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

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-Piccand, 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.
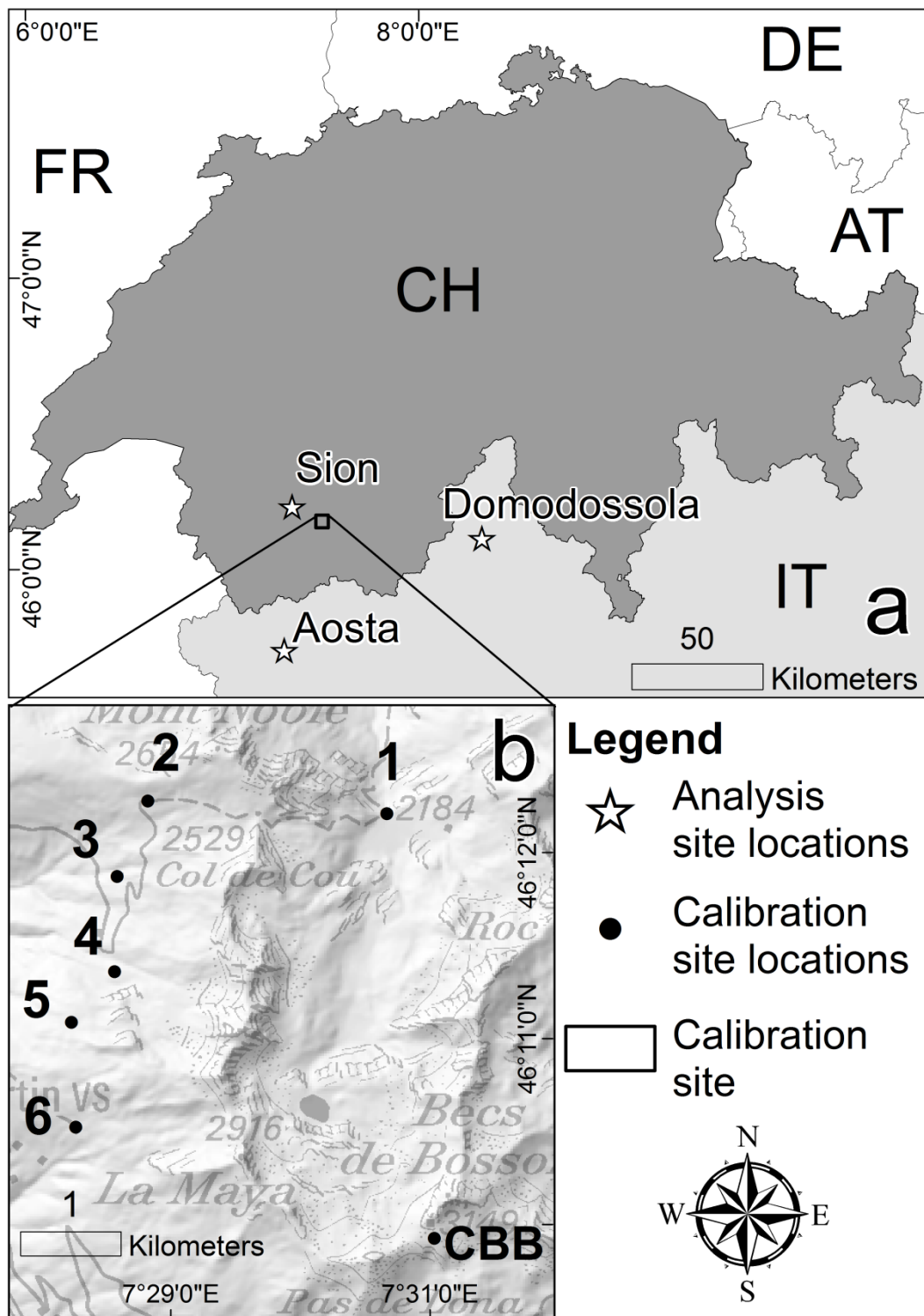

Figure 1. (a) Map of the analysis site including the locations of interest Sion, Domodossola, and Aosta, and the overview map of Switzerland (CH) and its surrounding countries: Italy (IT), France (FR), Germany (DE), and Austria (AT), and (b) the calibration site showing the six locations of interest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

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:

$$v = 6 \, exp(-3.5 * abs(s + 0.05))$$

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:

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

, 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).

