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Geospatial modelling of the glacial archaeological potential in the Pennine Alps

THESIS

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SUMMARY

Humans have a longstanding relationship with frozen environments. Although this relationship is not fully understood, humans are known to have frequented frozen regions for thousands of years to obtain resources or to move between locations. Recent changes in climate have increased melting of glaciers, ice patches, and permafrost at high latitudes and altitudes. In some regions, thawing of these environments has led to the accidental discovery of archaeological remains or artefacts. As a result, archaeologists have shifted their research to frozen areas in an attempt to collect and preserve unique glacial archaeological findings.

The Pennine Alps, located between the canton of Valais in Switzerland and the provinces of Aosta and Piedmont in Italy, is a region of glacial archaeological interest due to its vast glaciated terrain and rich cultural history dating back to the Mesolithic (12,000 – 9,000 years BP). The high altitude passes located on the border between Switzerland and Italy have been used as trade, commerce, and migration routes for thousands of years. The melting of glaciers in this region is freeing-up archaeological remains on passes or surrounding areas that support their prehistoric and historic use. Due to the organic composition of many potential remains (e.g. wood, clothing), there is an urgent need to collect these items before they are destroyed. However, the high altitudes at which potential sites are located are not conducive to regular systematic archaeological prospection due to their remoteness and inaccessibility.

Geospatial analyses, incorporating information from geographical, historical, and archaeological sources, offer a unique opportunity to determine glacial archaeological potential. In this thesis, geospatial analyses using Geographic Information Systems (GIS) and glaciological methods were employed to determine areas of highest glaciological potential in the Pennine Alps to help locate, collect, and preserve unique glacial archaeological objects in partnership with archaeologists and historians as part of a multidisciplinary project funded by the Swiss National Science Foundation (SNSF).

Using various geospatial methods, including least cost path and locational analyses and glaciological modelling, 31 high altitude passes of glacial archaeological interest and potential were identified in the Pennine Alps. A Bronze Age artefact was discovered after the archaeological prospection at one of these sites which was previously unknown to archaeologists and historians. This demonstrates that geospatial analyses can be used to focus archaeological prospection by narrowing down large, remote, study regions to sites of a few square kilometers to support decisions about where to conduct current and future archaeological prospection. Future efforts should continue to use geospatial analyses to focus on the archaeology of frozen regions to identify areas of potential in order to avoid losing unique information about past cultures and climates.

RÉSUMÉ

Les humains fréquentent les environnements froids et englacés depuis des milliers d'années, comme passage permettant de relier deux régions ou dans le but d'en exploiter les ressources. Dans certaines zones de haute montagne et situées sous les hautes latitudes, la fonte et le retrait des glaciers, des névés et du pergélisol, liés à des changements climatiques récents, a ainsi permis la découverte, souvent accidentelle, d'artéfacts et de restes archéologiques. Ces découvertes ont éveillé l'intérêt des archéologues pour ces régions englacées et ont ainsi contribué au développement de l'archéologie glaciaire. Le but des recherches dans ce domaine étant de collecter et de conserver ces objets uniques, fraîchement libérés des glaces, avant qu'ils ne disparaissent pour toujours.

Les Alpes pennines désignent la région comprise entre le canton du Valais en Suisse et les provinces d'Aoste et du Piémont en Italie. En raison de l'étendue des masses glaciaires et de sa longue histoire culturelle qui a débuté au mésolithique (12'000-9'000 années BP), cette région représente un grand intérêt pour l'archéologie glaciaire. Les cols de hautes altitudes situés à la frontière entre la Suisse et l'Italie ont servi de routes commerciales, ainsi que de voie de migration depuis des milliers d'années. Des objets archéologiques, mis à jour par le retrait glaciaire sur les cols et dans leurs environs, apportent des indices quant à leur utilisation historique et préhistorique. Or, ces artéfacts, étant fréquemment de composition organique (comme le bois ou les pièces de vêtements), se décomposent rapidement au contact de l'air. Il y a par conséquent une urgence de les collecter avant qu'ils ne se dégradent. Toutefois, ces sites potentiels sont souvent situés à une altitude élevée et donc inaccessibles, ce qui rend difficile toute prospection systématique et représente donc un défi pour les archéologues.

Pour répondre à ce défi, et dans le but d'identifier les zones de fort potentiel archéologique dans les Alpes pennines, cette thèse de doctorat se base sur les analyses géospatiales. Ces dernières ont la particularité de permettre l'intégration à la fois des informations géographiques, historiques et archéologiques. L'outil développé, basé sur des systèmes d'information géographique (SIG, ou GIS en anglais) et des méthodes d'étude glaciologiques, a pour ambition, à terme, de permettre de localiser, de collecter et finalement de conserver ces artéfacts archéologiques uniques libérés des glaces.

Une approche intégrative utilisant différentes méthodes géospatiales a été développée. Elle inclut deux types d'analyses spatiales, l'analyse du trajet optimal, et l'analyse de localisation, ainsi que des modélisations du retrait glaciaire. Cette approche permet d'identifier les zones archéologiques les plus intéressantes et de proposer des zones de prospection de quelques kilomètres carrés chacune. Trente et un cols d'intérêt pour l'archéologie glaciaire ont notamment été identifiés dans les Alpes pennines. Lors d'une prospection, un objet datant de l'âge du Bronze a été découvert dans une des zones définies, jusqu'à là inconnue aux archéologues et historiens. Ainsi, la méthodologie développée dans cette recherche fournit un outil d'aide à la décision aux archéologues, afin qu'ils puissent cibler et mener des campagnes de prospection sur les secteurs les plus prometteurs.

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LIST OF ABBREVIATIONS

%	Percent
~	Approximately
°	Degrees
°C	Degrees Celsius
°E	Degrees East
°N	Degrees North
°S	Degrees South
°W	Degrees West
2D	Two Dimensional
3D	Three Dimensional
ACDR	Accumulative Cost Distance Raster
AD	After Death
ALM	Archaeological Location Modelling
asl	Above Sea Level
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AT	Austria
BP	Before Present
c.f.	Confer
cal.	Calibrated
CBB	Cabin de Becs de Bosson
CH	Switzerland
CLPs	Current Landcover Paths
Corine	Coordination of Information on the Environment
DE	Germany
DEM	Digital Elevation Model
E	East
e.g.	For Example
ESRI	Environmental Systems Research Institute
FR	France
GDEM	Global Digital Elevation Model
GIS	Geographic Information Systems
GPS	Global Positioning System
GRASS	Geographic Resources Analysis Support System
HVR	Haut-Val de Réchy
i.e.	that is
IPCC	Intergovernmental Panel on Climate Change
IT	Italy
IVS	Inventory of Historical Traffic Routes in Switzerland
ka	One thousand years
km	Kilometers
km ²	Square kilometers
LCP	Least Cost Path
LCPA	Least Cost Path Analysis
LGM	Last Glacial Maximum
LIA	Little Ice Age
LOS	Line of Sight

m	Meters
MCDA	Multi-Criteria Decision Analysis
N	North
NASA	National Aeronautics and Space Administration
PLPs	Prehistoric Landcover Paths
QGIS	Quantum Geographic Information System
RCM	Regional Climate Models
S	South
SAGA	System for Automated Geoscientific Analyses
SGI2010	Swiss Glacier Inventory 2010
SNSF	Swiss National Science Foundation
TLP	Topographic Landcover Path
U.S.A.	United States of America
W	West
WGS84	World Geodetic System 1984
WPs	Wanderland Paths

1 GENERAL INTRODUCTION

This research is part of the multidisciplinary Swiss National Science Foundation (SNSF) project “Modelling archaeological potential in the Pennine Alps using Geographic Information System (GIS) tools” (CR21I2 130279). Geographers, historians, and archaeologists collaborated to achieve the common goal of identifying regions of high archaeological potential in the Pennine Alps between Switzerland and Italy. Here, the results of the geographical aspect of the project are provided.

1.1 MOTIVATION

Humans have a longstanding relationship with frozen environments. Although high latitudes and altitudes are relatively dangerous and inhospitable, they have proven to be prime locations for obtaining life’s basic necessities such as water (Reckin, 2013; Wiegandt and Lugon, 2008) and food (Dixon et al., 2005; Gotthardt et al., 1999; Hare et al., 2004, 2012; VanderHoek et al., 2012). These regions were also not an obstacle to travel, as high altitude mountain passes were often traversed for the purposes of commerce or migration (Ammann, 1992; Bezingue and Curdy, 1994 1995; Coolidge, 1912; Curdy et al., 2003; Curdy, 2007; Harriss, 1970, 1971). As a result of climate change, archaeological objects that have been preserved in glaciers, ice patches, and permafrost for hundreds or even thousands of years are melting out of their protective ice beds (Dixon et al., 2005; Molyneaux and Reay, 2010). The discovery of these objects has resulted in a new discipline within archaeology that is referred to by various names, such as ice patch (c.f. Andrews and MacKay, 2012; Reckin, 2013), Alpine (Hunt, 2007), frozen (Molyneaux and Reay, 2010), and glacial archaeology; the latter of which is used throughout this thesis. Glacial archaeological artefacts are at risk of being destroyed by decomposition if they are not located before, or soon after they have been exposed from their frozen environment, because they are often composed of organic materials such as leather, wood, or bones (Dixon et al., 2005). Because temperature increases are not expected to halt, (IPCC, 2013), additional glacial archaeological finds that provide deeper insights to past human cultures and climates are extremely likely to occur.

To date the majority of glacial archaeological discoveries have been encountered accidentally. Until recent decades, it was assumed that humans did not frequent areas above the treeline (2,000 m asl) during the Neolithic period (Hafner, 2012) (Table 1.1). Therefore, archaeologists did not originally undertake systematic prospection in these regions. After the chance discovery of the most famous glacial archaeological remain to date, Ötzi the Tyrolean Ice-man, archaeologists have shifted their research to frozen regions to prevent losing potentially irreplaceable objects which can provide important information about past cultures and climates (Dixon et al., 2005).

Ötzi was located by hikers in the Tyrolean Alps on the Italian side of the Italy/Austria border in 1991 (Prinoth-Fornwagner and Niklaus, 1994; Seidler et al., 1992) (Fig. 1.1a). The ice kept this approximately 5,300 year-old corpse in unprecedented condition, making Ötzi one of the most important archaeological finds to date (Dixon et al., 2005). Information such as origin, ancestry, diet, and disposition to diseases could be extracted from Ötzi due to his unique preservation (Janko et al., 2012; Keller et al., 2012). Other significant prehistoric and historic findings have been located on several continents. For example, in Asia melting permafrost surrounding previously frozen tombs located in the Altai mountains in Russia, Kazakhstan, Mongolia, and China are leading to the exposure and decomposition of hundreds of 2,500 year-old corpses (Goossens et al., 2007). There is a high level of cultural and societal significance associated with these frozen tombs; therefore, protective measures should be taken to protect the culture of the indigenous people of the region (Molyneaux and Reay, 2010).

Table 1.1. Archaeological time periods defined for Alpine regions (Hunt, 2007). BP refers to Before Present.

Name	Year range (BP)	Period
Palaeolithic	Pre-12,000	Prehistoric
Mesolithic	12,000 – 9,000	
Neolithic	9,000 – 6,000	
Copper Age	6,000 – 4,000	
Bronze Age	4,000 – 2,800	
Iron Age	2,800 – 2,200	
Roman	2,200 – 1,500	Historic
Medieval	1,500 – 500	
Modern Era	500 - Present	

In North America, the majority of glacial archaeological findings from high altitudes and latitudes in this region are associated with hunting. These finds date back to 13,000 BP and include dart shaft fragments (Kuzyk et al., 1999), throwing darts (Andrews et al., 2012; Hare et al., 2012; VanderHoek et al., 2012), and bow and arrows (Fig. 1.1d) (Dixon et al., 2005; Hare et al., 2004) which were all located on or surrounding ice patches (Reckin, 2013).

In South America, finds at high altitudes are associated with the religious ceremonial offerings of mummified children dating back to Inca times between 1438 – 1532 AD (Ceruti, 2004). Often located above 6,000 m asl, these are believed to be the world's highest archaeological sites (Ceruti, 2004; Reinhard and Ceruti, 2010; Reinhard, 1999; Wilson et al., 2013).

In Europe, glacial archaeological finds have been discovered in Norway, Sweden, and the Alps, specifically in Italy and Switzerland. Finds from Norway and Sweden are similar to those from North America and are predominantly associated with hunting. Weapons such as arrowheads

and shafts have been discovered on the margins of ice patches in these Scandinavian regions (Fig. 1.1c) (Callanan, 2012, 2013; Farbrege, 1972). The oldest find dates back to the Neolithic period and were discovered in 2010 and 2011 (Callanan, 2013).

In the Alps, glacial archaeological remains older than about 12,000 years are not expected to be found due to the Last Glacial Maximum (LGM) and glacier dynamics (see section 2.1 for more information about Switzerland's glacial history). As previously mentioned, Ötzi is one of the oldest (~5,300 years BP) and most famous glacial archaeological findings from the Alps. Also located in Italy was a pair of woolen leggings dated to 2,750 BP (Dal Ri, 1995), a worked green alder binding material, and a pine twig from 2,716 BP and 6,674 BP, respectively (Rom et al., 1999). The two latter artefacts were retrieved at the same site as Ötzi and indicate that the mountain pass on which he was located was probably used for millennia both before and after his time (Rom et al., 1999). In Switzerland, researchers have uncovered glacial archaeological finds in four locations: the Lötschenpass (2,690 m asl) and Schnidejoch pass (2,756 m asl) in the canton of Bern, the Porchabella glacier (2,680 m asl) in Graubünden, and the Theodulpass (3,000 m asl) in Valais (Hafner, 2012). At the Lötschenpass, bows from the late Neolithic/Early Bronze Age and Roman coins were discovered between 1934 and 1944 (Bellwald, 1992; Meyer, 1992). The site at Schnidejoch was recently under intensive archaeological investigation after hikers found artefacts in 2003 after an extremely warm summer led to glacial melt which had not been experienced for decades (Hafner, 2012; Zemp et al., 2006). Between 2004 and 2011, archaeologists collected a trove of artefacts ranging from the Neolithic, Early Bronze Age, Iron Age, Roman, and Medieval periods, making this one of the most prolific glacial archaeological sites in the Alps. Some of the oldest remains include fragments of an elm wood bowl and a bow kit made of birch bark dated to approximately 6,500 and 4,900 years BP, respectively (Fig. 1. 1b) (Hafner, 2012). In eastern Switzerland, the skeletal remains, hair, clothing, and other belongings of a 17th century woman who fell into a crevasse on the Porchabella glacier were located between 1988 and 1992 at the foot of the glacier (Rageth, 1995). Similar to that instance, the 16th century "Mercenary of Theodul" and his belongings were found on the margins of Oberer Theodul glacier just north of the Theodulpass beginning in 1985 and lasting until 1990. As the glacier continued to melt researchers discovered more of the Mercenary's belongings which included bones, leather clothing and shoe soles, weapons, and coins (Lehner and Julen, 1991; Meyer, 1992). Since that time, archaeologists have continued to conduct research in this region, making it one of the most intensively studied high altitude archaeological sites in the Pennine Alps between Switzerland and Italy. Other non-glacial archaeological finds located near the Theodulpass include the Alp Hermettji, a rock shelter occupied between the Mesolithic and Bronze Age (Curdy et al., 2003), and a Neolithic axe made of eclogite which was discovered on a path leading to the Theodulpass (Bezing and Curdy, 1994, 1995). Several hypotheses have

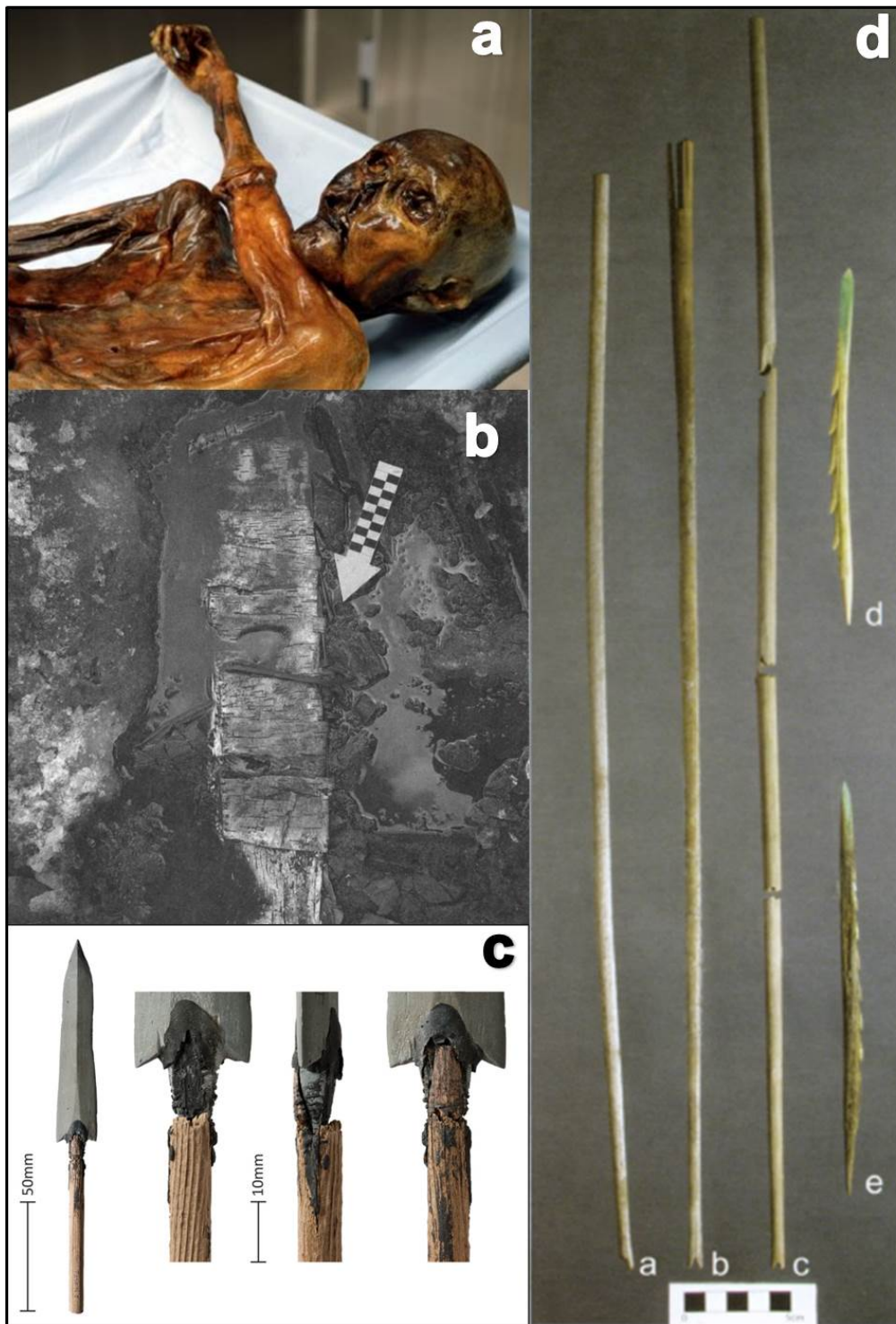


Figure 1.1. Examples of glacial archaeological finds from (a) Italian/Austrian border: Ötzi (~5,300 years BP) (South Tyrol Museum of Archaeology, 2014), (b) Birch case made of birch bark (~4,900 years BP) (Hafner, 2012), (c) slate point hafted on a shaft segment (~5,300 years BP) (Callanan, 2013), and (d) bow and arrow technology (370 years BP) (Dixon et al., 2005).

attempted to explain the location of this axe, including: confirmation that high-mountain passes in the Pennine Alps were used for trade and commerce, that the axe was accidentally misplaced by a shepherd, or that it was left as an offering to ensure safe passage over the Theodulpass, located at 3,000 m asl (Bezing and Curdy, 1994, 1995).

Other high altitude passes in the Pennine Alps, like the Theodulpass, have been used for thousands of years for the purposes of trade, commerce, and migration. Some passes are more familiar to archaeologists and historians than others. For example, the Grand Saint-Bernard, Fenêtre de Durand, Col Collon, Theodul, Monte Moro, Simplon, and the Albrun passes are considered to be the “principal” ones with well-documented use (Benedetti and Curdy, 2008; Curdy, 2007; Curdy et al., 2010). Other “secondary” passes were also used, although they are less well-documented and have likely become forgotten over time. Archaeologists believe, and recent evidence has demonstrated, that cultural artefacts are locked in the ice at high altitudes in the Pennine Alps between Switzerland and Italy. As snow and ice at high altitudes continue to melt, there is an urgent need to investigate these high altitude mountain passes as more archaeological finds, which hold the key to past cultures and climates, are expected to be revealed from their frozen environment. There are over 60 high altitude passes of potential archaeological interest between Switzerland and Italy. Ideally, each of these passes should be examined at the end of the summer each year, when snow and ice are at their minimum to promote prospecting conditions. However, the systematic prospection of each of these passes is constrained by limited resources.

Geospatial analysis technologies, like GIS, offer new, exciting opportunities to focus archaeological prospection on regions of greatest archaeological interest and potential. Information from various disciplines such as, geography (e.g. topographic information, landcover characteristics, glaciological modelling), archaeology (e.g. knowledge of previous archaeological sites), and history (e.g. archival texts and information about the past) can be spatially analyzed together. Thus, GIS provides an opportunity for an integrative approach to determine glacial archaeological potential in the Pennine Alps with the overall goal to obtain a better understanding about humans and their surrounding environments.

1.2 OBJECTIVES

The main objectives of this thesis are:

1. To contribute to the identification of areas of glacial archaeological interest in the Pennine Alps.
 - Determine which areas of the Pennine Alps could be most easily traversed by humans based on the physical characteristics of the terrain. This is based on the assumption that if areas are more accessible then they will have a higher glacial

- archaeological potential. Least cost path analyses (LCPA) will be used to calculate high altitude pass accessibility in the Pennine Alps.
- Determine which high altitude regions in the Pennine Alps are best suited to preserve glacial archaeological remains. Locational analysis will be used to forecast areas of glacial archaeological potential based on human accessibility and topographic characteristics.
2. To determine the level of importance for each of the high potential areas in regards to the effects of climate change and the preservation of cultural heritage.
- Glaciological modelling will be used to define regions susceptible to glacial melt for the current and future time periods.

It is expected that the methods used here will help to narrow down a large study areas into smaller, more manageable, regions for current and future efficient glacial archaeological prospection.

1.3 STRUCTURE OF THE THESIS

This thesis is organized into six chapters:

- An introduction to the research project, the field glacial archaeology, the rationale for the study, thesis objectives and structure of the thesis are provided (Chapter 1: General Introduction).
- The geographical and glaciological characteristics of the Pennine Alps are presented, and information about the construction of the geographical database and the derivation of the data layers for the study area is provided (Chapter 2: The Pennine Alps).
- Geospatial analysis is defined and discussed in regards to the field of glacial archaeology and in relation to **Paper I**, “An overview of selected GIS methods available for use in glacial archaeology”. Additional commentary (section 3.1.10) is provided at the end of the chapter to give an update about the use of geospatial analyses in the field (Chapter 3: Geospatial Analysis & Glacial Archaeology).
- The proposed methodology to determine glacial archaeological potential in the Pennine Alps is presented and highlighted in three papers. **Paper II**, “Least cost path analysis for predicting glacial archaeological site potential in central Europe”, highlights how the use of one GIS method helped to discover a new archaeological site in the Pennine Alps based on the principles of movement across terrains (section 4.1). **Paper III**, “Least cost path analysis for predicting glacial archaeological site potential: scale and parameter investigations”, revisits the topics discussed in Paper II and further elaborates on the model (section 4.2). Finally, **Paper IV**, “GlaciArch: applying glaciological methods for gauging glacial archaeological potential using GIS”, proposes a linkage between

glaciology and archaeology, and how glacier melt patterns can help predict where archaeological remains could be located in the future (section 4.3). (Chapter 4: Integrative Approach).

- The results are summarized with respect to the thesis objectives, the four papers are discussed in context with the overall theme of geospatial analysis in glacial archaeology, and conclusions and future outlooks are given (Chapter 5: General Discussion).
- The references used within the framework text are provided (Chapter 6: Bibliography).

2 THE PENNINE ALPS

The Pennine Alps, also known as the Valais Alps, are the section of the central Alps located on the border of the canton of Valais in southwestern Switzerland and the provinces of Aosta and Piedmont in northern Italy (Fig. 2.1). Their central location (45°N, 7°E) in western Europe has made them also historically accessible from the neighbouring regions of France to the west and Germany to the north. They run in an east-west direction and are bounded by the Mont Blanc massif to the southwest, the Rhone valley to the north, the Nufenen-Gries area to the northeast, the Antigorio valley to the southeast, and the Aosta valley to the south (Fig. 2.1). This region covers approximately 4,500 km² surface area and stretches between 372 m asl in the Rhone valley to 4,634 m asl at the highest peak, the Monte Rosa.

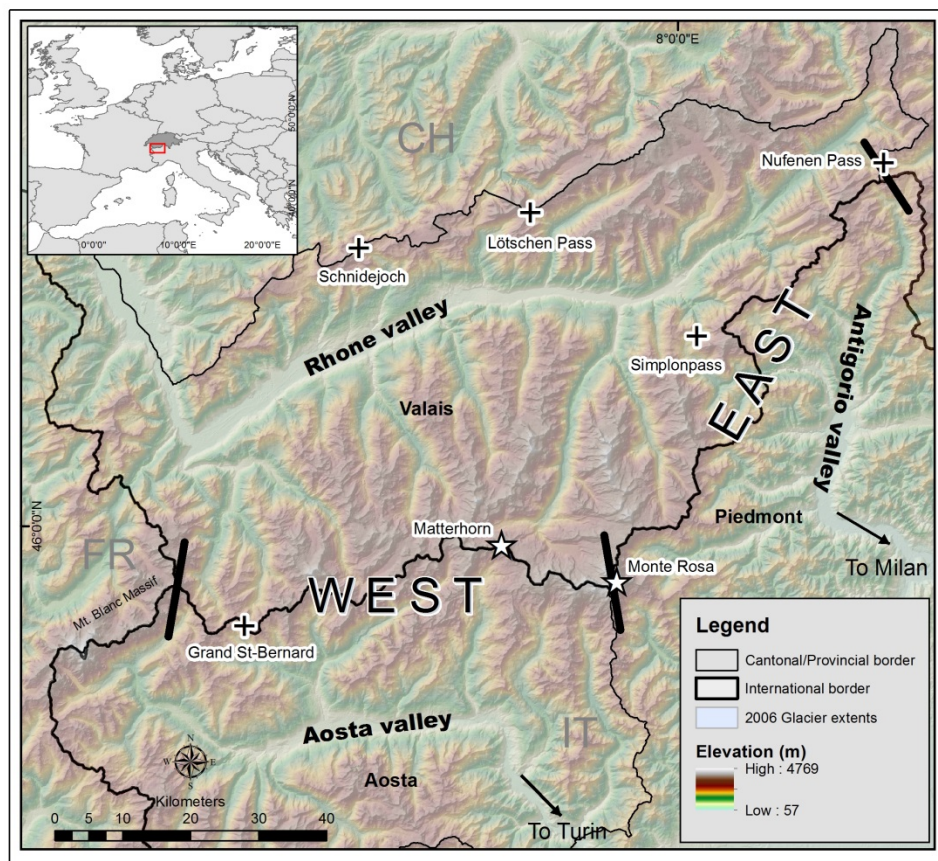


Figure 2.1. Overview of the study area. The study area is split into two sections; east and west. The two sections are separated by the Monte Rosa in the middle, the Mont Blanc Massif on the east and the Nufenen Pass on the west. High altitude passes of interest are shown with a cross while two of the highest peaks are symbolized by stars. Glacier extent from 2006 (European Environment Agency, 2012) are shaded in grey.

2.1 GLACIOLOGICAL CONTEXT

Variation between warm and cold periods over time has caused fluctuations in the extent and volume of glaciers in the Pennine Alps. These glacial changes have affected terrain geomorphology, causing some high altitude passes to have differing accessibility over time (Hafner, 2012). At the peak of the LGM, about 24,000 years ago, the Pennine Alps were covered by ice (Clark et al., 2009) (Fig. 2.2) with no human occupation at that time (Banks et al., 2008). Deglaciation of the Northern Hemisphere began approximately 20,000 to 19,000 years ago when the climate warmed, thus resulting in glacier retreat. According to geological time, we are currently living in the Holocene, which began around 10,500 years ago when the climate was considered to be similar to today (Holzhauser, 2007). The onset of the Holocene coincides with the beginning of the Mesolithic period in archaeological time (Hunt, 2007). Noncoincidentally, the oldest archaeological evidence in the Pennine Alps stems from the Mesolithic (c.f. Curdy, 2007). At this time, the newly ice-free Alpine biome, located on the margins of the receding glaciers, was a resource-rich area which humans were quick to benefit from (Pacher, 2003; Reckin, 2013). Between the onset of the Holocene and the Little Ice Age (LIA), i.e. the most recent glacial maximum occurring around the year 1850, glacier fluctuations in the region of the Pennine Alps varied between the LIA maximum (Ivy-Ochs et al., 2008), and a minimum which is significantly smaller than today (Grosjean et al., 2007; Holzhauser, 2007; Joerin et al., 2006, 2008). In fact, there were 12 major recession periods of Swiss glaciers during this time period (Joerin et al., 2006). Fluctuations in glacier extents have implications on the potential to locate and retrieve glacial archaeological remains. The discovery and retrieval of glacial archaeological remains is attributable to local ice conditions, characteristics, and dynamics as these can critically affect the probability of finding remains intact (Dixon et al., 2005). Large glaciers located on steep slopes would likely destroy any artefact located under or entrained in it within a few hundred years due glacier dynamics (Benn and Evans, 2010; Dixon et al., 2005; Hafner, 2012). Conversely, valley or small glaciers with slower movement could have a higher potential for the discovery of archaeological remains. The most ideal environment for retrieving in-tact archaeological remains would be ice with little or no movement, such as ice patches, slow-moving glaciers or dead ice (i.e. the ice that has been broken off from receding glaciers). An understanding of glacier dynamics and their effects on geomorphology of the terrain is required when prospecting for glacial archaeological artefacts or remains.

2.1.1 THE FUTURE OF SWISS GLACIERS

In 1850, the total glacierized area in Switzerland was 1,735 km² (Maisch, 2000). The most recent glacier inventory from 2010 shows a current area of 944 km² (Fischer et al., in press), an approximate loss of 45% of the 1850 glacier area. Consequently, some glaciers in the Pennine Alps have retreated several kilometers into their Alpine valleys causing significant changes to the appearance of the landscape (Fig. 2.3). Currently, an imbalance exists between glaciers and

the current climate conditions. This imbalance is expected to cause glaciers to continue to retreat even if the temperature ceases to increase (IPCC, 2013). In contrast, reaction times of ice patches to changes in climatic conditions differ from those of glaciers due to their reduced size. While disequilibrium exists between glaciers and the current climate, it is assumed that ice patches are currently at the minimum they have been since millennia (Nesje et al., 2012). Since temperature increases are predicted for the future, there is a dire outlook for both European glaciers and ice patches that could result in the majority of glaciers in the Alps being deglaciated within decades (IPCC, 2013; Zemp et al., 2006).



Figure 2.2. The Last Glacial Maximum (LGM) during its peak extent in the western Alps, approximately 24,000 years BP with 2003 (Paul et al., 2011) overlaid on top. Base map provided by the Swiss Federal Office of Topography (swisstopo, 2009).

