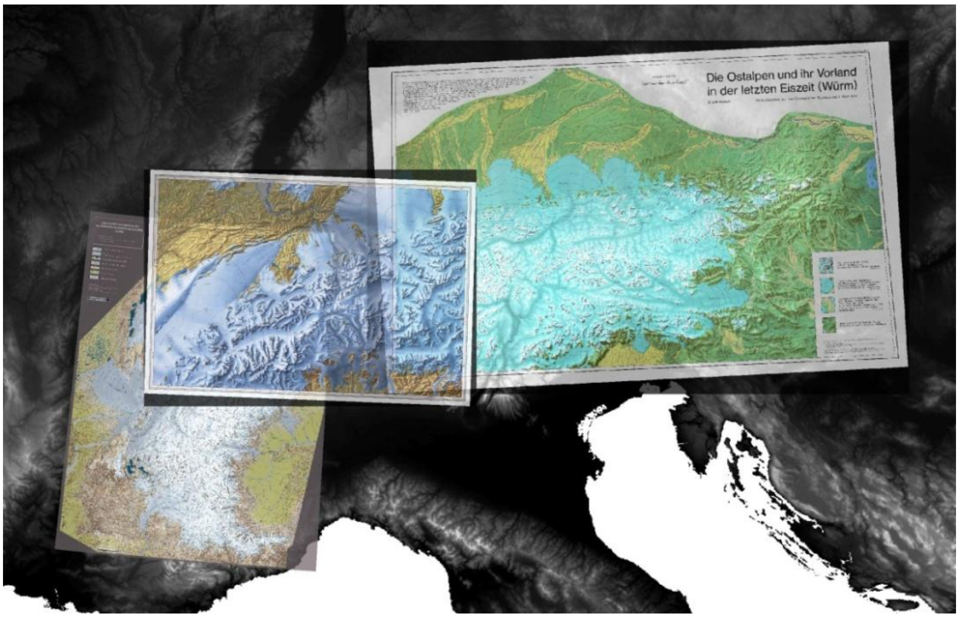


Figure 14 Maps of Alpine glaciation combined and georeferenced on top of GTOPO30 digital terrain model (DTM)

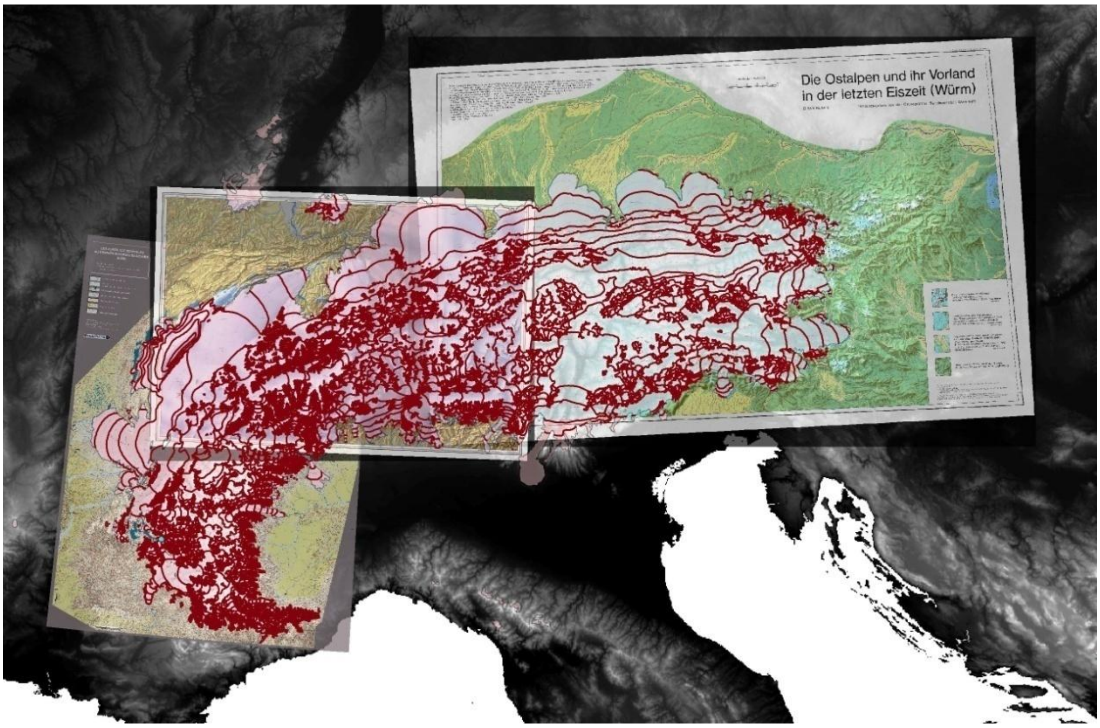


Figure 15 Digitized contour lines (200m intervals) of the Alpine glaciations

2.2 Scandinavia and the British Isles

Although the maximum ice extent of the last Ice Age was thousands of years ago, there are still some uncertainties as to whether the British Isles and Scandinavia were connected with an ice sheet or not. Over the last couple of decades, the opinions of researchers have changed back and forth. For this reason, special attention has been paid to this question during data gathering within this project.

During the LGM a lot of world's water was used to create glaciers. This of course means that there was less water covering land. According to Chuch et.al (2007) and Lambeck et.al (2000) the sea level was at least 120m lower during the LGM. In this way it uncovered some land forms that today are under water, including the connection between Great Britain and Europe. This theory is a good reason to believe that during the LGM the British Isles and Scandinavia might have been connected with an ice shield as well.

In many up to date atlases there are different visualizations of the ice sheets of Great Britain and Scandinavia. While in the world atlas of Diercke it is clearly shown that there was only one ice sheet covering both Great Britain and Scandinavia (see Fig.16), in the atlases of Alexander (see Fig.17) and Haak (see Fig.18) the ice sheets are not connected at all.

Also interesting to notice that in the maps of Haak and Diercke it is shown that the Ural Mountains seem to have a quite extensive ice coverage. But according to research by Jan Mangerud et. al (2007) glaciers in Polar Urals were not much larger than they are today.

Figure 16 Ice Age at its maximum from Diercke Atlas (Diercke Weltatlas, 2008)

Figure 17 Ice Age at its maximum in Alexander Atlas (Knippert, 2004)

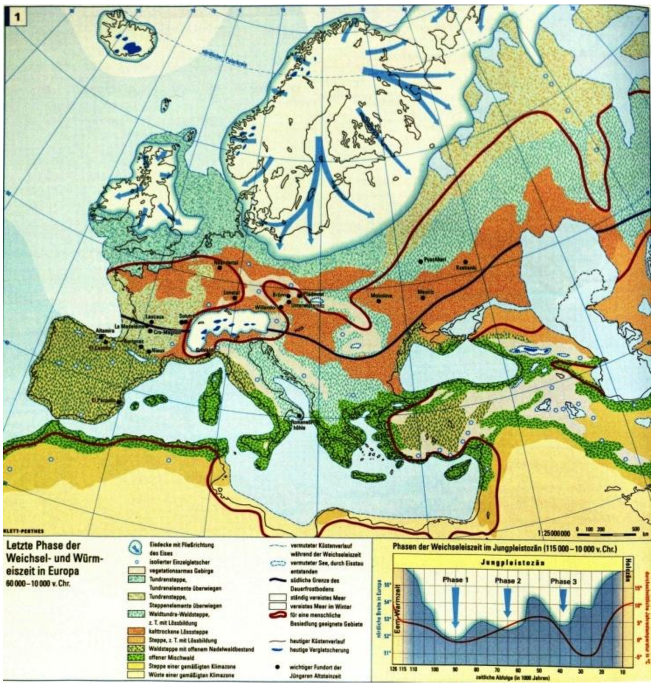


Figure 18 Ice Age at its maximum in Haak Atlas (Haak Weltatlas, 2011)

There have been many attempts to visualize the Scandinavian and the British Isles ice shields, whether they were connected or not. Some examples of them can be seen in Fig.19 to Fig.28. The first 4 images illustrate the two land masses separated while the rest show both parts connected.

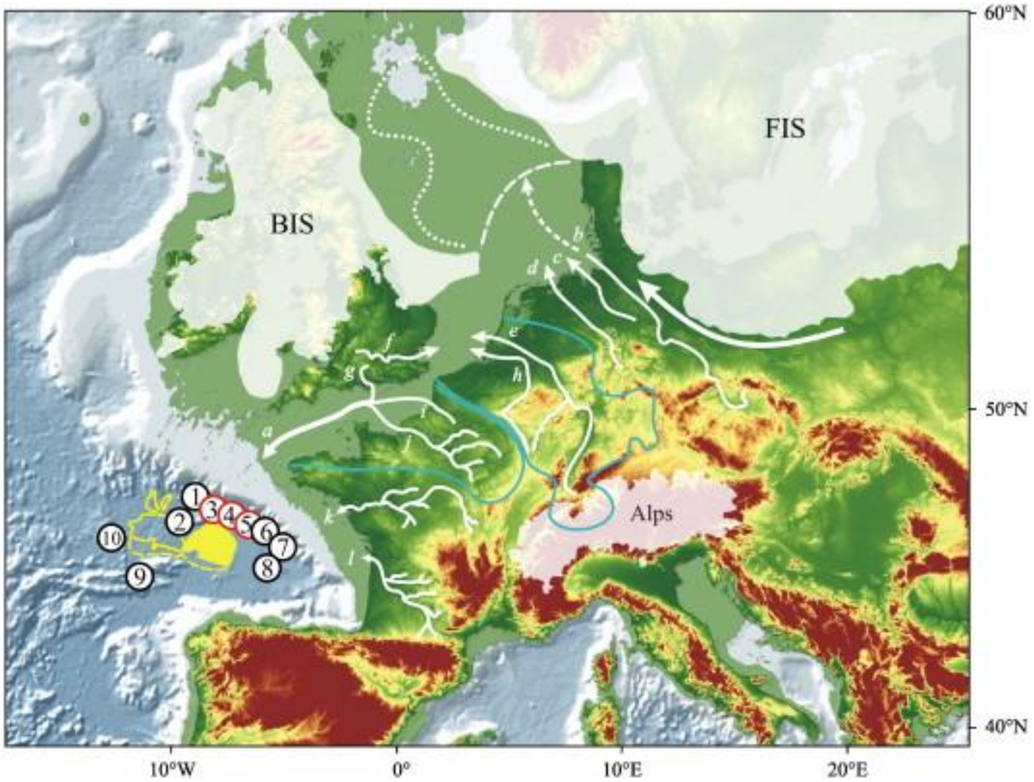


Figure 19 Map of NW Europe showing the glacial limits (white shaded area) of the British Ice Sheet (BIS), Fennoscandian Ice Sheet (FIS) and the Alps Glaciers during the LGM (Toucannea, 2010)

In figure 19 the two upper discussed ice shields are shown as separated but still indicate a possible connection between them (dashed line). The map also shows how the land mass used to look during the LGM. The sea level was lower and that uncovered land mass that connected the British Isles and Europe and increased the coastline overall the whole Europe.