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 (46º 11ˈ N, 7º 30ˈ 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).

2.2 Analysis sites
Based on the results from the calibration site (section 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).

2.2.1 Sion/Domodossola
The first analysis site was located between Sion (46º 14' N, 7º 22' E, 500 m asl), situated in the canton of Valais in the southwest corner of Switzerland, and Domodossola (46º 07' N, 8º 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.

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

2.2.2 Sion/Aosta

The second analysis site was between Sion and Aosta (45º 44' N, 7º 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.

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.

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 2nd 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

3 Results

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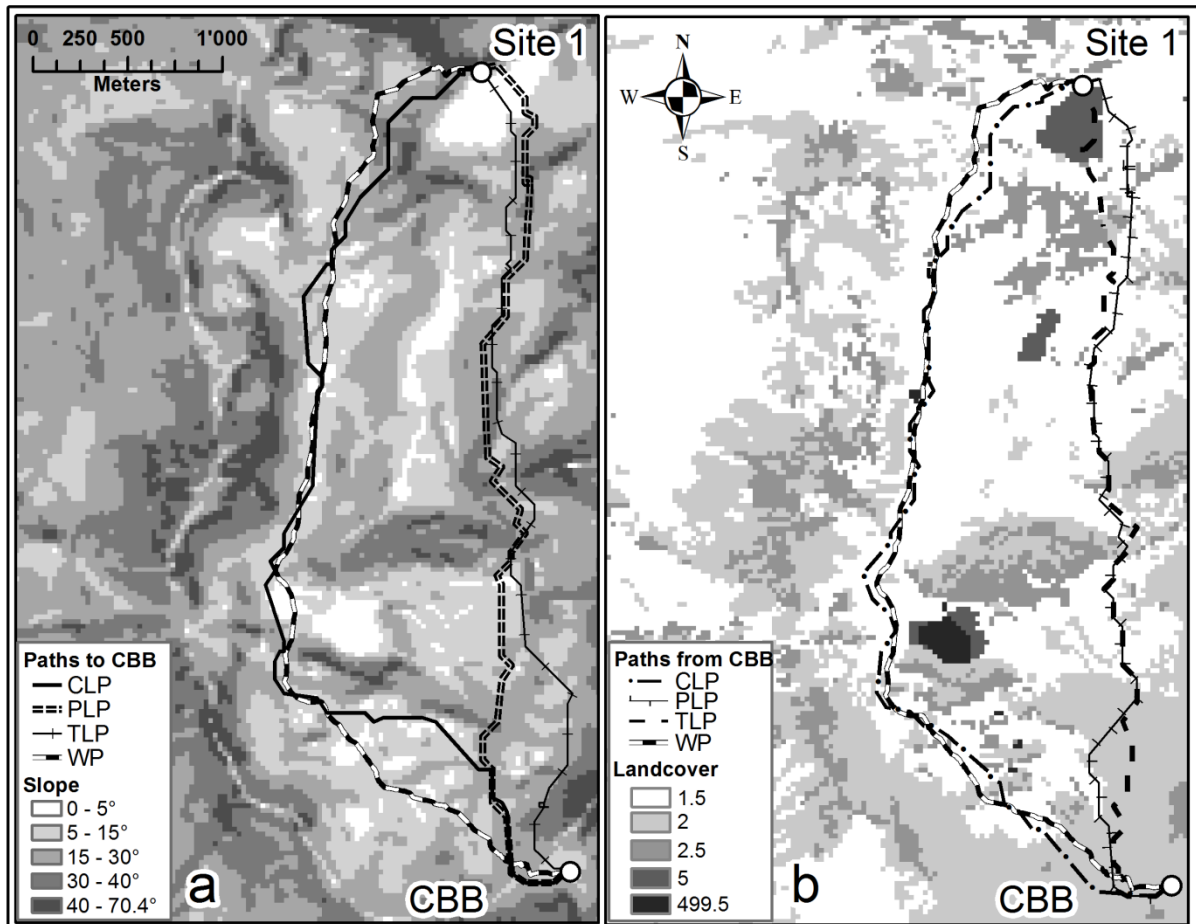
Figure 2. Least cost paths from Site 1 to the Cabin de Becs de Bosson (CBB) shown on DEM-derived slope raster (a) and paths from the CBB back to Site 1 shown with the prehistoric landcover (second weighted) cost raster in the background (b). The legend represents the current landcover path (CLP), the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

