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Combining glaciological and archaeological methods for gauging glacial archaeological potential

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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 4500 km^2 into several manageable square kilometre sites.

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) (19–20 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 (Prinoth-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

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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 deglacierized 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.

2. Study area and data

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 4500 km^2 and reach altitudes above 4000 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 to5.5 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 (Bezinge

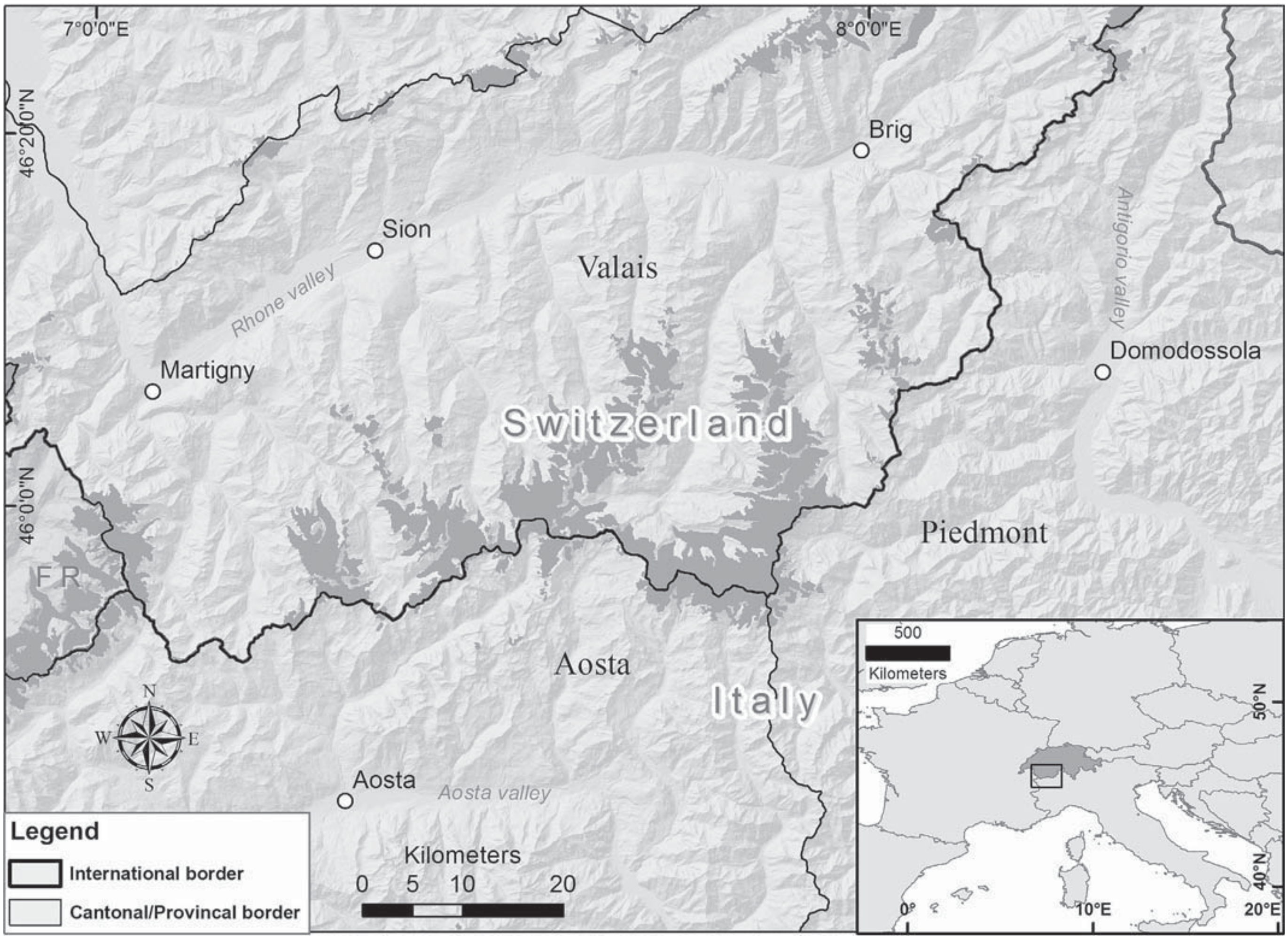

Fig. 1. Overview of study area. Glacierized areas are shaded in dark grey.

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).

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 deglacierized 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).

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.

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).

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).

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.

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; Schaefli 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. 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.

4.1. *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 deglacierized 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., 2014). 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 deglacierized, 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 (Rhone, 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.

4.2. *Locational analysis*

In this part of the analysis, multiple criteria were used to locate areas of high archaeological potential by analysing 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