Figures 20 to 22 show the British Isles ice shield as a separate ice mass. They are very similar, indicating the highest point over Scotland and leaving the south of the Ireland and United Kingdom ice free.

Figure 20 22 000 years BP corresponding to the adopted time of maximum glaciation over the British Isles (Isobase contour intervals are 50 m) (Lambeck K. , 1995)

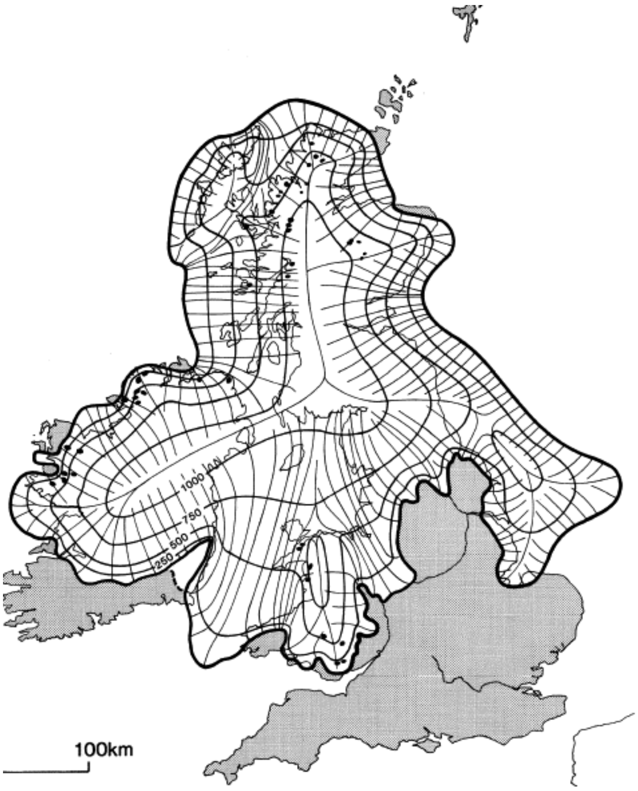


Figure 21An independent British Ice Sheet (Boulton & Hagdorn, 2006)

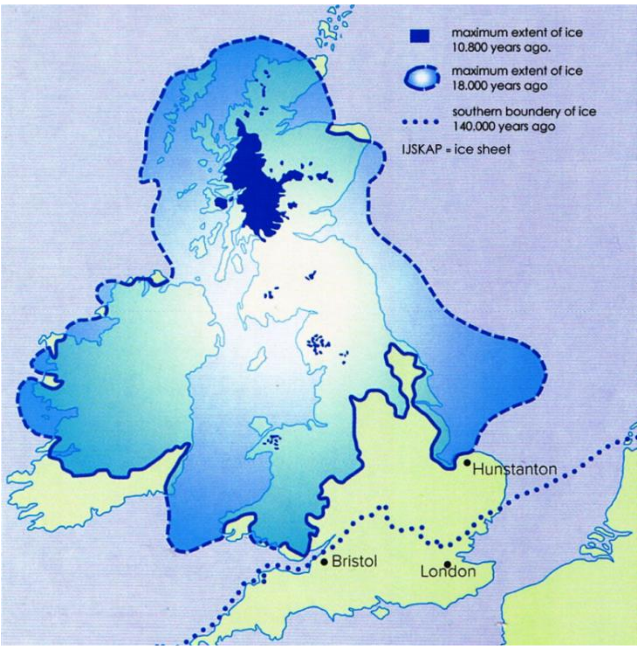


Figure 22 Maximum extent of the ice sheet in British Isles during last Ice Age (Fagan, 2009)

In figures 23 to 25 the ice sheet over the British Isles and Scandinavia is shown as connected. Even though these maps don't show any height information, they are still very useful for determining the approximate ice extent over the previously mentioned land masses. And besides this large ice mass they also indicate the location of 3 other glaciers in Europe: Iceland, The Alps and the Pyrenees.

Figure 23 Last Ice Age in North Europe; ice extent for 20,000 to 17,000 years ago (Sveriges Geologiska Undersökning)

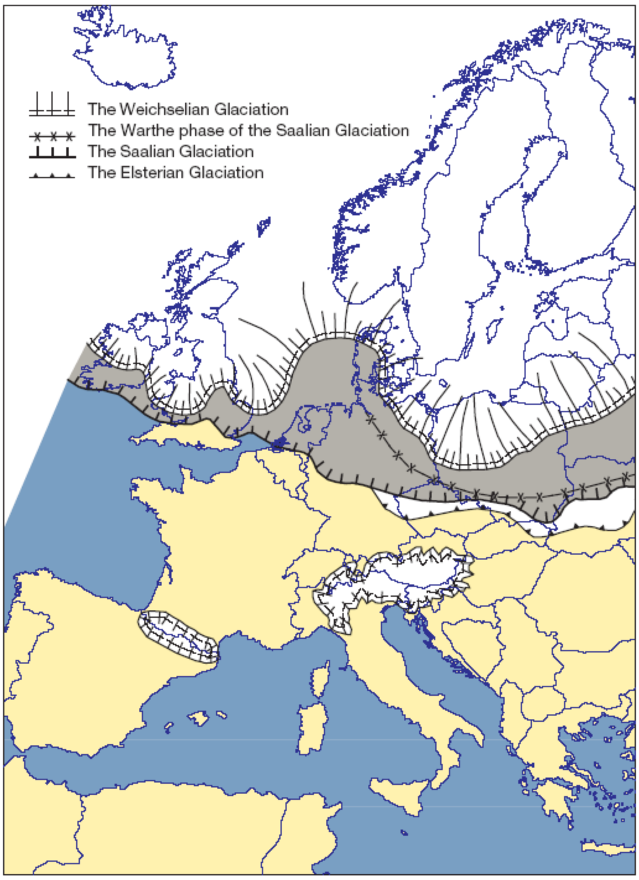


Figure 24 Maximum extent of the European ice sheet (J.A. Plant, 2005)

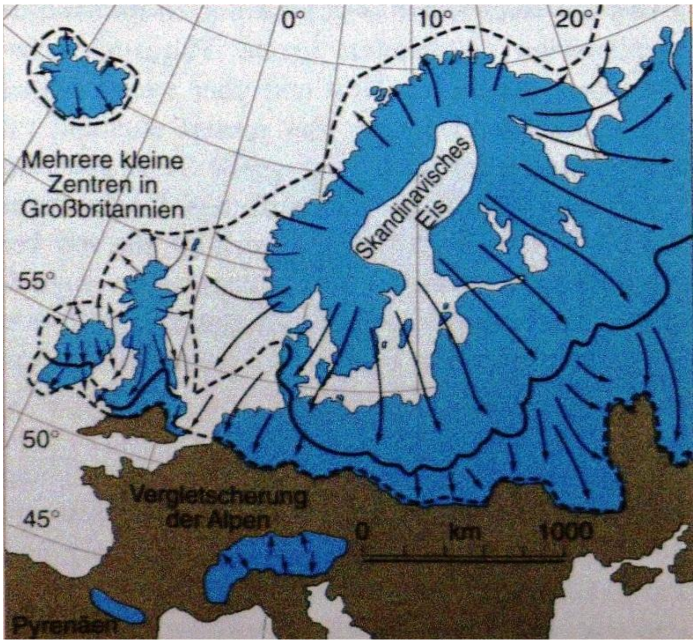


Figure 25 Ice Age in Europe about 22000 years ago (Strahler & Strahler, 1999)

Figure 26 also shows Scandinavia and the British Isles connected with one ice sheet. Although it also has indication marks that separate Scandinavian, the British Isles and Mainland ice sheets. These regions might have had higher ice extent while the connected parts were quite low.

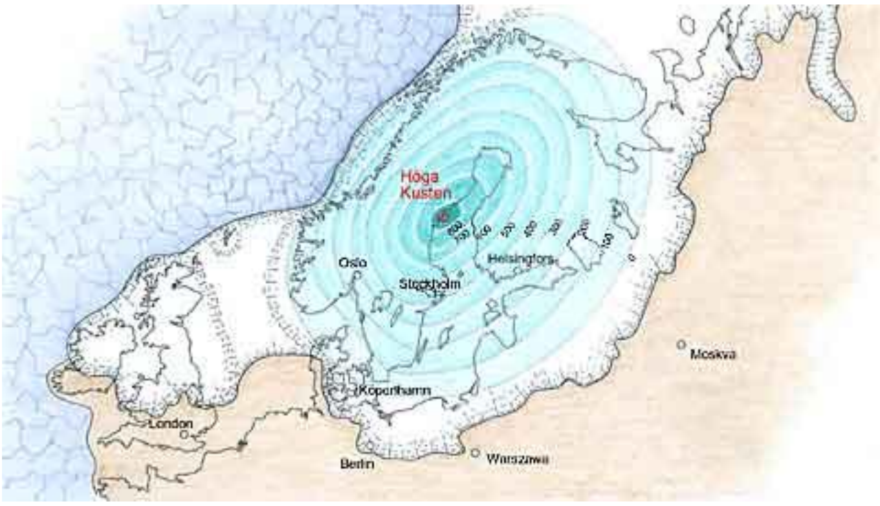


Figure 26 The maximum extent of the ice sheet in Europe during the last Ice Age 20,000 years ago. , the greatest depression of the land surface in the weight of the ice, more than 800 m, was present at the High Coast (The High Coast: A World Heritage Area)

In figure 27 and 28 not only it is shown the ice extent that connects Scandinavia and the British Isles, but also height information is given by including ice contour lines. Interesting to notice that the height information varies significantly: up to 3000m above mean sea level (amsl) in figure 27 and up to 2400m amsl in figure 28.