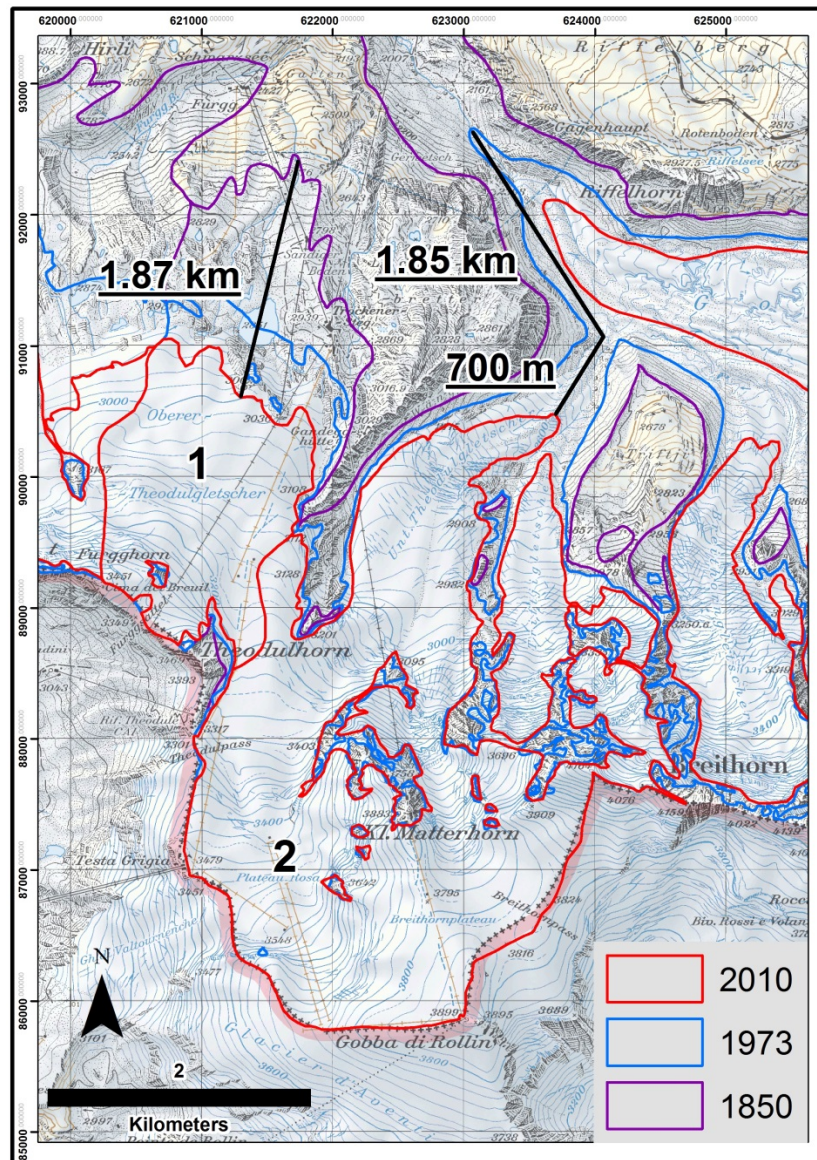


Figure 2.3. Glacier extents from 1850, 1973, and 2010 near the Theodulpass with retreat values for the Oberer Theodul Glacier (1) and the Unterer Theodul Glacier (2).

2.2 PRODUCTION OF A GEOSPATIAL DATABASE FOR THE PENNINE ALPS

The methods used in this thesis were largely geographically-based, but had a strong focus on the archaeological and historical components of the project. Thus, georeferenced data had to be collected from each of the three disciplines, i.e. history, archaeology, and geography, and organized into a geographic database so that the data could be compared and analyzed using a common frame of reference. Based on the objectives listed in section 1.2, the necessary data were obtained through the sources described below. These data were used as inputs to the models discussed in Papers II (section 4.1), III (section 4.2), and IV (section 4.3).

2.2.1 ARCHAEOLOGICAL INFORMATION

A database of all archaeological finds in the canton of Valais was provided by the Etat du Valais, Service des Bâtiments, Monuments et Archéologie (see Table 2.1. for list of fields and sample data). The database contains approximately 900 records ranging from prehistoric to historic time from both high and low elevations. Recent updates from high altitude regions were provided by the Musée d'histoire du Valais. The accuracy of each find ranged from a geographic coordinate to the location of the canton. The information in this database was important for determining the relationships between where archaeological finds were retrieved and the physical characteristics of the environments surrounding sites. An archaeological database for the Italian side could not be obtained due to data restrictions.

Table 2.1. List of fields and a sample of each type of data in the archaeological finds database.

Field	Example
ID	C1235
Site	Mont-Chemin
Discovery type	Prospection
X coordinate	575400 m E
Y coordinate	105100 m N
Z coordinate	1380 m asl
Precision	Plot
Commune	Martigny
Year discovered	1995
Dating	500-700 AD
Description	Notes about the find

2.2.2 HISTORICAL INFORMATION

Historical information was obtained from two sources: archival text analysis of passes and the Inventory of Historical Traffic Routes in Switzerland (IVS) (Swiss Confederation, 2006). Both are described below.

2.2.2.1 ARCHIVAL TEXT ANALYSES

Results from an archival text analysis conducted by another project member, historian Muriel Eschmann-Richon, were used as a source of information, additional to the geographic information datasets. For example, historical texts were used to validate the passes selected by the geospatial modelling procedures. If the pass was mentioned as a crossing place throughout history, the chances of finding archaeological objects at that pass were considered to be greater. Based on information given by geographers and archaeologists involved in the project, archival text analysis was conducted on the following high altitude passes: Theodulpass, col d'Hérens, col Collon, Antronapass, Monte Moropass, col de Crête-Sèche, Fenêtre de Durand, Grimselpass, Griespass, and the col de Cleuson. The historical work consisted of a collected of all information

relating to the previously mentioned passes for which the information was then verified in a critical manner and summarized into coherent documents for each pass. If the written sources did not provide exact information about the passes themselves or how frequently they were visited, the sources could still be used to demonstrate their regular usage thanks to related documentation linking political tensions or trade disputes between valleys. Thus, the research permitted the reassembly of various types of information sources related to these high altitude passes and improved the evaluation of the written sources which already existed. This analysis was conducted only for the Swiss side of the border.

2.2.2.2 IVS DATABASE

The IVS is an inventory of historical traffic routes in Switzerland which are categorized based on their level of local, regional, or national importance for the purpose of protecting and preserving the cultural landscape (Swiss Confederation, 2006; ViaStoria, 2014). In this thesis, the IVS GIS data were used as supplementary information to the information collected during the archival text analysis at the high altitude passes mentioned above. The database was not used as a direct input for any geospatial analyses which will be discussed in the further sections of this thesis.

2.2.3 GEOGRAPHICAL INFORMATION

The GIS layers relating to the physical characteristics of the terrain are listed and explained in the following sections.

2.2.3.1 DIGITAL ELEVATION MODEL

Digital Elevation Models (DEMs) are an integral part of any geospatial analysis as they contain elevation information across the terrain. Here, two different DEMs were used. The first was the 25 m resolution DEM from swisstopo (swisstopo, 2014) which was used for all analysis within Switzerland. The second was the 30 m resolution Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) (version 2) from NASA (NASA, 2012) used for cross border analyses between Switzerland and Italy. The use of the ASTER GDEM could have potentially introduced problems in some of the results as the resolution (30 m) is often too low to obtain a high level of certainty on the high altitude passes and ridges which are often smaller than 30 m in width. This DEM was used because a higher resolution one could not be obtained from the Italian authorities.

2.2.3.2 GLACIER EXTENTS

Glacier inventories over time were crucial to determining areas of glacial archaeological potential. Inventories from 1850 (Maisch, 2000), 1973 (Paul et al., 2002), 2003 (Paul et al., 2011), and 2010 (Fischer et al., in press) were used to observe glacier change over time and how this could be used to find artefacts or remains. The 1850 and 1973 inventories were digitized from topographic maps thus are dependent on the accuracy of the quality of the maps and the person

responsible for digitization. The 2003 inventory, which was used for all analysis involving the Italian glaciers due to a lack of a national inventory, was derived from Landsat TM satellite imagery and the accuracy is assessed to be slightly lower than that of manually digitized outlines from high resolution imagery (Paul et al., 2011). The 2010 inventory was manually delineated from 25 cm resolution orthoimagery and has a very high accuracy.

2.2.3.3 LANDCOVER

Landcover layers indicate the type of terrain covering a certain area on the ground (e.g. rock, grass, glacier, etc.). This information was important when calculating walking paths in the Pennine Alps region. The 25 m Primary Surfaces landcover layer (swisstopo, 2014) was used for analysis within Switzerland. The 100 m resolution, 2006 version of the Coordination of Information on the Environment (Corine) landcover layer (European Environment Agency 2012) was used for cross-border studies. The 100 m resolution of the Corine dataset could have led to some discrepancies in the results of this thesis as some of the research was based on the effects of the rock and glaciers landcover classifications on the walking paths across terrains.

2.2.3.4 SWISSNAMES

The SwissNames dataset from swisstopo (2014) provides all named locations on the Swiss topographic map at the 1:25,000 scale. This layer was useful when selecting places of interest as inputs to model, as well as for selecting all high altitude passes in the region.

3 GEOSPATIAL ANALYSIS & GLACIAL ARCHAEOLOGY

In recent decades, technological advances have led to increased access to geographic and spatial information across all research domains and disciplines (Burrough and McDonnell, 1998). The field of GIScience, which is the scientific study of geographic information, was first defined in 1990 and has since grown into a significant research discipline and incorporates countless types of spatial information (Goodchild, 2014). Spatial technology is the all-encompassing term which refers to any technology used for the acquisition, storage, or manipulation of spatial information (Wheatley and Gillings, 2002). Thus, spatial information is acquired using a spatial technology, such as a satellite or a hand-held Global Positioning System (GPS). These spatial data “know” where they are in space because they are linked to a location on the Earth’s surface through the use of a geographic or projected coordinate system (Longley et al., 1999). Spatial analysis is the broad term used to describe the process of analyzing the relationship between geographic data objects, or entities, in space. The type of spatial analysis which relates directly to geographic information and georeferenced data, and is conducted within the GIS environment, will be referred to herein as geospatial analysis (De Smith et al., 2007). GIS is a computer software system used to create, store, and analyze spatially referenced information (Burrough and McDonnell, 1998). It is multidisciplinary in nature as it can link all types of spatial data such as cultural, social, physical, and temporal (see section 3.1.3 for more information about GIS). Data from multiple scales, times, and research areas can be visualised, analyzed, and mapped together. Consequently, GIS methods and techniques have been widely adopted in the field of archaeology as GIS allows archaeologists to obtain a spatial understanding about the relationship that humans have with one another and with their surrounding environment (Kantner, 2008). As glacial archaeology is a relatively new phenomenon, the use of GIS in this field is still in its infancy. To date, only a few studies have integrated GIS or other spatial analysis methods into their archaeological research of frozen environments (Andrews et al., 2012; Dixon et al., 2005; Goossens et al., 2007). The physical environment is the main factor which differentiates glacial archaeology from other types of archaeology. High altitudes and latitudes, where glacial archaeological remains are found, are often an obstacle for geospatial research both from the accessibility and data collection perspectives. In the Pennine Alps, accurate high resolution base data exist which facilitates the geospatial investigation of glacial archaeology in the region.

In Paper I (section 3.1), three common geospatial analysis methods used in archaeology, i.e. visibility, locational, and least cost path analysis (LCPA), are reviewed and discussed in terms of how these methods could be used for the specific requirements of glacial archaeology. Additional commentary about the use of geospatial analysis in glacial archaeology is provided in section 3.1.10 as an update to the research that has been conducted since the paper was written.

3.1 PAPER I: AN OVERVIEW OF SELECTED GIS METHODS AVAILABLE FOR USE IN GLACIAL ARCHAEOLOGY

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ABSTRACT

In recent years, increased levels of glacial retreat and ice patch melt due to a warming climate in high altitudes have revealed new opportunities to study glacial archaeology. When artifacts become exposed, they are vulnerable to decomposition and should be collected promptly to protect their (pre)historic properties. Therefore, there is urgency to locate potential archaeological sites to avoid the loss of culturally significant remains. Geographic Information Systems (GIS) can be used to help focus or predict potential glacial archaeological study areas based on their environmental and cultural characteristics. Here, an overview of the possibilities for glacial archaeological research using the spatial analysis methods of visibility, locational, and least-cost path analyses (LCPA) in GIS is provided.

Keywords: archaeology, ice patch, glacier, GIS, spatial analysis, visibility analysis, locational analysis, least-cost path analysis

3.1.1 INTRODUCTION

Some of the most well preserved and complete prehistoric remains have been discovered in frozen environments (Dixon, Manley, and Lee 2005). Glacial archaeology pertains to the study of, and prospection for, these archaeological remains from glaciers, ice patches (sometimes referred to as snow patches in literature), and permafrost. Recent changes in global climate have produced regional warming events and subsequent glacial retreats that promote exposure of artifacts from ice. Because of the delicate nature of these artifacts, and in order to preserve their chemical and biological compositions, there is an urgency to collect these materials as decomposition begins almost immediately after exposure to the environment (Dixon, Manley, and Lee 2005; Andrews and MacKay 2012). In an attempt to locate these valuable materials, spatial technologies and predictive methods can be used to determine archaeologically sensitive areas and to focus search efforts by incorporating geographic (e.g. topography, geology), cultural (e.g. knowledge of previous archaeological remains), and historic (e.g. archival texts and information about the past) parameters into Geographic Information Systems (GIS).

Since Kvamme and Kohler (1988) introduced the field of archaeology to the “enormous” (Sebastian and Judge 1988, 17) archaeological prediction potential of GIS and its methods, most archaeologists have embraced the technology. To date, several detailed reviews highlight the uses of GIS and spatial technologies in archaeology (Kvamme 1999; Ebert 2004; McCoy and Ladefoged 2009). Spatial technologies have clearly benefitted archaeological endeavors. As the field of glacial archaeology is relatively new, and only few GIS-based studies have been conducted (Dixon, Manley, and Lee 2005; Andrews et al. 2012), it is appropriate to highlight the potential of GIS-based methods available to researchers. The purpose of this paper is to provide an overview of the current status of three GIS methods in archaeology: visibility, locational, and least-cost path (LCP) analyses. The aim is to stimulate the use of GIS methods for the specific purposes of frozen environments to potentially discover archaeological remains that will provide invaluable knowledge about (pre)historic cultures that traversed high altitude or mountainous terrains, but first I will briefly introduce the types of glacial archaeological environments and GIS.

3.1.2 GLACIAL ARCHAEOLOGICAL ENVIRONMENTS

It is important to distinguish the differences between the archaeology of glaciers, ice patches, and permafrost as each represents a different geosystem with distinct dynamics and characteristics that require unique prospection and spatial analysis methods. Ice patches are formed after the gradual compression of many years of annual net snow accumulation that have gradually been compacted into ice (Andrews et al. 2012); whereas glaciers are usually much larger systems that involve inputs and outputs from the atmosphere, oceans, and rivers. Due to large masses of ice and their topographic locations, glaciers have an inherent potential energy

that forces ice downslope (Benn and Evans 2010). Unlike glaciers, where archaeological remains older than a few hundred years are not expected to be discovered due to their speed of movement and mechanics (Hafner 2012), ice patches left behind from receding glaciers may yield much older relicts. Permafrost, defined as bedrock, earth, or soil that has been below the freezing temperature of water for at least two consecutive years (Woo 1986), has also yielded significant prehistoric and historic archaeological remains (Rainey 1939). In the last century, glacial archaeology has revealed significant discoveries in high altitude, as well as in mountainous regions (Farbregd 1972; Farnell et al. 2004; Hare et al. 2004; 2012; Dixon, Manley, and Lee 2005; VanderHoek, Tedor, and McMahan 2007; Andrews et al. 2012; Callanan 2012; Hafner 2012; Lee 2012). Perhaps the most substantial frozen archaeological find to date has been a ~5300 year old frozen corpse in the Tyrolean Ötztaler Alps, bordering Austria and Italy that is now known as Ötzi (Seidler et al. 1992; Prinoth-Fornwagner and Niklaus 1994).

3.1.3 A BRIEF INTRODUCTION TO GIS

A GIS is a computer software system that can be used for data processing, database management, statistical analysis, and a visualization and mapping interface for georeferenced data which represents real-world entities (Longley et al., 1999). GIS data are characterized by their geometric properties, attributes, and topology (how the objects relate to each other in space) (Burrough and McDonnell, 1998). Georeferenced GIS data “know” where they are in space and can be overlaid, calculated, manipulated and analyzed along with other data layers that use the same coordinate system, and are the basis of all GIS analysis. GIS data comes in two structures: vector and raster. Vector layers represent discrete features in space in the forms of points, lines, and polygons, while raster layers represent continuous data, such as elevation.

The roots of GIS were established in the 1960s when the process of linking map layers was originally conducted (Tomlinson 1989). Afterwards, GIS grew into a natural resources development platform in the 1970s and 1980s along with the rise of the microcomputer and an increased interest in environmental issues by governmental institutions (Tomlinson 1989). During the past two decades, the use of GIS has increased exponentially into a robust data creation, storage, and analysis platform, and has expanded to incorporate various disciplines, such as earth science, urban planning, civil engineering, law enforcement, medical sciences, as well as archaeological prospection and prediction (Burrough and McDonnell 1998). Before GIS was used for predictive modeling in archaeology, predictive analyses were performed using algorithms and programming on an advanced calculator (Kvamme 1983; 1984; 1985; Verhagen and Whitley 2011). The rise of popularity and accessibility of GIS methods and tools in the 1990s saw more archaeologists embrace the diverse functionalities of the platform’s spatial technologies and predictive models (Verhagen and Whitley 2011) as programs and softwares become more user-friendly, less labour intensive, and more reliable (Kvamme 1999). Spatial

technologies can help to determine general or specific areas of archaeological interest in order to save time in the field, or to discover new archaeologically significant locations. These methods can act as a filter to narrow large study areas into smaller, more specific areas with potentially greater archaeological potential (Gietl, Doneus, and Fera 2008). In the following sections, visibility, locational, and LCP analyses will be discussed in terms of how they can be integrated in glacial archaeological research in order to locate potentially significant archaeological remains.

3.1.4 VISIBILITY ANALYSIS

The use of GIS for visibility analysis in archaeology has been an efficient method for helping to better understand how (pre)historic people gave meaning to, and viewed, space (Wheatley 1995; Wheatley and Gillings 2000; Paliou, Wheatley, and Earl 2011). It has been speculated that humans relate to and interpret their landscapes through visibility, thus the analysis of this social characteristic has been investigated repeatedly in archaeological endeavours (Chapman 2006; Murrieta-Flores 2010). By associating vision with movement, visibility analyses could be beneficial for predicting hunting patterns between settlements and ice patches or for understanding commerce or migration routes over mountain passes. For example, in North America and Europe ice patches were used as refugia by caribou during the warm summer months as an escape from the heat and insects of lower altitudes (Ion and Kershaw 1989). Hunters were aware of these movement patterns and would travel to ice patches in pursuit (Farbregd 1972; Kuzyk et al. 1999; Farnell et al. 2004; Hare et al. 2004; 2012; Dixon, Manley, and Lee 2005; VanderHoek, Tedor, and McMahan 2007; Andrews et al. 2012; Callanan 2012; Lee 2012). The visibility between settlement locations and ice patches were of particular importance for monitoring and tracking game (Lake, Woodman, and Mithen 1998). In the Yukon, Canada, ice patch hunting locations were situated within a three hour walk from the adjacent valley bottom (Hare et al. 2004). Therefore, it could be assumed that hunters moved to ice patches when game were observed. Visibility analyses in glacial archaeology could also be applied in the Pennine Alps between Switzerland and Italy. For thousands of years, people have used high altitude mountain passes in this region to traverse terrains for migration and commercial purposes (Harriss 1970; 1971). Various archaeological remains dated to the Neolithic period have been found in ice patches and near glaciers of this region (Hafner 2012). From the tops of mountain passes such as Theodulpass (3301 m asl) valley bottoms can be seen. Perhaps visions of distant settlements encouraged travel for commerce, protection, or migration. This type of scenario could be of potential interest for future visibility research endeavours in glacial archaeology. In fact, glacial archaeological studies could be the perfect candidate for visibility analyses. For example, glacial archaeological sites are located in frozen environments, thus, high latitudes and/or altitudes where there is naturally little vegetation, which leads to fewer obstructions for visibility analyses. In the Swiss Alps region, the current regional treeline is

about 2200 m asl (Berthel, Schwörer, and Tinner 2012), and between 8,700 and 5,000 calibrated carbon years before present (cal. BP) (Wick and Tinner 1997) the uppermost position of the treeline was 2,420 and 2,530 m asl, respectively (Tinner and Theurillat 2003). Therefore, sites located above these levels, which is not uncommon (Hafner 2012), can be assumed to have been free of trees for thousands of years and a Digital Elevation Model (DEM) based on modern landscape topography could be used in visibility analysis as a sufficient representative for the paleoenvironment at high altitudes in the Swiss Alps region.

The two GIS visibility analysis methods, line of sight (LOS) and viewshed are calculated from a DEM. These methods have been used in previous archaeological studies to aid and provide archaeologists with insights about ancient security systems (Gaffney and Stančič 1991), Celtic road systems (Madry and Rakos 1996), prehistoric settlement locations (Jones 2006), the intervisibility between site locations (Ozawa, Kato, and Tsude 1995; Lock and Harris 1996), and the defensibility of sites (Lock and Harris 1996; Smith and Cochrane 2011). LOS, which is the most basic form of visibility analysis, is used for calculating the intervisibility between two locations (Kvamme 1999; Ebert 2004). If no obstructions occur along the viewing plane between two locations the result of the LOS analysis will be positive, and the target can be observed from the original point of interest, or negative if it cannot (Wheatley and Gillings 2002). Viewsheds calculate the visible area surrounding a point of interest. Viewsheds are made up of lines of sight spanning 360 degrees from the point of interest (Kvamme 1999; Ebert 2004), and result in a binary raster that is either visible or not from the point of interest. Drawing from the methods used in previous archaeological studies, similar visibility analyses could be used in glacial archaeology to calculate the LOS or viewshed area from known hunting sites at ice patches to predict where settlements may have been located, or for simulating possible travel routes over mountain passes based on the principle visibility between locations.

3.1.5 LOCATIONAL ANALYSIS

Locational analysis in GIS is valuable for identifying patterns in landscapes and ultimately determining archaeological potential of an area (Sebastian and Judge 1988; Kvamme 1999; Ebert 2004; Dixon, Manley, and Lee 2005; Madry et al. 2005; Conolly and Lake 2006; Krist 2006; Howey 2007; Whitley and Burns 2008; Egeland, Nicholson, and Gasparian 2010; Kondo, Omori, and Verhagen 2012; Carleton, Conolly, and Ianonne 2012; Carrer 2013). Uniquely, it considers a wide range of data layers from a variety of disciplines that include biological, cultural, physical, geological, historical, and paleoenvironmental. In glacial archaeological research, Dixon, Manley, and Lee (2005) were first to incorporate locational analysis using a weighted combination of biological, cultural, and geologic raster layers (Table 1) to successfully determine archaeological potential of specific ice patches in Alaska, U.S.A. Factors influencing and restricting the discovery of remains were analyzed separately and then combined into a final

cost raster. The locational analysis method which was created in this research helped aid archaeological research in the field. A total of nine historic and five prehistoric sites were located using their method. Similarly, Andrews et al. (2012) used locational analysis along with inputs of remotely sensed data to define areas of archaeological potential in remote mountainous areas in the Northwest Territories, Canada. Their selected criteria (Table 1) allowed for the identification of eight ice patches of archaeological potential that were not previously known, and subsequently resulted in the discovery of throwing-dart, bow and arrow, snares, and faunal remains.

Table 1. List of criteria used in locational analyses in glacial archaeological studies

Influencing criteria	Restricting criteria	Reference
Habitat ranges (e.g. caribou, sheep, goats) Mineral licks Lithics Trails Proximity to documented sites	Debris covered ice Ice Snow Barren ground Slope Aspect Distance	Dixon, Manley, and Lee, 2005
Multi-year ice Presence of caribou dung Altitudes between 1676-1981 m North-facing slopes Bowl or cirque shaped ice patches Caribou habitat range Traditional landuse patterns	Areas below 1524 m	Andrews et al., 2012

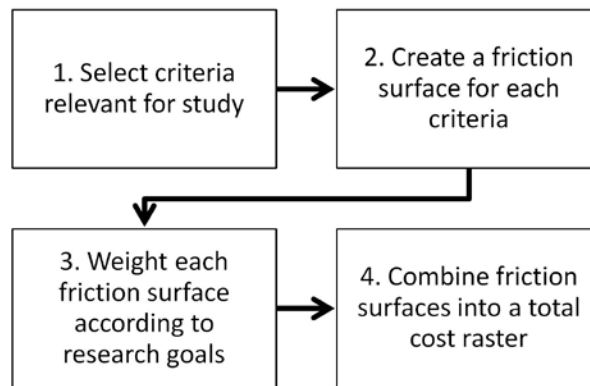


Figure 1. Process of building a cost raster for locational and least-cost path analyses. Altered from Howey (2007)

In the previously discussed studies, the main goal was to perform locational analysis by creating an archaeological potential model in the form of a cost raster which was the culmination of multiple weighted inputs. To build an archaeological potential model using locational analysis, the first step in the process is the selection of relevant criteria (e.g. Table 1), followed by

reclassification of each criterion into a friction surface (Figure 1; Table 2). Each friction surface is a raster that represents the level of archaeological potential of each particular cell (or pixel) based on the respective criteria. In regard to the basic example in Table 2, the slope and landcover values were originally classified in degrees and landcover type, respectively. After reclassification into integer values, the new friction layers represented the calibrated level of archaeological potential based on the original slope or landcover properties. The probability of finding archaeological remains near steep slopes or in lake or swamp environments is lower therefore the friction values are higher in those situations. All friction layers should use a consistent measurement scale for calibration purposes and to maintain a direct comparison among layers (Howey 2007). For example, criteria should have the same friction value if they represent similar friction levels (e.g. steep slopes and lakes or low slopes and grassy terrain). Next, weights should be assigned to each friction layer to denote their percentage of importance to the total cost raster which should equal 100% in the end. For the example in Table 2, slope was believed to be more indicative to the model than landcover (e.g. 60% versus 40% in the final cost raster) therefore a heavier weight was given to the slope layer. Finally, weighted layers are combined to create the total cost raster with all input layers. In the Dixon, Manley, and Lee (2005) study, a similar process was followed for reclassifying and weighting criteria, but also included the accumulated cost of crossing terrains (see least-cost path analysis (LCPA) section) into each friction layer. In glacial archaeology, further studies using locational analysis could benefit site location and archaeological prospection in the field.

Table 2. Example of reclassifying criteria into friction layers and weights of each layer

Criteria	Classes	Friction value	Weight
Slope	0-8.5	1	60%
	8.6-15.4	2	
	15.5-21.6	3	
	21.7-27.1	4	
	27.2-32.2	5	
	32.3-37.1	6	
	37.2-41.9	7	
	42.0-47.4	8	
	47.5-54.2	9	
	54.2-72.8	10	
Landcover	Grass	1	40%
	Scree	2	
	Shrub	4	
	Rock	5	
	Forest	6	
	Swamp	9	
	Lake	10	
Total			100%

3.1.6 LEAST-COST PATH ANALYSIS (LCPA)

Least-cost paths are based on the assumption that human movement follows the least physically demanding route possible when traveling from one location to another (Gorenflo and Gale 1990; Gaffney and Stančič 1991; Anderson and Gillam 2000; Bell and Lock 2000; Llobera 2000; Hare 2004; Rees 2004; Howey 2007; Egeland, Nicholson, and Gasparian 2010). The topic of movement across terrains and landscapes is a well-studied area of research stemming from various models of geographic theory (Tobler 1993) as movement is a mechanism through which humans organize their landscape (Llobera, Fábrega-Álvarez, and Parcero-Oubiña 2011). Thus, human movement and least-cost paths have recently become a popular research topic in archaeology (Murrieta-Flores 2010; 2012; Verhagen and Jeneson 2012), and could be applied in the field of glacial archaeology to aid in the discovery of potential travel routes across mountainous terrain. LCPA can supplement previous research in glacial archaeology (Dixon, Manley, and Lee, 2005; Andrews et al., 2012) by utilizing the multi-criteria cost rasters in LCPA. This could be particularly interesting for studying movement patterns of hunters between settlements and ice patches, as well as paths which traversed mountain passes for the purposes of migration or commerce. LCPA could be used to simulate travel routes over glaciated passes at high altitudes using known archaeological sites as start and end points, or for determining patterns of movement through different landscapes and environments which can help to reveal important aspects of (pre)historic movement patterns (Murrieta-Flores 2010). When no sites of archaeological potential have been previously identified, LCPA could promote insight about optimal paths or corridors based on terrain alone. For example, to identify hunting, migration, or trade routes over high altitude passes in the Pennine Alps between Switzerland and Italy used by (pre)historic people (Harriss 1970; 1971; Lugon 2011; Hafner 2012).

The calculation of the cost raster, which represents the amount of effort required to cross one cell, is the first step in the LCPA process and can be based on one or more criteria. For example, previous archaeological studies have used LCPA to predict locations of (pre)historic travel routes using cost rasters based solely on the slope of the terrain (Gorenflo and Gale 1990; Gaffney and Stančič 1991; Bell and Lock 2000; Egeland, Nicholson, and Gasparian 2010; Kondo and Seino 2011; Herzog and Posluschny 2011; Verhagen and Jeneson 2012), slope and LOS information (Madry and Rakos 1996), slope and roughness (Anderson and Gillam 2000), or slope, land cover, and waterways (Howey 2007). Although slope is the fundamental component of how people choose to travel across landscapes, it is by no means the all-encompassing decision factor in movement (Bell and Lock 2000; Murrieta-Flores 2010) and natural, social, and cultural features of the landscape should be taken into consideration to find the optimal, or the LCP, to move from one point to another (Lee and Stucky 1998; Howey 2007). Most authors agree that the cost of travel should incorporate multiple criteria into the cost raster, including both isotropic and anisotropic frictions (Bell and Lock 2000; van Leusen 1999). Isotropic frictions

represent the cost of moving across a surface with equal friction in all directions (van Leusen 1999; Wheatley and Gillings 2002), for example, landcover. The cost of crossing a certain landcover type is the same irrespective of the direction of travel (Conolly and Lake 2006). Anisotropic modeling incorporates the cost of travel based on variable frictions with respect to the direction of movement (Bell and Lock 2000; Wheatley and Gillings 2002). Slope, which is calculated from a DEM, should be modeled using an anisotropic surface as different frictions are incurred when traveling up, down, or perpendicular to slope (Eastman 2003). The resolution and accuracy of the DEM also play important roles in the model (Herzog and Posluschny 2011).

After all relevant factors have been considered and calculated together, the LCP is calculated from the accumulated cost raster which represents the amount of effort required to reach a destination from a defined starting point (Kvamme 1999; Bell and Lock 2000; Ebert 2004; Verhagen and Jeneson 2012) with longer distances and steeper slopes having higher costs. This second step of LCPA is calculated from the cost raster using a software or user-defined algorithm (Bell and Lock 2000; van Leusen 2002; Wheatley and Gillings 2002; Chapman 2006; Conolly and Lake 2006; Herzog and Posluschny 2011; Kondo and Seino 2011; Verhagen and Jeneson 2012). The majority of LCPA studies input Tobler's (Tobler 1993) equation for walking speed in hilly terrain into GIS to determine the amount of time required for crossing terrains (e.g. Gorenflo and Gale 1990; Whitley and Hicks 2003; Hare 2004; Verhagen and Jeneson 2012). However, it has been speculated that modeling movement based on energy consumption is more efficient due to differing perceptions of time among societies and eras, thus other algorithms have been used to reflect those issues (Llobera and Sluckin 2007; Herzog and Posluschny 2011; Kondo and Seino 2011).

3.1.7 DISCUSSION

GIS-based methods can be used to enrich and enhance archaeological investigation and prospection in frozen environments to prevent the loss of potentially significant archaeological remains. In this paper, the three GIS methods of visibility, locational, and LCP analyses were discussed in regards to their relationship to the emerging field of glacial archaeology. Here I will discuss the benefits and possible limitations to these methods, as well as the issue of data and software accessibility in GIS.

Visibility analysis has been useful in various archaeological studies (e.g. Gaffney and Stančić 1991; Lock and Harris 1996; Smith and Cochrane 2011) but has been theoretically questioned due to its inability to incorporate human perceptions in space (Llobera 2003). However, researchers have taken this into consideration and have been developing methods for incorporating the influences of perception into visibility analyses (Llobera 2000; 2003; Murrieta-Flores 2010; 2012) making the method stronger and more applicable to archaeological studies. The DEM used in visibility analysis calculations is another source of criticism. It is argued that a modern

landscape DEM cannot accurately predict visibility because it does not take the paleoenvironment into account (Wheatley and Gillings 2000). However, in some situations, the landscape has not changed significantly (e.g. in high altitudes) and a modern landscape DEM could be sufficient for calculating visibility. Other unknowns such as vegetation cover, weather, and human visual acuity make it difficult to definitively assess viewsheds or lines of sight (Murrieta-Flores 2012). Nevertheless, visibility analyses can provide valuable information about the study of the visual structure of landscapes and help to explain spatial and social phenomena in relation to movement patterns and archaeological remains (Sorensen and Lanter 1993).

Locational analyses have been useful in the broad archaeological sense (e.g. Howey 2007; Whitley and Burns 2008; Carrer 2013), as well as in glacial archaeology (Dixon, Manley, and Lee 2005; Andrews et al. 2012). This type of analysis is particularly beneficial for the assembly of multi-spatial, -scale, and -temporal data layers into one comprehensive index so that criteria can be evaluated based on their shared or varying characteristics (Kvamme 1999). Locational analysis effectively allows the user to define the important or relevant factors to their study, thus tailoring the analysis to the needs of the researcher (Howey 2007). However, since methods of selection and weighting are subjective, it is important to be overt about the selection and justification process used. Methods such as Multi-Criteria Decision Analysis (MCDA) provide good opportunities for selection and weighting of criteria in multi-factorial situations (e.g. Ahamed, Rao, and Murthy 2000; Joerin, Thériault, and Musy 2001; Malczewski 2006; Chen, Yu, and Khan 2010).