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

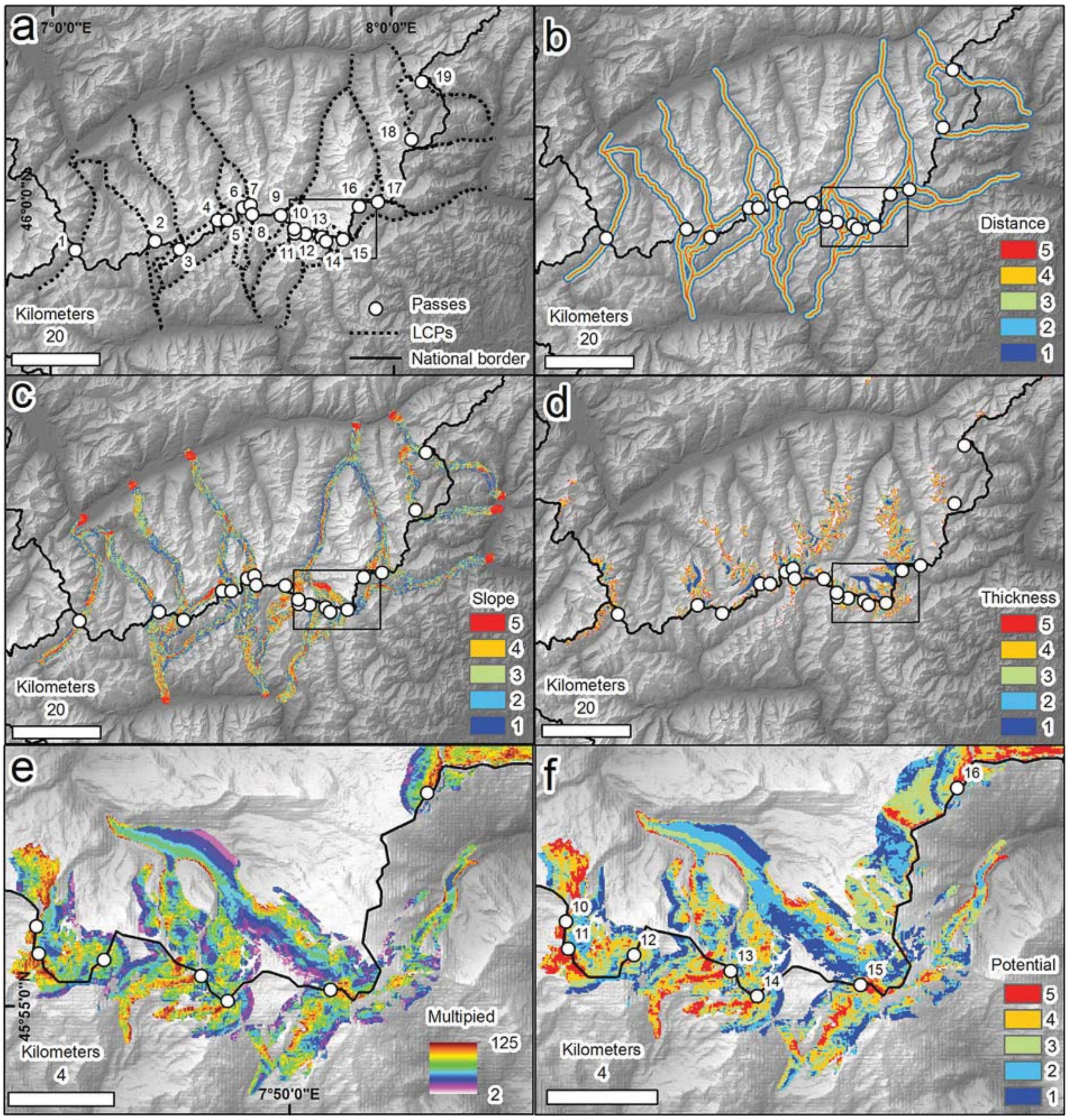

Fig. 2. Visualization of the locational analysis processing steps: (a) calculation of least cost paths with pass number corresponding to Table 1, (b) calculation of buffers around each path, (c) weighted slope values derived from DEM, (d) weighted glacier thickness layer, (e) selected close-up of slope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

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 to 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° were given a value of 1, thus very low

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

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° were determined to be the easiest to walk across and thus were given the highest potential value of 5. Slopes between 10 and 40° were assigned with a respective linearly increasing potential value for 10° 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, archeological 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 25–50 m, 50–75 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. 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. (2014) 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 CO_2-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.

4.4. 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 deglacierized 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.

5. Results and discussion

5.1. Locational analysis

The locational analysis results defined regions which were glacierized, or recently deglacierized, 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 deglacierized 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 4500 km^2 to a 114 km^2 area of interest, 8.16 km^2 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 5.3).

5.2. Glaciological modelling

Future glacier extents for 10-year increments between 2020 and 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 km^2 and calculated to decrease in future years. For example, a reduction of 37%–280 km^2 in 2030, 80% to 91 km^2 in 2060, and 93% to 30 km^2 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 CO_2-emission storyline until 2100 only had a small effect on calculated total glacier area.

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 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 km^2 and the high potential region is 3.24 km^2, compared to the decreased areas between 2060 and 2090 with 13.7 km^2 and