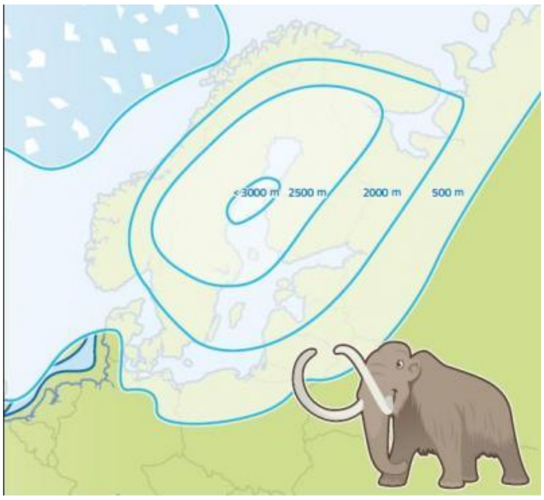


Figure 27 The ice extent and thickness in the Nordic countries during the last ice age (Gustafsson, 2001)

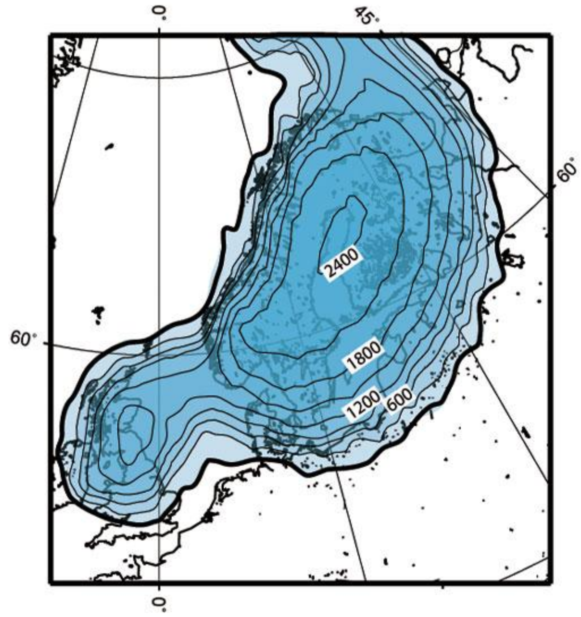


Figure 28 Simulated distribution and height of the ice sheet when it reached a peak of around 18 000 years ago (Svensk Kärnbränslehantering AB, 2009)

Despite all the contradictory information, within this project it has been chosen to believe that the ice sheets of Scandinavia and the British Isles actually were connected. The main reason for this is the most recent research on this topic carried out by Clark and his working team in 2010.

At Sheffield University has been reconstructed the ice retreat in the British Isles from 27 000 years BP up to 15 000 BP. This research was led by Professor Chris Clark from the University's department of Geography. A team of experts worked on this project for more than ten years and developed several maps (varying in their content and time scale) to understand what effect the current shrinking of ice sheet in parts of the Antarctic and Greenland will have on the speed of sea level rise. After carrying out several investigations and researches they came up with unique maps that record the pattern and speed of the shrinking of the large ice sheet that covered the British Isles during the last Ice Age (see Fig. 29).

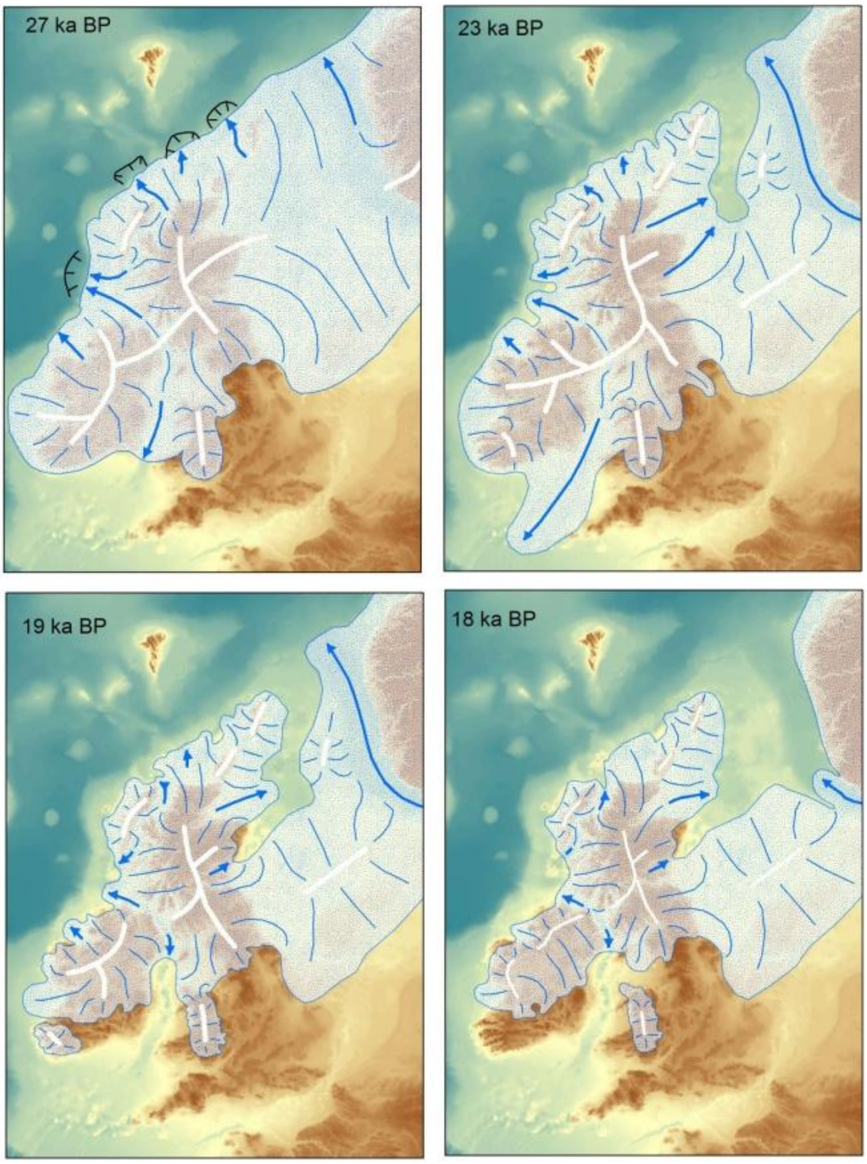


Figure 29 Ice retreat in the British Isles in different periods of time (Clark, Hughes, Greenwood, Jordan, & Sejrup, 2010)

From observing the final map, it is clear that according to Clark et al. (2010) the ice sheets of the British Isles and Scandinavia were connected during the LGM. Even if we assume that the LGM would have occurred around 21 000 BP like it is said to be for the rest of Europe (the research of Clark claims it to be 27 000 BP), the maps of Clark et al. (2010) still show an ice bridge between Great Britain and Scandinavia. In their research it is presumed that ice cover was mostly initiated over the uplands of Britain and Norway and made a lower bridge that connected both sides.

Scandinavian ice sheet

In 1981, an ice height model over Scandinavia was proposed by Denton and Hughes (see Fig.30). Though almost 20 years later Lambeck et.al (2000) concluded that the ice model of Denton and Hughes contains more ice than is acceptable from the sea level change data. They modeled another ice height profile showing the ice almost 2km less thick than claimed before (see Fig.30).

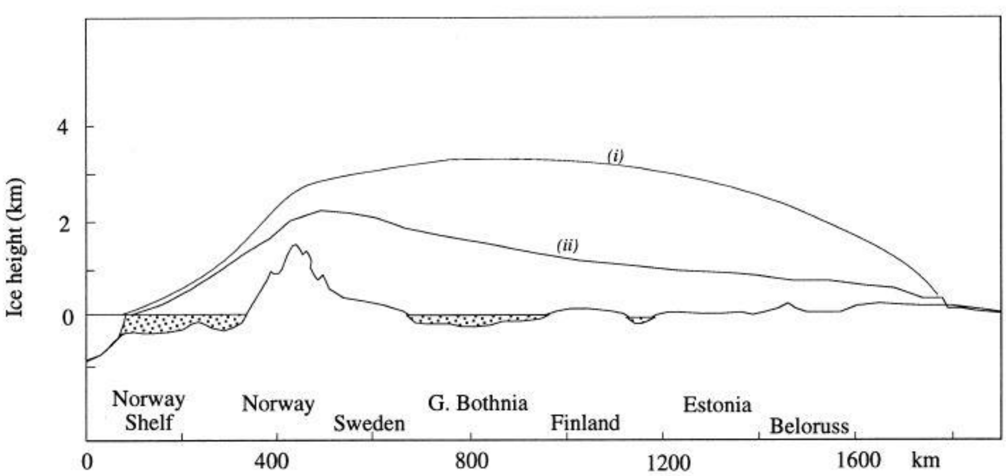


Figure 30 Ice-height profile across Scandinavia at the LGM according to: (i) Denton and Hughes (Denton & Hughes, 1981); and (ii) the model that is consistent with the inversion of sea-level data from the region (Lambeck, Yokoyama, Johnston, & Purcell, 2000)

M.G. Hewitt (1999) stated that Scandinavia was completely glaciated during the last ice age. The boundaries of the ice sheet are well defined through both numerical modeling and geological data sets (see Fig.31). The western margin and parts of the northern margin are well defined by sequences of marine sediments on the adjacent continental shelf edge, indicating that the ice sheet reached the shelf break. (Death, Siegert, Bigg, & Wadley, 2006).