Until recently, LCP analyses were considered to be an under-utilized GIS method in archaeology (Howey 2007). However, interest in (pre)historic movement patterns has been growing and the applications of least-cost paths have broadened (Herzog and Posluschny 2011; Kondo and Seino 2011). Similarly to visibility analyses, more emphasis is being placed on the integration of social and cultural aspects into modeling (Murrieta-Flores 2010; 2012). In reality, the chosen path of travel across a landscape is not always the shortest, nor the easiest, but may have been chosen based on social and cultural factors that are often unknown (Llobera 2000; Lock and Pouncett 2010; Murrieta-Flores 2010; Verhagen and Jeneson 2012). Despite these unknowns, simulations of optimal paths can be useful for understanding potential travel routes through terrain based on the natural accessibility of the landscape (Egeland, Nicholson, and Gasparian 2010; Wheatley et al. 2010; Murrieta-Flores 2012). This could be particularly useful in remote areas such as high latitudes/altitudes and mountainous environments.

These three methods could also be used collectively to enhance their GIS performance. For example, the results of visibility analysis have been used as input criteria in locational analysis cost rasters (e.g. Lee and Stucky 1998), and cost rasters created in locational analysis could be slightly adjusted and used as the basis of an LCPA. The integration of multiple criteria from

multiple disciplines into multiple methods in GIS could aid in the production of beneficial archaeological results. To date, visibility and LCP analyses have not been used in glacial archaeology but could enhance the level of understanding about how (pre)historic people interacted with their environments based on their visual perceptions (Murrieta-Flores 2010) or movement patterns for revealing potential travel routes across archaeologically unknown terrains (Egeland, Nicholson, and Gasparian 2010).

When conducting research using any GIS method, the choice of resolution and scales are vital because they can directly influence outcomes (Lock and Pouncett 2010; Herzog and Posluschny 2011). When conducting glacial archaeological research in remote locations, often spatial data are sparse and difficult to obtain. Now, thanks to platforms like Google Earth (Google 2013) and World Wind (NASA 2011), access to satellite imagery from varying time periods, from anywhere in the world, has increased and has consequently made visual analyses of study sites easier. The MapTiler (Přidal 2012) application allows users to upload aerial images and other map data in a very high resolution to Google Earth. This allows data of varying types and time periods to be overlaid onto each other for visual comparisons outside of a traditional GIS interface. Additionally, a free global 30 m resolution DEM is currently available to download from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) from the NASA Jet Propulsion Laboratory (NASA 2012). This provides free access to a medium resolution DEM which can be used as the basis of GIS investigations. The accuracy of spatial data should also be taken into consideration. For example, Herzog and Posluschny (2011) emphasize the importance of an accurate DEM as it is the basis of most spatial analyses. Knowing the specifications of data will give more insight and knowledge at the primary level of modeling and help to negate the adverse implications of the GIS seen as systematic button-pushing without questioning of the results (Verhagen and Whitley 2012). Arguments for GIS methods in archaeology have been strengthened by the robust dissections of results. In the early stages of GIS-based studies in archaeology, more focus was directed to computer generated models rather than archaeological theory (Wheatley and Gillings 2000), and results were not carefully examined but merely assumed to be accurate. This created debate within the domain of theoretical thinking in archaeology, resulting in the validity of computer generated visibility models and predictions to be doubted (Wheatley and Gillings 2000). To lessen the negative aspects of spatial technologies, researchers have improved spatial methodologies by investigating the results with statistical analyses and rigorous testing (van Leusen 1993; Wheatley 1995; Fisher et al. 1997; Lake, Woodman, and Mithen 1998; Carleton, Conolly, and Ianonne 2012; Carrer 2013).

GIS users should also be aware that different computer softwares use different algorithms in their calculations. With open-source softwares these are outwardly stated however, commercial softwares often do not make this information available (Verhagen and Jeneson 2012). Recently,

open-source GIS programs such as the Geographic Resources Analysis Support System (GRASS) (GRASS Development Team 2013), Quantum GIS (QGIS) (QGIS 2013), and the System for Automated Geoscience Analyses (SAGA) (SAGA 2013) have grown in popularity due to their capabilities for information and data sharing, as well as full access to the implementation details, including algorithms of all tools. In order to fully understand and have confidence in GIS methods, the calculation details should be taken into consideration, and recent advancements in open-source softwares are allowing this to happen.

As with any type of spatial analysis or modeling, there are challenges and uncertainties. Unknown variables make it complicated, but not unrealistic nor impossible, to make predictions about how past landscapes were used by (pre)historic people. Incorporation of GIS, specifically visibility, locational, and LCP analyses into archaeological research has proven to provide significant insights into (pre)historic settlements and movement patterns. GIS methods could benefit research endeavors in frozen environments and mountainous terrains by focusing efforts that promote the discovery of vulnerable materials from decomposition once they have been exposed from the ice.

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3.1.10 ADDITIONAL COMMENTARY

Since the time Paper I was written (2012), there have been no further publications, other than the ones included in this thesis, using geospatial technology in glacial archaeology. However, one pertinent upcoming publication spatially analyses geographical and cultural information in GIS to select high altitude study sites for long-term glacial archaeological monitoring in the canton of Grisons in eastern Switzerland (Naef and Reitmaier, submitted). Another promising research project is that of the Norwegian University of Science and Technology's (NTNU) Snow Patch Archaeology Research Cooperation (SPARC, 2014), which uses geospatial and geophysical approaches to study snow and ice patch characteristics and how they relate to archaeological finds. Notable publications in the field of glacial archaeology itself, include a review of high altitude archaeological finds from around the world (Reckin, 2013), and a publication highlighting newly collected Neolithic finds from a Norwegian ice patches (Callanan, 2013).

4 INTEGRATIVE APPROACH

The overall goals of the geographical component of this SNSF funded research project were listed in the objectives in section 1.2. To reach the objective of determining the overall glacial archaeological potential of the Pennine Alps, an integrative approach compiling three geospatial methods was applied (Fig. 4.1). Geospatial analyses, including methods from GIS, (i.e. LCPA and locational analysis, Paper I for more information) and glaciology (i.e. regional scale modelling) were developed. The first method, LCPA, was used in Papers II, III, and IV with the aim of identifying where people could most easily travel based on the topographical and physical properties of the terrain. As discussed in Paper I (section 3.1), this method is based on the assumption that humans desire to take the easiest route possible from one location to another, if there are no other outside factors acting on the situation. LCPA was used in the subsequent papers to define areas of glacial archaeological potential based on the principles of human accessibility. In Paper II (section 4.1), archaeologically significant locations on each side of the Pennine Alps were chosen as start and end points to calculate least cost paths (LCPs) using LCPA. Areas of archaeological interest were highlighted based on the assumed travel behaviour of humans based on topographic constraints of the terrain. In Paper III (section 4.2), the LCPA model was further investigated by analyzing results from discrete points as well as lines, and the effects of changing input parameters on the resulting LCPs which helped to validate and improve the model.

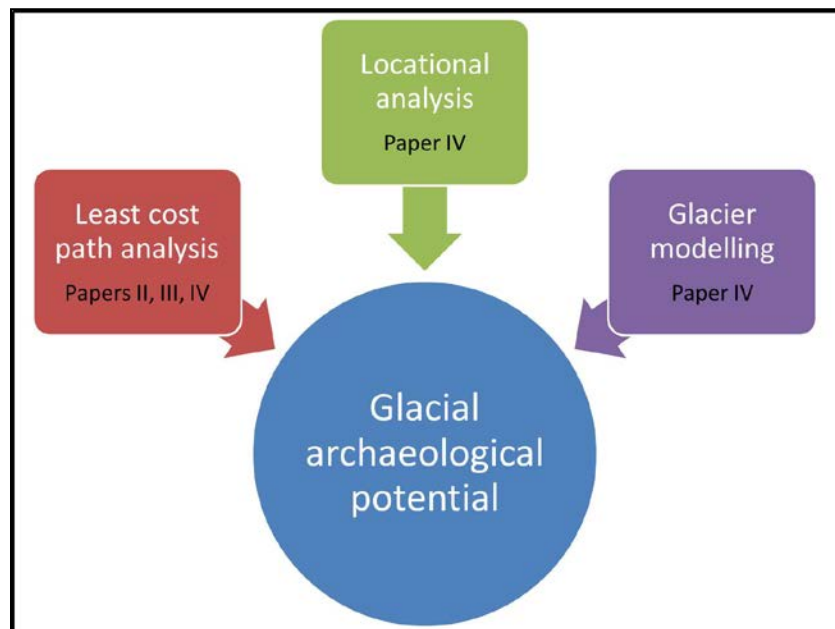


Figure 4.1. A schema of the integrative approach used to incorporate various geographic methods together to determine glacial archaeological potential in the Pennine Alps

The second method, locational analysis, was used in Paper IV and aims to identify the parts of the terrain which are best suited to preserve glacial archaeological artefacts (section 4.3). As discussed in the introduction of this thesis, glacial archaeological remains are highly fragile and susceptible to decomposition once uncovered from ice or snow. Certain environments, such as stable ice patches or slow moving glaciers, are more appropriate for preserving artefacts.

The third and final method, glaciological modelling, was used in association with locational analysis in Paper IV to define areas of current and future areas of archaeological interest based on future glacier geometries. A regional scale approach integrating state-of-the-art methods was used to model glacier geometries in 10-year increments until 2100.

The culmination of the results of these three methods leaves us with a better general understanding of the glacial archaeological potential of the region and is further discussed in the general discussion chapter (section 5).

4.1 PAPER II: LEAST COST PATH ANALYSIS FOR PREDICTING GLACIAL ARCHAEOLOGICAL SITE POTENTIAL IN CENTRAL EUROPE

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ABSTRACT

Recent changes in climate have led to an increased exposure of glacial archaeological artefacts due to the melting of glaciers and ice patches. Here we calculated Least Cost Paths (LCPs) between archaeologically significant locations in Switzerland and Italy using a Least Cost Path Analysis (LCPA) method in which cost rasters were first calibrated at a study site near Haut-Val de Réchy, Switzerland to develop a prehistoric cost raster. Tools were used to calculate the LCPs based on DEM-derived slope using Tobler's anisotropic hiking function and landcover. Our results have since provided a focus for prehistoric glacial archaeological prospection in the Pennine Alps of central Europe, as well as led to the discovery of an artefact from the Bronze Age (~2,800 years BP). This methodology could be used as an example for identifying additional sites of prehistoric glacial archaeological remains around the world.

Key Words: Glacial Archaeology, GIS, Least Cost Path Analysis

4.1.1 INTRODUCTION

The current warming period is leading to a rise in the exposure of archaeological artefacts due to increased melting in the cryosphere (Dixon, Manley, and Lee 2005; Molyneaux and Reay 2010). As a result, prehistoric and historic archaeological remains have been discovered near the margins of melting glaciers, ice patches, and permafrost in various places around the world (Krajick 2002). The frozen setting in which these artefacts have been found provides a unique preservation environment that withstands decomposition and allows organic biological and cultural materials to remain intact, enabling the collection and scientific analysis of rare and irreplaceable objects (Molyneaux and Reay 2010; Andrews and MacKay 2012). For example, one of the most complete prehistoric finds, Ötzi the Tyrolean Iceman, was found protruding from a high altitude ice patch near the border of Austria and Italy in 1991 (Seidler et al. 1992; Prinoth-Fornwagner and Niklaus 1994). Because the corpse was so well-preserved for the last ~5,300 years, the study of this specimen has provided unique information about the place of origin, ancestry, genetics, diet, and diseases that inflicted prehistoric people from this region (Shouse 2001; Janko, Stark, and Zink 2012; Keller et al. 2012). The accidental discovery of Ötzi led to the stark realisation that similar finds could be expected as temperatures continue to rise. As a result, archaeologists in North America (Farnell et al. 2004; Hare et al. 2004; 2012; Dixon, Manley, and Lee 2005; VanderHoek, Tedor, and McMahan 2007; Andrews and MacKay 2012; Andrews et al. 2012; Lee 2012), Asia (Goossens et al. 2007), and Europe, specifically Norway (c.f. Farbregd 1972; Callanan 2012) and Switzerland (Lugon 2011; Hafner 2012), have increased efforts to investigate high altitudes with the aspirations of intercepting materials which have been, or will soon be, exposed in order to protect and conserve cultural heritage before it decomposes or becomes destroyed by the current environment or anthropogenic causes. Some interesting finds include prehistoric hunting materials in Alaska and northern Canada (c.f. Dixon, Manley, and Lee 2005; VanderHoek, Tedor, and McMahan 2007; Hare et al. 2012) and a 6,000 year record of archaeological remains from an ice patch in the Bernese Alps in Switzerland (Hafner 2012), which attests to the use of high mountain passes by humans in the Swiss Alps for thousands of years.

The Pennine Alps (sometimes referred to as the Valais Alps) located along the Swiss-Italian border, are an area of glacial archaeological interest due to their topographic location, rich cultural past, and prominent glaciated territory. The Pennine Alps are characterised by their high peaks; the highest being the Dufour peak (4,634 m above sea level (asl)) and the most well-known, the Matterhorn (4,478 m asl). High mountain passes connect Switzerland's canton of Valais to northern Italy's provinces of Aosta and Piemonte. Archaeological finds have demonstrated that mountain passes between Switzerland and Italy have been used as trade and travel routes for thousands of years (Coolidge 1912; Harriss 1970; 1971; Curdy 2007), with the earliest indication of human usage originating from the Mesolithic period (Curdy, Leuzinger-

Piccard, and Leuzinger 2003). Numerous written documents from medieval times attest to the existence of close ties between the Swiss and Italian sides of the Pennine Alps through small alpine passes. For example the exchange of wine and sheep between the Aosta and Zermatt valleys was important for the commercial development in those areas (Ammann 1992). However, navigating through mountainous terrain is often a difficult task, especially when travelling with goods for trade or commerce, or a large number of people for migration. For this reason, many archaeologists have assumed that these remote, high altitude regions were marginal and not used excessively by humans (Walsh, Richer, and de Beaulieu 2006). Due to recent accidental finds in high altitude locations around the world, there is increased interest in the archaeology of glaciated and frozen regions, especially in the Pennine Alps, whose geographical and cultural attributes make them a region of great archaeological interest.

In the Pennine Alps, numerous glaciated mountain passes exist which allow the passage between Switzerland and Italy. However, the vast glaciated surface area and high altitudes pose problems for archaeological investigation. Due to the size of the study area and the inaccessibility of some passes, it is impossible to visit all of the potential sites of interest due to time and cost constraints. Therefore, Least Cost Path Analysis (LCPA), a Geographic Information Systems (GIS) method, was used to aid in glacial archaeological investigations by narrowing down potential site locations based on the principle that people want to take the least physically demanding route possible to get from one location to another. LCPA is one of a variety of predictive methodologies developed in GIS that has been adapted for archaeological investigations and has been increasingly applied in research along with the expansion and ease of access to GIS data, tools, and software (c.f. Gorenflo and Gale 1990; Gaffney and Stančič 1991; Madry and Rakos 1996; Anderson and Gillam 2000; Bell and Lock 2000; Howey 2007; Egeland, Nicholson, and Gasparian 2010; Kondo and Seino 2011; Herzog and Posluschny 2011; Verhagen and Jeneson 2012). It has been used to link together archaeological site locations (c.f. Gorenflo and Gale 1990; Bell, Wilson, and Wickham 2002; Tripcevich 2008), to track prehistoric migration patterns (c.f. Krist and Brown 1994; Egeland, Nicholson, and Gasparian 2010), and also as a first step in research to predict potential travel routes (c.f. Anderson and Gillam 2000; Verhagen and Jeneson 2012). Here, we followed the latter approach and used LCPA as a decision support tool and a stepping stone for further archaeological investigation in remote high altitude regions of the Pennine Alps.

Using LCPAs, we attempted to predict which high mountain passes were most-likely travelled in prehistoric times based on topographic properties and landcover characteristics. Our main objective was to aid in understanding the effects of the slope of the terrain and differing landcover types on travel routes through mountainous terrain using a calibration site and later applying those results to two analysis sites in order to aid archaeologists in high altitude investigations. By first implementing a series of LCPAs on a calibration site in the Haut-Val de

Réchy (HVR), Switzerland, a prehistoric cost raster weighting scheme was established and later applied to two analysis sites between Sion, Switzerland and both Aosta and Domodossola, Italy (Fig. 1). The region around Sion has an archaeological record dating back to the Mesolithic (Curdy 2007) while northern Italy has a record dating back to the Epipaleolithic, although the Ossola and Aosta Valleys have provided few artefacts (Crotti, Pignat, and Rachoud-Schneider 2002; Di Maio 2007). From these archaeologically significant locations, we determined potential travel routes between sites and discovered a previously unstudied mountain pass from which an archaeological artefact was retrieved. Thus, showing the possibility to use LCPA as a first step in glacial archaeological investigations by narrowing down potential travel routes across mountainous terrain in order to ultimately find, protect, and conserve archaeological remains.

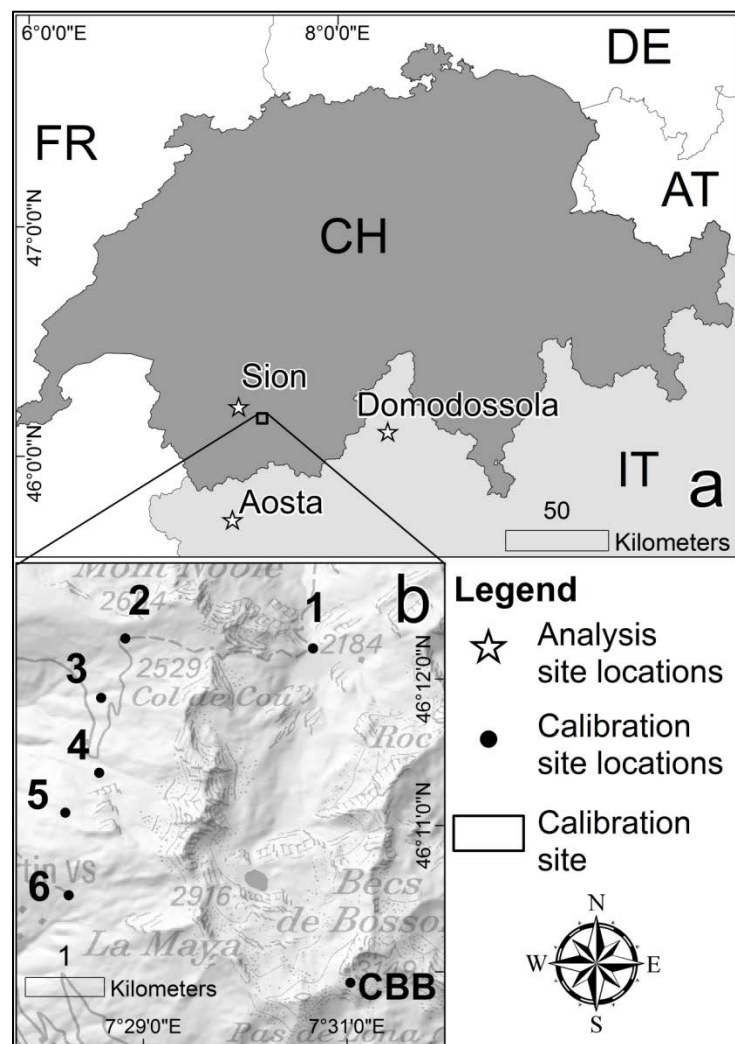


Figure 1. (a) Map of the analysis site including the locations of interest Sion, Domodossola, and Aosta, and the overview map of Switzerland (CH) and its surrounding countries: Italy (IT), France (FR), Germany (DE), and Austria (AT), and (b) the calibration site showing the six locations of interest and the Cabin of Becs de Bosson (CBB). The geographic coordinates in all figures and tables refer to World Geodetic System 1984 (WGS84) projection

4.1.2 METHODS

In ArcGIS 10.1, the process of creating Least Cost Paths (LCPs) requires two steps: 1) the creation of the accumulative cost distance raster (ACDR) using the Path Distance tool and 2) the calculation of the LCP with the aforementioned ACDR as an input into the Cost Path tool. The ACDR defines the cost value for each cell in the raster initiating from the point of interest. The cost grows as the distance from the source location increases, thus each cell in the resulting ACDR represents the cost of travel back to the source location (c.f. Whitley and Hicks 2003; ESRI 2013). Along with the surface distance, landcover and slope were also included in the Path Distance calculation in order to account for the impeding costs of differing landcovers and slope values when traversing terrains. Landcover can be modelled isotropically as the direction of travel does not affect the cost of crossing a certain landcover type (van Leusen 1999; Wheatley and Gillings 2002). However, when incorporating slope into travel calculations, anisotropic modelling should be implemented to account for the changes in cost incurred when travelling up, down, or perpendicular to the slope (Bell and Lock 2000; van Leusen 2002; Eastman 2003). For this reason, Tobler's hiking function for undulating terrain (Tobler 1993), which was elaborated from Imhof (1968), was used to calculate walking times based on DEM-derived slope value calculations. Tobler's original equation:

$$v = 6 \exp(-3.5 * \text{abs}(s + 0.05))$$

where:

v , the walking velocity in km/h

s , the dh/dx = slope = $\tan(\theta)$

calculates walking on flat terrain at approximately 5 km/h. The walking speed is greatest when travelling downslope at a slight decline, with speeds progressively declining as slopes decrease and increase (Gorenflo and Gale 1990). To facilitate the integration of the algorithm into the Path Distance tool in ArcGIS, the reciprocal of the equation was used as suggested by Tripcevich (2008; 2009) in order to directly calculate walking times:

$$\text{Time (hours)/m} = 0.000166666 * (\exp(3.5 * \text{abs}(s + 0.05)))$$

thus the time in hours/m was calculated as the vertical factor for each slope value and multiplied by the surface distance and isotropic friction values to obtain the ACDRs. The Cost Path tool was then used to calculate the LCPs from the ACDRs and the cost backlink rasters. The backlink raster, which is also an output of the Path Distance tool, defines the neighbouring raster cell which is the next on the least accumulative cost path back to the source, while also accounting for the surface distance and the vertical factor (ESRI 2013).

4.1.2.1 CALIBRATION SITE

The Haut-Val de Réchy (HVR), Switzerland was used as the calibration site for this study and is located at the southern end of the Val de Réchy (46° 11' N, 7° 30' E – World Geodetic System 1984 (WGS84)) (Fig. 1b). This relatively small (~40 km²) calibration site was used as a control site to create a prehistoric cost raster which was later integrated into the LCPA between the larger study area (~4,500 km²) between Switzerland and Italy. This calibration site was chosen based on its topographic features, including various mountain passes, its altitude range (~1,000 m), its differing landcovers, its geomorphologic familiarity (Tenthorey 1993; Gardaz 1998; Lugon and Delaloye 2001), and its accessibility for future ground-truthing purposes. The HVR is distinguished by its flat bottomed U-shaped valley and steep surrounding ridge formed by glacial activity (Tenthorey 1993). Six starting locations were strategically chosen from which walking times to and from the Cabin de Becs de Bosson (CBB) were calculated (Fig. 1b). The CBB is located at an elevation of 2,988 m asl on the southern side of the ridge that surrounds the HVR, and is adjacent to the Becs de Bosson mountain (3,129 m asl). The starting locations for the LCPs were selected based on their geographic locations (i.e. near mountain passes or swamps) to investigate how different landcovers and slopes affected the corresponding LCPs. Five of the six starting locations were situated on the western side of the ridge to test the effects of varying topography on paths, while one starting location (number 1, Fig. 1b) was situated to the north of the valley directly behind a swamp to test the effects of varying landcover characteristics.

For the calibration site, the inputs to the Path Distance tool included the following (Table 1): point locations for each site, four reclassified landcover layers, the 25 m DEM from Swisstopo, and Tobler's value table. The original landcover layer was the Swisstopo Vector25 Primary Surfaces shapefile (Federal Office of Topography 2007) which, in this specific study region, had 12 different landcover classes of which some could be amalgamated for the purposes of this analysis (e.g. the four differing types of scree were grouped into the same category). Subsequently, four different weighting schemes were used to represent four different scenarios: current landcover, prehistoric landcover (with two different weighting schemes), and the topographic landcover (Table 2). Weights were established and assigned after a consensus between the authors and other research group members was reached regarding the ease or difficulty to traverse respective landcover classes. For example, for the current landcover raster, the "Other" category, which incorporates open spaces and grassy areas, was assumed to be the easiest to traverse and was therefore assigned a weight of 1. The "Forest, Bushes" category was decided to be three times more difficult to traverse and was therefore assigned a weight of 3. The "Scree" category was given a weight of 4 as it was deemed more difficult to cross than forest, although less difficult to cross than "Residential/Rock", which was given a weight of 5. The "Swamp" category was given a weight of 10 as it was assumed that people would avoid these, however they were not deemed impossible to cross. The "Water" category was given a

weight of 999 assuming that people would not be willing to swim across a water body, but instead go around it. For both prehistoric landcover weighting schemes a treeline of 2,000 m was assumed (Colombaroli et al. 2010), therefore everything below that level was covered with trees. The first prehistoric landcover weighting scheme was similar to the current landcover, except that the treeline was a determining factor for forest cover. The “Other” and “Forest, Bush” categories were given values of 3 or 4 depending on whether they were located above or below the treeline, respectively. The weights of the remaining categories stayed the same as the current landcover weighting scheme. After some preliminary testing, it was decided that travel times were highly exaggerated when these weights were applied so a second prehistoric landcover weighting scheme was created which divided each weight in half. The final weighting scheme, representing the topographic landcover, was used to test the effects of the slope of the terrain on LCPs. Thus, each class was given a weight of 1, except “Water” which remained at 999. The respective landcover layers were used as the cost raster input to the Path Distance tool to model isotropic friction across the surface. The resulting LCPs were analysed and visually compared with current hiking trails on the 1:25,000 topographic map and their respective travel times. The control travel times were calculated using the Switzerland Mobility Wanderland website (Suisse Rando 2013a) which computes walking times based on the calculation used by the Swiss Hiking trail network, Suisse Rando (Suisse Rando 2013b). Suisse Rando calculates path travel times based on the horizontal distance, height difference, and slope between start and end locations (Suisse Rando 2013b). Henceforth, these paths will be referred to as the Wanderland Paths (WPs).

Table 1. Explanation of inputs into the Path Distance tool in ArcGIS 9.3.1 for both the calibration and analysis sites

Input to Path Distance tool	Function	Layers used: calibration site	Layers used: analysis sites
Feature source data	Start point; cost distance raster will be created based on this point	Sites 1 to 6, Cabin de Becs de Bosson (CBB)	Sion, Aosta, Domodossola
Input cost raster (Isotropic friction layer)	Landcover raster which denotes the weight of each landcover type	Swisstopo's Vector 25 m Primary Surfaces layer reclassified as: Current LC, Prehistoric LC (first and second weightings), Topographic LC (see Table 2 for reclassification schemes)	Corine 2006 100 m landcover layer reclassified (Table 3) using the Prehistoric LC second weighting scheme and resampled to 25 m
Input surface raster	The raster from which the true distance is calculated	25 m DEM from Swisstopo	30 m ASTER DEM resampled to 25 m
Input vertical raster	The layer used to calculate the slope. The slope value is then multiplied by the vertical factor	25 m DEM from Swisstopo	30 m ASTER DEM resampled to 25 m
Vertical factor (Anisotropic friction table)	The input table which defines the walking speeds required to traverse each degree of slope	Values calculated from Tobler's walking function in table format	Values calculated from Tobler's hiking function in table format

Table 2. Reclassification and weighting values of the Vector25 landcover layer for the creation of current landcover, prehistoric landcover, and topographic landcover cost rasters using the calibration site of Haut-Val de Réchy, Switzerland. In the column headings, "LC" refers to the word landcover. The resulting path names, which correspond to figures 2 and 3, are also indicated (*PLP refers to both weightings)

Original LC class	Current LC	Weight	Prehistoric LC	Weight 1	Weight 2	Topo LC	Weight
Other	Other	1	Other , Forest Above 2000 m	3	1.5	Other	1
			Other , Forest, Bush, Residential, All Scree Below 2000 m	4	2		
Forest	Forest, Bushes	3	Other, Forest Above 2000 m	3	1.5		
			Other, Forest , Bush, Residential, All Scree Below 2000 m	4	2		
Sparse forest		3	Other, Forest Above 2000 m	3	1.5		
Bush		3	Other, Forest, Bush , Residential, All Scree Below 2000 m	4	2		
Scree	Scree	4	Other, Forest, Bush, Residential, All Scree	4	2		
Scree in forest		4		4	2		
Scree with bushes		4		4	2		
Scree in sparse forest		4		4	2		
Residential Zone	Residential, Rock	5	Other, Forest, Bush, Residential , All Scree	4	2		
Rock		5	Rock	5	2.5		
Swamp	Swamp	10	Swamp	10	5		
Lake	Water	999	Water	999	499.5	Water	999
Resulting path name	Current LC Path (CLP)		Prehistoric LC Path (PLP)*			Topographic LC Path (TLP)	

4.1.2.2 ANALYSIS SITES

Based on the results from the calibration site (section 4.1.3.1), the second weighting of the prehistoric landcover cost raster was used as the isotropic input to calculate the LCPs between the analysis sites. The inputs to the Path Distance tool varied slightly due to the lack of availability of data layers for this cross-border study. The landcover layer and DEM were downloaded from free sources online; the 2006 version of the Coordination of Information on the Environment (Corine) 100 m resolution landcover layer (European Environment Agency 2012) and the research grade Advanced Spaceborne Thermal Emission Radiometer Global DEM (ASTER GDEM V2) (NASA 2012) of 30 m resolution, respectively. Each layer was resampled to 25 m for analysis. The landcover layer was reclassified into five categories and weighted based on the results from the calibration site: open space above 2,000 m (assuming a treeline of 2,000 m), everything below 2,000 m (except rock, swamp, and water), rock, swamp/watercourse, and water body (Table 3).

Table 3. Reclassification and weighting values of Corine landcover layer for Sion/Aosta study area. In the column headings, "LC" refers to the word landcover.

Original CORINE Landcover class	Reclassification categories	Prehistoric LC 2 nd weight
Pastures (above 2000 m)	Open space above 2000 m	1.5
Coniferous forest (above 2000 m)		1.5
Natural grasslands (above 2000 m)		1.5
Moors and heathland (above 2000 m)		1.5
Sparsely vegetated areas (above 2000 m)		1.5
Glaciers and perpetual snow		1.5
Continuous urban fabric	Everything below 2000 m	2
Discontinuous urban fabric		2
Industrial or commercial units		2
Road and rail networks and associated land		2
Port areas		2
Airports		2
Mineral extraction sites		2
Construction sites		2
Green urban areas		2
Sport and leisure facilities		2
Non-irrigated arable land		2
Rice fields		2
Vineyards		2
Fruit trees and berry plantations		2
Pastures (below 2000 m)		2
Complex cultivation patterns		2
Land principally occupied by agriculture		2
Broad-leaved forest		2
Coniferous forest (below 2000 m)		2
Mixed forest (below 2000 m)		2
Natural grasslands (below 2000 m)		2
Moors and heathland (below 2000 m)		2
Transitional woodland-shrub		2
Beaches, dunes, sands		2
Sparsely vegetated areas (below 2000 m)		2
Burnt areas		2
Bare rocks	Rock	2.5
Inland marshes	Swamp, watercourse	5
Peat bogs		5
Water courses		5
Water bodies	Water body	499.5

4.1.2.2.1 SION/DOMODOSSOLA

The first analysis site was located between Sion (46° 14' N, 7° 22' E, 500 m asl), situated in the canton of Valais in the southwest corner of Switzerland, and Domodossola (46° 07' N, 8° 17' E, 272 m asl), located in the northwest of the province of Piemonte, Italy (Fig. 1a). The straight line distance between these two locations is approximately 74 km.

4.1.2.2.2 SION/AOSTA

The second analysis site was between Sion and Aosta (45° 44' N, 7° 19' E, 583 m asl), which is the name of the town, but also the province, in the northwestern part of Italy (Fig. 1a). The straight-line distance between the two locations is approximately 55 km.

4.1.2.2.3 ARCHAEOLOGICAL PROSPECTION

After the LCPs for the analysis sites were analysed and discussed with archaeologists and historians familiar with the area, various passes were selected for archaeological prospection. From the Sion/Domodossola LCP, archaeological prospection was undertaken at the Forca d'Aurona on September 20th, 2012. From the Sion/Aosta site, the region surrounding the Col de Cleuson and the Grand Désert glacier were investigated on July 30th, 2012 from the north side of the Col de Cleuson and September 11th, 2012 from the south side. A handheld Garmin GPS receiver was used to mark the location of finds.