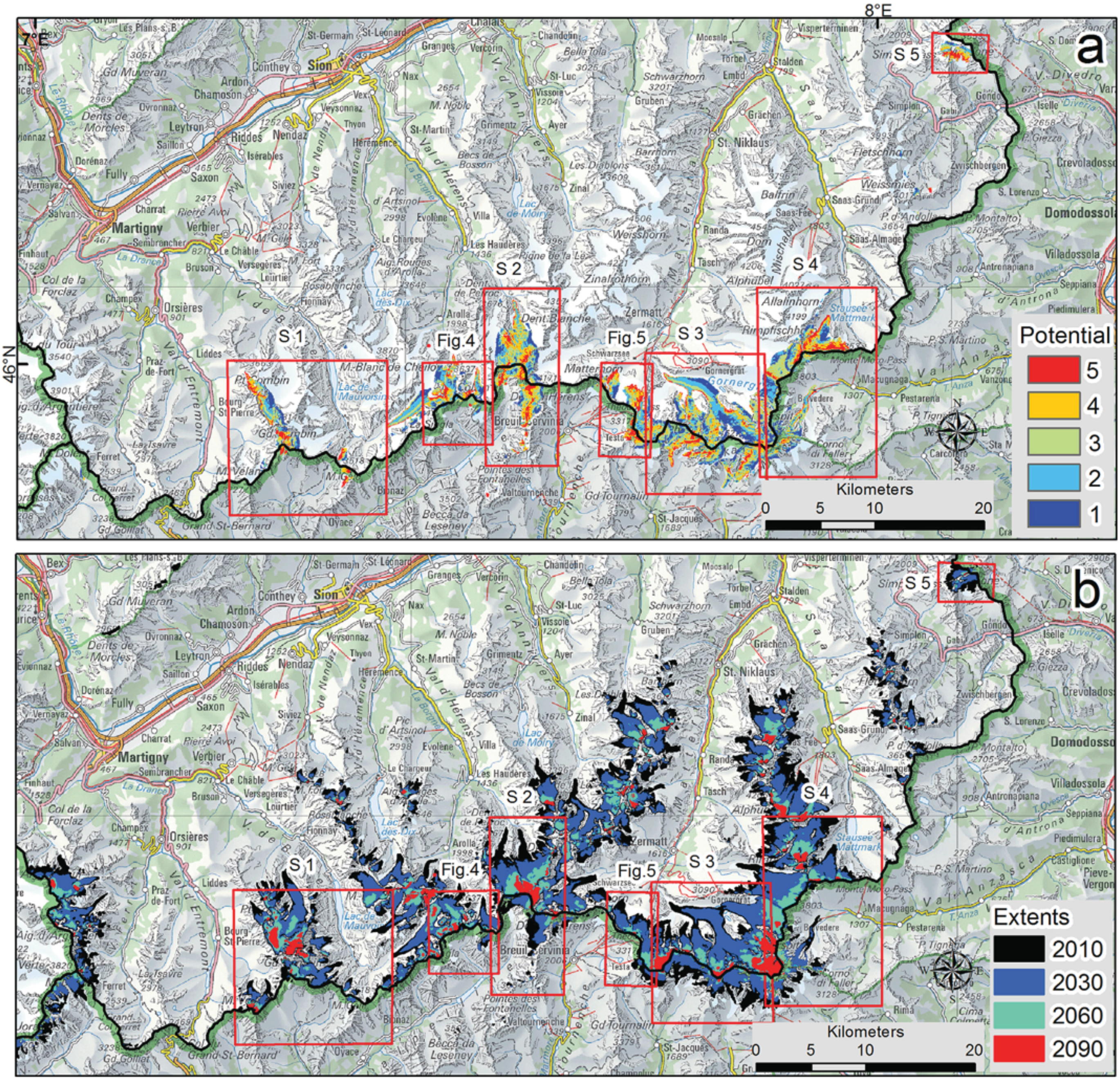

Fig. 3. Results from (a) locational analysis and (b) glaciological modelling from the whole study area. The Swiss Glacier Inventory for 2010 is shown along with the modelled glacier extents for 2010 on the Italian side of the border. The projected glacier extents for 2030, 2060, and 2090 are shown for both sides of the border of the Pennine Alps. The boundaries for Figs. 1 and 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

0.58 km^2, for area of interest and high potential, respectively (see Table 3 for all values).

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 (Bezinge 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

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 (km^2)	High potential (km^2)
2010	114	8.16
2010–2030	30.1	3.24
2030–2060	40.5	2.31
2060–2090	13.7	0.58

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.

Already briefly discussed in Section 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.

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 (Figs. 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 Fig. 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

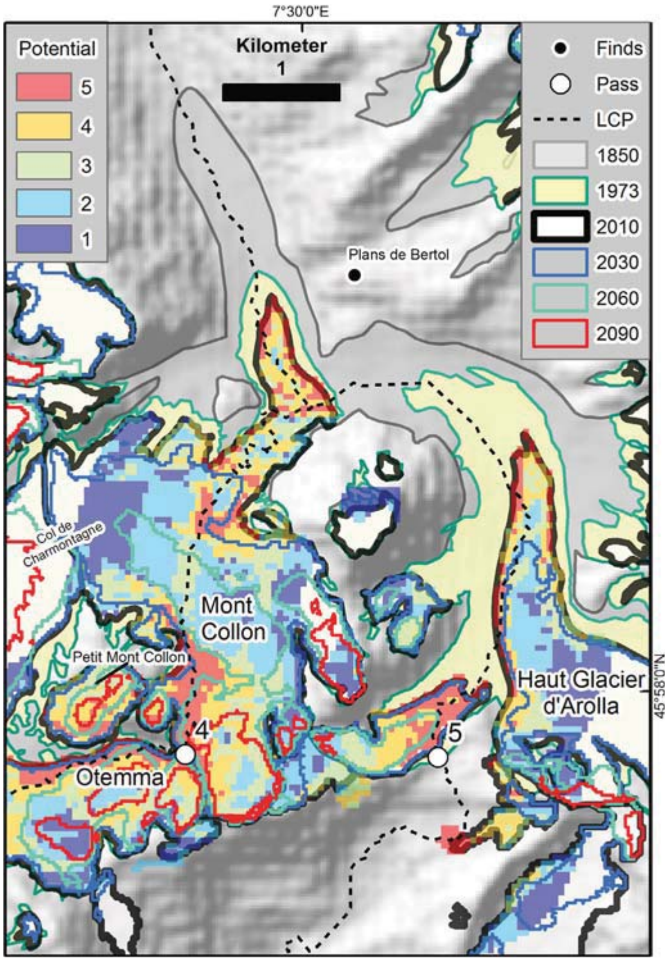

Fig. 4. GlaciArch results around the Mont Collon which includes the Col de Petit Mont Collon (4) and the Col Collon (5). The Glacier du Mont Collon, Glacier d'Otemma, and Haut glacier d'Arolla are labelled as well as locations mentioned in the text: Petit Mont Collon, Col de Charmontagne, and Plans de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