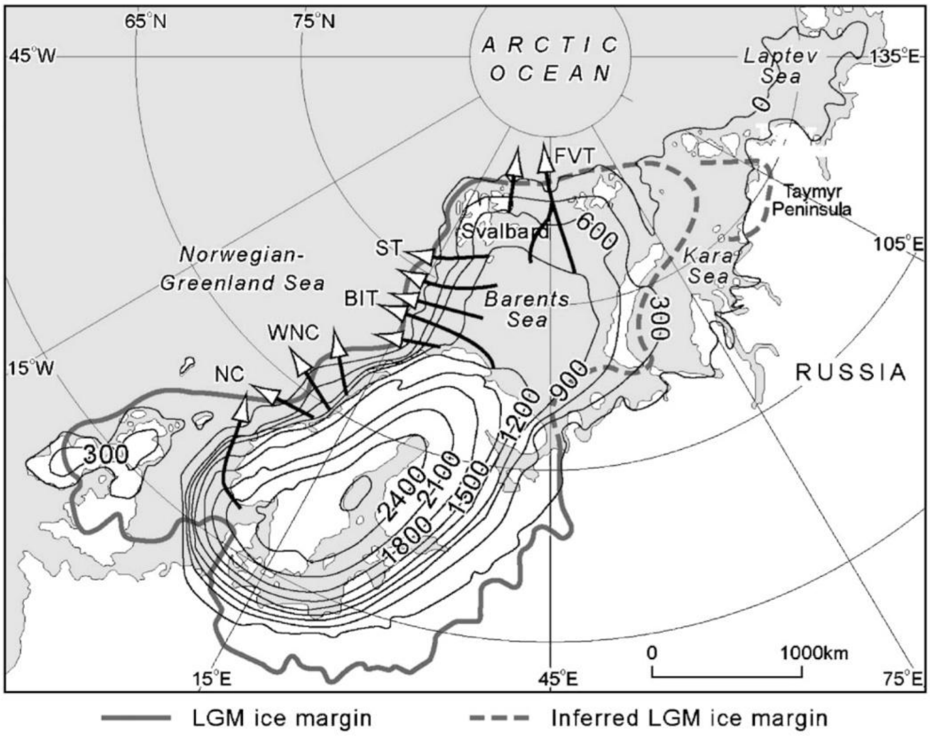


Fig. 1. The Eurasian Ice Sheet thickness at the LGM as modelled by Siegert et al. (1999). Contours are provided every 300 m. The flow directions and locations of major ice streams within the Norwegian Channel (NC), a series of western Norwegian Channels (WNC), the Bear Island Trough (BIT), Storfjorden (ST) and the Franz Victoria Trough (FVT) are denoted by arrows. Also shown is the ice sheet margin derived from geological evidence as a thick grey line (after Svendsen et al., 1999).

Figure 31 LGM ice sheet in Scandinavia (Death, Siegert, Bigg, & Wadley, 2006)

2.3 Smaller glaciated regions

Mediterranean

During the last cold stage across the Mediterranean only small cirque and valley glaciers formed. Periglacial rock glaciers also formed above altitudes of c. 1800 m and show that temperatures at the time of formation would have been c. 8–9°C lower than today (Hughes, Gibbard, & Woodward, 2003). Fig.32 shows the ice distribution around the Mediterranean. As the LGM and maximum ice volume timings differ, all of the ice sheets shown in figure 32 did not occur at the same time period.

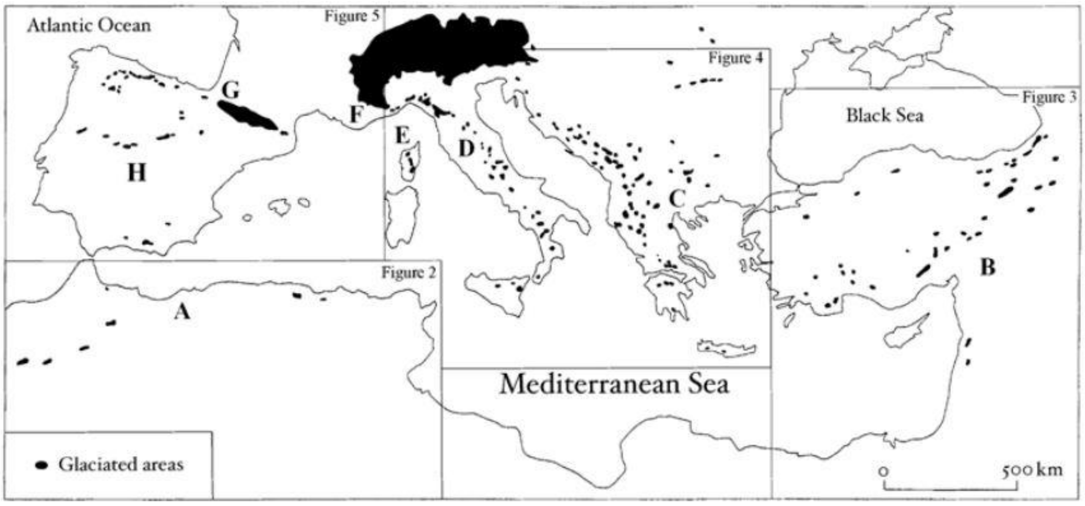


Figure 32 Distribution of Quaternary glacial features in the Mediterranean region (Woodward & Hughes, 2011)

In the Fig.32: (A) Atlas Mountains; (B) the eastern Mediterranean (Lebanon and Turkey); (C) Greece and the Balkans; (D) the Italian Apennines; (E) Corsica; (F) the Alpes Maritimes; (G) the Pyrenees; and (H) the Iberian peninsula

Ice sheet in Faroe Islands

According to (Morosa, Kuijpersb, Snowballc, Lassenb, & Bäckströmd, 2002) the icecaps from nearby ice sheets, like Iceland, Norway and Scotland, did not have contact with the Faroe Island ice cover. There is a theory that at the beginning of the ice age there were already snow filled valleys and depressions in the landscape. Over time, the snow fans developed into glaciers which then flowed towards the ocean. When a glacier reached the ocean, it would float on water and lose its grip on the land (Mortensen, 2008). The islands were never covered by a continuous ice cap, but rather by valley glaciers which at maximal glaciation would expand up towards selected mountain tops, and in places partly merge with one another.

Icelandic Ice Sheet

There have been several researches about the ice coverage in Iceland during the LGM. The timing of the LGM in Iceland is still uncertain; the dating varies between different researchers. According to Thordarson (2012) the ice extent was at its max-imum in the time period between 25-30ka BP, while others (Hubbard, Sugden, Dugmore, Norddahl, & Pétursson, 2006) (Jennings et al., 2000) state that it was about 20-22ka BP.

In Iceland, the ice sheet extended well beyond the present shores and covered the coastal shelf up to a distance of 130 km. Iceland was totally covered with ice during the LGM (see Fig.33) (Norðdahl & Pétursson, 2005). To locate the border of the ice sheet at the LGM, geological evidence in the sea has been gathered. As a result, moraine ridges have been discovered at depths of ~200m at distances of 50–150 km from the present coast (Hubbard, Sugden, Dugmore, Norddahl, & Pétursson, 2006). In addition to moraines, the Icelandic shelf is dissected by a series of broad and relatively deep troughs (narrow depressions) which gently slope from onshore valleys seaward to depths of 200–650m at the shelf break (Andrews, et al., 2000). Taken together with offshore moraines they indicate a substantial ice sheet with an area of ~300 000 km² (Norddahl, 1991b).

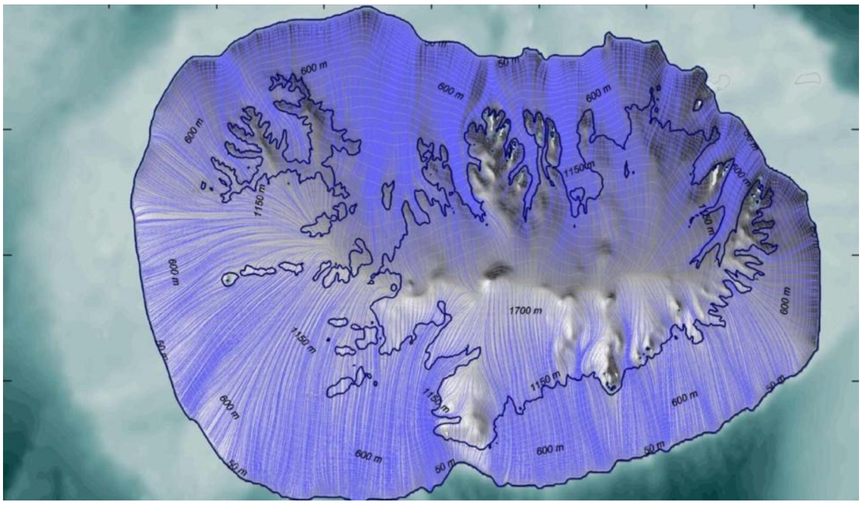


Figure 33 ice sheet over Iceland [50m isolines] (Hubbard, Sugden, Dugmore, Norddahl, & Pétursson, 2006)

A nice addition to the ice model map above is the flowlines. They are modeled to be most compatible with the found offshore evidence corresponding to a cooling of 12.5 1C and a 35% decrease in precipitation with an additional 30% suppression applied north of the 65th parallel (Hubbard, Sugden, Dugmore, Norddahl, & Pétursson, 2006).

3 Data visualization

When visualizing any kind of geographical data, it is important to know the best way this particular information could be perceived. In modern cartography it is more and more important to show information as realistically as possible (if that helps the viewer). In a case when visualized data contains information about heights; cartographers have to find the best way to deliver this information to the audience. In an experiment carried out by the TU of Dresden, turned out that about 60% of people have problems deriving height information from a topographical map (Buchroithner, True-3D visualisation of remote sensing data of high-alpine terrain, 2005). The best way to solve this problem is to visualize the given information in 3D. Thanks to improvements in cartography, and in science in general, today there are several ways to view spatial information in 3D. This is possible not only with the help of special glasses (anaglyph or polarized), but also without any help of visual aids (autostereoscopy). One such technique is called ‘lenticular foil display’ where the 3D effect is gained with the help of specially formed optical material (see chapter 4.3).