4.1.3 RESULTS

4.1.3.1 CALIBRATION SITE

At each site, paths created using the topographic landcover raster resulted in the shortest walking times. At Site 1 (Fig. 2), the topographic landcover path (TLP) was the only path which went through the swamp located directly south of the starting location (Fig. 2b). At Site 2 (Fig. 3), all paths followed similar routes by travelling along the valley bottom, except the TLP stayed outside of the valley until the Pas de Lovégno, avoiding the multiple slope changes (Fig. 3a). The majority of the other paths followed the lowest landcover weightings (Fig. 3b) while the TLP was unaffected by those values. Consequently, in comparison to the times calculated by the Wanderland Paths (WPs), the TLPs underestimated the walking times required.

The paths created using the current landcover cost raster (CLPs) took into account the reclassified landcover types both above and below the treeline. At the majority of sites, the CLPs followed a similar path as the WPs (Fig. 2 and Fig. 3). In general, CLP walking times were on average about 20 minutes more than the walking times calculated by the WPs (Table 4), therefore slightly overestimating the walking times required.

The paths created using the Prehistoric landcover cost raster were identical for both the first and second weighting schemes. Visually, the prehistoric landcover paths (PLPs) were similar to the majority of other calculated paths. In terms of time, the first weighting for the prehistoric landcover produced very long walking times, often three times longer than the rest. The paths created using the second weighting scheme better estimated the walking times compared to the WPs but still slightly overestimated walking times by about 30 minutes on average.

Based on these results, paths created with the prehistoric landcover cost raster using the second weighting scheme were most similar to both the hiking trails on the 1:25,000 topographic map

and the walking times calculated by Suisse Rando. Therefore, the prehistoric landcover cost raster with the second weighting scheme was used as the input to the Path Distance tool for the analysis site between Sion and Aosta.

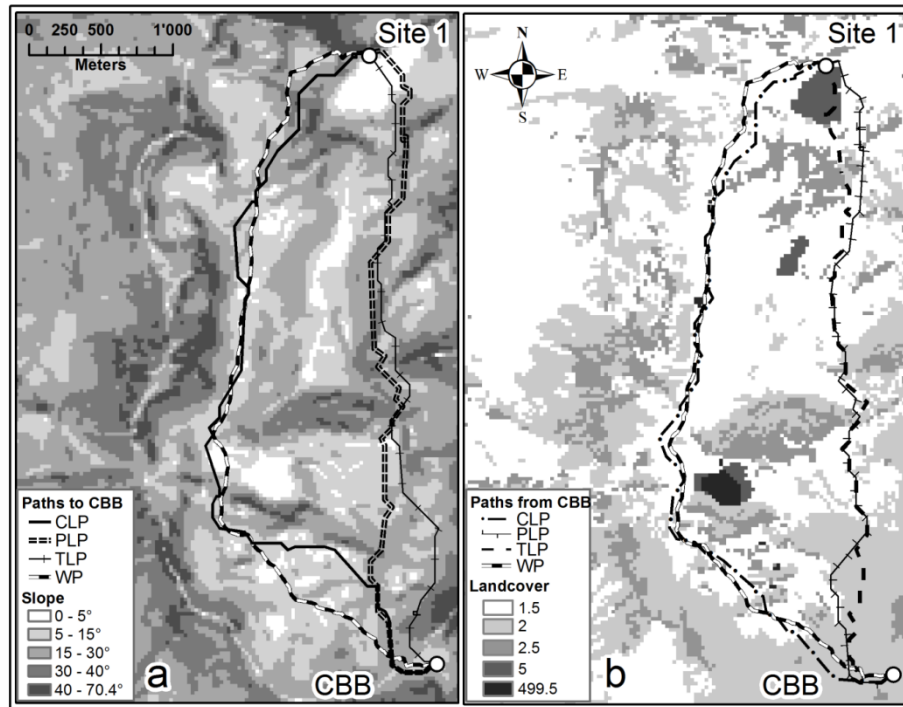


Figure 2. Least cost paths from Site 1 to the Cabin de Becs de Bosson (CBB) shown on DEM-derived slope raster (a) and paths from the CBB back to Site 1 shown with the prehistoric landcover (second weighted) cost raster in the background (b). The legend represents the current landcover path (CLP), the prehistoric landcover paths (both weightings) (PLP), the topographic landcover path (TLP), and the Wanderland path (WP). See Table 4 for calculated travel times.

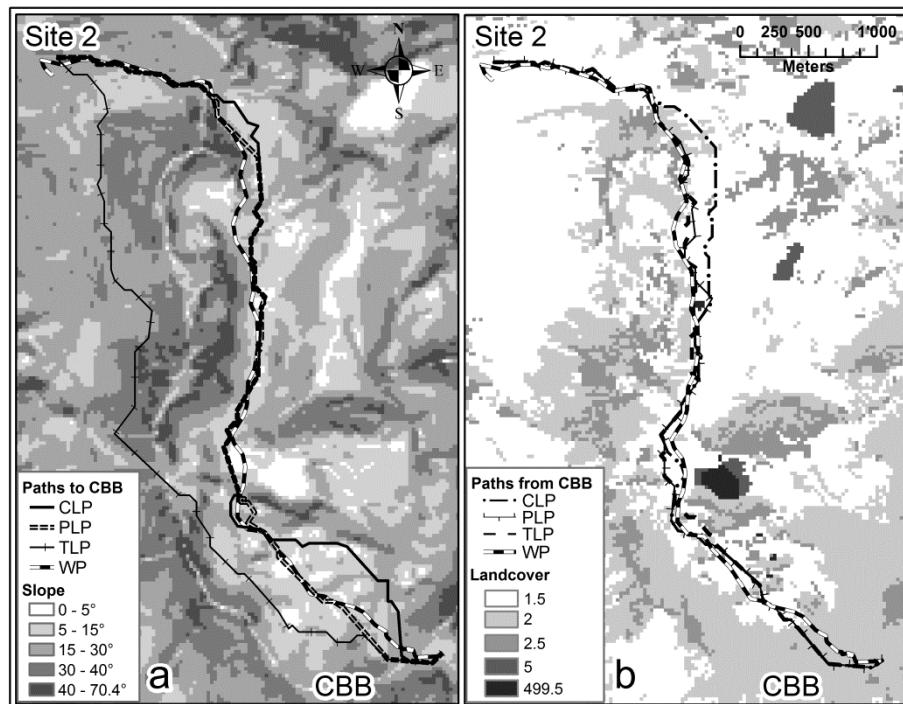


Figure 3. Least cost paths from Site 2 to the Cabin de Becs de Bosson (CBB) shown with slope values (a) and paths from the CBB back to Site 2 shown with the prehistoric landcover (second weighted) cost raster in the background (b). The legend represents the current landcover path (CLP), the prehistoric landcover paths (both weightings) (PLP), the topographic landcover path (TLP), and the Wanderland path (WP). See Table 4 for calculated travel times.

Table 4. Site numbers, geographic coordinates, altitudes, and calculated walking times from the starting locations to the CBB (away) and vice versa (return) at the calibration site. The titles represent the current landcover path (CLP), the prehistoric landcover paths (both weightings) (PLP), the topographic landcover path (TLP), and the Wanderland path (WP).

Site	Latitude	Longitude	Alt(m)	CLP		PLP (1st)		PLP (2nd)		TLP		WP	
				Away	Return	Away	Return	Away	Return	Away	Return	Away	Return
1	46° 12' 12" N	7° 30' 40" E	2,184	03:06:40	02:13:06	06:27:00	04:38:36	03:13:30	02:19:18	01:54:11	01:19:58	02:38:00	01:47:00
2	46° 12' 17" N	7° 28' 49" E	2,326	03:12:21	02:26:56	06:39:29	05:14:49	03:19:44	02:37:24	02:02:16	01:36:11	02:41:00	01:54:00
3	46° 11' 52" N	7° 28' 35" E	2,126	03:27:33	02:33:32	07:08:15	05:17:09	03:34:08	02:38:34	02:08:56	01:34:38	02:48:00	01:53:00
4	46° 11' 22" N	7° 28' 34" E	2,190	03:12:35	02:21:46	06:29:32	04:48:59	03:14:46	02:24:30	01:56:53	01:25:48	03:10:00	02:16:00
5	46° 11' 5" N	7° 28' 14" E	2,240	03:02:40	02:16:06	06:05:50	04:32:46	03:02:55	02:16:22	01:49:42	01:20:50	02:40:00	01:52:00
6	46° 10' 31" N	7° 28' 16" E	2,171	02:52:11	02:12:46	05:56:32	04:17:20	02:58:23	02:08:40	01:49:14	01:18:44	02:28:00	01:34:00

4.1.3.2 ANALYSIS SITES

4.1.3.2.1 SION/DOMODOSSOLA

From Sion to Domodossola (Fig. 4), the LCP travelled firstly through the Rhône valley in a northeast direction and continued through the valley on low-weighted landcover values (Fig. 4b) and flat terrain (Fig. 4c) for approximately 50 km before reaching the town of Brig. From Brig, the path ascended to the Forca d'Aurona (2,686 m asl) which is a currently unglaciated mountain pass south of the Punta d'Aurona (2,985 m asl). From the pass, the LCP descended into Italy in a southeast direction toward Varzo and then continued following the Val Divedro until reaching Domodossola in 48:54:39. The return path from Domodossola to Sion was visually similar but was calculated to take 48:34:00 in total.

4.1.3.2.2 SION/AOSTA

The LCPs from Sion to Aosta and Aosta to Sion also followed similar routes in both directions. From Sion, the LCP moved in a southerly direction through the Val de Nendaz, continuing on flat terrain below 2,000 m asl, depicted by the landcover value change, until it made an ascent to the west of the Rosablanche mountain (3,336 m asl) (Fig. 5a). To cross this mountain pass, the LCP passed over the Grand Désert glacier and through the Col de Cleuson (3,018 m asl) (Figs. 5 and 6). After passing the col, the path descended into the Val de Bagnes and continued on a southeast route perpendicular to the slope, across an area of low landcover values, past the Lac de Mauvoisin (Fig. 5b, c). After the lake, the path remained along the flat slopes and lowly-weighted landcover values until turning southwest near the Grand Charmotane and began the ascent to the Fenêtre de Durand (2,805 m asl) along the northwest side of the Glacier de Fenêtre. After crossing the Fenêtre de Durand mountain pass, the LCP descended into Italy's Valle d'Aosta in a southwest direction. The path moved southwest around an area of steep slopes before heading directly south, continuing on the low slopes and low-valued landcover regions, until reaching Aosta. The journey in the southern direction took a total of 39:56:08. The path

from Aosta to Sion differed only significantly in a few places, namely just south of the Col de Cleuson (Fig. 5) and near the Grand Charmotane. The path from Aosta to Sion took a total of 39:56:40.

4.1.3.2.3 ARCHAEOLOGICAL PROSPECTION

As a result of the Sion/Domodossola LCPA, the mountain pass of Forca d'Aurona (Fig. 4) which separates Switzerland and Italy, was archaeologically investigated. The recent construction of a cabin on this currently non-glaciated pass made the retrieval of archaeological remains impossible as the original landcover had been destroyed. Only modern artefacts were found at the remaining ice patches.

The LCP from Sion/Aosta led to two days of prospection at the Col de Cleuson (Fig. 6). A total of 16 items, all pieces of wood, were discovered at the margin of the Grand Désert glacier, on the pass of the Col de Cleuson, or directly on the glacier (Fig. 6). Five of the six dated items were modern (~180 – 125 BP), but one piece of wood, which was found directly on the Col de Cleuson (3,018 m asl), partially concealed under rocks, was dated to $2,795 \pm 35$ BP (Poz-52269). This piece of wood was approximately 40 cm long and 3 cm in diameter. The presence of this artefact attests to the use of this pass in prehistoric times.

4.1.4 DISCUSSION

In this study we found a Bronze Age piece of wood on top of a previously unstudied mountain pass by using least cost path analyses in conjunction with Tobler's hiking function and by testing the effects of differing landcover weights on paths at a calibration site. In doing so, certain assumptions and estimations had to be made in order to gain a better general understanding of movement through mountainous terrain. Tobler's hiking function, which was calibrated from empirical data of soldiers walking through varying topography, assumes that topography affects the walking speeds of people travelling through it (Imhof 1968; Tobler 1993; Gorenflo and Gale 1990). Although it has been criticised for not being based on scientific experiments (Herzog 2012), it is still the most used algorithm for LCPA in archaeological studies (Gorenflo and Gale 1990; Bell and Lock 2000; Whitley and Hicks 2003; Verhagen and Jeneson 2012). The integration of this algorithm into GIS and LCPA is useful for the estimation of time required and potential paths taken when traversing undulating terrains. Another algorithm which calculates walking times is the *r.walk* function from GRASS (Neteler and Mitsova, 2008; GRASS Development Team 2013). Research using this function has also shown interesting results (c.f. Madry and Rakos 1996; Ullah and Bergin 2012). However, a greater body of literature supports the use of Tobler's hiking function, therefore it was deemed most suitable for this study (e.g. Gorenflo and Gale 1990; Bell and Lock 2000; Whitley and Hicks 2003; Verhagen and Jeneson 2012). Furthermore, instead of using time as the measure, it has been stated that perhaps energy is a better indicator of human travel as time can be perceived differently in

different cultures and time-periods (van Leusen 2002; Llobera and Sluckin 2007; Herzog and Posluschny 2011; Kondo and Seino 2011). Some researchers have developed and implemented energy based algorithms into their calculations (c.f. van Leusen 2002; Kondo and Seino 2011), which would be interesting to adapt and implement in this study area.

When conducting any type of prehistoric analysis in GIS, it is important to take into account the paleoenvironment, or past environmental characteristics (Wheatley and Gillings 2002). In this study, a prehistoric landcover raster was created by experimenting at the calibration site. The landcover reclassification schemes used at the calibration site were based on discussions between archaeologists, historians, and geographers to obtain a consensus about friction levels for each type of terrain. The 2,000 m asl treeline level was an estimation of the upper limit of the forest influenced by the first important prehistoric human impact (Colombaroli et al. 2010). Although this method was relatively crude, it was important to acknowledge that landcover is constantly evolving due to natural and anthropogenic reasons and this should be taken into account when conducting GIS analysis (Wheatley and Gillings 2000).

The analysis of the results from the calibration site indicated that the walking times and routes taken by the LCP varied depending on the inputs to the LCPA model. For example, the paths calculated using the topographic landcover cost raster were the shortest in terms of time, because they were influenced only by the slope of the terrain and did not take into effect the landcover weights. The use of the topographic landcover cost raster allowed visualisation of the effects of both the isotropic and anisotropic inputs into the model. The majority of past archaeological studies using LCPA have relied solely on the slope of the terrain, thus anisotropic friction, in LCPA models (Gorenflo and Gale 1990; Gaffney and Stančič 1991; Bell and Lock 2000; Tripcevich 2008; Egeland, Nicholson, and Gasparian 2010; Kondo and Seino 2011; Herzog and Posluschny 2011; Verhagen and Jeneson 2012), therefore neglected the isotropic aspect. The incorporation of both isotropic and anisotropic frictions integrates both the magnitude and force of frictions across the cost surface (Bell and Lock 2000) and thus results in a more representative model of the terrain (van Leusen 2002). Similar to Howey (2007), in this study landcover was integrated as the isotropic friction along with slope as the anisotropic friction. However, it was not assumed that landcover and slope of the terrain were the only factors affecting the travel patterns of prehistoric people. In fact, it has been suggested that numerous social and cultural factors affected their travel decisions (Llobera 2000; Lock and Pouncett 2010; Murrieta-Flores 2010; 2012). Times calculated by the first weighting scheme of the prehistoric landcover cost raster were highly exaggerated, and took approximately three times longer than the paths calculated by the WPs. However, visually they seemed to be most consistent with the trails on the current topographic map. When each weight was divided in half to create the second prehistoric weighting scheme, the resulting paths were visually the same but had more accurate

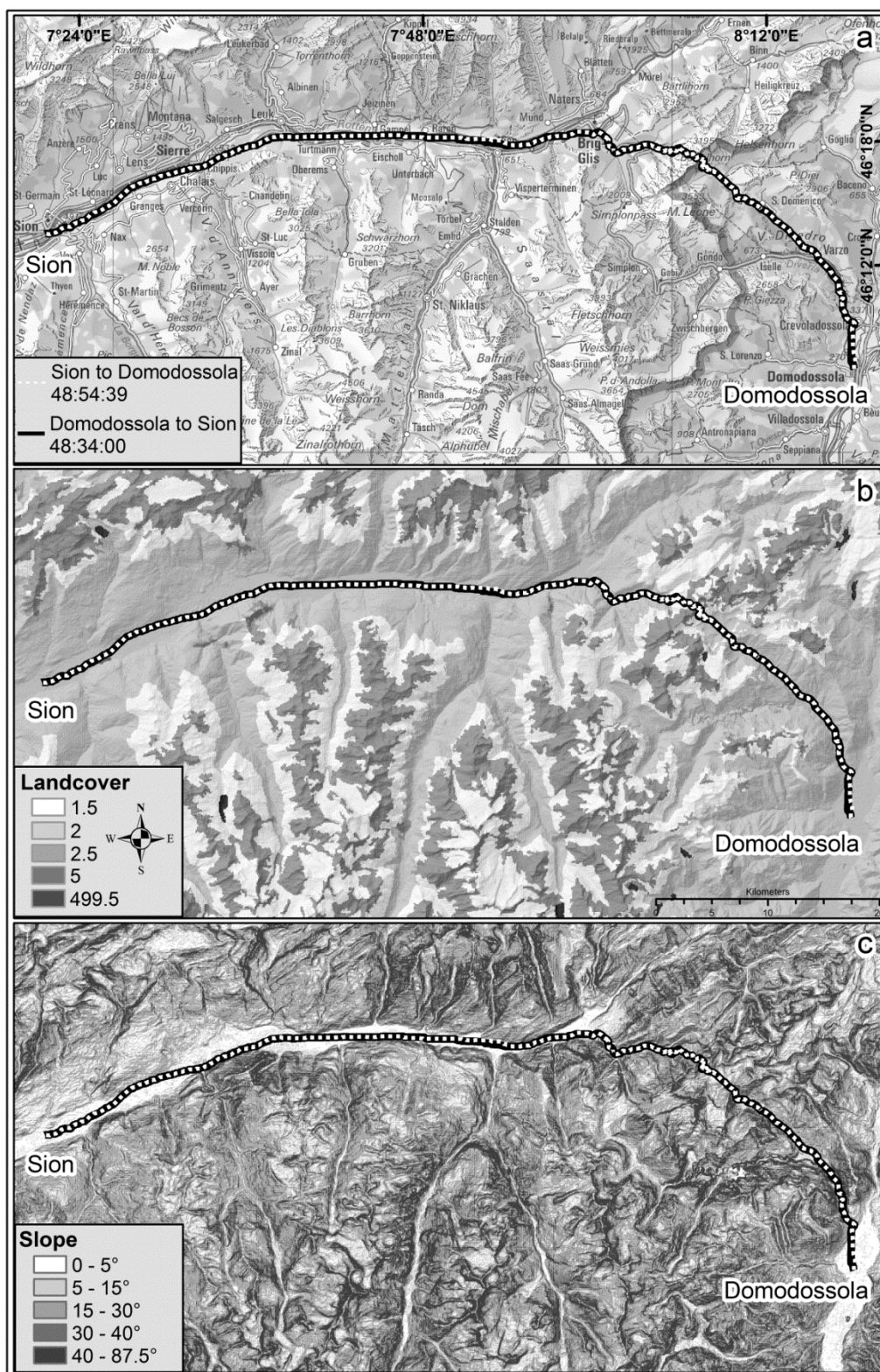


Figure 4. Least cost paths from Sion to Domodossola and vice versa on 1:500,000 topographic map with travel times (a), second weighted prehistoric landcover cost raster (b), and DEM-derived slope (c) backgrounds. Landcover values correspond to the reclassification categories in Table 3

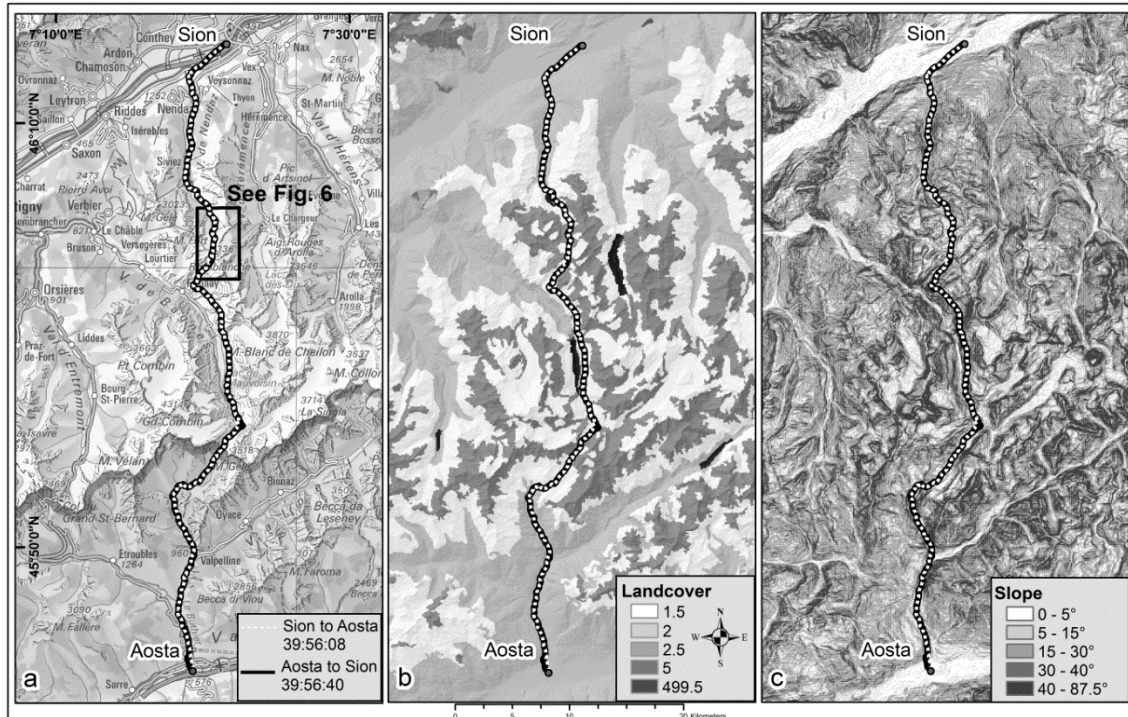


Figure 5. Least cost paths from Sion to Aosta and vice versa on 1:500,000 topographic map with travel times (a), second weighted prehistoric landcover cost raster (b), and DEM-derived slope (c) backgrounds. Landcover values correspond to the reclassification categories in Table 3

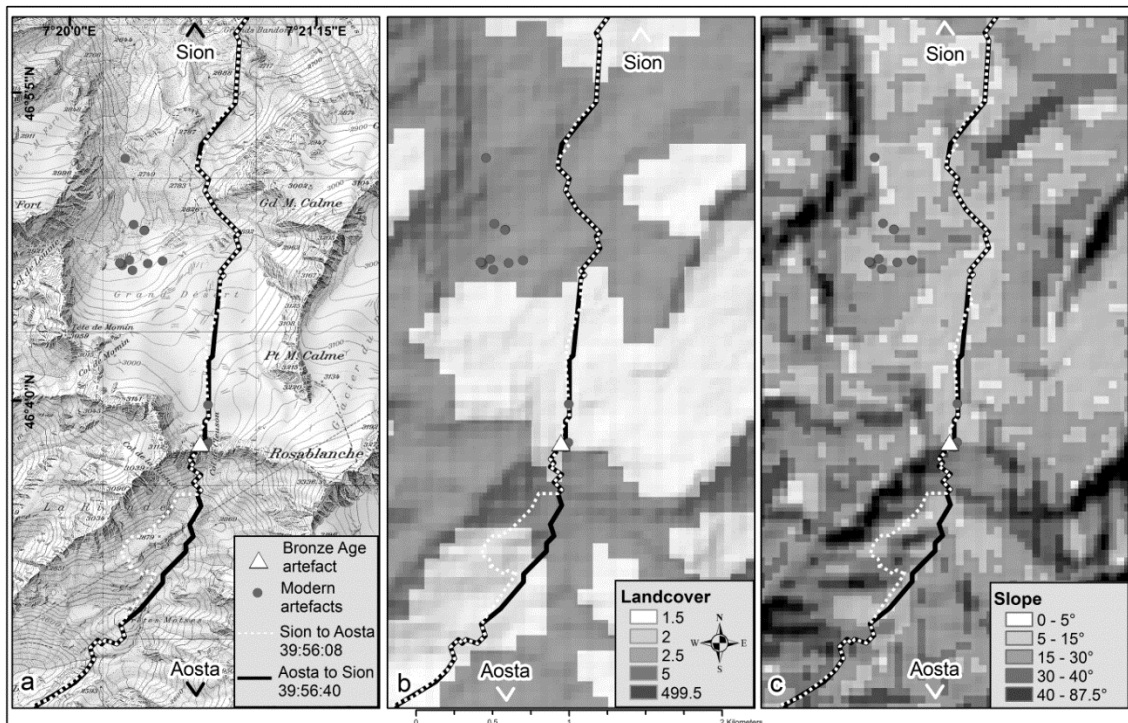


Figure 6. Zoomed in area of Col de Cleuson from the results of least cost path analysis from Sion to Aosta and vice versa on 1:25,000 topographic map (a), second weighted prehistoric landcover cost raster (b), and DEM-derived slope (c) backgrounds. Landcover values correspond to reclassification categories in Table 3

walking times compared to the WPs calculated by Suisse Rando. Thus, the prehistoric landcover with the second weighting scheme was adopted for the analysis between Sion and Aosta. The comparison of the LCP with present day walking trails was based on the assumption that the walking trails that exist today are based upon the same principle that people desire to take the easiest route possible when walking over mountainous terrain. The model could be further strengthened through ground-truth validation of walking times at the calibration site and it should be reiterated that the concept of time was not necessarily the same in the past as it is today.

The LCPA at the analysis sites narrowed down vast, mountainous study regions to aid glacial archaeological prospection and proved to be beneficial for discovering a previously unknown archaeological site with the detection of a prehistoric artefact at the Sion/Aosta site. Because of high elevations and low-accessibility in mountainous regions, it was physically impossible to visit every site of interest within the Pennine Alps. Thus, LCPA enabled a focused study area to be more thoroughly investigated with field recognisance and site visitation. With the aid of archaeologists and historians, the Forca d'Aurona and Col de Cleuson were chosen for further investigation based on the outcomes of the LCPA. The Forca d'Aurona was once a glaciated pass, but with the current climate situation, there was no ice or snow on the pass in the late summer of 2012 when archaeological prospection was conducted. From a glacial archaeological perspective, sites free of ice and snow yield fewer archaeological remains because the majority have decomposed or been destroyed by anthropogenic causes, as was the case at this site. Conversely, the region surrounding the Col de Cleuson is currently glaciated and had not been previously studied, archaeologically nor historically. Thus a new location of interest was discovered. The 16 pieces of wood retrieved from the Col de Cleuson and near the margin of the Grand Désert glacier attest to the fact that people have used this pass for thousands of years and could be of future interest to archaeologists. It should be noted that any piece of wood found at such high elevation (almost 1,000 m above the current treeline) was not a natural phenomenon, but had to be transported there by someone or something. According to Verhagen and Jeneson (2012), despite being a popular research technique LCPA does not usually result in predictive success. The Forca d'Aurona showed the limit to this method, and perhaps for the future, more emphasis should be placed on passes which are still glaciated or surrounded by snow and ice. On the other hand, the results at the Col de Cleuson showed that in a region rich in cultural occurrences and terrain which often determines travel routes, that this method was effective as a decision support tool for the purposes of finding new sites for glacial archaeological investigation.

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4.1.7 ADDITIONAL COMMENTARY

Since the acceptance of this paper (January 2014), various topics of discussion have arisen which will be discussed in the following paragraphs.

4.1.7.1 CHOICE OF WEIGHT VALUES AND TREELINE LEVEL

The weighting schemes chosen for the cost rasters at the calibration site will be further discussed here as there is often a level of controversy associated with arbitrary weighting schemes in archaeological predictive modelling. In this case, the Current LC weighting scheme was created after a consensus between group members consisting of archaeologists, historians, and geographers, regarding the amount of effort assumed to be required for crossing each landcover type. It is a relative weighting scheme which measures difficulty in respect to the 'Other' category which was assumed to be the easiest to cross and given a weight of 1. All other categories were decided based on the assumed difficulty of crossing various terrains in relation to the 'Other' category. For example, the forest category was assumed to be three times as difficult to cross and therefore was assigned a weight of 3. Another point to note is that throughout this process, slope values were kept consistent to reflect Tobler's hiking algorithm values as this was a method used in many archaeological studies and assumed to be sufficient for these tests.

The prehistoric landcover weights were adapted from the Current LC weights and the level of the treeline. The treeline was shifted from the current level, which is approximately 2,200 m, to 2,000 m. This may seem counter-intuitive as it is assumed that the treeline was a few hundred meters higher (i.e. 2,500 m) in Mesolithic and Neolithic times due to a different climate. However, research conducted by Berthel et al. (2012) at the Sanetsch pass (2,288 m asl), which is at a similar elevation as the Haut-Val de Réchy (~2,200 – 3,000 m asl) and located about 20 km away on the opposite side of the Rhone valley, suggested that the Sanetsch pass had been free of trees for the last 12,000 years. Therefore, the treeline of 2,000 m was used for the Haut-Val de Réchy to represent an area free of trees and thus, a prehistoric landcover. In hindsight, perhaps this was unreasonable as the elevation of most of the test site is above the 2,000 m threshold thus the LCPs results were not significant. Nevertheless, the prehistoric landcover weights were assigned based on their location above or below the treeline. Unlike the Current LC raster, the Prehistoric LC raster's "Other" category started at 3. This was due to the fact that in the Corine landcover layer the "Glaciers and perpetual snow" category was included in the "Other" category above 2,000 m thus the higher value of 3 aimed to account for walking across snow and ice instead of purely meadow. The remaining categories were assigned weights accordingly (i.e. whether they were located above or below the treeline).

After the first round of calculations with the Prehistoric LC cost raster, the results showed that the LCP times were overestimated by about double. Therefore, a second weighting scheme was

applied to the Prehistoric LC where the weights were divided by two. The resulting times of the LCPs were more representative of the actual time required for travel according to field testing.

4.1.7.2 RESOLUTION OF DEMs AND LANDCOVER LAYERS

Following the thoughts provided in the previous section, it is also important to discuss the use of differing DEMs and landcover layers for each of the calibration and analysis sites. The reason for this was purely due to data access. For the calibration site, the best possible data layers (in terms of accuracy and resolution) were used to obtain the best results. They were the primary surfaces landcover layer and 25 m DEM from Swisstopo. Unfortunately, those layers only exist for Switzerland. At the international scale between Switzerland and Italy, lower quality (in terms of accuracy and resolution) layers had to be used in order to obtain consistent datasets from both sides of the border. Also, higher resolution datasets from the Italian side of the border could not be collected. Therefore the 30 m ASTER GDEM and the 100 m Corine landcover layers were used and resampled to 25 m in an attempt to keep the results as consistent as possible with the tests from the calibration site. The result of using different input layers for the international scale caused inconsistencies in the results. In hindsight, both sets of tests should have been conducted on the same input layers to observe potential differences.

4.1.7.3 LCP CALCULATION ISSUES

One of the problems with the LCP model was that LCPs often traversed horizontally across slopes as if those were the same as flat terrain. In fact, the model cannot distinguish between walking across flat terrain and walking horizontally across slopes which is problematic because a person would be affected differently in each situation and it is easier to walk on flat terrain than across a steep slope. To avoid this problem, steep slopes (e.g. $> 40^\circ$) should be restricted in the model. For further discussion on this matter, see section 4.3.10.2.

4.2 PAPER III: LEAST COST PATH ANALYSIS FOR PREDICTING ARCHAEOLOGICAL POTENTIAL: SCALE AND PARAMETER INVESTIGATIONS

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ABSTRACT

Increasing global temperatures are causing shrinkage in Earth's frozen environments due to the melting of ice and snow at high latitudes and altitudes. This phenomenon is relevant from many environmental perspectives as well as from an archaeological standpoint. Archaeological remains or artefacts which have been locked in frozen environments for hundreds or thousands of years are at risk of becoming exposed due to increased melting at high altitudes and latitudes. In an attempt to gauge archaeological potential in a mountainous region in western Europe, we further develop the least cost path analysis (LCPA) work conducted by Rogers et al. (2014) to investigate the results of least cost path (LCP) modelling in mountainous terrain. Different geographic scales and various parameter weighting schemes are used to test the effects of these changes on the resulting LCPs. The results show both similarities and differences between the paths calculated from the point and line scales and that increasing parameter weights in the LCPA model affect the spatial distribution of paths, and their respective travel times.