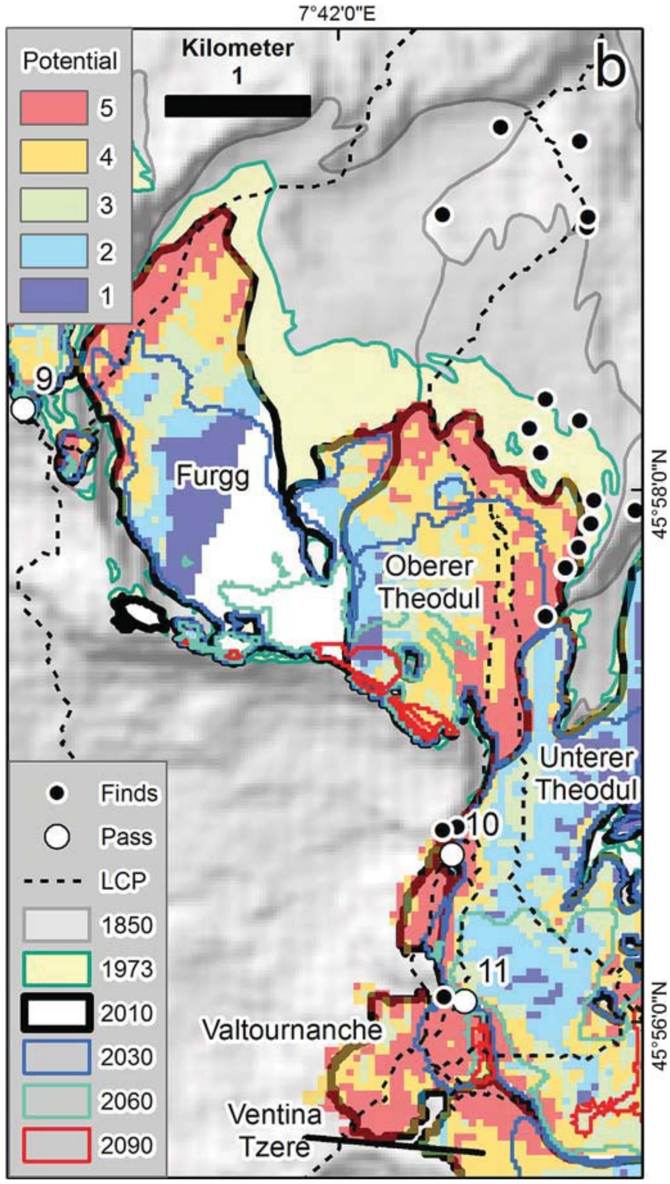

Fig. 5. GlaciArch results around the Theodulhorn. Passes listed are the Breuiljoch (9), Theodulpass (10), and the Passo di Ventina Nord (11). The Furgg glacier, and Oberer and Unterer Theodul glaciers are labelled. LCP refers to least cost path.

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 contraints do not permit dynamic visualisation of this type of results. An interactive interface would be the best way to visualize the end results.

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.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jas.2014.09.010.