But 2D maps are still a standard way to visualize spatial information. With these maps come larger demands to show all necessary information in two dimensions, even though the data also contains the third dimension. Pattern, color and textual information can make or break the way that given information will be perceived.

3.1 Software utilized

The main software was used to carry out the work of data gathering and visualization was Esri’s ArcGIS. This software is well known for spatial data processing. It is used for: creating and using maps; compiling geographic data; analyzing mapped information; sharing and discovering geographic information; using maps and geographic information in a range of applications; and managing geographic information in a database. Several ArcGIS components, like ArcMap, ArcCatalog, ArcToolbox and ArcScene, were used during the working process.

The final work of creating the designs for the paper maps of Europe and the Alps was done by using Adobe Illustrator CS5 and Adobe Photoshop CS5. Adobe Illustrator is a good option when working with vector data. In this case all the created labels, signs and the legend were created in this software. The final maps consist of a raster background with all the non written information and a vector layer with written information. These both layers were combined using the software Adobe Photoshop.

3.2 Digitization process

None of the gathered information was available already digitized, in vector format. This means that all maps that had some information about the ice extent during LGM were in raster format (jpeg, png or tiff) and had to be digitized manually. The digitalization work was carried out in ArcMap which is the main component of ArcGIS.

The whole digitization process included a tremendous work of several people. It took several months to combine and digitize all the findings. The digitized data includes very detailed information. Not only for the larger ice sheets height information had to be digitized but also for ice sheets as small as few hundred meters, height information had to be manually drawn.

Reference system

Before starting any kind of digitization work, a reference system had to be chosen and used throughout all the working process. As a reference system for this project the European Terrestrial Reference System 89 (ETRS89) was chosen. ETRS89 is the EU-recommended frame of reference for geodata for Europe. It is the only geodetic datum to be used for mapping and surveying purposes in Europe (JRC-IES-LMU-ESDI, 2004). As for the projection the ‘Lambert azimuthal equal-area projection’ (LAEA) was used.

Georeferencing

As the idea of this project is to combine different data in one dataset, they had to be visualized in the correct geo-location. This means that every raster map that was digitized, was georeferenced first. This was easily managed with the ArcMap georeferencing tool. An example of how a map looks after georeferencing can be seen in Fig.34.

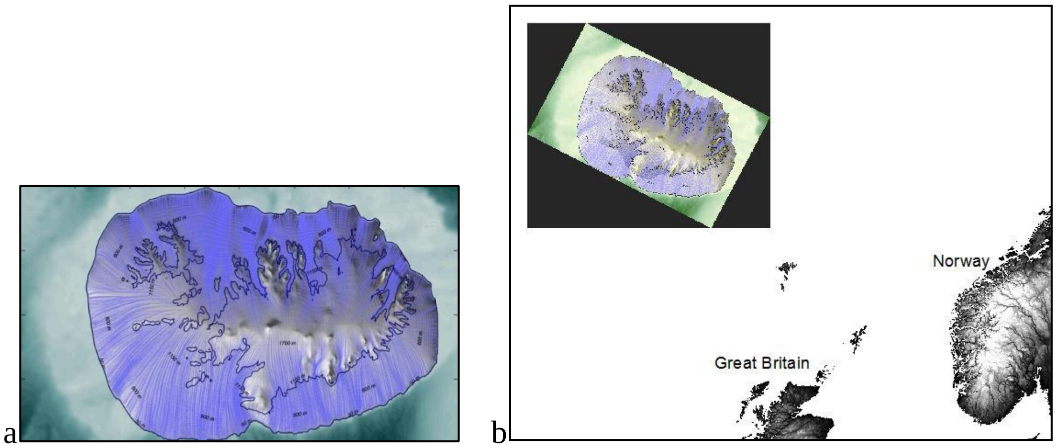


Figure 34 Ice extension on Iceland: a) not georeferenced, b) georeferenced in ETRS89_LAEA (image of Iceland from Fig. 33)

3.3 Height modeling

In the process of data gathering, most of the maps that were found had some kind of height information about the ice. But at the same time there were some sources that provided only information on the horizontal extent of the ice. These snow and ice areas without height information are relatively small compared to the big ice sheets that cover, for example, the Alps or Scandinavia. Some of them are just few hundred meters in diameter. Since the goal of the project is to make a database with 3D information, the missing height information had to be manually modeled.

One of the best ways to model surfaces in three dimensions is by using a 3D software package. Here the selection of software is quite broad, though all of them have one big disadvantage – they are not suitable for GIS data. The moment you import the data into a 3D software, it uses its own coordinate system.

For this reason, it was chosen to deal with this problem in ArcGIS where it is possible to visualize data in 3D and still retain the original coordinate system. To generate a modeled ice surface, 3 main working steps had to be performed:

- contour generation from a DTM
- new contour creation for the ice region
- new surface creation with interpolation

Contour generation

Because some of the ice surfaces were as small as few hundred meters in diameter, a very detailed DTM had to be used for height reference. Shuttle Radar Topography Mission (SRTM) data was chosen. The SRTM has obtained data on a near-global scale to generate the most complete high-resolution digital topographic database of Earth. It has coverage of the majority of the Earth's surface (from 56° S to 60° N) with high resolution data (up to 30m within the USA and 90m for the rest of the world). From the SRTM DTM contours were generated. ArcGIS has a special tool for this operation (it can be found in ArcToolbox→3D Analyst Tools→Raster Surface→Contour). This tool uses the height information that is incorporated in the DTM and creates contour lines at the desired contour interval. An example of how this tool works can be seen in figure 34.

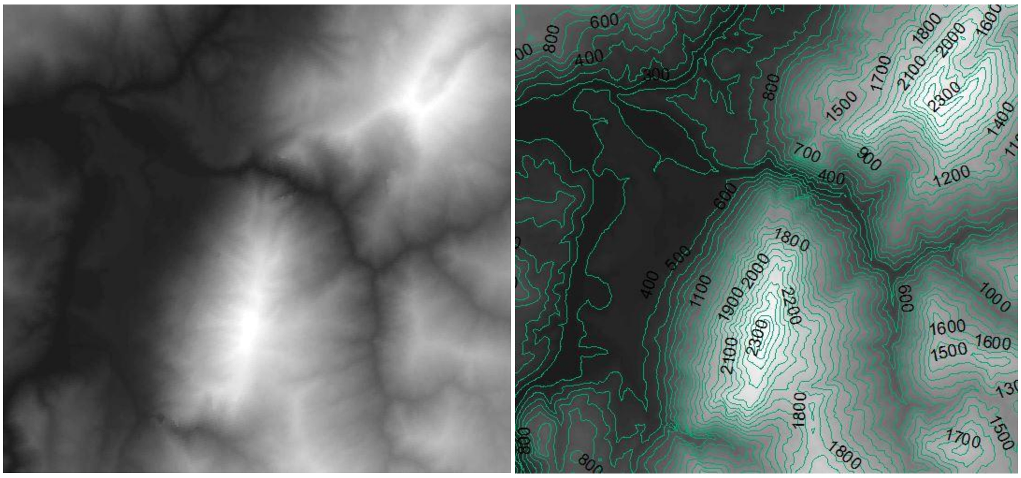


Figure 35 Contour generated from a DTM (in the region of Greece, about 18x18 km)

New contour creation

In the next step new contour lines were drawn while taking into account the actual terrain topography underneath the ice surface. The ice horizontal extent polygons were overlaid on the generated DTM contour lines, and the new contour lines were created on top of it all (see Fig. 36). While creating the new surfaces, it was kept in mind how the ice looked on the Alps, for example, to have an understanding of what kind of shape the ice would have had. The new modeled surfaces are smoother and higher than the actual terrain underneath them. The valleys have thicker ice coverage than other parts of the ice sheets.

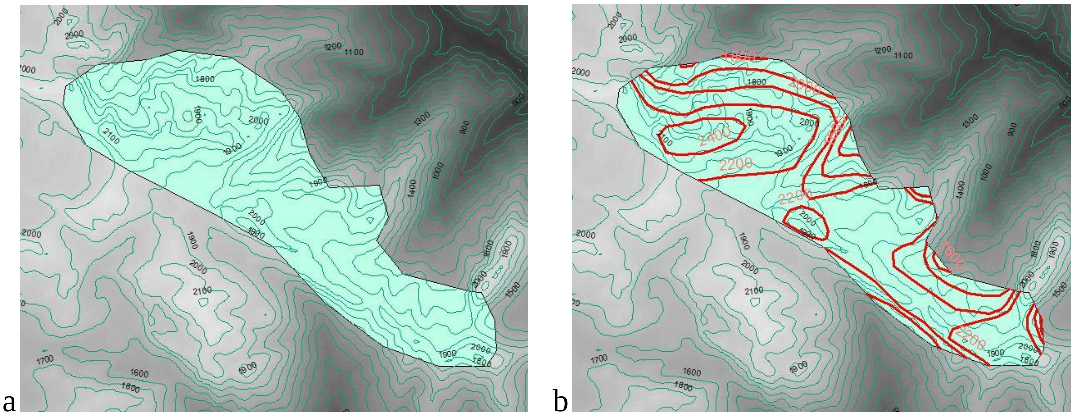


Figure 36 Border of an ice sheet overlaid on a DTM, b) New modeled horizontals of the ice sheet (location: Greece, area extent about 7x9km)

New surface creation with interpolation

In the last step, a new raster surface was created with the help of interpolation. ArcGIS has a tool that can make interpolation in between contours for a specific region. This tool can be found in ArcToolbox→3D Analyst Tools→Raster Interpolation→Topo to Raster. By defining the ice boundaries and the newly modeled contours, new ice surfaces can be created (see Fig.37).