4.2.1 INTRODUCTION

The Pennine Alps, a mountainous region located on the border of south-western Switzerland and northern Italy, have been used as a crossing point between valleys on each side of the border for thousands of years (Ammann 1992; Bezingue and Curdy 1994; 1995; Coolidge 1912; Curdy et al. 2003; Curdy 2007; Harriss 1970; 1971; Lehner and Julen 1991) (Fig. 1). First indications of their use stem from the Mesolithic period and range until historic times (Curdy 2007). The high altitude, often glaciated, mountain passes located along the border are of interest to historians and archaeologists in the region. Some of these passes are well-studied, for example, the Grand Saint-Bernard and Simplon passes are known to be two of the principle crossing points between Switzerland and Italy over history (Benedetti and Curdy 2008; Curdy et al. 2010; Vesan 2008). However, other less documented secondary passes exist which also have historical significance. These secondary passes are said to have been used for the purposes of commerce and migration as a direct, although often difficult route between the valleys. Several archaeological remains have been uncovered on the way to, and on top of, these secondary mountain passes of the Pennine Alps; among these discoveries, the remains and artefacts discovered near the margins of the Oberer Theodul glacier which is located south of the town of Zermatt in Switzerland. These findings are said to have belonged to the “Mercenary of Theodul”, and include bones, weapons, leather clothing, shoe soles, and coins dating back to the 16th century (Julen-Lehner and Lehner 2012; Lehner and Julen 1991; Meyer 1992). Due to recent increases in global temperatures, finds such as these are becoming more common in the Alps as well as in frozen environments on other continents (Alix et al. 2012; Andrews and MacKay 2012; Andrews, MacKay and Andrew 2012; Beattie et al. 2000; Callanan 2012; 2013; Dixon et al. 2005; Farbregd 1972; Farnell et al. 2004; Hafner 2012; Hare et al. 2004; 2012; Lee 2012; VanderHoek et al. 2007; 2012). With each uncovered glacial archaeological remain, researchers are able to piece together how frozen environments have been used over history. These findings, which have melted out of glaciers, ice patches, or permafrost, have led to the development of a new archaeological domain which will refer to here as “glacial archaeology”. In general, glacial archaeology refers to any archaeological finding which has melted out of a frozen environment.

Glacial archaeology in the Pennine Alps has attracted substantial interest because of its prehistoric reputation and topographic characteristics. This region is at particularly high risk of glacier retreat and melting due to its high altitude and the inherent properties of glacier sensitivity to climate change (WGMS 2013; Zemp et al. 2009). Between the Little Ice Age (LIA) maximum in 1850 and now, glacier area has declined by approximately 50% in the European Alps (Fischer et al. submitted; Zemp et al. 2006) because of climate change acting on the region. Thus, increasing temperatures are responsible for releasing archaeological remains which have been locked in their respective frozen environments for centuries. These remains are at risk of rapid decomposition as they are often made up of organic materials. To collect and preserve

these remains, systematic prospection is needed to identify specific areas of archaeological potential. Rather than undertaking the impossible task of visiting every site of interest in the Pennine Alps - which cover 4,500 km² - and to narrow down this large study region, we have used least cost path analysis (LCPA) to obtain a better understanding about how people could have crossed the Pennine Alps based on the assumption that they would have taken the easiest route possible from one location to another. Various archaeological studies have used this decision-support tool successfully for archaeological investigations in large and remote study regions (Bell and Lock 2000; Egeland et al. 2010; Gaffney and Stancic 1991; Howey 2007; Verhagen and Jeneson 2012). The first step in LCPA is to calculate an accumulated cost raster from which the least cost path (LCP) is calculated in the second step (Yu et al. 2003). The cost raster can be made up of single or multiple isotropic and anisotropic variables, that is, variables with friction that is equal in all directions (i.e. landcover), or variables where the friction varies depending on the direction of movement (i.e. slope), respectively (Bell and Lock 2000; Conolly and Lake 2006; van Leusen 1999; Wheatley and Gillings 2002). The selection of weights for the input variables into the LCPA model can also affect the outcomes of the calculated LCPs and should be taken into selected with care (Berry 2004; Howey 2007).

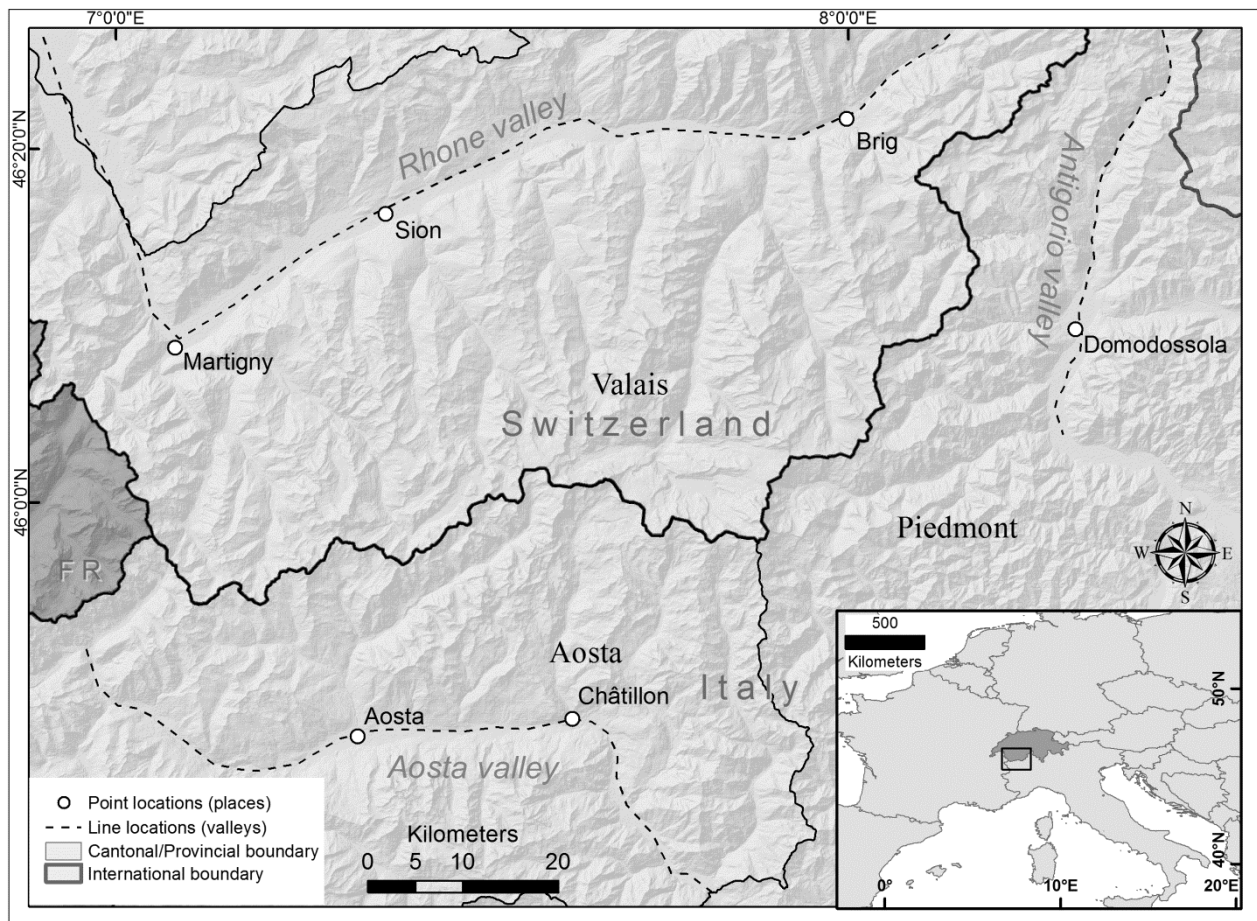


Figure 1. Overview of the study region.

Here, we provide an update to the work by Rogers et al. (2014), which calculated LCPs in the Pennine Alps taking into account the slope and prehistoric landcover properties of the terrain. We will hereby refer to the Rogers et al. (2014) study as the “original study”. First, we calculate LCPs from six point locations, i.e. modern agglomerations situated in strategic positions, well-known for their rich archaeological and historical past, including the three already used in the original study. Next, we calculate LCPs from lines, i.e. along entire valleys, to investigate the effects of using different geographic scales on the results of the LCPA. Furthermore, we test the effects of altering the input variable weights in the LCPA model with the ultimate goal of obtaining a better understanding about how the inputs to the LCPA model affect the results. Additional historical and archaeological information about each of the selected passes is discussed in the Supplementary Information section at the end of the document (section 4.2.5).

4.2.2 METHODS

The LCPA method proposed by Rogers et al. (2014) was used as a base of investigation. Briefly, walking times of LCPs were calculated using the Path Distance and Cost Path tools in ArcGIS 10.1 by accounting for surface distance, landcover, and slope of the terrain. Landcover was modelled isotropically while slope was modelled anisotropically, using Tobler’s hiking function to calculate walking times across the terrain (Tobler 1993). The inputs to the model included a digital elevation model (DEM) from the Advanced Spaceborne Thermal Emission Radiometer Global DEM 30 m (ASTER GDEM V2) (NASA 2012), and a prehistoric landcover layer which was adapted from the 2006 version of the Coordination of Information on the Environment (Corine) 100 m resolution landcover layer (European Environment Agency 2012) (Rogers et al. 2014). Both layers were resampled to 25 m resolution for calculations.

The LCPA methods presented in the original study were further developed in three ways. First, LCPs were calculated using six point locations, including the three from the original study, to obtain a comprehensive overview of the high mountain passes selected and the respective times it took for the paths to get from one side of the Pennine Alps to the other. These point locations included: Martigny, Sion, and Brig in Switzerland, and Aosta, Châtillon, and Domodossola in Italy (Fig. 1). Aosta, Sion, and Domodossola were selected because they are well-known historical points of departure to the Grand Saint-Bernard and Simplon passes, which were the most frequented passes in history between Sion and Aosta or Brig and Domodossola. Châtillon was used because of its strategic location in the Aosta valley, located at the foot of the Theodulpass, between the Upper Rhone valley (Brig) and the release of the Aosta valley in the Po valley. Second, LCPs were calculated from lines along the Rhone valley in Switzerland, and the Aosta and Antigorio valleys in Italy (Fig. 1), to obtain a regional scale view of LCPS. Third, the “Rock” and “Glacier/Perpetual snow” variables from the landcover input layer were altered by changing their isotropic friction weights, which are a set of relative values, to test the effects

of the weighting scheme on the overall results of the LCPA (Table 1). These two variables were selected because they constitute the majority of the landcover parameters at high altitudes in this region thus they were assumed to be most pertinent to this study.

Table 1. Landcover parameter weightings from respective landcover rasters. *The Original raster corresponds to the one used in Rogers et al. (2014). **This parameter was originally included in the “Open space above 200m” category in the Rogers et al. (2014) study.

Landcover category	Cost raster name and weights					
	Original*	Rock4	Rock10	Rock100	Glac3	Glac10
Open space above 2000m	1.5	1.5	1.5	1.5	1.5	1.5
Forest below 2000m	2	2	2	2	2	2
Rock	2.5	4	10	100	2.5	2.5
Glacier/Perpetual snow**	1.5	1.5	1.5	1.5	3	10
Swamp	5	5	5	5	5	5
Lake	499.5	499.5	499.5	499.5	499.5	499.5

4.2.3 RESULTS

4.2.3.1 LCPs FROM POINTS

The LCPs calculated from the point scale took direct routes across the Pennine Alps from one side of each valley the other (Fig. 2). From Martigny to Aosta, the shortest calculated route using the original landcover friction values selected the Col Ouest de Barasson as the crossing pass in both directions (Table 2). In the southern direction, this path took 32 hours, 29 minutes, and 21 seconds (32:29:21), and in the northern direction, it took 32:45:20 (Table 2). From Sion to Aosta, the Fenêtre de Durand was selected in both directions. In the southern direction this path took 39:56:08, and in the northern direction, it took 39:56:41. Between Sion to Châtillon, the Col de Bouquetins was selected for both directions. It took the southern path 42:20:41 to reach the destination and the northern path 42:11:54. The paths between Sion and Domodossola took the greatest amount of time due to the sheer distance between them. The Bortellicke pass was selected in both directions. The path moving east from Sion took 48:54:39 to reach Domodossola, while the path in the western direction took 48:34:00. The paths between Brig and Châtillon were the only ones to select different passes when moving in the south and north directions. From Brig to Châtillon, the Theodulpass was selected and took 43:34:05. In the northern direction from Châtillon to Brig, the Furggjoch was selected and took a total of 43:15:42.

Table 2. Results from point scale analysis including passes selected and the time required.

Points	Direction	Pass selected	Time	Direction	Pass selected	Time
Martigny/Aosta	South	Col O. de Barasson	32:29:21	North	Col O. de Barasson	32:45:20
Sion/Aosta	South	Fenêtre de Durand	39:56:08	North	Fenêtre de Durand	39:56:41
Sion/Châtillon	South	Col des Bouquetins	42:20:41	North	Col des Bouquetins	42:11:54
Sion/Domodossola	East	Bortellicke	48:54:39	West	Bortellicke	48:34:00
Brig/Châtillon	South	Theodulpass	43:34:05	North	Furggjoch	43:15:42

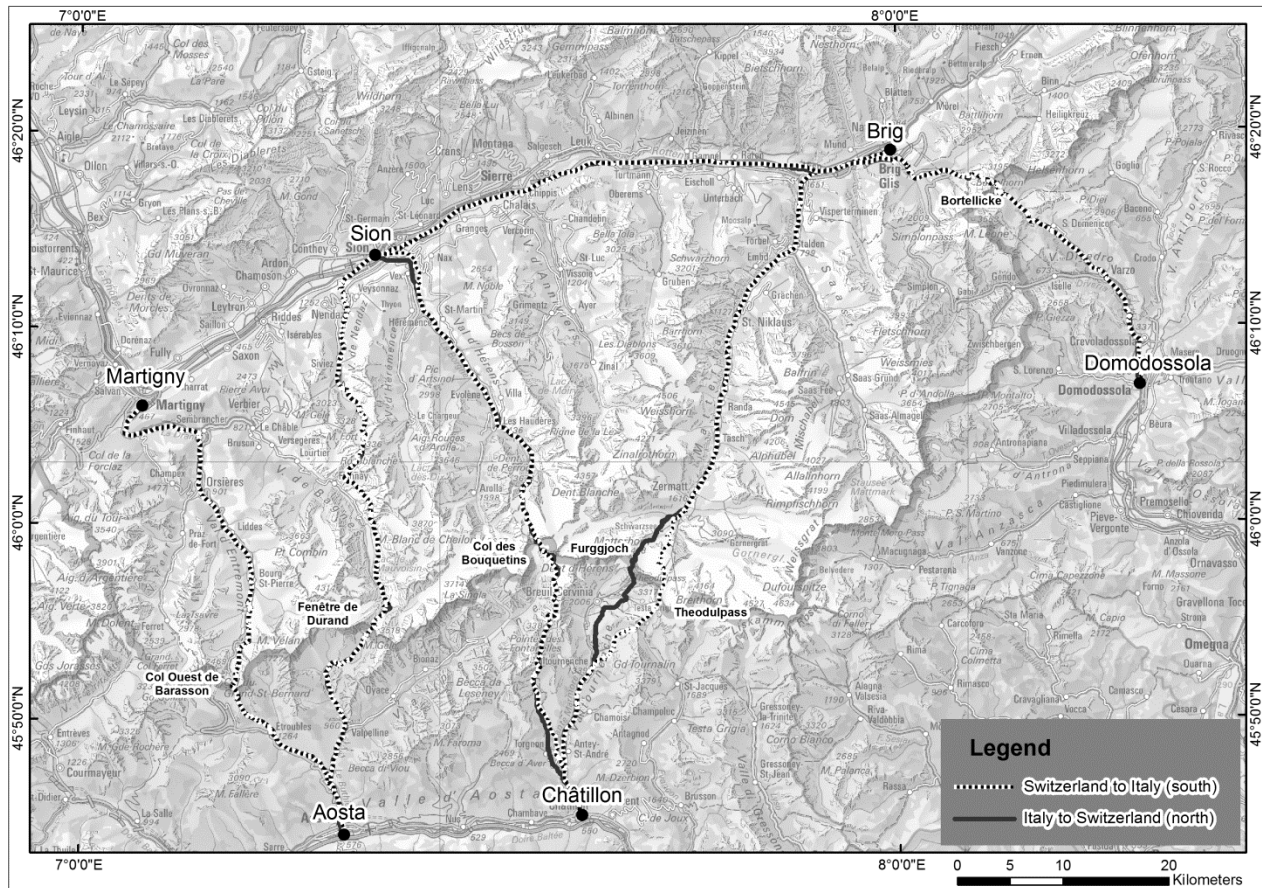


Figure 2. Results of LCPA from the point scale.

4.2.3.2 LCPs FROM LINES

LCPs were calculated from the Rhone to Aosta and Antigorio valleys, and vice versa, using the original landcover classification by Rogers et al. (2014) (Table 1). Results are provided in average times which were calculated by summarizing all paths from one valley to another (Table 3, Original). From the Rhone to Aosta valley, the average time was calculated to take 37:44:34 (Table 3). The high mountain passes used were the Grand Col Ferret, the Theodulpass, and the Albrunpass (Fig. 3).

From the Aosta and Antigorio valleys to the Rhone valley, the average calculated time was 36:50:04. The passes used in this direction were the Grand Col Ferret, the Col du Fourchon, the Col Ouest de Barasson, the Furggloch, the Theodulpass, the Bortellicke, the Chriegalppass, and the Albrunpass. From the Rhone to Antigorio valleys the average time was 22:17:31 and the only pass used was the Albrunpass. From the Antigorio back to the Rhone, the average time was 22:49:31 and the passes used were the Bortellicke, the Chriegalppass, and the Albrunpass (Fig. 3, Table 3).

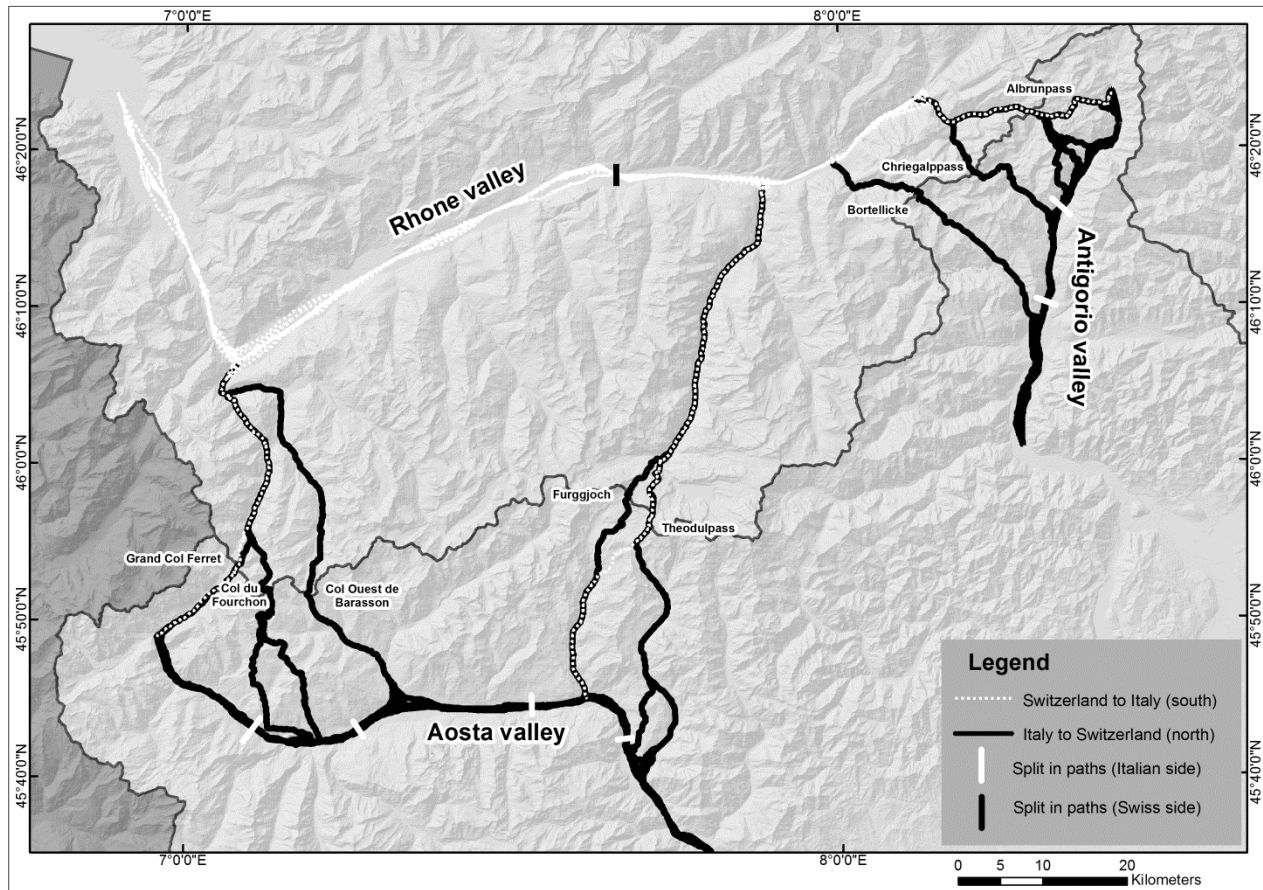


Figure 3. Results of LCPA from the line scale. The splits in the paths indicate when a path starts moving in the opposite direction.

Table 3. Results, shown in average times, from line scale analysis.

Valleys	Cost raster name and average times					
	Original	Rock4	Rock10	Rock100	Glac3	Glac10
Rhone to Aosta	37:44 :34	37:06:39	38:05:20	39:25:28	37:15:49	37:40:43
Aosta to Rhone	36:50 :04	38:15:13	39:03:07	39:00:21	38:34:21	38:31:04
Rhone to Antigorio	22:17:31	22:45:48	23:16:42	23:20:55	22:19:18	22:46:48
Antigorio to Rhone	22:49:31	23:13:41	23:17:04	23:19:32	22:48:42	22:45:32

4.2.3.3 PARAMETER INVESTIGATIONS

As weights for the “Rock” and “Glacier/Perpetual snow” parameters were increased (Table 1), the average times (Table 3) changed and the resulting LCPs were spatially different (Fig.5a, b). From the Swiss side to the Italian side of the border, as Rock values were increased from 2.5 (Original) to 4 (Rock4), the average time decreased because the Furggjoch was selected instead of the Theodulpas (Table 3, Fig. 4a). The other two passes taken were the Grand Col Ferret and the Albrunpass. As Rock values increased to 10 (Rock10), the paths kept their same spatial distribution for this direction (Fig. 4b) but the average time increased. When the Rock value was set at 100 (Rock100) the paths avoided the entire middle section of the study region to avoid the rocky areas and thus only the Grand Col Ferret and Albrunpass were used (Fig. 4c). As the

Glacier/Perpetual snow parameter was increased to 3 (Glac3), the high mountain passes used were the Col Grand Ferret, the Furggjoch, and the Albrunpass, with slightly different times (Fig. 4d). As the Glacier/Perpetual snow weight was increased to 10 (Glac10), the average time remained despite the path crossing the Theodulpass instead of the Furggjoch (Fig. 4e).

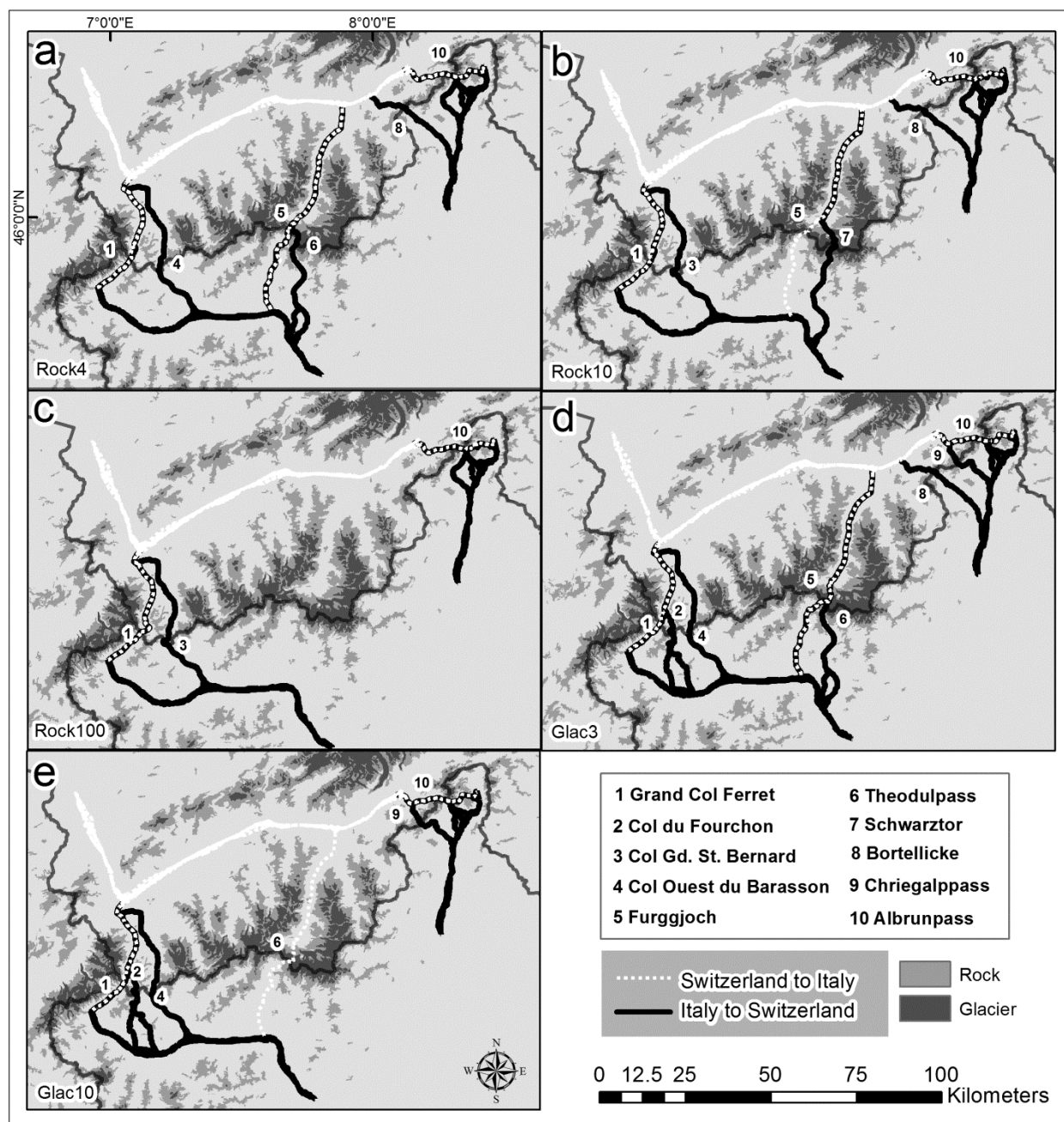


Figure 4. Results of parameter weighting investigations from the (a) Rock4, (b) Rock10, (c) Rock100, (d) Glac3, and (e) Glac10 cost rasters. Cost rasters correspond to the weighting schemes in Table 1.

In the opposite direction from Italy to Switzerland, changes could also be observed when parameter weightings were altered. As Rock values were increased to 4, the average times increased and the Grand Col Ferret, Col Ouest de Barasson, Furggjoch, Theodulpass, Bortellicke, and Albrunpass were used (Fig. 4a). As Rock was increased to 10, the Grand Col Ferret, Col Grand Saint-Bernard, Schwarztor, Bortellicke, and Albrunpass were used and times decreased slightly (Fig. 4b, Table 3). When Rock was increased to 100, the spatial distribution of paths was decreased and the only passes used were located on the east and west of the study area; those were the Grand Col Ferret, Col Grand Saint-Bernard, and the Albrunpass (Fig. 4c). The average time remained approximately the same. As the Glacier/Perpetual snow parameter was changed to 3, the Grand Col Ferret, Col du Fourchon, Col Ouest du Barasson, Furggjoch, Theodulpass, Bortellicke, Chriegalppass and Albrunpass were selected. The resulting passes were identical to those selected in the original weighed landcover raster. As Glacier/Perpetual snow was increased to 10, the selected passes decreased from 8 to 5 and were the Grand Col Ferret, Col du Fourchon, Col Ouest du Barasson, Chriegalppass and Albrunpass and the average times decreased slightly from the Glac3 instance.

To summarize the results, Fig. 5 shows the time differences between the averages calculated for the LCPs using seven different cost rasters. Between the Rhone and Aosta valleys, it generally took more time to cross in the northern direction (from Aosta to Rhone) than in the southern direction (from Rhone to Aosta), except for if the Rock category is weighted at a high value (Fig. 5). Between the Antigorio and Rhone valleys, average times were more similar, however, the northern route took more time to cross overall.

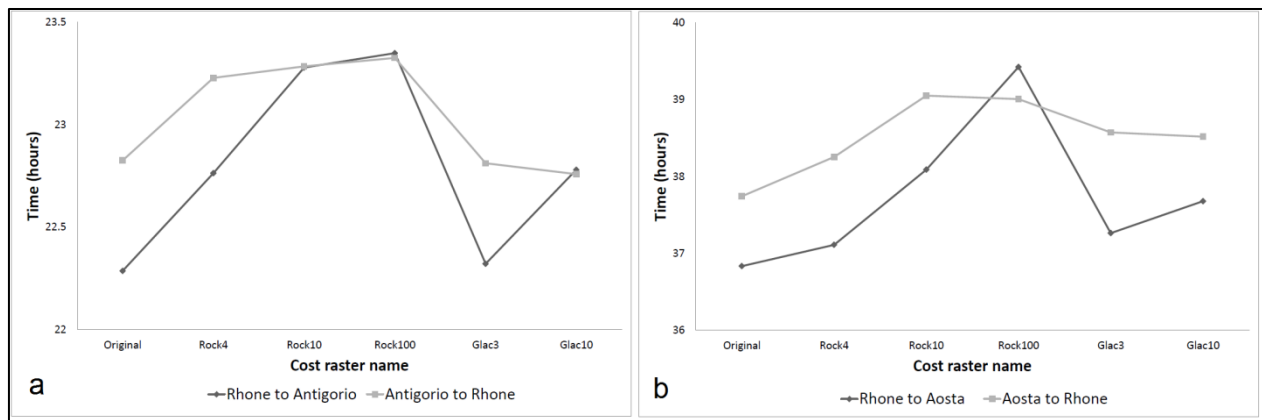


Figure 5. Results of average times from LCPs from the a) Rhone to Antigorio valleys and b) Rhone to Aosta valleys using different parameter weights and cost rasters from the line scale.

4.2.4 DISCUSSION

By further investigating the LCPA methods developed by Rogers et al. (2014) we gained a better understanding about the importance of scale and parameter weighting selection on the results of

the final LCPs. We identified similarities in the results from both geographic scales, for example, the Col Ouest de Barasson, Furggloch, Theodulpass, and Bortellicke were selected as passes at both the point and line scale. Differences also exist between the results at each scale. For example, at the line scale fewer passes were selected from the middle of the study area. This shows that it is easier to traverse further down the valley and then selecting a pass, instead of crossing the mountains where there is the highest concentration of rocks or snow and ice. For that reason the Fenêtre de Durand and the Col de Bouquetins were avoided. By starting from a point at the point scale, the paths are forced through potentially inaccessible terrains based on the fact that that is the easiest out of the other options. By taking a regional scale approach, and starting from the line scale, one is more confident in the results because the cost raster incorporates more of the surrounding terrain and thus can calculate the true LCP in that area. Another benefit of taking a regional scale approach is that no previous archaeological knowledge is required. Rogers et al. (2014) selected start and end locations for the LCPA based on their previously archaeological significance. This could be beneficial to some studies but if researchers are interested in a new study area with no former archaeological significance a regional scale approach could be more effective.

There were noticeable differences in the results when weights of the parameters for Rock and Glacier/Perpetual snow were changed. As their weights were increased, walking times generally increased and the spatial distribution of paths decreased. With higher weights, paths were forced to the east and west of the study area. For example, with the Rock100 cost raster it was easier for the paths to travel to the ends of each valley, where there was less topography, rock, snow, and ice, than to cross directly over the middle of the Pennine Alps. The west side of the study area has not been glaciated for at least 150 years (Maisch 2000), therefore that area is more attractive for crossing based on the current parameters of the LCPA model. For that reason, the west side of the study area was unaffected when the weights of the Glacier/Perpetual snow layer was increased (Fig. 4d,e). We were also interested in knowing how past glacier extents would affect the model results. However, the oldest glacier inventory is from 1850 and is only available for the Swiss side. None the less, calculations were performed using the 1850 glacier extents instead of the 2006 Corine glacier extents but results were found to be nearly identical to the ones already calculated. Unfortunately the calculations were not completely representative as the information from the 1850 glacier extents on the Italian side was missing. Also, the 1850 and 2006 extents do not vary enough to make a significant difference in the results. It would be interesting to know what glacier extents looked like between the Last Glacial Maximum (about 10,500 years BP) and 1850, although those datasets do not yet exist for this region. With that information, we could better understand the effects of changing geomorphology and ice cover on the potential of finding archaeological remains.