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.
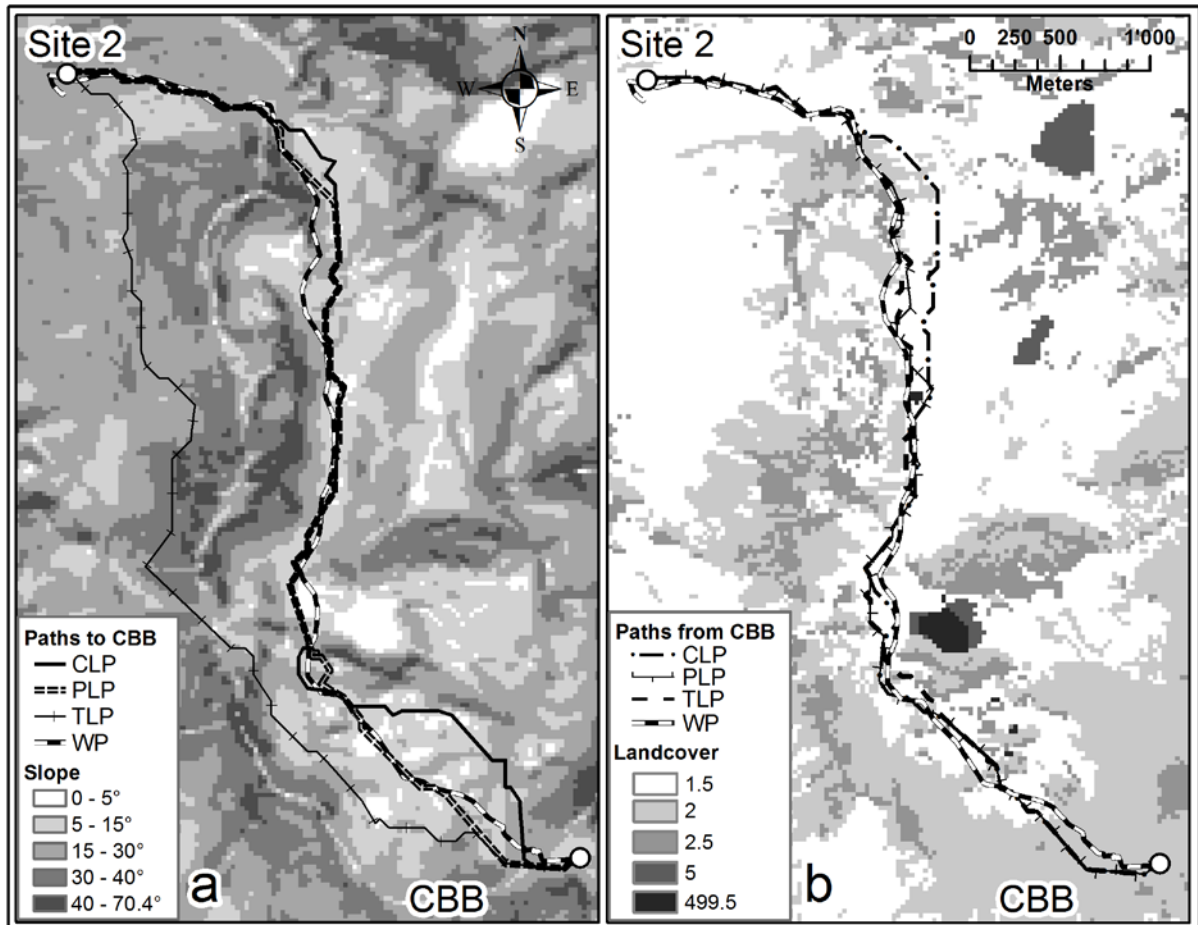

Figure 3. Least cost paths from Site 2 to the Cabin de Becs de Bosson (CBB) shown with slope values (a) and paths from the CBB back to Site 2 shown with the prehistoric landcover (second weighted) cost raster in the background (b). The legend represents the current landcover path (CLP), the prehistoric 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).

				CLP		PLP (1st)		PLP (2nd)		TLP		WP	
Site	Latitude	Longitude	Alt(m)	Away	Return	Away	Return	Away	Return	Away	Return	Away	Return
1	46º 12´12" N	7º 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	46º 12´17" N	7º 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	46º 11´52" N	7º 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	46º 11´22" N	7º 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	46º 11´5" N	7º 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	46º 10´31" N	7º 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

3.2 Analysis sites
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.

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.