References

Addor, N., Roessler, O., Koeplin, N., Huss, M., Weingartner, R., Seibert, J., 2014. Robust changes and sources of uncertainty in the projected hydrological regimes of Swiss catchments. Water Resour. Res. (in press).
Aldenderfer, M., 2006. Modelling plateau peoples: the early human use of the world's high plateaux. World Archaeol. 38, 357–370. http://dx.doi.org/10.1080/00438240600813285.
Anderson, D.G., Gillam, J.C., 2000. Paleoindian colonization of the Americas: implications from an examination of physiography, demography, and artifact distribution. Am. Antiq. 65, 43–66. http://dx.doi.org/10.2307/2694807.
Andrews, T.D., MacKay, G., 2012. The archaeology and paleoecology of Alpine ice patches: a global perspective. Arctic 65, iii–vi.
Andrews, T.D., MacKay, G., Andrew, L., 2012. Archaeological investigations of Alpine ice patches in the Selwyn Mountains, Northwest Territories, Canada. Arctic 65, 1–21.
Beattie, O., Apland, B., Blake, E.W., Cosgrove, J.A., Gaunt, S., Greer, S., Mackie, A.P., Mackie, K.E., Straathof, D., Thorp, V., Troffe, P.M., 2000. The Kwädāy Dän Ts'ìnchi discovery from a Glacier in British Columbia. Can. J. Archaeol. J. Can. Archéol. 24, 129–147.
Bell, T., Lock, G.R., 2000. Topographic and cultural influences on walking the Ridgeway in later prehistoric times. In: Lock, G.R. (Ed.), Beyond the Map: Archaeology and Spatial Technologies. IOS Press, Oxford, pp. 85–100.
Bellwald, W., 1992. Drei spätneolithisch/frühbronzezeitiche Pfeilbogen aus dem Gletschereis am Lötschenpass. SGUF.
Benedict, J.B., Olson, B.L., 1978. The Mount Albion Complex: a Study of Prehistoric Man and the Altithermal. Research Report 1. Center for Mountain Archaeology, Ward, Colorado.
Benn, D.I., Evans, D.J.A., 2010. Glaciers and Glaciation. Hodder Education, London.
Berthel, N., Schwörer, C., Tinner, W., 2012. Impact of Holocene climate changes on alpine and treeline vegetation at Sanetsch Pass, Bernese Alps, Switzerland. Rev. Palaeobot. Palynol. 174, 91–100. http://dx.doi.org/10.1016/j.revpalbo.2011.12.007.
Bezinge, A., Curdy, P., 1994. Les Alpes pennines au temps d'Oetzi vers 3200 av. J.-C. (momie du Hauslabjoch). Bull. Muritienne 65–77.
Bezinge, A., Curdy, P., 1995. Les Alpes pennines au temps d'Oetzi vers 3200 av. J.-C. (momie du Hauslabjoch). Houille Blanche 111–115. http://dx.doi.org/10.1051/lhb/1995055.
Callanan, M., 2012. Central Norwegian snow patch archaeology: patterns past and present. Arctic 65, 178–188.
Callanan, M., 2013. Melting snow patches reveal Neolithic archery. Antiquity 87, 728–745.
Cannone, N., Diolaiuti, G., Guglielmin, M., Smiraglia, C., 2008. Accelerating climate change impacts on alpine glacier forefield ecosystems in the European Alps. Ecol. Appl. 18, 637–648. http://dx.doi.org/10.1890/07-1188.1.
Carleton, W.C., Conolly, J., Ianonne, G., 2012. A locally-adaptive model of archaeological potential (LAMAP). J. Archaeol. Sci. 39, 3371–3385. http://dx.doi.org/10.1016/j.jas.2012.05.022.
Carrer, F., 2013. An ethnoarchaeological inductive model for predicting archaeological site location: a case-study of pastoral settlement patterns in the Val di Fiemme and Val di Sole (Trentino, Italian Alps). J. Anthropol. Archaeol. http://dx.doi.org/10.1016/j.jaa.2012.10.001.
CH2014-Impacts, 2014. Toward Quantitative Scenarios of Climate Change Impacts in Switzerland. OCCR, FOEN, MeteoSwiss, C2SM, Agroscope, ProClim, Bern.
Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., McCabe, A.M., 2009. The Last Glacial Maximum. Science 325, 710–714. http://dx.doi.org/10.1126/science.1172873.
Conolly, J., Lake, M., 2006. Geographical Information Systems in Archaeology. Cambridge University Press, Cambridge.
Coolidge, W.A.B., 1912. Alpine Studies. Longmans, Green and Co., London.
Curdy, P., 2007. Prehistoric settlement in middle and high altitudes in the Upper Rhone Valley (Valais-Vaud, Switzerland): a summary of twenty years of research. Preist. Alp. 42, 99–108. http://dx.doi.org/10.1111/j.1472-4642.2012.00930.x.
Curdy, P., 2010. Les passages des Alpes centrales à l'âge du fer, quelques réflexions. In: Le Bihan, J.P., Guillaumet, J.P. (Eds.), Routes du monde et passages obligés. Centre de recherche archéologique du Finistère, Quimper.
Curdy, P., Leuzinger-Piccand, C., Leuzinger, U., 2003. Zermatt Alp Hermettji et les cols secondaires du Valais. In: Besse, M., Stahl Gretsch, L.-I., Curdy, P. (Eds.), ConstellaSion. Hommage à Alain Gallay. Cahiers d'archéologie romande, Lausanne, pp. 73–88.
Dixon, E.J., Manley, W.F., Lee, C.M., 2005. The emerging archaeology of glaciers and ice patches: examples from Alaska's Wrangell-St. Elias National Park and preserve. Am. Antiq. 70, 129–143.
Ebert, D., 2004. Applications of archaeological GIS. Can. J. Archaeol. J. Can. Archéol. 28, 319–341.
Egeland, C.P., Nicholson, C.M., Gasparian, B., 2010. Using GIS and ecological variables to identify high potential areas for Paleoanthropological Survey: an example from Northern Armenia. J. Ecol. Anthropol. 14, 89–98. http://dx.doi.org/10.5038/2162-4593.14.1.8.
Farbregd, O., 1972. Pilefunn fra Oppdalsfjella. NTNU Vitenskapsmuseet.
Farinotti, D., Usselmann, S., Huss, M., Bauder, A., Funk, M., 2012. Runoff evolution in the Swiss Alps: projections for selected high-alpine catchments based on ENSEMBLES scenarios. Hydrol. Process. 26, 1909–1924. http://dx.doi.org/10.1002/hyp.8276.
Farnell, R., Hare, P.G., Blake, E., Bowyer, V., Schweger, C., Greer, S., Gotthardt, R., 2004. Multidisciplinary investigations of Alpine Ice Patches in Southwest Yukon, Canada: paleoenvironmental and paleobiological investigations. Arctic 57, 247–259.
Federal Office of Topography, 2014. Swisstopo. Retrieved from: http://www.swisstopo.admin.ch/internet/swisstopo/en/home/products/landscape/toponymy.html (accessed 22.04.14.).
Fischer, A., Olefs, M., Abermann, J., 2011. Glaciers, snow and ski tourism in Austria's changing climate. Ann. Glaciol. 52, 89–96.
Fischer, M., Huss, M., Barboux, C., Hoelzle, M., 2014. The new Swiss Glacier Inventory SGI2010: relevance of using high-resolution source data in areas dominated by very small glaciers. Arct. Antarct. Alp. Res. 64.
Gardner, A.S., Moholdt, G., Cogley, J.G., Wouters, B., Arendt, A.A., Wahr, J., Berthier, E., Hock, R., Pfeffer, W.T., Kaser, G., Ligtenberg, S.R.M., Bolch, T., Sharp, M.J., Hagen, J.O., Broeke, M.R., van den Paul, F., 2013. A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. Science 340, 852–857. http://dx.doi.org/10.1126/science.1234532.
Gorenflo, L.J., Gale, N., 1990. Mapping regional settlement in information space. J. Anthropol. Archaeol. 9, 240–274. http://dx.doi.org/10.1016/0278-4165(90)90008-2.
Graves, D., 2011. The use of predictive modelling to target Neolithic settlement and occupation activity in mainland Scotland. J. Archaeol. Sci. 38, 633–656.