In conclusion, taking a regional scale approach from lines seems to be more realistic when thinking in terms of where people could have begun and ended their journeys in the past. It is unrealistic to consider that all journeys began and ended from a single point on the terrain. The findings in this study highlight the importance of scale and parameter weighting and choice within a LCPA model. By understanding the effects of different weighting schemes, the model can be further validated and improved for the future.

4.2.5 ARCHAEOLOGICAL INFORMATION OF PASSES CITED IN MODEL

Grand Col Ferret 2537 m

This pass is situated above the Val Ferret in Switzerland; to the south it leads to the Val Ferret in Italy. Several historical records suggest that this was an important pass in the 14th century AD (Aerni and Herzig 2014b b). In Aerni and Herzig (2014b), the Col Ferret and the Grand Saint-Bernard are mentioned together which gives it a certain importance. A Roman shoe nail is the only archaeological artefact found in this area. It was located about 3 km below the pass in 2004 during archaeological prospection (Poget 2006).

Col du Fourchon 2696 m

To the north, this pass is located above the Swiss Val Ferret. To the south, it leads to the Aosta valley. There is currently easy access to this pass. There are no indications as to whether this pass has been used in history, only recent touristic documentation about this pass exists. For the moment, no archaeological artefacts have been located at this pass.

Grand Saint-Bernard 2469 m

The pass connects the Rhone valley via the Val d'Entremont with the Aosta valley. Due to its easy accessibility, it is currently the only pass of the ones we present in this article, which is passable today. It has a lengthy international reputation and has been the subject of many studies. The majority of archaeological remains found on the pass are from the Roman and Medieval periods. It is impossible to say what it was used for in earlier times because the few objects from the Iron Age that were discovered could be items recovered from the Roman epoch (Vesan 2008).

Col Ouest Barasson 2635 m

This pass, which is above the Val d'Entremont, leads directly to the Aosta valley. Access from the north is relatively easy, but steep slopes, a few hundreds of meters in length, make access on the south side difficult. There is no historical information about this pass. The presence of an undated stone fortification and a Roman shoe nail give indication that this pass was used at certain times to control access to either side of the border (Benedetti and Curdy 2008).

Fenêtre de Durand 2805 m

This pass is located at the end of the Val de Bagnes and leads directly into the Valpelline to the south. Despite its distance from the lower part of the Val de Bagnes, it is an easy route with fairly steep slopes to the north and south. Since at least the 14th century AD, it was an important route for trade purposes or for moving herds of cattle (Coolidge 1912; Eschmann in press). Archaeological surveys conducted in 2004 found a Roman shoe nail, but nothing prior to that (Poget 2006).

Col des Bouquetins 3357 m.

This pass, which is located between the Mont Miné glacier, at the end of the Val d'Hérens to the north and the Tsa de Tsan glacier, above the Valpelline, to the south, is currently covered in ice and is difficult to access. There are no indications of its past or current use other than information from a high altitude mountaineering course. Of all the passes proposed by the LCPA model, along with the Schwarztor, these are currently the most inaccessible passes due to the presence of glaciers, crevasses, and rocky terrain.

Furggjoch 3246 m

This pass is partially covered by glaciers and is difficult to access. The Furgg glacier (Mattertal) overlooks the north. To the south is the Della Forca glacier (Valtournenche). From the north, a 60 m rock wall currently makes this a difficult route to cross. To the south, the path crosses steep slopes but no cliffs. There is no historical mention of its use, apart from high altitude mountaineering guides.

Theodulpass 3301 m

This pass connects the Oberer Theodul glacier to the north and the Valtournenche glacier to the south. It is mentioned regularly throughout the Middle Ages and Modern times as a frequently accessed pass between the Rhone valley and northern Italy (Eschmann, in press). Evidence of Roman and Celtic coins found on the pass prove that its use dates back to at least Roman times (Thüry 2012). A neolithic stone axe was also found near the pass (Pétrequin et al. 2012). A rock shelter, less than three hours away from the pass by foot, was occupied during the Mesolithic-Neolithic and Bronze age approximately 7,500 – 1,600 years BC (Curdy et al. 2003). It is also assumed that this pass was used during the colonization of the Rhone valley by the first Neolithic pastoralists (Curdy et al. 2003). Since the 1980's, the melting Oberer Theodul glacier has uncovered a number of objects dating back to the 17th century (Julen-Lehner and Lehner 2012; Providoli and Elsig in press).

Schwarztor 3731 m

This pass connects the Matteral valley (Zermatt) to the Val d'Ayas. It is the highest pass proposed by the LCPA, is currently covered in ice, and one of the most difficult to access. To the north it is situated above the Schwärze glacier (connected to the Gorner glacier). To the south, it joins the Val d'Ayas via the Verra glacier (Grande Giacchiaio di Verra). It is part of the high mountains paths that can only be visited by experienced mountaineers. According to some legends and oral traditions, it was used by Walser communities who had colonized the Val d'Ayas in the 13th century AD. It was said to directly link this valley to the Zermatt valley (Lüthy 1977, Zinsli 1968).

Bortellicke 2742 m

This secondary pass connects the Gantertal on the north to the Alpe Veglia to the south, in the direction of the Ossola valley. From the north this pass is relatively easy to access. On the contrary, the south is characterized by extremely steep slopes and generally inaccessible. The pass was covered in ice at the beginning of the 20th century. The presence of Roman coin has been mentioned in literature (ASSPA 1915).

Chriegalppass 2536 m

This pass lies between the Chriegalkptal (Binntal) to the north and the Val Devero to the south. It seems to have already been mentioned on a map from 1768 (Aerni and Herzig 2014). No archaeological discoveries have been proven at this site. Because of its location near the Albrunpass, it seems possible that this was the last pass which was busiest in the entire region.

Albrunpass 2409 m

This important pass connects the Binntal (north) to the Val Devero (south). The Binntal was occupied since prehistoric times and discoveries of burial sites from the Iron Age and Roman period indirectly reflect the frequentation of this pass. A series of archaeological finds from the Bronze Age and Roman coins were discovered on the pass and on the path which leads to it (Aerni and Herzig 2014; Di Maio 2007; Sauter 1955). On the flat areas to the north, under the pass, there are traces of prehistoric occupation, dated to the Mesolithic and Bronze Age (Curdy et al. 2010). Historical texts also mention the importance of this pass (Aerni and Herzig 2014).

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4.2.7 ADDITIONAL COMMENTARY

This paper allows the reader to see the direct effects of changing inputs into the LCP model. For example, when points are used as starting locations there is no flexibility for the path to find the best way across to the other side; it is forced to start from a certain location. On the other hand, if a line is used as the starting location, the LCP can travel further along the valley in either direction before selecting a place to cross to the other side, thus starting from a line gives a better indication about LCPs if a discrete starting point (i.e. a village) is unknown. There is still a benefit to starting from a point because it provides insight into how people might travel between two known locations.

The effects of changing input landcover parameters were also clearly evident. For example, as the weights of the categories of Rock and Glacier/perpetual snow were increased, fewer LCPs crossed between Switzerland and Italy in the middle of the study area. That is due to the fact that the highest mountains, thus the areas with the most rock, ice, and snow, are located in that region. Increasing the weights of those categories forced the paths to move to the east and west sides of the study area to avoid the rock, snow, and ice in the middle. Also, it was found that more time was generally required to move from the south to the north (from Italy to Switzerland). This can be attributed to the steeper climb when moving in the northern direction as compared to the southern direction which has a more gradual climb from the Swiss side to the border, and then the steep descent into Italy.

4.2.7.1 RIDGE PREFERENCE

The results of this paper highlight the problem of ridge preference within the LCP model. Upon investigation of the results of the LCPs in the previous paper, it became evident that some of the proposed high altitude passes are impossible to cross by foot. In some cases paths tend to follow ridge lines which would not necessarily be the case in reality as ridges are difficult to walk across by foot. The ridge preference in the model can be explained by the resolution of the DEM used in calculations. Most ridges are very narrow but in the LCP model they are calculated to be flat, 30 m wide sections due to the DEM resolution. This poses a problem as the resulting paths tend to be biased towards these areas which would not be the case in reality.

4.3 PAPER IV: COMBINING GLACIOLOGICAL AND ARCHAEOLOGICAL METHODS FOR GAUGING GLACIAL ARCHAEOLOGICAL POTENTIAL

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ABSTRACT

Recent climate changes have led to an increase in the exposure of archaeological remains in frozen environments due to the melting of glaciers and ice patches, and the thawing of permafrost. In some cases, the discovery of glacial archaeological findings has occurred due to chance. In order to avoid the risk of losing exceptional, often organic, cultural remains due to decomposition, systematic and predictive methods should be employed to locate areas of high glacial archaeological potential. Here, we merged archaeological and glaciological methods to create a new type of archaeological prediction model in the field of glacial archaeology. Locational analysis and glaciological modelling were used to highlight current and future areas of archaeological potential in the Pennine Alps, located between Switzerland and Italy. Future glacier area was calculated in 10 year increments until 2100. By 2090, 93% of glacier area is expected to have disappeared. The results from the final model, GlaciArch, provide new insights into future glacial archaeological prospection in the Pennine Alps by narrowing down a study region of 4,500 km² into several manageable square kilometer sites.

Key Words: glacial archaeology, glaciology, GIS, locational analysis, least cost path analysis, archaeological prediction

4.3.1 INTRODUCTION

Due to the alternation of various warm and cold periods, glacier extents and ice volume storage have fluctuated in the entire European Alps during the Holocene (10.5 ka to present). Compared to the Last Glacial Maximum (LGM) (19 to 20 ka BP) and latest Pleistocene, when large piedmont lobes of vast valley glaciers reached the Alpine foreland (Clark et al., 2009; Ivy-Ochs et al., 2008), glacier changes have been rather minor during the Holocene. The glacierized area varied between the stage of the Little Ice Age (LIA) maximum, around 1850, and a minimum which was significantly smaller than the present day extents (Grosjean et al., 2007; Holzhauser, 2007; Joerin et al., 2006, 2008).

Glacier-climate interactions have affected humans for millennia. In the European Alps, glacier fluctuations directly influenced human interaction with Alpine areas (Benedict and Olson, 1978; Wiegandt and Lugon, 2008). For example, as glaciers receded after the LGM, humans took advantage of the newly ice-free Alpine biome which offered plenty of food and resources during the Paleolithic period (Pacher, 2003; Tagliacozzo and Fiore, 2000). The present atmospheric warming has caused shrinkage of glaciers and ice caps all over the world (IPCC, 2013). In consequence, melting ice and snow has uncovered archaeological remains in Arctic and Alpine environments (Andrews et al., 2012; Beattie et al., 2000; Callanan, 2012, 2013; Dixon et al., 2005; Farbregd, 1972; Farnell et al., 2004; Hafner, 2012; Hare et al., 2004, 2012; Lee, 2012; Rogers et al., 2014; VanderHoek et al., 2007) which further attests to the use of frozen regions on a global scale. These artefacts which have melted out of ice patches and glaciers, and thawed out of permafrost, have created a new sub-discipline of archaeology: glacial archaeology. “Glacial archaeology” has also been referred to as ice patch archaeology (c.f. Andrews and MacKay, 2012; Reckin, 2013) and frozen archaeology (Molyneaux and Reay, 2010). Perhaps one of the most famous examples of a glacial archaeological find is that of Ötzi the Tyrolean Iceman who was accidentally discovered by hikers in 1991 on the Italian/Austrian border, protruding from an ice patch (Prinöth-Fornwagner and Niklaus, 1994; Seidler et al., 1992). The uniqueness of Ötzi and other glacial archaeological discoveries is that they have often been preserved by ice for thousands of years, thus protecting them and providing scientists with unparalleled information about past cultures and climates (Dixon et al., 2005; Reckin, 2013). There is urgency to collect these delicate, often organic, glacial archaeological remains before, or soon after, they melt out of the ice and become destroyed by decomposition (Andrews and MacKay, 2012; Dixon et al., 2005; Molyneaux and Reay, 2010). As melting in high altitudes and latitudes is not anticipated to halt in the near future (c.f. Radić et al., 2014), more glacial archaeological finds can be expected and there is a need to further develop predictive methods in this research domain.

In this paper, archaeological and glaciological methods are merged together to create a new type of predictive model to determine areas of glacial archaeological potential. The results will be

used as a decision support tool for future prospection of archaeological findings in high mountain environments. Our approach, referred to as “GlaciArch” in the following, is based on current ice thickness distribution, future evolution of glacierized areas, and topographic characteristics of the terrain which could have influenced past human accessibility. First, currently glacierized or recently deglaciated high altitude mountain passes located on the border of Switzerland and Italy are selected to be used as sites on which to perform the locational analysis. Next, least cost paths (LCPs) are calculated between valleys and respective passes. Then, locational analysis is used to determine areas of glacial archaeological potential based on the physical characteristics of the terrain. After, the future evolution of glaciers is modelled for the Pennine Alps using a glacier evolution model (Huss et al., 2010a). Finally, the results of glacier modelling are combined with the results of locational analysis to create GlaciArch, a predictive model which ultimately defines regions of highest archaeological interest for now and the future. This paper highlights how the intersection of glaciological and archaeological methods provides a new approach for looking at glacial archaeological prospection.

4.3.2 STUDY AREA AND DATA

4.3.2.1 STUDY AREA

The Pennine Alps (centered at approximately 45°57'N, 7°32'E) are located between the canton of Valais, Switzerland, and the provinces of Aosta and Piedmont, Italy (Fig. 1). The whole region is of particular glacial archaeological interest due to its large glacierized area and rich cultural heritage. The Pennine Alps cover approximately 4,500 km² and reach altitudes above 4,000 m a.s.l. The main valleys to the north, south, and east of the Pennine Alps, the Rhone valley (Switzerland), and the Aosta and Antigorio valleys (Italy) respectively, are scattered with archaeological remains dating from Mesolithic (9.5 ka to 5.5 ka BC) to historic times (Curdy, 2007; Radmilli, 1963). Although most travellers reached these valleys from lower altitudes, each valley could also be reached by crossing the Pennine Alps between them. This relatively short distance was often traversed for commercial purposes. Archaeological remains collected on the way to, and on top of, mountain passes between Switzerland and Italy demonstrate the use of these passes as trade and travel routes for thousands of years (Bezing and Curdy, 1994, 1995; Coolidge, 1912; Curdy, 2007; Curdy et al., 2003; Harriss, 1970, 1971; Lehner and Julen, 1991; Rogers et al., 2014). In fact, early Neolithic culture seems to have spread to Valais via the high altitude passes of the Pennine Alps from the south, possibly due to the grazing of small herds in the high pastures in summer (Curdy et al., 2003; Curdy, 2007). Throughout Prehistory and the Roman Period, there were indications of a strong cultural relationship between Aosta and the Rhone valley; later, the Aosta and Upper Rhone valleys were integrated as the unique ecclesiastical province of Tarentasia for several centuries (Harriss, 1970; Curdy 2010). The relatively few archaeological remains found at high altitudes in this region should not be

considered to be a direct result of the use of these high altitude passes. In the past, contrary to current beliefs, high altitude regions were used more often than assumed, and proved to be more hospitable than they seem to modern day people (Aldenderfer, 2006; Reckin, 2013; Walsh et al., 2006).

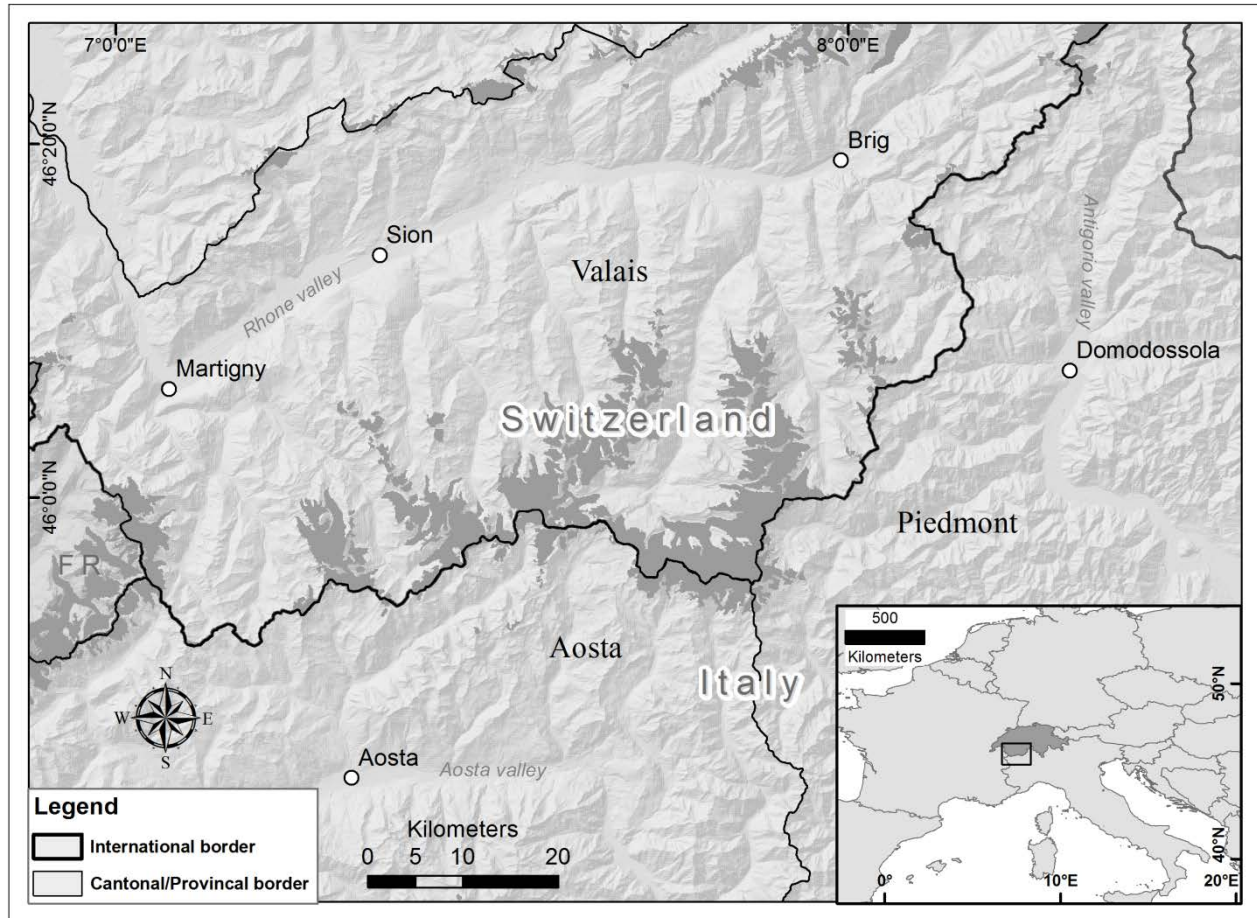


Figure 1. Overview of study area. Glacierized areas are shaded in dark grey.

4.3.2.2 DATA

The high altitude pass names and locations used in the first step of the locational analysis are derived from the 25 m resolution SwissNames database provided by the Swiss Federal Office of Topography (swisstopo) (Federal Office of Topography, 2014) which contains all names given on the 1:25,000 national topographic maps. The 1973 Swiss glacier inventory (Müller et al., 1976) was used to determine glacierized or recently deglaciated passes. The Digital Elevation Model (DEM) used in both the Least Cost Path Analysis (LCPA) and slope calculation was the global 30 m resolution Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) (version 2) (NASA, 2012). Although more accurate DEMs exist, it was not possible to obtain a consistent DEM for each side of the Pennine Alps. The

ASTER GDEM provides a consistent and sufficient data accuracy for these regional scale calculations in this study.

For the Swiss glaciers, the new Swiss Glacier Inventory SGI2010 (Fischer et al., in press) was used. This layer was created by manual digitization from high resolution (50 cm) aerial orthoimagery acquired between 2008 and 2011. For the Italian glaciers, outlines based on satellite imagery of 2003 were used (Paul et al., 2011). Surface topography for each glacier was extracted by intersecting glacier outlines with terrain elevation data. Glacier ice thickness distribution and bedrock topography were calculated based on a flux-gate approach and using the principles of ice flow dynamics (Huss and Farinotti, 2012). Information on surface mass balance of a large sample of glaciers in the Pennine Alps over the last decades is available from a combination of direct field observations, geodetic ice volume changes and distributed modelling (Huss, 2012). Scenarios for the future evolution of climatological variables are obtained from Regional Climate Models (RCM) from the CH2014 project (CH2014-Impacts, 2014).

4.3.3 BACKGROUND

In the Swiss Alps, glacial archaeological finds have been located at four locations: two sites on the border of the cantons of Valais and Bern in the Bernese Alps, the Lötschenpass (Bellwald, 1992; Meyer, 1992) and Schnidejoch pass (Hafner, 2012); one site in eastern Switzerland, the Porchabella glacier (Rageth, 1995); and in Valais, located in the Pennine Alps, near the Theodulpass (Lehner and Julen, 1991; Meyer, 1992). The oldest and most notable finds were discovered between 2004 and 2011 at the Schnidejoch pass from a melting ice patch which was formerly attached to the Chilchli glacier on the north side of the pass. The ages of the finds range from the Neolithic, Early Bronze Age, Iron Age, Roman, and Medieval periods making this one of the most prolific glacial archaeological sites in the Alps (Hafner, 2012). The abundance of finds can be attributed to the location of the ice patch which is in a small depression facing northeast where ice has accumulated over centuries. The Pennine Alps' most prolific glacial archaeological site to date has been that of the Theodulpass. The finds, which include skeletal remains, leather clothing and shoe soles, weapons, and coins from the "Mercenary of Theodul", date back to the 16th century (Lehner and Julen, 1991; Meyer, 1992). These items were found between 1985 and 1990 along the margins of the Oberer Theodul glacier on the Swiss side of the border. It is believed that the Mercenary fell into a crevasse and was preserved for hundreds of years until glacial dynamics and melting eventually released him and his belongings.

4.3.3.1 ARCHAEOLOGICAL PREDICTIVE MODELLING

In archaeology, the use of predictive modelling began in the 1980's and has since grown into a wide research field, mostly due to an increase in the accessibility to Geographic Information Systems (GIS) software and the ever-improving spatial resolution of data (c.f. Ebert, 2004; Kvamme, 1999; McCoy and Ladefoged, 2009). In most cases, archaeological predictive modelling

is used to forecast the location of archaeological sites based on the presence or absence of defined criteria, in order to allocate information about known patterns onto unknown places (Conolly and Lake, 2006; Warren and Asch, 2003; Wheatley and Gillings, 2002). Inputs to predictive models usually include sampled sites and have the main goal of finding new sites which were used for human occupation (Carleton et al., 2012; Carrer, 2013; Graves, 2011; Kohler and Parker, 1986). Put simplistically, predictive methods have been used to determine the level of archaeological potential in a region and provide decision-makers with a tool to justify why certain areas are more archaeologically interesting than others (McCoy and Ladefoged, 2009).

In glacial archaeology specifically, predictive methods have been used in relatively few instances but show promising results (Andrews et al., 2012; Dixon et al., 2005). For example, in Alaska, Dixon et al. (2005) were the first to use predictive modelling for glacial archaeological purposes by using a weighted combination of cultural, biological, and geological input layers to successfully determine areas of high glacial archaeological potential. Similarly, Andrews et al. (2012) used remotely sensed data and other weighted input layers to determine areas of glacial archaeological potential in northern Canada. Both previous studies were conducted at various ice patch sites. This study, which focuses on the potential of locating glacial archaeological remains on or near glaciers, differs from previous ones based on the distinctive environments. Ice characteristics and glacier dynamics can strongly affect the potential of locating glacial archaeological remains, and thus should be researched according to local conditions. For example, glaciers composed of thick ice or located on steep slopes move relatively quickly and would destroy anything entrained within it in a matter of a few hundred years based on the principles of ice dynamics (Benn and Evans, 2010; Dixon et al., 2005; Hafner, 2012). The margins of slower-moving glaciers could prove to be a better environment for finding glacial archaeological remains, with the ideal environment being surrounded by ice with little or no movement such as ice patches (like the Schnidejoch site) or slow-moving small glaciers located on relatively flat terrains (like the Theodul site).

The application of computerized predictive methodologies to archaeology began in the 1980's and has since grown into a wide research field, mostly due to an increase in the accessibility to Geographic Information Systems (GIS) software and the ever-improving spatial resolution of data (c.f. Ebert, 2004; Kvamme, 1999; McCoy and Ladefoged, 2009). In most cases, archaeological predictive modelling is used to forecast the location of archaeological sites based on the presence or absence of defined criteria, in order to allocate information about known patterns onto unknown places (Conolly and Lake, 2006; Warren and Asch, 2003; Wheatley and Gillings, 2002). Inputs to predictive models usually include sampled sites and have the main goal of finding new sites which were used for human occupation (Carleton et al., 2012; Carrer, 2013; Crema et al., 2010; Graves, 2011; Kohler and Parker, 1986). Put simplistically, predictive methodologies can be used to determine the level of archaeological potential in a region and provide decision-

makers with a tool to justify why certain areas are more archaeologically interesting than others (McCoy and Ladefoged, 2009). However, the terms “prediction” and “potential” are often used interchangeably, and sometimes incorrectly, leading to confusion (Carleton et al., 2012). This study deviates from usual prediction models because 1) there have been relatively few high altitude glacial archaeological remains found in the Pennine Alps to date. Thus the addition of those instances to the model would bias the results. 2) Humans did not occupy mountain passes for long periods of time, but used them as a means to travel from one location to another. Thus, in this situation it is important to consider where people were *able* to travel based on topographic characteristics and where archaeological remains *could* be located based on glacial characteristics.

4.3.3.2 LEAST COST PATH ANALYSIS

LCPA is one type of archaeological prediction method used in GIS to calculate the “optimal” path across a landscape based on one or more predefined input criteria (Anderson and Gillam, 2000; Bell and Lock, 2000; Egeland et al., 2010; Gorenflo and Gale, 1990; Howey, 2007; Madry and Rakos, 1996; Rogers et al., 2014; Verhagen and Jeneson, 2012). It allows archaeologists to gain a better understanding about movement patterns in prehistoric or historic terrains (Llobera et al., 2011; Murrieta-Flores, 2010, 2012; White and Surface-Evans, 2012). It is based on the principal that humans will take the easiest path from one location to another if there are no other social or cultural forces directing them otherwise. The concept is not unique to archaeology and was developed firstly in psychology and has since been used in various research fields (Zipf, 1949).

4.3.3.3 LOCATIONAL ANALYSIS

Locational analysis, also referred to as archaeological location modelling (ALM) or site predictive modelling, is a predictive method which calculates archaeological potential based on multiple weighted inputs, often including known archaeological site locations (Andrews et al., 2012; Carleton et al., 2012; Carrer, 2013; Dixon et al., 2005; Egeland et al., 2010). Like the term predictive modelling, locational analysis has various meanings and a definition which has developed over time (Kvamme, 1999; McCoy and Ladefoged, 2009). Therefore, we define locational analysis using McCoy and Ladefoged’s (2009) description whereby the potential of undiscovered sites will be determined by calculating zones of future prospection without spatially analysing known site locations. This method is often used in vast areas from which archaeological remains are sparse, possibly due to a lack of prospection.

4.3.3.4 GLACIER RETREAT MODELLING

The atmospheric warming observed during the last decades has caused a considerable reduction in area and mass of glaciers and ice caps all around the globe (Zemp et al., 2009). As an immediate response, changes in the climatic forcing acting on glaciers lead to changes in the

surface mass balance, that is, to changes in the quantity of snow and ice added to or melted from the glacier. The effects of the observed glacier changes are numerous and apply to a broad range of spatio-temporal scales, from global sea level rise (Gardner et al., 2013) to regional impacts on runoff in major river catchments (Kaser et al., 2010), to local consequences for landscape evolution, hydropower production, natural hazards and tourism (Cannone et al., 2008; Farinotti et al., 2012; Fischer et al., 2011). Consequently, the projection of future glacier evolution has gained increasing attention in glaciology.

In recent years, various glacier modelling approaches have been developed. For individual glaciers, they range from simple 2D flowline models (Oerlemans et al., 1998; Van de Wal and Wild, 2001) to complex 3D coupled mass-balance ice-flow models (Jouvet et al., 2011; Schneeberger et al., 2003). To calculate glacier response at the regional scale, simpler approaches neglecting transient changes and the effect of ice dynamics were used (Paul et al., 2007; Schaepli et al., 2005). More advanced models driven by distributed surface mass balance input and employing a parameterization of glacier ice flow have also been applied both at the single-glacier scale and to the entire European Alps (Huss, 2012; Huss et al., 2010a; Salzmann et al., 2012).

4.3.4 METHODS

GlaciArch is composed of various steps which culminate in the creation of a predictive model which gauges the glacial archaeological potential of the Pennine Alps. The respective steps are presented in the next sections.

4.3.4.1 HIGH ALTITUDE PASS SELECTION AND LCPs

The first step was to determine which high altitude passes on the Swiss/Italian border were glacierized in 1973. This coincides with the notion that recently deglaciated passes have a higher glacial archaeological potential and should be prospected first based on the fragility of glacial archaeological remains and artefacts. The 1973 glacier inventory (Müller et al. 1976) was chosen because it covers an ideal time frame as archaeological items exposed over the last 40 years might have a better chance to persist compared to 160 years if using the glacier inventory from orthoimagery prior to the SGI2010 (Fischer et al., in press). The passes were chosen using the selection tools in ArcGIS 10.1. First, the select by attributes tool was used to query all mountain passes which could be crossed by either foot or by road from the SwissNames database for the canton of Valais, resulting in the selection of 670 records. Next, the select by location tool was used to query those passes which were glacierized in 1973 from the currently selected records, to highlight the ones that were recently deglaciated, or still currently glacierized, leaving 111 passes. From those 111 passes, the ones on and near the border between Switzerland and Italy were selected as it is known that some of the high altitude passes in this

study region have been used for thousands of years. This resulted in the final extraction of 19 border passes which were glacierized in 1973 from which to calculate LCPs (Table 1, Fig. 2a).

LCPs were calculated using the method described by Rogers et al. (2014) from each of the 19 passes to their nearest respective main valleys (Rhône, Aosta, or Antigorio) (Fig. 2b). This method used Tobler's (1993) hiking algorithm to calculate walking times based on slope and prehistoric landcover as inputs (Bell and Lock, 2000; Gorenflo and Gale, 1990; Rogers et al., 2014; Tobler, 1993; Verhagen and Jeneson, 2012; Whitley and Hicks, 2003). The path distance and cost distance tools in ArcGIS, which calculate the accumulative cost across the terrain from a starting location and the shortest path from a destination back to starting location, respectively, were used for the calculations.

Table 1. Names and locations of high altitude passes on the border between Switzerland and Italy which were glacierized in 1973.

Number	Name	Latitude (N)	Longitude (E)	Altitude (m)
1	Petit Col Ferret	45° 53' 58"	7° 4' 9"	2490
2	Col d'Amiante	45° 55' 6"	7° 18' 9"	3319
3	Col de la Balme	45° 54' 7"	7° 22' 27"	3321
4	Col du Petit Mont Collon	45° 57' 42"	7° 29' 11"	3292
5	Col Collon	45° 57' 41"	7° 30' 51"	3087
6	Col des Bouquetins	45° 59' 13"	7° 33' 36"	3357
7	Col de la Tête Blanche	45° 59' 33"	7° 34' 53"	3579
8	Tiefmattenjoch	45° 58' 22"	7° 35' 13"	3543
9	Breuiljoch	45° 58' 18"	7° 40' 18"	3313
10	Theodulpass	45° 56' 38"	7° 42' 35"	3301
11	Passo di Ventina Nord	45° 56' 4"	7° 42' 39"	3450
12	Breithornpass (south)	46° 14' 36"	8° 5' 12"	3368
13	Zwillingsjoch	45° 55' 36"	7° 47' 24"	3845
14	Felikjoch	45° 55' 5"	7° 48' 11"	4066
15	Lisjoch	45° 55' 18"	7° 51' 12"	4169
16	Neues Weisstor	45° 59' 20"	7° 54' 4"	3509
17	Seewjinenlücke	45° 59' 53"	7° 57' 22"	3095
18	Tossenjoch	46° 7' 31"	8° 3' 22"	2923
19	Breithornpass (east)	45° 55' 56"	7° 44' 34"	3845

Table 2. Weight values for the layers used in the locational analysis.