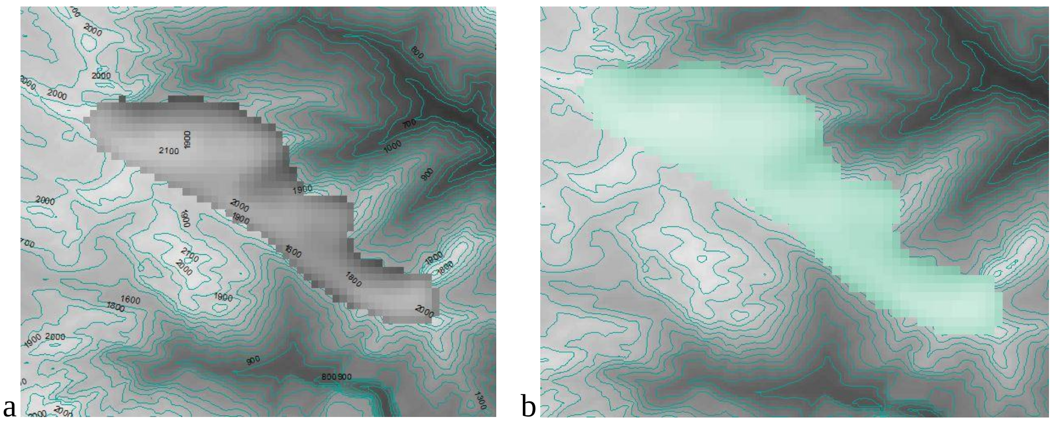


Figure 37 Interpolated surface: a) gray scale, b) assigned color scheme to better simulate ice surface

4 Data usage

The compiled data can be used in different ways. The term "Cross media" implicates that the same or minor variations of content can be placed or pushed onto different platforms in different forms. This means that from the created database it is possible to deliver different information about the LGM. Examples of paper maps of Europe and the Alps are described in section 4.1 and 4.2 as well as an example of a 3D data representation using lenticular foil is described in section 4.3.

4.1 Paper map "Europe at the Last Ice Age"

Maps can deliver much more than just geographical information. They can give a feeling of certain time or place that is depicted, or just make you look at things slightly differently.

Scale and size: For the map of all of Europe, a scale of 1:5 000 000 was chosen. Geographical information from 33°0'0" W to 58°0'0" E longitude and 33°0'0" N to 66°0'0" N latitude was combined in a 75x80 cm data frame.

DTM: As a topographical base layer a DTM of GTOPO30 was chosen. GTOPO30 is a digital terrain model for the world, developed by United States Geological Survey (USGS). It has a 30-arc second resolution (~1km), and is split into 33 tiles stored in the USGS DTM file format.

Ice data: The outcome from ice sheet data gathering, digitization and interpolation is stored in raster format. For better data access and modification, all data was divided in smaller regions according to their location:

- Iceland and the island of Jan Mayen
- Scandinavia and the British Isles
- The Alps
- Massif Central and Vosges mountains
- The Pyrenees
- Spain

- Italy and Corsica
- Balkan region
- Romania

Generalization: The map of Europe is in the scale 1:5,000,000. This means that many of the digitized small ice sheets would not be recognizable in this scale. Elements of about 2mm can be still distinguished in this size of map. In this map 2mm stands for 10km. By taking that into account, generalization of ice sheets has been made. All ice sheets which area is smaller than 10 km^2 have been removed and the rest combined in to 3 groups:

- 10 - 50 km^2 (visualized with a symbol)
- 50 – 100 km^2 (visualized with a symbol)
- > 100 km^2 (visualized with an actual border)

Additional topographic information: The physical map underneath the ice sheets contains information of today's topography:

- 21 main rivers of Europe:

Danube, Douro, Ebro, Elbe, Guadalquivir, Guadiana, Loire, Nemunas, Odra, Rhine, Rhone, Sava, Seine, Tagus, Tisa, Vistula, Zap. Dvina, Po, Vuoksa, Kemijoki and Tisa.

- 16 elevation points:

Gerlach (2655m), Corno Grande (2912m), Pico de Aneto (3404m), Torre de Cerredo (2648m), Mulhacn (3479m), Galdhpiggen (2469m), Mt. Olympus (2917m), Musala (2925m), Grossglockner (3798m), Mt. Blanc (4807m), Pico de Almanzor (2592m), Maja e Jezercs (2694m), Ben Nevis (1343m), Hvannadalshnkur (2110m), Monte Cinto (2706m) and Monte Etna (3322m).

- 45 European countries and their capitals:

Albania (Tirana), Andorra (Andorra la Vella), Austria (Vienna), Belarus (Minsk), Belgium (Brussels), Bosnia and Herzegovina (Sarajevo), Bulgaria (Sofia), Croatia (Zagreb), Czech Republic (Prague), Denmark (Copenhagen), Estonia (Tallinn), Finland (Helsinki), France (Paris), Germany (Berlin), Greece (Athens), Hungary (Budapest), Iceland (Reykjavík), Ireland (Dublin), Italy (Rome), Latvia (Riga), Liechtenstein (Vaduz), Lithuania (Vilnius), Luxembourg (Luxembourg), Republic of Macedonia (Skopje), Malta (Valletta), Moldova (Chisinau), Monaco (Monaco), Montenegro (Podgorica), Netherlands (Amsterdam), Norway (Oslo), Poland (Warsaw), Portugal (Lisbon), Romania (Bucharest), Russia (Moscow), San Marino (San Marino), Serbia (Belgrade), Slovakia (Bratislava), Slovenia (Ljubljana), Spain (Madrid), Sweden (Stockholm), Switzerland (Bern), Turkey (Ankara), Ukraine (Kiev), United Kingdom (London) and Vatican City (Vatican City).

- Borders between the countries.

All the data was accessed free of charge from European Environment Agency (http://www.eea.europa.eu/).

Layout: The overall layout of the whole map consists of 4 parts: title, geographical information, legend and imprint. The placement of all details can be seen in Fig.38.

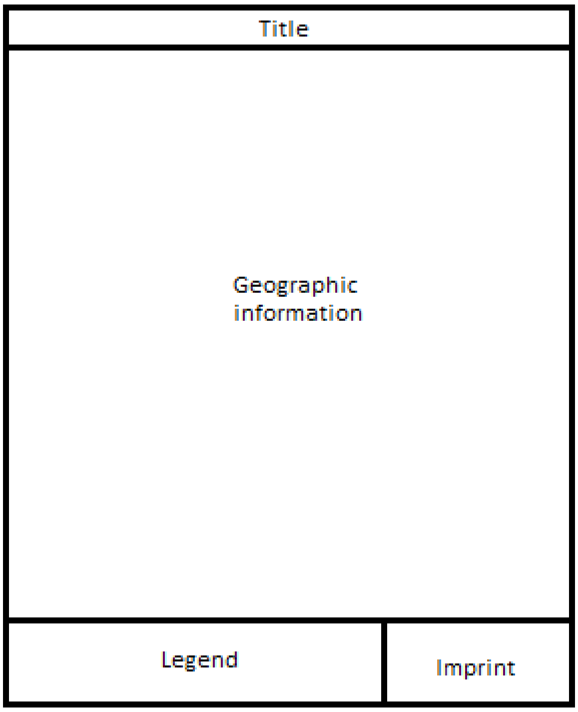


Figure 38 Layout of the paper map "Europe at the Last Ice Age"

Design: When the concept of the map has been finalized and the data has been gathered, the actual map design process can begin. There are several basic design rules to follow when a map is being created (Krygier, 2008):

- Concept before compilation
- Hierarchy with harmony
- Simplicity from sacrifice
- Maximum information at minimum cost
- Engage the emotion to engage the understanding

One of the biggest problems while working on the design of the map was the color ramp for land and ice masses. For the land mass, a natural color scheme based on hypsometric principles was used: from green to dark brown (from lower to higher elevation accordingly) (see Fig.39).

Figure 39 Hypsometric tinting for land

To emphasize the elevation on the map, a hillshade model was created from the GTOPO30 DTM. This was done in ArcToolbox→3D Analyst Tools→Raster Surface→Hillshade. Next, it was overlaid onto the colored DTM and set to 80% transparency (see Fig.40). Not only does the relief stand out better but also the colors become less saturated and thereby more pleasant to the eyes.