Grosjean, M., Suter, P.J., Trachsel, M., Wanner, H., 2007. Ice-borne prehistoric finds in the Swiss Alps reflect Holocene glacier fluctuations. J. Quat. Sci. 22, 203–207. http://dx.doi.org/10.1002/jqs.1111.
Hafner, A., 2012. Archaeological discoveries on Schnidejoch and at other ice sites in the European Alps. Arctic 65, 189–202.
Hare, P.G., Greer, S., Gotthardt, R., Farnell, R., Bowyer, V., Schweger, C., Strand, D., 2004. Ethnographic and archaeological investigations of alpine ice patches in southwest Yukon, Canada. Arctic 260–272.
Hare, P.G., Thomas, C.D., Topper, T.N., Gotthardt, R.M., 2012. The archaeology of Yukon Ice Patches: new artifacts, observations, and insights. Arctic 65, 118–135.
Harriss, B., 1970. The Theodulpass: a history. Alp. J. 75, 87–94.
Harriss, B., 1971. The Monte Moro Pass and the Col D'Herens. Alp. J. 127–132.
Holzhauser, H., 2007. Holocene glacier fluctuations in the Swiss Alps. In: Richard, H., Magny, M., Mordant, C. (Eds.), Environnements et cultures à l'âge du bronze en Europe occidentale. Editions du Comité des travaux historiques et scientifiques, Paris, pp. 29–43.
Howey, M.C.L., 2007. Using multi-criteria cost surface analysis to explore past regional landscapes: a case study of ritual activity and social interaction in Michigan, AD 1200–1600. J. Archaeol. Sci. 34, 1830–1846. http://dx.doi.org/10.1016/j.jas.2007.01.002.
Huss, M., 2012. Extrapolating glacier mass balance to the mountain-range scale: the European Alps 1900–2100. Cryosphere 6, 713–727. http://dx.doi.org/10.5194/tc-6-713-2012.
Huss, M., Farinotti, D., 2012. Distributed ice thickness and volume of all glaciers around the globe. J. Geophys. Res. Earth Surf. 117, F04010. http://dx.doi.org/10.1029/2012JF002523.
Huss, M., Jouvet, G., Farinotti, D., Bauder, A., 2010a. Future high-mountain hydrology: a new parameterization of glacier retreat. Hydrol. Earth Syst. Sci. 14, 815–829. http://dx.doi.org/10.5194/hess-14-815-2010.
Huss, M., Hock, R., Bauder, A., Funk, M., 2010b. 100-year mass changes in the Swiss Alps linked to the Atlantic Multidecadal Oscillation. Geophys. Res. Lett. 37 http://dx.doi.org/10.1029/2010GL042616.
IPCC, 2013. Climate Change 2013: the Physical Science Basis. Cambridge University Press, Cambridge.
Ivy-Ochs, S., Kerschner, H., Reuther, A., Preusser, F., Heine, K., Maisch, M., Kubik, P.W., Schlüchter, C., 2008. Chronology of the last glacial cycle in the European Alps. J. Quat. Sci. 23, 559–573. http://dx.doi.org/10.1002/jqs.1202.
Jenks, G.F., Caspall, F.C., 1971. Error on choroplethic maps: definition, measurement, reduction. Ann. Assoc. Am. Geogr. 61, 217–244. http://dx.doi.org/10.1111/j.1467-8306.1971.tb00779.x.
Joerin, U.E., Stocker, T.F., Schluechter, C., 2006. Multicentury glacier fluctuations in the Swiss Alps during the Holocene. Holocene 16, 697–704. http://dx.doi.org/10.1191/0959683606hl946rp.
Joerin, U.E., Nicolussi, K., Fischer, A., Stocker, T.F., Schlüchter, C., 2008. Holocene optimum events inferred from subglacial sediments at Tschierva Glacier, Eastern Swiss Alps. Quat. Sci. Rev. 27, 337–350. http://dx.doi.org/10.1016/j.quascirev.2007.10.016.
Jouvet, G., Picasso, M., Rappaz, J., Huss, M., Funk, M., 2011. Modelling and numerical simulation of the dynamics of glaciers including local damage effects. Math. Model. Nat. Phenom. 6, 263–280. http://dx.doi.org/10.1051/mmnp/20116510.
Kaser, G., Grosshauser, M., Marzeion, B., 2010. Contribution potential of glaciers to water availability in different climate regimes. Proc. Natl. Acad. Sci. 107, 20223–20227. http://dx.doi.org/10.1073/pnas.1008162107.
Kohler, T.A., Parker, S.C., 1986. Predictive models for archaeological resource location. Adv. Archaeol. Method Theory 397–452.
Kvamme, K.L., 1999. Recent directions and developments in geographical information systems. J. Archaeol. Res. 7, 153–201. http://dx.doi.org/10.1007/BF02446276.
Lee, C.M., 2012. Withering snow and ice in the mid-latitudes: a new archaeological and Paleobiological record for the Rocky Mountain Region. Arctic 65, 165–177.
Lehner, P., Julen, A., 1991. A man's bones with 16th-century weapons and coins in a glacier near Zermatt, Switzerland. Antiquity 65, 269–273.
Llobera, M., Fábrega-Álvarez, P., Parcero-Oubiña, C., 2011. Order in movement: a GIS approach to accessibility. J. Archaeol. Sci. 38, 843–851. http://dx.doi.org/10.1016/j.jas.2010.11.006.
Madry, S., Rakos, L., 1996. Line-of-sight and Cost-surface Techniques for Regional Research in the Arroux River Valley. In: New Methods Old Probl. Geogr. Inf. Syst. Mod. Archaeol. Res, pp. 104–126.
McCoy, M.D., Ladefoged, T.N., 2009. New developments in the use of spatial technology in archaeology. J. Archaeol. Res. 17, 263–295. http://dx.doi.org/10.1007/s10814-009-9030-1.
Meyer, W., 1992. Der Söldner vom Theodulpaß und andere Gletscherfunde aus der Schweiz. In: Höpfel, F., Platzer, W., Spindler, K. (Eds.), Der Mann im Eis. Springer, Innsbruck.
Molyneaux, K., Reay, D.S., 2010. Frozen archaeology meltdown. Nat. Geosci. 4, 2. http://dx.doi.org/10.1038/ngeo1043.
Müller, F.B., Caflisch, T., Müller, G., 1976. Firn und Eis der Schweizer Alpen: Gletscherinventar. ETH, Geographisches Institut, Zurich.
Murrieta-Flores, P.A., 2010. Travelling in a prehistoric landscape: exploring the influences that shaped human movement. In: Frischer, Bernard, Crawford, Jane Webb, Koller, David (Eds.), Making History Interactive. Computer Applications and Quantitative Methods in Archaeology (CAA). Proceedings of the 37th International Conference, Williamsburg, Virginia, United States of America, March 22–26, 2009, BAR International Series 2079. Archaeopress, pp. 249–267. Presented at the Computer Applications and Quantitative methods in Archaeology.