Weights	Distance from LCPs (m)	Slope (°)	Ice thickness (m)
5	0-100	0-10	0-25
4	100-250	10-20	25-50
3	250-500	20-30	50-75
2	500-750	30-40	75-100
1	750-1000	>40	>100

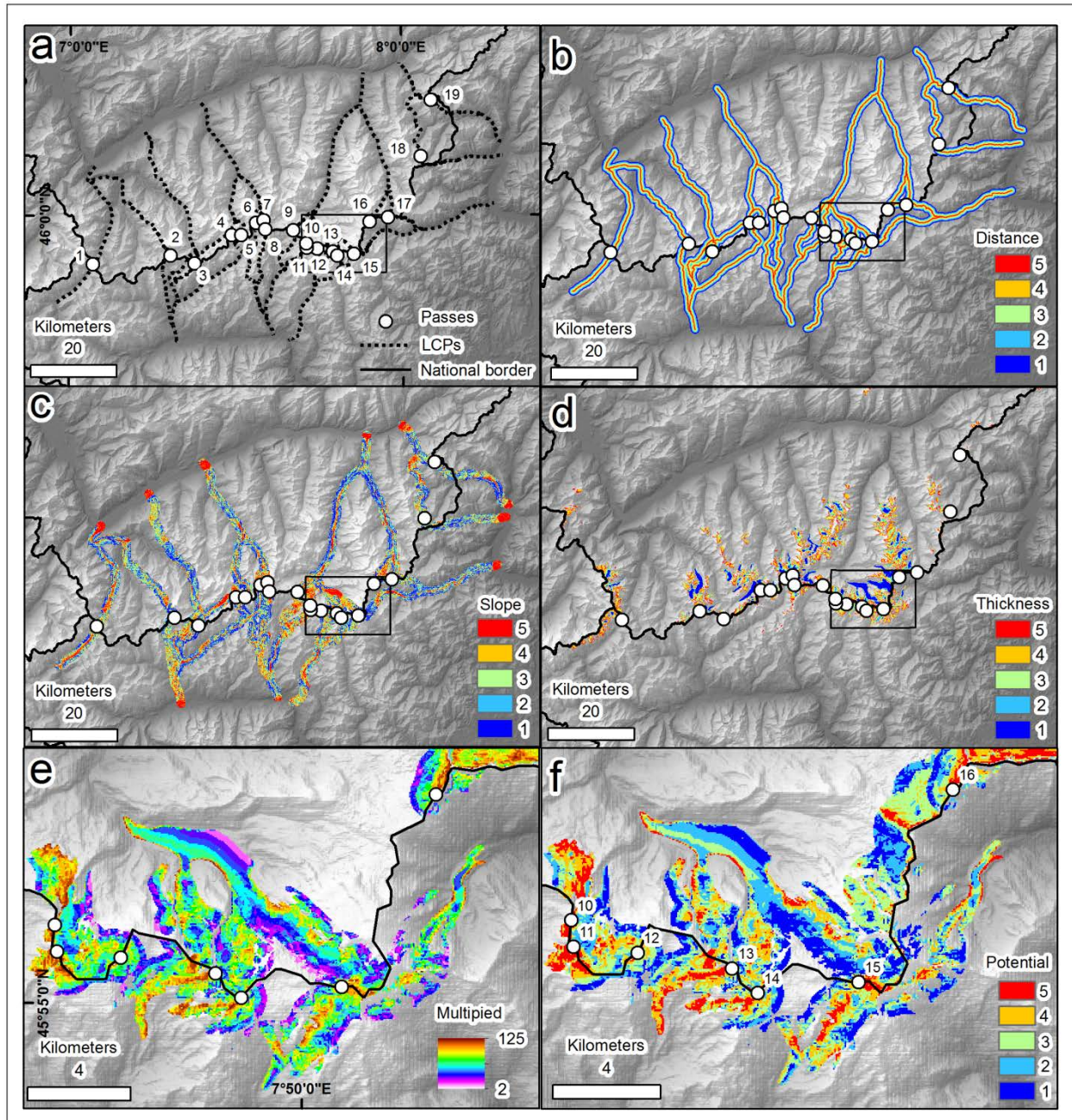


Figure 2. Visualization of the locational analysis processing steps: (a) calculation of least cost paths with pass number corresponding to Table 1, (b) calculation of buffers around each path, (c) weighted slope values derived from DEM, (d) weighted glacier thickness layer, (e) selected close-up of slope multiplied by thickness, and (f) the final weighted locational analysis layer with pass numbers (see Table 1).

4.3.4.2 LOCATIONAL ANALYSIS

In this part of the analysis, multiple criteria were used to locate areas of high archaeological potential by analyzing where people were able to travel based on the topographic characteristics of the terrain by measuring the distance from LCPs and the slope of the terrain, and where

archaeological remains might be located based on glacial characteristics and ice thickness. The input layers are described in the following paragraphs.

Buffers were constructed around each path in 100, 250, 500, 750, and 1000 m intervals on each side of the path to represent the notion that archaeological potential decreases with distance from the paths. The zones within the 100 m buffers were assumed to have the highest archaeological potential and weighted with the value of 5, while the zones located within the 1 km buffer were assumed to have the lowest potential and weighted with the value of 1 (Table 2). The values in between are listed in Table 2.

The 1000 m buffers calculated above were used to define the study area surrounding the paths from which to calculate slope values. The extract by mask tool was used to isolate the study area for the DEM and the slope tool was used to calculate the steepness of the terrain (Fig. 2c). The slope values were calculated and weighted based on the potential of finding archaeological remains. Slopes greater than 40 degrees were given a value of 1, thus very low archaeological potential, as they are difficult to climb and would probably have been avoided. Furthermore, at steep slopes archaeological remains are more likely to be washed out by erosion. Slopes between 0 and 10 degrees were determined to be the easiest to walk across and thus were given the highest potential value of 5. Slopes between 10 and 40 degrees were assigned with a respective linearly increasing potential value for 10 degree classes (Table 2).

Next, the glacier ice thickness layer was weighted from low to high archaeological potential. The ice thickness range between 0 and 25 m was assigned a weight of 5 as those are the areas with the highest potential now and in future years because they will likely be the first to become ice-free (Table 2). Even more importantly, archaeological remains are only likely to be preserved below relatively thin ice. Thicker ice tends to flow faster and is generally more destructive in terms of bedrock erosion. The classes with 25 to 50 m, 50 to 75 m, and 75–100 m were weighted with 4, 3, and 2, respectively (Fig. 2d).

The weighted layers for distance from LCPs, slope, and thickness were multiplied together to obtain one layer containing all possible value combinations. The results ranged from 2 to 125 in 29 different classes (Fig. 2e). As a final step in the locational analysis, these classes were combined into five final potential categories using the Natural Breaks classification scheme which arranges classes into “natural” objectively selected categories (Fig. 2f) (Jenks and Caspall, 1971).

4.3.4.3 GLACIOLOGICAL MODELLING

Future changes in glacier coverage over the entire Pennine Alps were assessed by a combination of different glaciological models at high spatial resolution. First, the current glacier ice thickness distribution was derived using the glacier outlines from Fischer et al. (in press) for Switzerland

and from Paul et al. (2011) for Italy based on the approach by Huss and Farinotti (2012). Next, surface mass balance and 3D glacier geometry change were modelled transiently for 50 Swiss glaciers from 2010 to 2100 based on a detailed glacier model (Huss et al., 2010a). The model runs at daily resolution on a 25 m grid and takes into account snow accumulation distribution, the influence of radiation on ice melting, and calculated glacier retreat based on a mass-conservation approach. Model calibration and validation for the 50 investigated glaciers was achieved with a variety of field data covering the entire 20th century (Huss et al., 2010b). For calculating future glacier change, we chose to use one single regional climate scenario for simplicity although the projected evolution of meteorological variables is subject considerable uncertainties. Seasonal changes in air temperature and precipitation as projected by the Eidgenössische Technische Hochschule Zürich (ETHZ, Swiss Federal Institute of Technology) RCM were used as inputs into the model. This climate model was driven by the A1B CO₂-emission scenario (Nakicenovic, 2000). Until 2100, a mean annual air temperature rise of +4.7°C relative to 1980-2009 is expected for the study region and precipitation is found to increase in winter but to decrease in summer (CH2014-impacts, 2014). Finally, we extrapolated annual mass balance from the 50 glaciers to every glacier in the Pennine Alps (Huss, 2012). Thus, for each glacier, a glacier-specific transient annual series of the glacier mass budget was obtained which was used to drive the glacier retreat model (Huss et al., 2010a). From the transient model runs, we extracted glacier ice coverage for 10-year time steps between 2020 and 2100. These glacier masks were overlaid onto the results of the locational analysis.

4.3.4.4 GLACIARCH

In this step, past (1850 and 1973), current (2010), and selected future (2030, 2060, and 2090) glacier extents were overlaid onto locational analysis results to create the GlaciArch predictive model. The current archaeological potential of a region was assessed differently than that of the future potential. Current archaeological potential is considered to exist in the regions that have been deglaciated since 1973; that is, between the 1973 and 2010 extents. Those are the general areas where archaeological remains could be currently located based on the principles of glacier dynamics. Future archaeological potential is ultimately gauged by comparing the modelled glacier extents for 2030, 2060, and 2090, to the results obtained by the locational analysis.

4.3.5 RESULTS AND DISCUSSION

4.3.5.1 LOCATIONAL ANALYSIS

The locational analysis results defined regions which were glacierized, or recently deglaciated, located near LCPs, in areas with less than 40° slope, and where ice thickness is at a minimum. The consideration of currently glacierized or recently deglaciated passes is important when dealing with glacial archaeological remains, as previously suggested. The calculation of LCPs enabled a better understanding about how people might have travelled from one location to

another based on the principles of walking across different landscapes. Although prehistoric and historic landscapes are often uncertain, paleoecological research gives a good general understanding about past landscapes (Berthel et al., 2012; Tinner and Theurillat, 2003; Wick and Tinner, 1997). The final product of the locational analysis displays the overlapping areas of the weighted distance from LCPs, slope, and ice thickness layers in the range of 5 (high potential) to 1 (low potential) for the region (Fig. 3a). The results of locational analysis alone reduced a region of over 4,500 km² to a 114 km² area of interest, 8.16 km² of which is considered as high potential (Table 3). Similar to the work conducted by Dixon et al. (2005) and Andrews et al. (2012), locational analysis provided a means to define small, manageable regions for glacial archaeological prospection. The areas are more finely delimited in the final GlaciArch model (section 4.3.5.3).

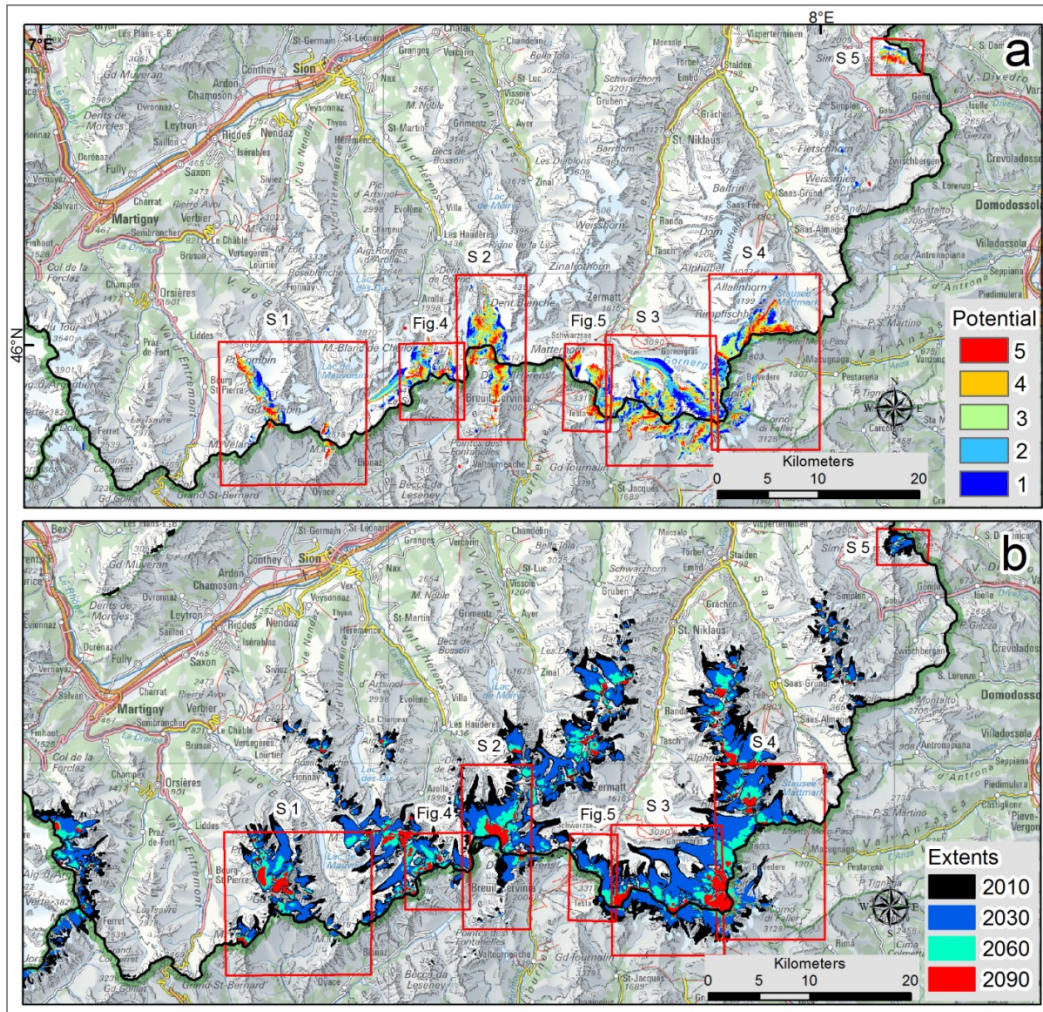


Figure 3. Results from (a) locational analysis and (b) glaciological modelling from the whole study area. The Swiss Glacier Inventory for 2010 is shown along with the modelled glacier extents for 2010 on the Italian side of the border. The projected glacier extents for 2030, 2060, and 2090 are shown for both sides of the border of the Pennine Alps. The boundaries for Fig. 1 and Fig. 2 are shown in red. Boundaries S1 – S5 refer to additional maps not discussed in the text which can be found in the supplementary data section (4.3.9).

4.3.5.2 GLACIOLOGICAL MODELLING

Future glacier extents for 10-year increments between 2020-2100 in Switzerland and in Italy were calculated (shown for 2030, 2060, and 2090 in Fig. 3b). This regional scale modelling method provided a high resolution projection of future glacier extents. The total area of glaciers in 2010 in the Pennine Alps was 446 km² and calculated to decrease in future years. For example, a reduction of 37% to 280 km² in 2030, 80% to 91 km² in 2060, and 93% to 30 km² in 2090 was modelled based on the climate scenario used. In this study we did not assess the impact of different assumptions on future climate evolution and other glaciological model uncertainties on the results. However, Addor et al. (in press) showed that the CO₂-emission storyline until 2100 only had a small effect on calculated total glacier area.

4.3.5.3 GLACIARCH

The results of the GlaciArch model show current and future areas of archaeological potential spread over the Pennine Alps region (see supplementary maps covering the entire region). As mentioned in section 4.3.5.2, the locational analysis results provided a broadly defined research area. The addition of glaciological modelling results allows the delineations to be further defined. For example, between 2010 and 2030, the total area of interest is 30.1 km² and the high potential region is 3.24 km², compared to the decreased areas between 2060 and 2090 with 13.7 km² and 0.58 km², for area of interest and high potential, respectively (see Table 3 for all values).

Table 3. Locational analysis areas calculated for 2010 and the time periods between 2010-2030, 2030-2060, and 2060-2090. The high glacial archaeological potential (value 5) areas are also calculated for each time period.

Year(s)	Total area (km²)	High potential (km²)
2010	114	8.16
2010 – 2030	30.1	3.24
2030 – 2060	40.5	2.31
2060 – 2090	13.7	0.58

Taking a closer look at the results, the area surrounding the Mont Collon (Fig. 4) is an area of interest due to its archaeological significance in the surrounding regions, although no glacial archaeological finds have been retrieved from that site to date (Fig. 4). In 1948, a Neolithic tool made of flint was located on the Plans de Bertol, which is located on the way to the Col Collon, which leads archaeologists to believe that it was a pass which was used by humans for thousands of years (Bezingue and Curdy, 1994, 1995; Sauter, 1950) (Fig. 4). Currently, the model indicates that there is high glacial archaeological potential on the margins of the Haut Glacier d'Arolla and the Glacier du Mont Collon, as well as the area between the Petit Mont Collon and the northern section of the Glacier d'Otemma, just south of the Col de Charmontagne (Fig. 4). For the future, the results from GlaciArch show that between 2010 and 2030, there will be high potential areas on the margins of the tongue of the Glacier du Mont Collon, as well as the Haut Glacier d'Arolla. Between 2030 and 2060, the Col Collon (5) is expected to become an area of

high archaeological potential as well as some regions surrounding the Petit Mont Collon. Sections in the middle of the Glacier du Mont Collon and to the north of the southern section of the Glacier d'Otemma also show high potential. According to the results, it appears that by 2060, the Haut Glacier d'Arolla will have almost completely disappeared. By 2090, very little ice will remain, however, the section to the north of the Col du Petit Mont Collon (4) could be of interest at that time.

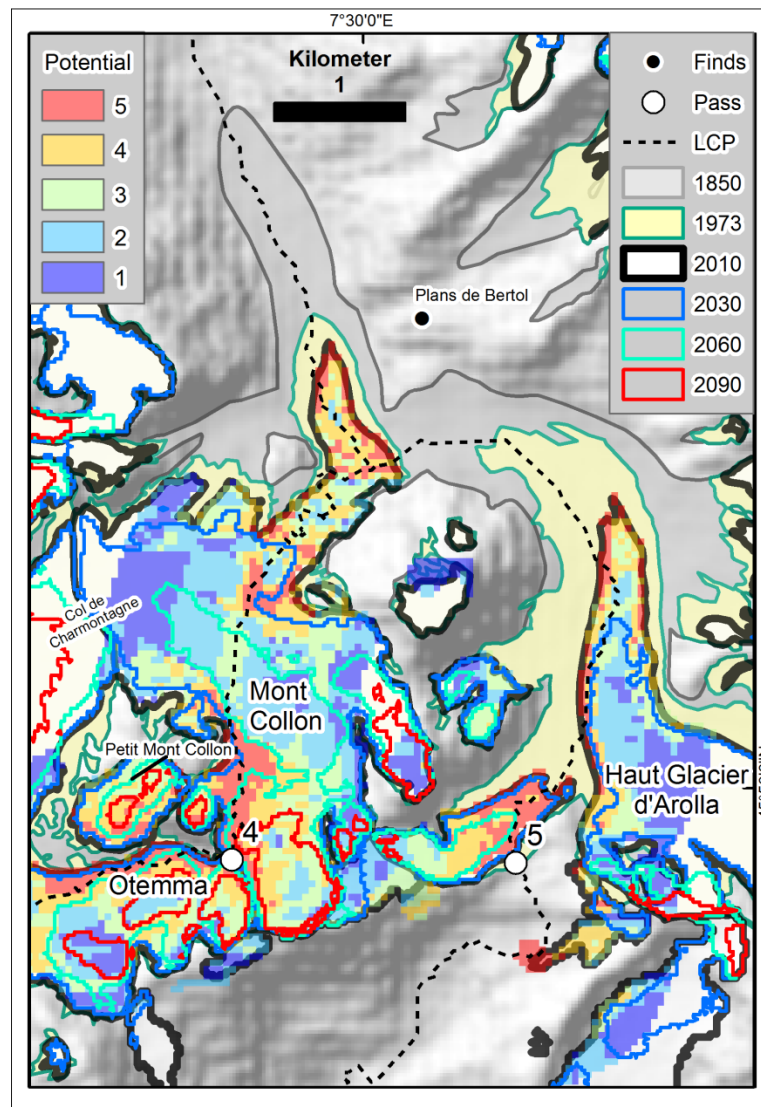


Figure 4. GlaciArch results around the Mont Collon which includes the Col de Petit Mont Collon (4) and the Col Collon (5). The Glacier du Mont Collon, Glacier d'Otemma, and Haut glacier d'Arolla are labelled as well as locations mentioned in the text: Petit Mont Collon, Col de Charmontagne, and Plans de Bertol. LCP refers to least cost path.

Already briefly discussed in section 4.3.3, the area surrounding the Theodulpass will now be revisited. The high altitude passes of interest near the Theodulpass resulting from this analysis are the Breuiljoch (9), Theodulpass (10), Passo di Ventina Nord (11), and the Breithornpass (12) (Fig. 5). From 2010 to 2030 there are regions of high archaeological potential on the extents of the

Furgg, Oberer Theodul, and Valtournanche glaciers, as well as on the Theodulpass and Passo de Ventina Nord. Between 2030 and 2060, the east side of the Oberer Theodul glacier becomes a predominant area of interest, while the Furgg glacier has decreased archaeological potential. The area south of the Passo de Ventina also shows high potential during that time period. From 2060 to 2090 The Furgg and Oberer Theodul glaciers are predicted to almost completely disappear therefore their glacial archaeological potential decreases significantly.

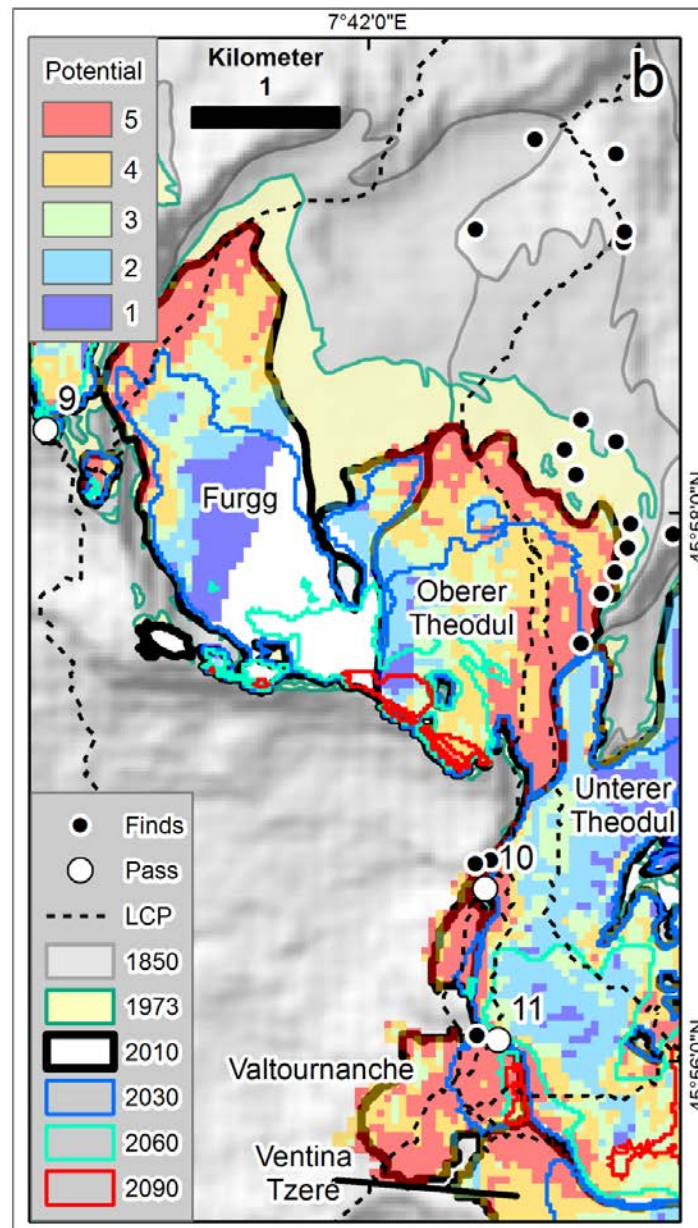


Figure 5. GlaciArch results around the Theodulhorn. Passes listed are the Breuiljoch (9), Theodulpass (10), and the Passo di Ventina Nord (11). The Furgg glacier, and Oberer and Unterer Theodul glaciers are labelled. LCP refers to least cost path.

The performance of this model has yet to be tested in the field, however the results seem to correspond well to glaciological principles and the few glacial archaeological finds already located in the region, for example at the Oberer Theodul site (Fig. 4 and 5). In theory, high archaeological potential is expected near the glacier margins as those are the areas with the thinnest ice, while areas of low potential should occur mid-glacier where the ice is thickest. An example of this can be seen in Figure 4 at the Haut Glacier d'Arolla; high potential exists on the extents of the glacier tongue and potential decreases as inward movement onto the glacier continues. One problem with this model is that it is difficult to convey inherently dynamic movement on a static map. In fact, potential maps should be calculated for each year to obtain a greater understanding about the true and temporally varying archaeological potential of the region, however 2D mapping constraints do not permit dynamic visualisation of this type of results. An interactive interface would be the best way to visualize the end results.

4.3.6 CONCLUSION

In this paper, the new integrated model GlaciArch was used to identify areas of current and future archaeological interest and potential in the Pennine Alps. The model highlights areas which correspond to the retrieval of archaeological remains based on glaciological principles and the topographic properties of the terrain. Thus, the GlaciArch results can be used as a decision support tool for the selection of glacial archaeological prospection sites. The definition of small regions of high glacial archaeological potential means less time, effort, and money spent in the field or on flight reconnaissance missions. By combining archaeological and glaciological methods for the first time, a new perspective has been given to the field of glacial archaeology. The integration of locational analysis and regional scale glacier modelling proved to be beneficial for narrowing down a large, often inaccessible, and remote study region to identify zones of archaeological interest based on glaciological characteristics and human accessibility. The glacier modelling results forecast a 93% loss in area by 2090. With these alarming melting rates, immediate focus should be given to high archaeological potential areas in hopes to locate and recover possibly irreplaceable, culturally significant items. In order to protect and conserve these exceptional and rare relics, further multidisciplinary predictive methods should be developed and employed in sensitive areas such as the Pennine Alps.

4.3.7 ACKNOWLEDGEMENTS

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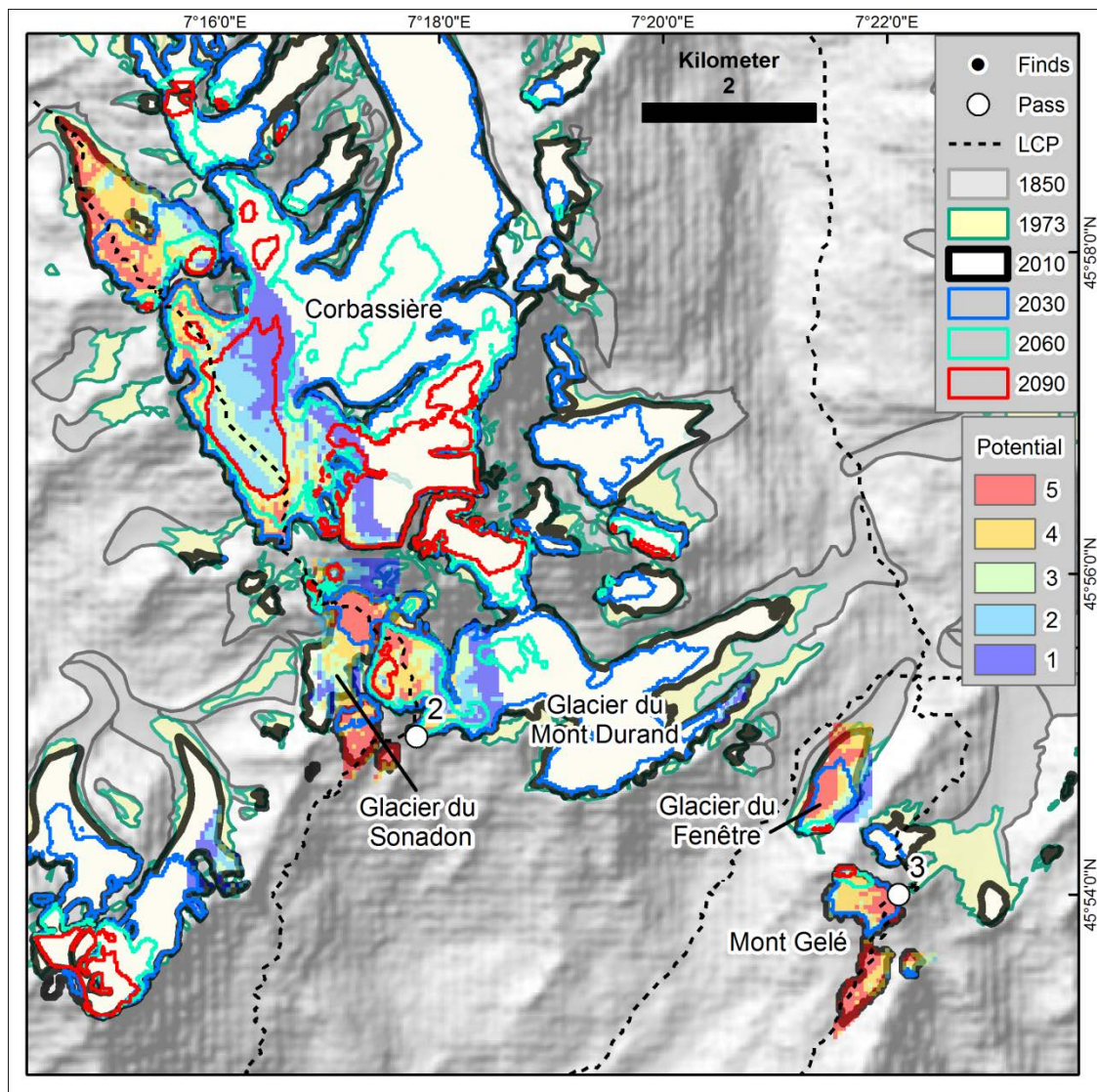
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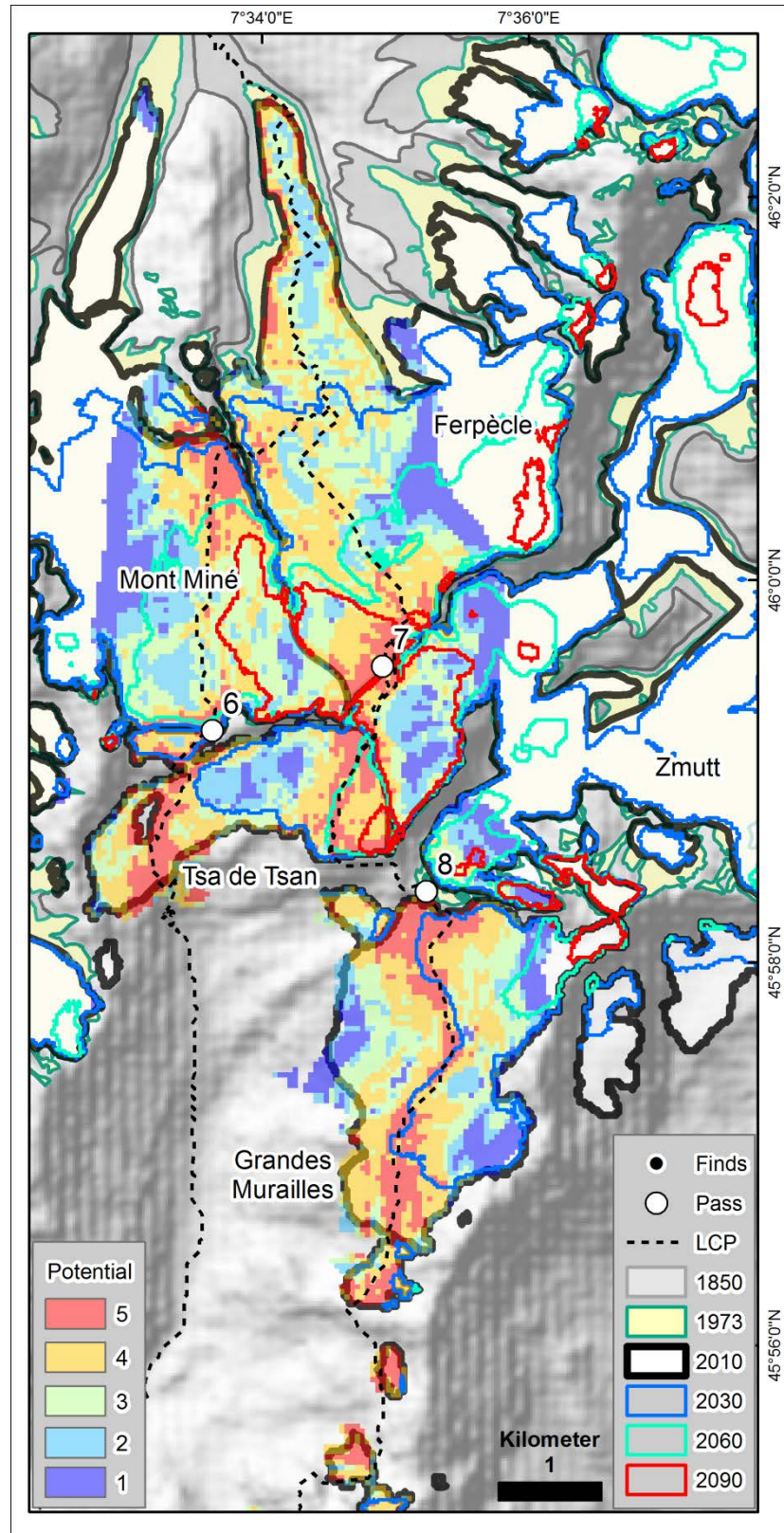
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4.3.9 SUPPLEMENTARY FIGURES