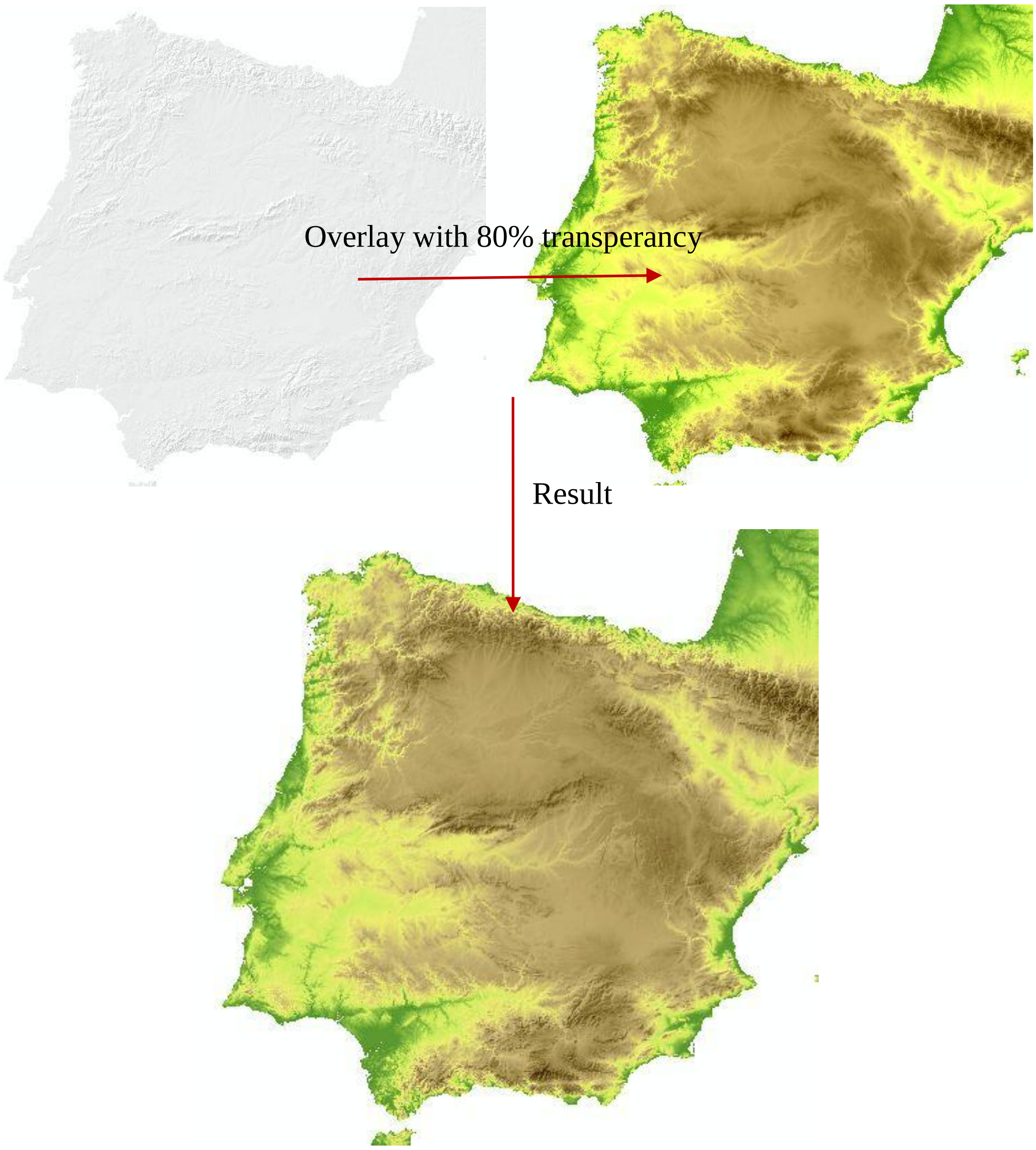


Figure 40 Hillshading overlaid on colored DTM (data location-Iberian peninsula)

The color scheme for the glaciated areas was chosen from green/blue (turquoise) to white (from lower to higher elevation accordingly) (see Fig.41). As the colors for lower to higher parts don't differ too much, additional ice isohypses have been added.

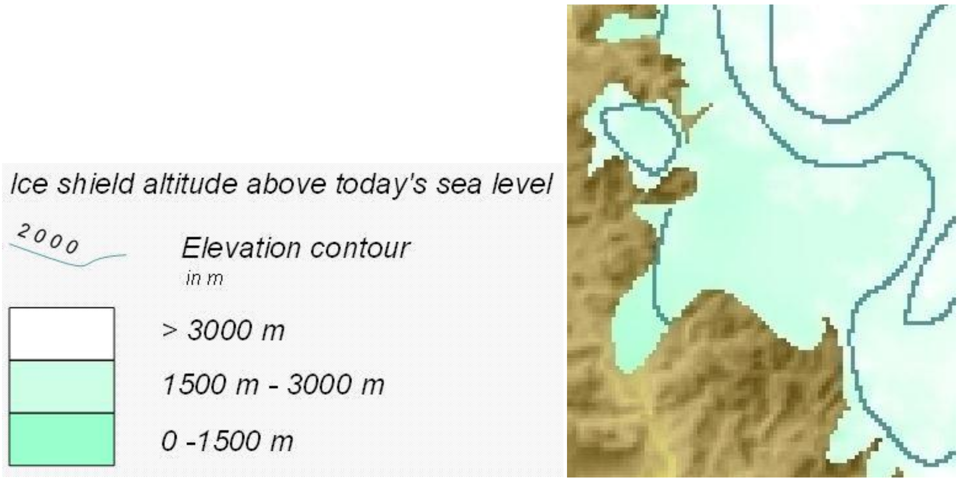


Figure 41 Hypsometric tinting and ice isohypses for the glaciated areas and an example of it in a 1:5,000,000 scale map (data location- part of the Western Alps)

In the end some extra GIS data was added for better information perception. As the main focus on the map should be on the ice, only a few main rivers and elevation points were added. The borders and the names of countries and cities were visualized to not stand out too much but still help to identify the location of ice. Figure 42 shows an example of harmonized information display on the Ice Age map.

Figure 42 Example of data harmonization in a 1:5,000,000 scale map (Part of map 'Europe at the Last Ice Age')

4.2 Paper map "The Alps at the Last Ice Age"

Scale and size: For the map of the Alps a scale of 1: 1,000,000 has been chose. Geographical information from 4°0'0" E to 17°0'0" E longitude and 43°0'0" N to 49°0'0"N latitude was combined in a 65x100 cm data frame.

DTM: As a topographical base layer a DTM of SRTM was chosen. SRTM is an international research effort that obtained digital elevation models on a near-global scale from 56° S to 60° N, to generate the most complete high-resolution digital topographic database of Earth. The resolution of the data is three arcseconds (90 m). The data was obtained from the CGIAR Consortium for Spatial Information (CGIAR – CSI) [http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp].

Ice data: The ice data included in the map cover the region of the Alps, the south part of Vosges Mountains and some northern Apennines areas.

Additional topographic information: The physical map underneath the ice sheets contains information of today's topography:

- Big rivers: Po, Rhine, Danube, Sava and Ardeche. Addtionally some other smaller rivers that drain together with the main rivers.
- Elevation points: Mont Agel (140m), Mt. Blanc (4807m), Crt de la Neige (1718m); Monte Rosa (4634m), Matterhorn (3883m), Finsteraarhorn (4274m), Feldberg (1493m), Grauspitze (2599m), Zugspitze (2963m), Grossglockner (3798m), Triglav (2864m) and other.
- 11 countries and some major cities in them: Austria, Croatia, France, Germany, Italy, Liechtenstein, San Marino, Slovenia, Switzerland, Hungary, Bosnia and Herzegovina.
- Borders between the countries.

All the data was accessed free of charge from European Environment Agency (http://www.eea.europa.eu/) and Natural Earth (http://www.naturalearthdata.com/).

Design: For the ice visualization only one color was chosen but as the data include height information, additional information had to be added. This information included ice isohypses with height information written on them and a hillshading DTM.

To emphasize the elevation on the map (outside the ice covered areas), a hillshade model was created from the SRTM DTM. overlaid onto the colored (see workin procedure in section 4.1). The ice and land hillshades combined can be seen in figure 43.

For the land mass, a natural color scheme based on hypsometric principles was used: from green to dark brown (from lower to higher elevation accordingly).

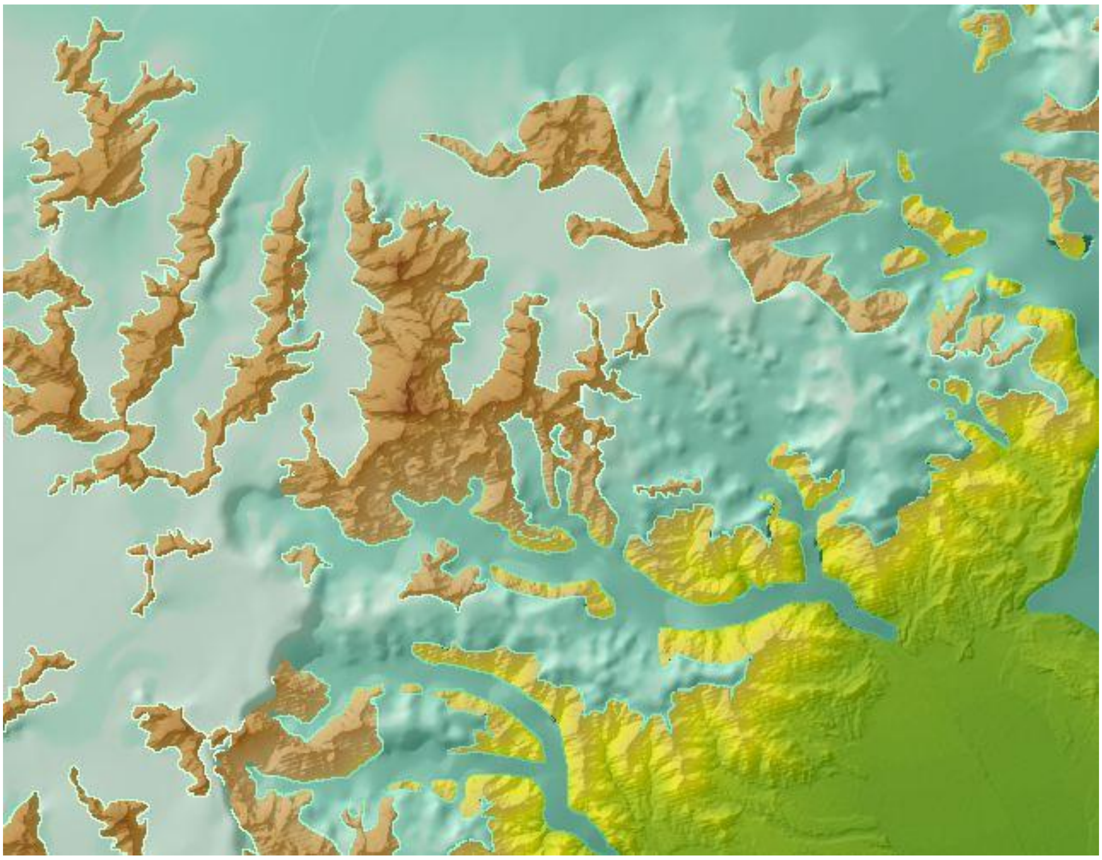


Figure 43 Ice and land hillshades combined

4.3 Lenticular foil map

Lenticular visualization methods are a major step forward in modern presentation media in cartography. This is one of the few techniques that allow you to perceive real 3D information without any additional visual aids (like anaglyph or polarized glasses). The technique is based on half cylindrical lenses that divide the image behind them. In this way a 3D perspective of two or more stereo images is possible. Besides the 3D effect, lenticular foil can be used for other types of representation. For example, 2D or 3D flip mode, morphing, animation or even zooming. It is also possible to change from 2D to 3D. Everything depends on what kind of information is placed behind the lenticular foil.