Murrieta-Flores, P.A., 2012. Understanding human movement through spatial technologies. The role of natural areas of transit in the Late Prehistory of South-western Iberia. Trab. Prehist. 69, 103–122. http://dx.doi.org/10.3989/tp.2012.12082.
Nakicenovic, N., 2000. Special Report on Emissions Scenarios: a Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.
NASA, 2012. ASTER Global Digital Elevation Map. ASTER GDEM. URL: http://asterweb.jpl.nasa.gov/gdem.asp (accessed 02.02.13.).
Oerlemans, J., Anderson, B., Hubbard, A., Huybrechts, P., Jóhannesson, T., Knap, W.H., Schmeits, M., Stroeven, A.P., Wal, R.S.W. van de, Wallinga, J., Zuo, Z., 1998. Modelling the response of glaciers to climate warming. Clim. Dyn. 14, 267–274. http://dx.doi.org/10.1007/s003820050222.
Pacher, M., 2003. Upper Pleistocene cave assemblages et alpine sites in Austria and adjacent region: 128. Preist. Alp. 115–128.
Paul, F., Maisch, M., Rothenbühler, C., Hoelzle, M., Haeberli, W., 2007. Calculation and visualisation of future glacier extent in the Swiss Alps by means of hypsographic modelling. Glob. Planet. Change 55, 343–357. http://dx.doi.org/10.1016/j.gloplacha.2006.08.003.
Paul, F., Frey, H., Le Bris, R., 2011. A new glacier inventory for the European Alps from Landsat TM scenes of 2003: challenges and results. Ann. Glaciol. 52, 144–152. http://dx.doi.org/10.3189/172756411799096295.
Prinoth-Fornwagner, R., Niklaus, T.R., 1994. The man in the ice: results from radiocarbon dating. Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms 92, 282–290. http://dx.doi.org/10.1016/0168-583X(94)96020-8.
Radić, V., Bliss, A., Beedlow, A.C., Hock, R., Miles, E., Cogley, J.G., 2014. Regional and global projections of twenty-first century glacier mass changes in response to climate scenarios from global climate models. Clim. Dyn. 42, 37–58. http://dx.doi.org/10.1007/s00382-013-1719-7.
Radmilli, A.M., 1963. Il Mesolitico nel Carso Triestino. In: Atti VII Riun. Sci. IIPP, pp. 39–43.
Rageth, J., 1995. Ein Gletscherleichenfund im Piz Kesch-Gebiet. Bündner Monatsblatt.
Reckin, R., 2013. Ice patch archaeology in global perspective: archaeological discoveries from Alpine ice patches worldwide and their relationship with paleoclimates. J. World Prehistory 26, 323–385. http://dx.doi.org/10.1007/s10963-013-9068-3.
Rogers, S.R., Collet, C., Lugon, R., 2014. Least cost path analysis for predicting glacial archaeological site potential in central Europe. In: Traviglia, A. (Ed.), Across Space and Time. Computer Applications and Quantitative Methods in Archaeology (CAA), Proceedings of the 41st International Conference (Perth, Australia, March 25–28, 2013).
Salzmann, N., Machguth, H., Linsbauer, A., 2012. The Swiss Alpine glaciers' response to the global "2 °C air temperature target". Environ. Res. Lett. 7, 044001. http://dx.doi.org/10.1088/1748-9326/7/4/044001.
Sauter, M.-R., 1950. Préhistoire du Valais, des origines aux temps mérovingiens. Vallesia 1–297.
Schaefli, B., Hingray, B., Niggli, M., Musy, A., 2005. A conceptual glacio-hydrological model for high mountainous catchments. Hydrol. Earth Syst. Sci. Discuss. 2, 73–117.
Schneeberger, C., Blatter, H., Abe-Ouchi, A., Wild, M., 2003. Modelling changes in the mass balance of glaciers of the northern hemisphere for a transient 2 × CO_2 scenario. J. Hydrol. Mt. Hydrol. Water Resour. 282, 145–163. http://dx.doi.org/10.1016/S0022-1694(03)00260-9.
Seidler, H., Bernhard, W., Teschler-Nicola, M., Platzer, W., zur Nedden, D., Henn, R., Oberhauser, A., Sjovold, T., 1992. Some anthropological aspects of the prehistoric Tyrolean ice man. Science 258, 455–457. http://dx.doi.org/10.1126/science.1411539.
Tagliacozzo, A., Fiore, I., 2000. La chasse au bouquetin au Paléolithique supérieur en zone alpine. Anthropozoologica 69–76.
Tinner, W., Theurillat, J.-P., 2003. Uppermost limit, extent, and fluctuations of the timberline and treeline ecocline in the Swiss Central Alps during the past 11,500 years. Arct. Antarct. Alp. Res. 35, 158–169. http://dx.doi.org/10.1657/1523-0430(2003)035[0158:ULEAFO]2.0.CO;2.
Tobler, W., 1993. Three Presentations on Geographical Analysis and Modeling. NCGIA, Santa Barbara.
Van de Wal, R.S.W., Wild, M., 2001. Modelling the response of glaciers to climate change by applying volume-area scaling in combination with a high resolution GCM. Clim. Dyn. 18, 359–366. http://dx.doi.org/10.1007/s003820100184.
VanderHoek, R., Tedor, R.M., McMahan, J.D., 2007. Cultural Materials Recovered from ice patches in the Denali Highway Region, Central Alaska, 2003–2005. Alsk. J. Anthr. 5, 185–200.
Verhagen, P., Jeneson, K., 2012. A Roman Puzzle. Trying to find the via Belgica with GIS. In: Chrysanthi, A., Murrieta-Flores, P., Papadopoulus, C. (Eds.), Thinking beyond the Tool. Archaeological Computing and the Interpretive Process. Archaeopress, Oxford.
Walsh, K., Richer, S., de Beaulieu, J.L., 2006. Attitudes to altitude: changing meanings and perceptions within a "marginal" Alpine landscape – the integration of palaeoecological and archaeological data in a high-altitude landscape in the French Alps. World Archaeol. 38, 436–454. http://dx.doi.org/10.1080/00438240600813392.
Warren, R.E., Asch, D.L., 2003. A predictive model of archaeological site location in the eastern Prairie Peninsula. In: Wescott, K.L., Brandon, R.J. (Eds.), Practical Applications of GIS for Archaeologists: a Predictive Modelling Toolkit. Taylor & Francis, London, pp. 5–32.