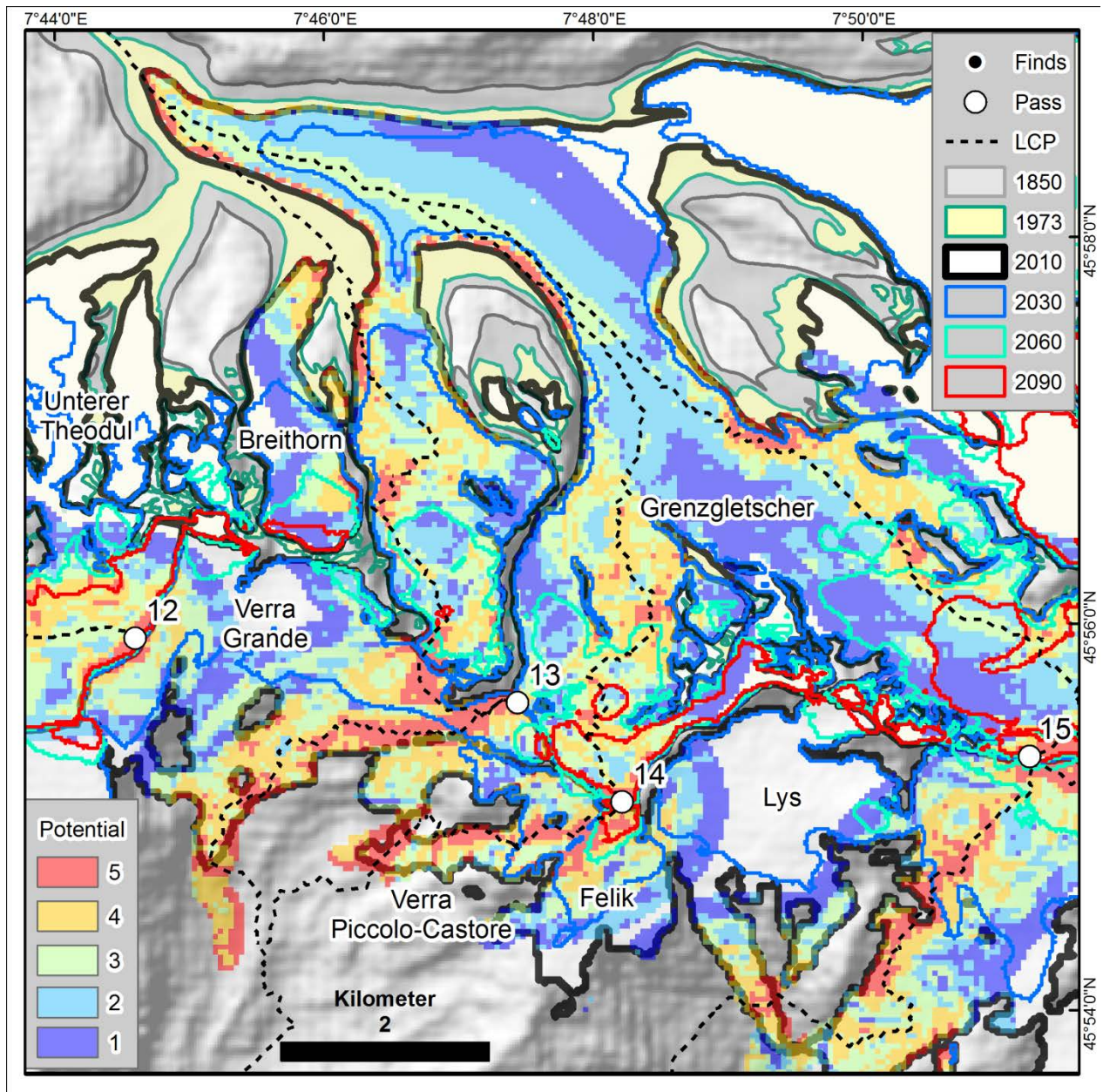
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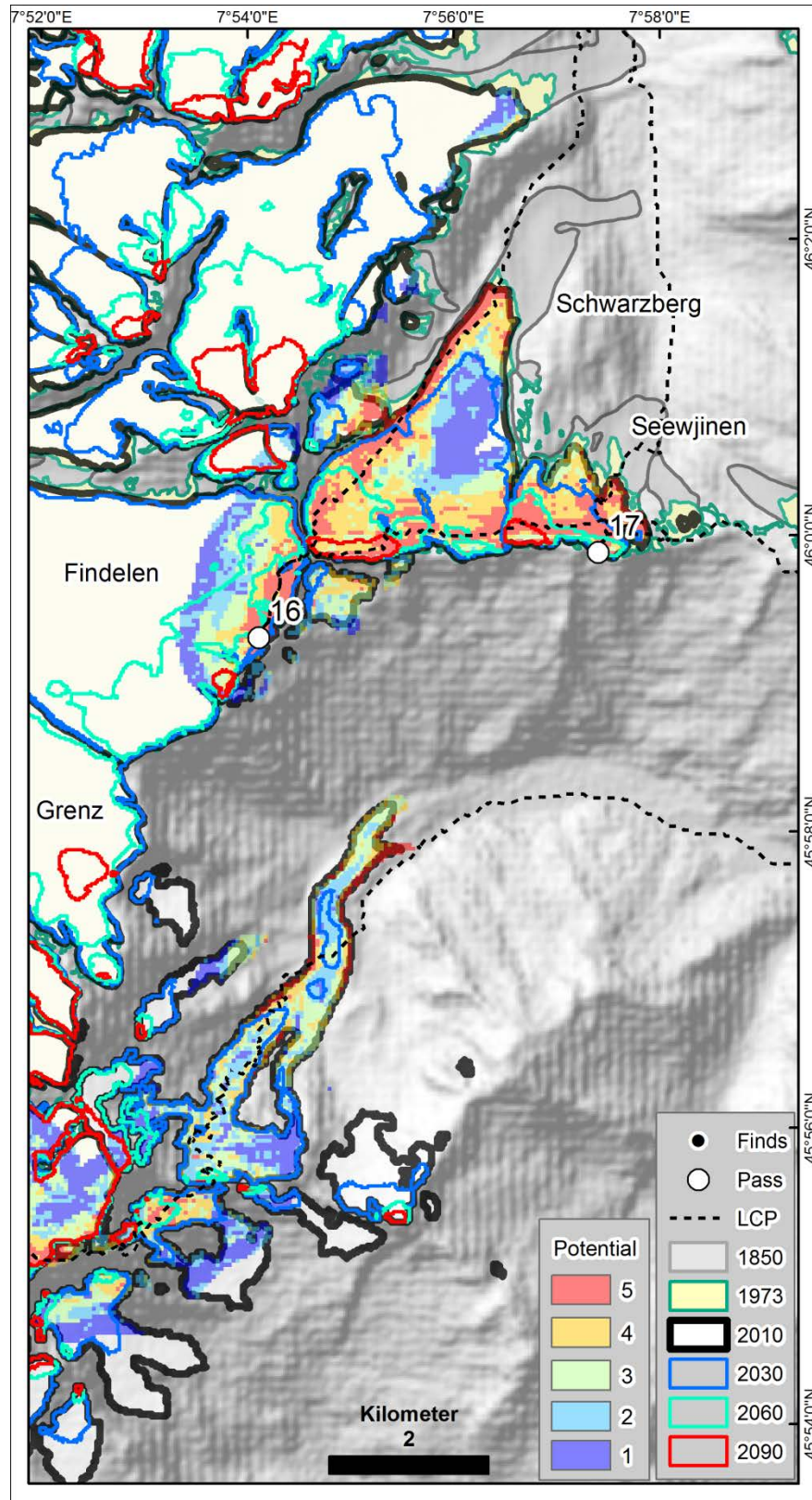
S1: GlaciArch results for the S1 region depicted on Figure 3. The included passes are the Col d'Amiante (2) and Col de la Balme (3). LCP refers to least cost path.



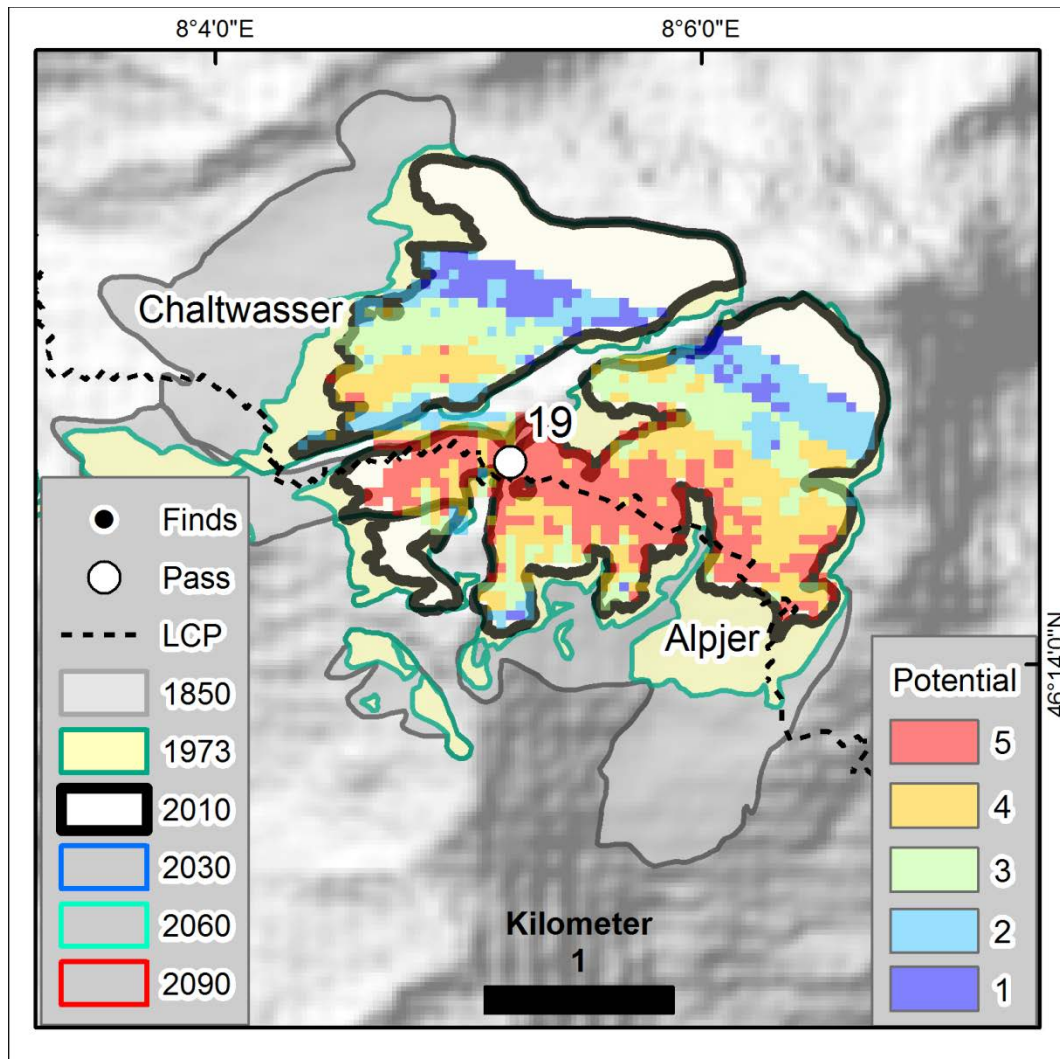
S2: GlaciArch results for the region depicted on Figure 3. The included passes are the Col des Bouquetins (6), Col de la Tête Blanche (7), and Tiefmattenjoch (8). LCP refers to least cost path.



S3: GlaciArch results for the region depicted on Figure 3. The included passes are the Breithornpass -south (12), Zwillingssjoch (13), Felikjoch (14), and Lisjoch (15). LCP refers to least cost path.



S4: GlaciArch results for the region depicted on Figure 3. The included passes are the Neues Weisstor (16) and the Seewjinenlücke (17). LCP refers to least cost path.



S5: GlaciArch results for the region depicted on Figure 3. The included pass is the Breithornpass – east (19). LCP refers to least cost path.

4.3.10 ADDITIONAL COMMENTARY

The following sections highlight additional discussion topics which require further explanation than what was given in the paper.

4.3.10.1 MULTIPLICATION OF INPUT LAYERS IN LOCATIONAL ANALYSIS

Frequently, when archaeologists perform locational analysis in GIS, criteria are added together using a weighted overlay to find the highest potential areas based on the combined high potential inputs of the criteria (see section 3.1.5 for more information about weighted overlay). In this case, a weighted overlay using addition was insufficient as it resulted in far too many “high potential” areas, which in turn, led to no results. Because the goal was to define manageable areas for the purpose of archaeological investigations and prospection in the field, multiplication of input layers was used instead. The results from multiplication led to better

defined classes of potential categories and thus smaller regions for archaeologists to visit for prospection. The problem encountered when multiplying the layers together was the difficulty in visualization of the results. To better facilitate the final visualization, the classes were then classified using the Natural Breaks classification scheme (Jenks and Caspall, 1971) which created categories based on natural break points in the data (Fig. 4.2). In this method, groups are created based on their similar values and the maximum differences between classes (Esri, 2014) which allow messages to be conveyed in regard to the visualization of results.

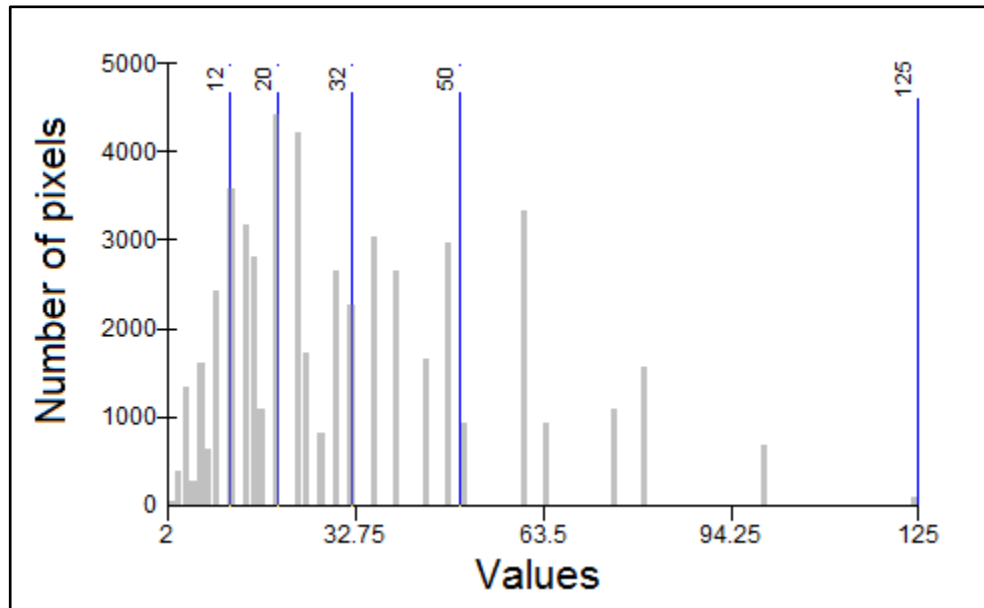


Figure 4.2 Break values of Natural Breaks classification scheme for visualization of locational analysis results.

4.3.10.2 ADDITIONAL TEST ALTERING SLOPE CLASSIFICATION

In an attempt to negate the issues which arose from the LCP calculations due to a low resolution DEM (i.e. horizontal movement across slopes and ridge preference), a small test was conducted to test the effects of changing slope values in the model. First, I attempted to change the values of Tobler's hiking function table (which is used as an input in the Path Distance tool in ArcGIS) to make slopes above 40 degrees impossible to cross by assigning very high values and then I also tried to use negative values to convert those areas to "no data". The results of both of those tests did not alter the directions of the LCPs; they only increased the travel costs for the resulting paths. Thus, the costs were extremely high in the instance where I assigned high values. For the second part of the test, I created a new cost surface landcover raster of which slopes above 40 degrees were given very high values so they would be avoided. The resulting LCPs differed (avoiding the steepest areas) which led me to make the following conclusions about the LCP model in ArcGIS: the direction of the path is only affected by the input cost raster while the calculated cost is affected by both the cost raster and the anisotropic algorithm used in

the calculation. In the future, the cost raster should be calculated based on both slope and landcover inputs if those are assumed to both alter the trajectory of the LCP.

5 GENERAL DISCUSSION

5.1 SUMMARY OF RESULTS

Here, the overall results of this thesis are summarized and presented in respect to the main objectives defined in the introduction (section 1.2). In brief, the first objective was to identify areas of glacial archaeological interest in the Pennine Alps by analyzing where people could travel using LCPA, and determining places across the landscape where glacial archaeological remains had the highest chance of being preserved based on terrain characteristics using locational analysis. The second objective was to determine the level of importance of each identified area with respect to its potential for containing glacial archaeological artefacts or remains based on current and future glacier extents using glaciological modelling. Results were categorized based on the current and future glacial archaeological significance of each pass as determined using glacier inventories from 1850 (Maisch, 2000), 1973 (Paul et al., 2002) and 2010 (Fischer et al., in press); classification criteria are described in Table 5.1. For this, all high altitude passes of archaeological interest identified in Paper II, III, or IV were categorized into one of three groups based on unique glacial archaeological potential at each location. It was assumed that objects have a higher chance to be located if the pass is currently glacierized or recently deglaciated due to the unique preservation characteristics of ice and the rapid decomposition of objects or remains once they have melted out of the ice (Table 5.2, Fig. 5.1) (Dixon et al., 2005; Hafner 2012).

Table 5.1. Categorization description and criteria.

Group	Description	Criteria
A	No current or future glacial archaeological potential.	Pass not glacierized in 1850, 1973, or 2010
B	Pass recently deglaciated; current and future glacial archaeological potential.	Pass glacierized in 1850, 1973, but not 2010.
C	Pass currently glacierized; no current glacial archaeological interest, but potential future interest.	Pass glacierized in 1850, 1973, and 2010.

5.1.1 GROUP A

Passes within this group have been deglaciated for at least 150 years (except for the Petit Col Ferret which had ice a few meters wide on top of the pass in 1850). Although these passes are no longer of glacial archaeological interest, they still could be of archaeological significance. For example, the Grand Saint-Bernard pass is a well-known corridor for historical trade and commerce dating back to at least the Roman Period (Benedetti and Curdy, 2008; Vesan, 2008). Additionally, the Col de Cleuson, which was identified as a site of interest in Paper II, contained

a piece of wood dated to the Bronze Age. Before that, there were no historical or archaeological information about this pass. Other passes in this group, including the Grand Col Ferret, Col du Fourchon, Col Ouest du Barasson, Fenêtre de Durand, Col des Bouquetins, Furggjoch, Bortellicke, Chriegalppass, and Albrunpass, were discussed in more detail in Paper III (section 4.2). Many may still be interesting from an archaeological perspective, but perhaps no longer from a glacial archaeological one due to the fact that there has been no ice to protect the artefacts for over 150 years.

5.1.3 GROUP B

Passes in Group B are ones that have been recently (since 1973) deglaciated. These passes have the highest current archaeological potential out of all listed passes. The Col Collon is a site familiar to archaeologists and is assumed to have been used as a crossing point for thousands of years (section 4.3.5.3). Archaeological artefacts have been located on the way to the pass, but to date, nothing has been discovered on top of the pass (Bezing and Curdy, 1994, 1995; Sauter, 1950). The Col Collon, along with the other passes in this category, the Col de la Balme, Tiefmattenjoch, Seewjinenlücke, and Tossenjoch could have the highest potential based on this classification scheme.

5.1.2 GROUP C

The passes within Group C are those which were glacierized in 1850, 1973, and 2010. Two of these passes, the Felikjoch and Lisjoch, are above 4,000 m in elevation and were likely avoided by foot travellers due to their high elevation. It is therefore assumed that they have no archaeological potential. Other passes in that region, the Zwillingsjoch, Breithornpass (south), Schwarztor, and Neues Weisstor, are also well above 3,500 m and thus were not ideal to cross. The Col des Bouquetins, which is discussed in Paper III, also seems like an unlikely candidate for glacial archaeological potential due to its thick ice cover and rugged terrain (section 4.2). Passes at lower altitudes (e.g. between 3,000 and 3,500 m), were probably more attractive for foot travellers. For example, historical and archaeological evidence attest to the use of the Theodulpass (section 4.2.5 and 4.3.5.3), for centuries.

5 General Discussion

Table 5.2. Categorization of identified passes. The number corresponds to the number on the map (Fig. 5.1), the name is the name of the pass. The x and y coordinates are in the Swiss projected coordinate system (CH1903 LV03), altitude is in meters, the paper number corresponds to the paper that the pass was mentioned in. The 1850, 1973, and 2010 columns identify if the pass was glacierized (y) or not (n) in that year.

	Group A		Group B		Group C
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Number	Name	x	y	Altitude	Paper #	1850	1973	2010
1	Petit Col Ferret	571255	83046	2490	IV	y	n	n
2	Grand Col Ferret	571992	81990	2537	III, IV	n	n	n
3	Col du Fourchon	575926	79356	2696	III	n	n	n
4	Col du Grand Saint-Bernard	579226	79733	2469	III	n	n	n
5	Col Ouest de Barasson	580181	78770	2635	III	n	n	n
6	Col d'Amiante	589373	85080	3280	IV	y	y	y
7	Col de Cleuson	592695	101240	3024	II	n	n	n
8	Fenêtre de Durand	593617	84289	2805	IV	n	n	n
9	Col de la Balme	594934	83258	3321	IV	y	y	n
10	Col du Petit Mont Collon	603646	89897	3292	IV	y	y	y
11	Col Collon	605801	89874	3087	IV	y	y	n
12	Col des Bouquetins	609351	92696	3357	III, IV	y	y	y
13	Col de la Tête Blanche	610999	93321	3579	IV	y	y	y
14	Tiefmattenjoch	611422	91140	3543	IV	y	y	n
15	Breuiljoch	617990	91037	3313	IV	y	y	y
16	Furggjoch	618212	90766	3246	II	n	n	n
17	Theodulpass	620964	87933	3301	III, IV	y	y	y
18	Passo di Ventina Nord	621049	86909	3450	IV	y	y	y
19	Breithornpass	623534	86675	3845	III	y	y	y
20	Schwarztor	626286	86543	3750	III	y	y	y
21	Zwillingsjoch	627202	86059	3845	IV	y	y	y
22	Felikjoch	628206	85108	4066	III	y	y	y
23	Lisjoch	632113	85542	4169	IV	y	y	y
24	Neues Weisstor	635769	93005	3509	IV	y	y	y
25	Seewjinenlücke	640014	94069	3095	IV	y	y	n
26	Tossenjoch	647652	108246	2923	IV	y	y	n
27	Breithornpass	649901	121371	3363	III	y	y	y
28	Forca d'Aurona	651126	125114	2686	II, III, IV	n	n	n
29	Bortellicke	652409	126505	2742	III	n	n	n
30	Chriegalppass	659338	128809	2536	III	n	n	n
31	Albrunpass	665943	135899	2409	III	n	n	n

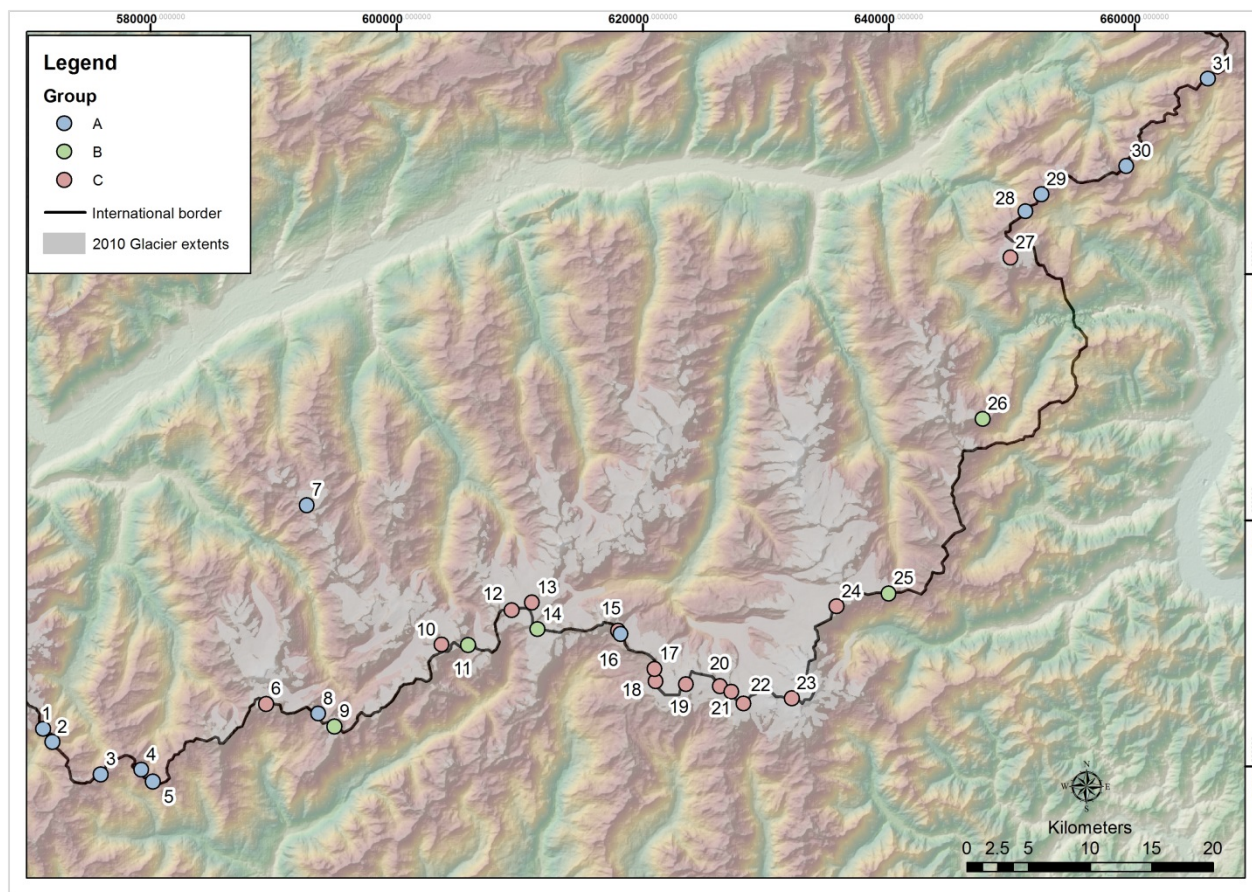


Figure 5.1. Results of categorization of passes shown for Group A (blue), Group B (green), and Group C (red).

5.2 THE USE OF GEOSPATIAL TECHNOLOGIES

The four papers presented in this thesis have shown how geospatial analyses can improve glacial archaeological research. A review of common GIS methods used in archaeology was presented (Paper I) to show how three GIS methods, visibility analysis, locational analysis, and least cost path analysis (LCPA), can be used in glacial archaeology. Furthermore, it was demonstrated that special considerations should be made when working with geospatial technologies in high latitudes and altitudes compared to other archaeological locations. For example, data access and availability is often scarce in some remote areas. As technology continues to advance and this field moves toward a free and open source environment, constraints should diminish.

One method discussed in Paper I, LCPA, calculated least cost paths (LCPs) across mountainous terrain (Paper II, III, and IV) and identified a new site of glacial archaeological interest at the Col de Cleuson between Sion, Switzerland and Aosta, Italy (Paper II). Archaeological prospection at this site uncovered an artefact from the Bronze Age. Prior to that discovery, the site's historical and archaeological potential was considered to be negligible. Thus, the LCPA was successful in

determining a new area for archaeological investigation based on movement through mountainous terrain. However, as described throughout this thesis, there were problems with this method related to the low resolution DEM and the calculation in GIS. The problems such as the horizontal slope issue and ridge preference could be ameliorated using a higher resolution DEM or directly integrating fixes into the mode, such as avoiding slopes over 40°. As GIS tools are increasingly becoming more open source and defined for the specific needs of users, I can see these problems being rectified in the near future.

The concept of modelling movement across prehistoric or historic landscapes using GIS has been investigated by others both practically (c.f. Bell and Lock, 2000; Egeland et al., 2010; Verhagen and Jeneson, 2012), and theoretically (Llobera et al., 2011; Murrieta-Flores, 2010, 2012). From a conceptual perspective, modelling movement is arguably easier to conduct in mountainous terrain based on the possibilities of human travel and accessibility. Furthermore, some places are more attractive than others. For example, steep, rocky, cliff faces are generally considered a deterrent. Thus, parts of the terrain can be excluded from archaeological investigations. Landscapes are continuously altered by erosion due to weathering processes and their own internal dynamics. Mountainous areas are particularly dynamic and in the Pennine Alps, the terrain geomorphology has changed significantly over long time periods. This concept was integrated into the LCPA by using a prehistoric landcover raster instead of a present day one. In an ideal situation, prehistoric geomorphological information would be integrated into the model but this does not yet exist for all of the Pennine Alps.

One argument against using LCPA for archaeological purposes is because it does not include social or cultural aspects of movement across the terrain. However, with the integration of archaeological knowledge and theories into data layers, these factors can be indirectly incorporated into the GIS environment. Recent advancements in GIS, including the increase in free and open source software and tools (including Quantum GIS, GRASS, SAGA, gvSIG), have increased the flexibility and functionality of this and other GIS tools whereby researchers are not constrained by the limitations of the tools as they were in the past (McCoy and Ladefoged, 2009). Instead of the tools determining the types of analyses that can be done using geospatial technologies, researchers now have the ability to create their own tools to fit within their theoretical frameworks.

Another method discussed in Paper I, locational analysis, was used along with predicted future glacier geometries to determine areas of glacial archaeological potential based on the topographic and landcover characteristics of the terrain (Paper IV). The GlaciArch model showed areas of current and future archaeological potential, and can be used to support archaeological prospection decisions. Currently GlaciArch results have not been validated; however, field prospection is planned for the near future whereby archaeologists can use the

model's results to decide where to conduct their archaeological field prospection.. State-of-the-art glaciological modelling techniques provided highly accurate, reliable results which could only be facilitated by glaciologists themselves. The integration of glaciological concepts is imperative for the understanding of where glacial archaeological remains could be located on the terrain. Glacier dynamics and movement have strong effects on the landscape and thus can determine where archaeological object could persist. The results of glaciological modelling were integrated into the geospatial database and analyzed together with the other geographical, archaeological and historical information already obtained. Thus, this multidisciplinary and integrative approach was essential for obtaining a holistic view about the glacial archaeological potential in the Pennine Alps.

Difficulty was experienced when integrating historical information into the geospatial database. We assume that historical information ties closely to the archaeological potential of passes because passes mentioned more frequently in the historical texts were potentially visited more often by humans. However, information from historical texts is not always linked to a known location with a geographical coordinate; therefore, it cannot be directly integrated into geospatial analyses. High altitude pass names and places are often mentioned, however place names, i.e. toponyms, change over time and the validity of the source is not always known. Therefore, the historical information was used as a secondary source of information in this research. For example, as place names or passes were suggested to historians by archaeologists and geographers, an archival analysis was performed. If nothing could be found about that location of pass, it was not assumed to have been frequently used throughout history. Conversely, if the location or pass was mentioned frequently, its archaeological potential was determined to be higher. Ideally, that information would be linked directly into the geospatial database. There have been recent developments in the field of GIScience which aim to incorporate this qualitative information into geographical databases. In the future, these historical texts could be directly integrated into GIS and accessed in the geospatial database via key words using qualitative GIS techniques.

The geospatial analysis methods discussed and used in the four papers within this thesis have facilitated the identification of areas of archaeological interest and potential for now and in the future. Thus, the main objectives of this thesis were reached using a geographical approach to solve an archaeological problem, with inputs from historical texts. This resulted in a holistic analysis of the glacial archaeological potential of the Pennine Alps.

5.3 FUTURE OUTLOOK

The field of GIScience and the use of geospatial technologies continue to advance and are gaining the ability to include both quantitative and qualitative types of information and data.

The inclusion of qualitative historical information (such as stories, legends, or texts) directly into GIS would be beneficial for obtaining a better understanding about the linkage between historical use and archaeological potential for the future. Another possibility for the future would be to integrate the third method discussed in Paper I, visibility analysis, into the geospatial research for the Pennine Alps. This method could be useful for calculating the field of view from on top of each high altitude pass, or from a valley up to the passes based on the assumption that vision affects the decisions made while travelling (Chapman, 2006; Murrieta-Flores, 2010). A geomorphological map and landcover classification of some areas in the region would also enable a better understanding about the effects of past glacier movement on the current landcover and the terrain and how that relates to the location and retrieval of glacial archaeological remains. The geospatial methods used in this thesis can be applied to other high altitude and latitude locations around the world to obtain a better understanding about how humans interacted with frozen environments over time.

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