A lenticular display consists of two components: a lenticular foil and lenticular image. One side of the lenticular foil is totally flat (the one placed directly on the image) and the other side consists of an array of half-cylindrical lenses (see Fig.43) (Buchroithner, Walder, Habermann, & Konig, 2003).

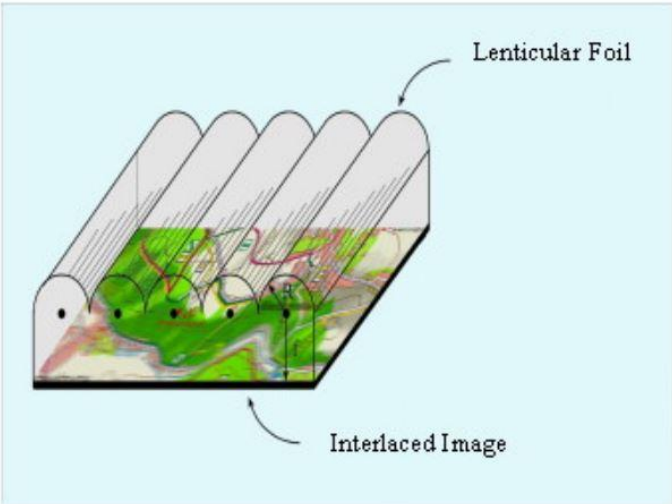


Figure 43 Principle of lenticular foil display (Buchroithner, Walder, Habermann, & Konig, 2003)

The image behind the foil is specially prepared: two or more existing images are dissected into various small stripes, and then these stripes are systematically merged into one image (see Fig.44). Depending on the viewing angle, different stripes of the image shift into the focus of the lenses. Thanks to this optical flip effect, the different original images can be seen (Dickmann, 2010).

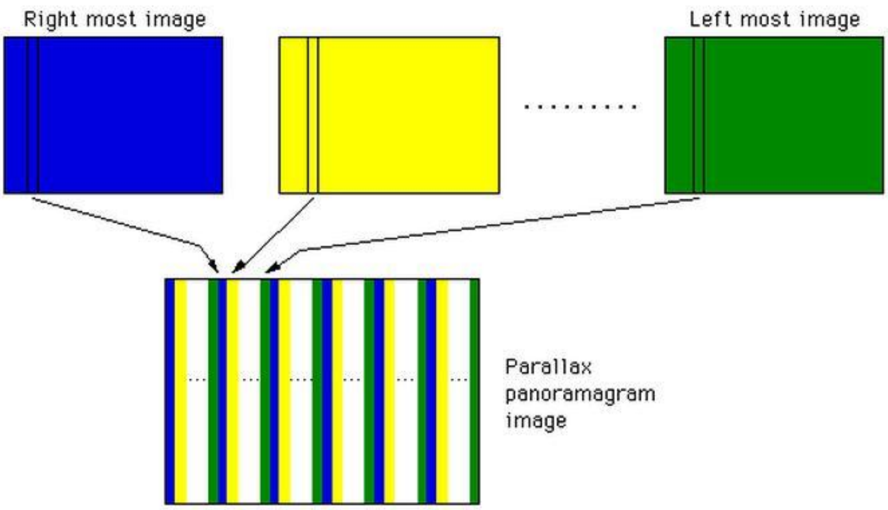


Figure 445 Slicing and resampling of images for lenticular display (Bourke, 1999)

Lenticular foil technique has already been proven to be very successful in visualizing relief information. Besides giving a good overview of the height information, it is also possible to display additional information, like textual descriptions, extra signs, design elements etc., in a way that it doesn't cover any topographic information; the information hovers above the main data (Knust, Buchroithner, Dickmann, & Bröhmer, 2011).

There is a 50 percent chance the viewer will be in the wrong position and see an incorrect, pseudoscopic image (inside out or inverse). For best perception the viewer must remain quite still. Movement from side to side or moving forward or backward from the ideal distance greatly reduces the chance of seeing a correct image. This problem can be solved by increasing the number of stereomate views used to create the underlying lenticular image (Dodgson, 2005).

4.4 Further use of the data

The data about the last Ice Age that have been gathered and combined in one data base are appropriate for cross-media purposes. Out of this database, it is possible to create different 2D and 3D representations of the last Ice Age for different regions in Europe, or as shown in section 4.1, it is possible to make an overview map of the whole of Europe.

The data provided are in raster and vector format:

- Vector data - Polygons showing ice covered areas and isohypses with height information of the ice
- Raster data - Tiff files of the ice coverage (in grayscale according to height information)

Conclusions

1) Research on the last Ice Age in Europe has proven that there is a vast amount of data about this time period. With new improvements in technology (increasing image resolution), more accurate and detailed information about the ice extent can be presented. This thesis includes up to date information, which might be made obsolete in the future by improved research results.
2) Within this project a huge amount of data has been gathered but nevertheless it is possible that there is more information to be added. New discoveries about ice extents are very likely to be made.
3) As the last glacial period ended about 10 000 years ago, there is no sure way to determine whether the gathered information depicts the actual situation. When dealing with historical data, the author's interpretation is always involved to some extent. This is also true for this thesis: the manually modeled ice surfaces described in chapter 3.3 are just a suggestion about how the ice might have looked at some particular locations.
4) It was decided that the ice sheet over Scandinavia and the British Isles be displayed as one ice mass. This was done based on many older information sources, but mainly based on the most recent research by Clark (2010). It is not ruled out that there might have been two separate ice sheets on each land mass, but the newest results presented by Clark (2010) are assumed to be the situation for this date.
5) The two types of maps described in this thesis are just examples of what can be done with the compiled data. Recent improvements in cartography have shown that it is possible to create different types of maps from just one data set.
6) When creating a map from the compiled data in various scales, the problem of 3D data generalization might occur.

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Appendix 1

Additional data concerned during the work on this thesis.

Wegberg Compass

In March 2005 in the Schmitzhofs Golf Club, Wegberg-Merbeck, Germany a "man-made" engraved stone was found by Hans Grams. It is believed by Hans Grams to represent Europe about 70 000 years ago. On this stone several presumably recognizable places of Europe can be distinguished (see Fig.45). By carrying out several measurements and experiments in the University of Duisburg-Essen, it was assumed that this stone has been used as map of Europe. Not only it shows the relief of Europe as we might know it today but it also displays two historical factors about Europe during the Ice Age: ice caps covering some parts of Europe and some previously existing land connections (like Great Britain and France as well as Africa and Italy) (information was taken from the description of Finding W274S, Europa-Kompass (http://www.ldi5.com/paleo/hansgrams1.php, http://www.hans-grams.de/page6.php, http://hans-grams.de/Dissertation/Dissertation.pdf)).

Even though the measurements carried out on the stone might – with a good deal of "geo-fantasy" – indicate some geometric similarities with Europe, still the lack of evidence and the high probably of coincidence make doubt the authenticity of it. For this reason it cannot be used as a reliable source to reconstruct the ice extent. Further, the question arises how – some 100 000 to 10 000 years ago – the information about the ice extent during the Last Glacial Period (LGP) or Last Glacial Maximum (LGM) could at all have been acquired by the ancient population.

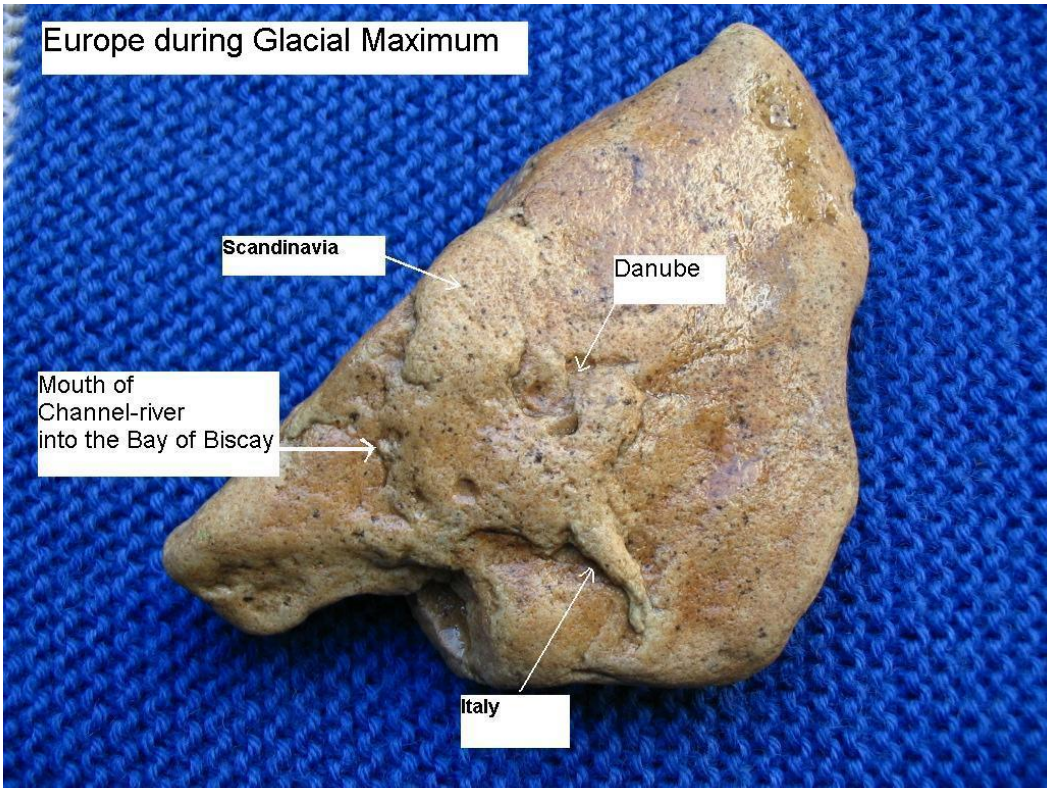

Figure 45 A stone (European Compass) that represents Europe during Ice Age

Appendix 2

Poster presented at the International Cartography Conference held in Dresden, Germany, August 2013.