Wheatley, D., Gillings, M., 2002. Spatial Technology and Archaeology: the Archaeological Applications of GIS. Taylor & Francis, London.
White, D.A., Surface-Evans, S.L., 2012. Least Cost Analysis of Social Landscapes: Archaeological Case Studies. University of Utah Press.
Whitley, T.G., Hicks, L.M., 2003. A geographic information systems approach to understanding potential prehistoric and historic travel corridors. Southeast. Archaeol. 22, 77–91.
Wick, L., Tinner, W., 1997. Vegetation changes and timberline fluctuations in the Central Alps as indicators of Holocene climatic oscillations. Arct. Alp. Res. 29, 445–458. http://dx.doi.org/10.2307/1551992.
Wiegandt, E., Lugon, R., 2008. Challenges of living with glaciers in the Swiss Alps, past and present. In: Orlove, B.S., Wiegandt, E., Luckman, B.H. (Eds.), Darkening Peaks: Glacier Retreat, Science, and Society. University of California Press, Los Angeles, pp. 33–48.
Zemp, M., Hoelzle, M., Haeberli, W., 2009. Six decades of glacier mass-balance observations: a review of the worldwide monitoring network. Ann. Glaciol. 50, 101–111.
Zipf, G., 1949. Human Behavior and the Principle of Least Effort. Addison-Wesley Press, Oxford.