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 ± 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 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
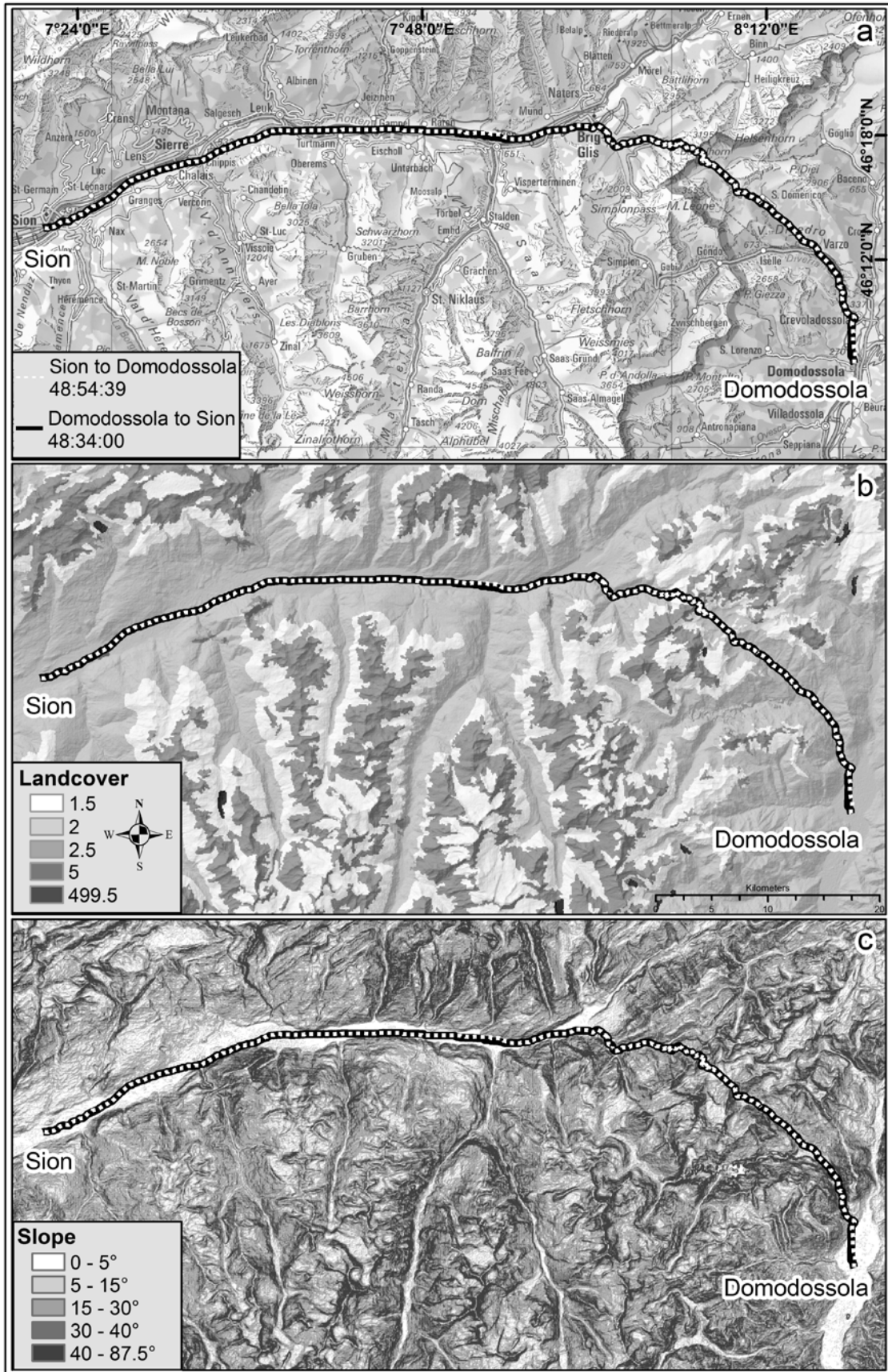
Figure 4. Least cost paths from Sion to Domodossola and vice versa on 1:500,000 topographic map with travel times (a), second weighted prehistoric landcover cost raster (b), and DEM-derived slope (c) backgrounds. Landcover values correspond to the reclassification categories in Table 3
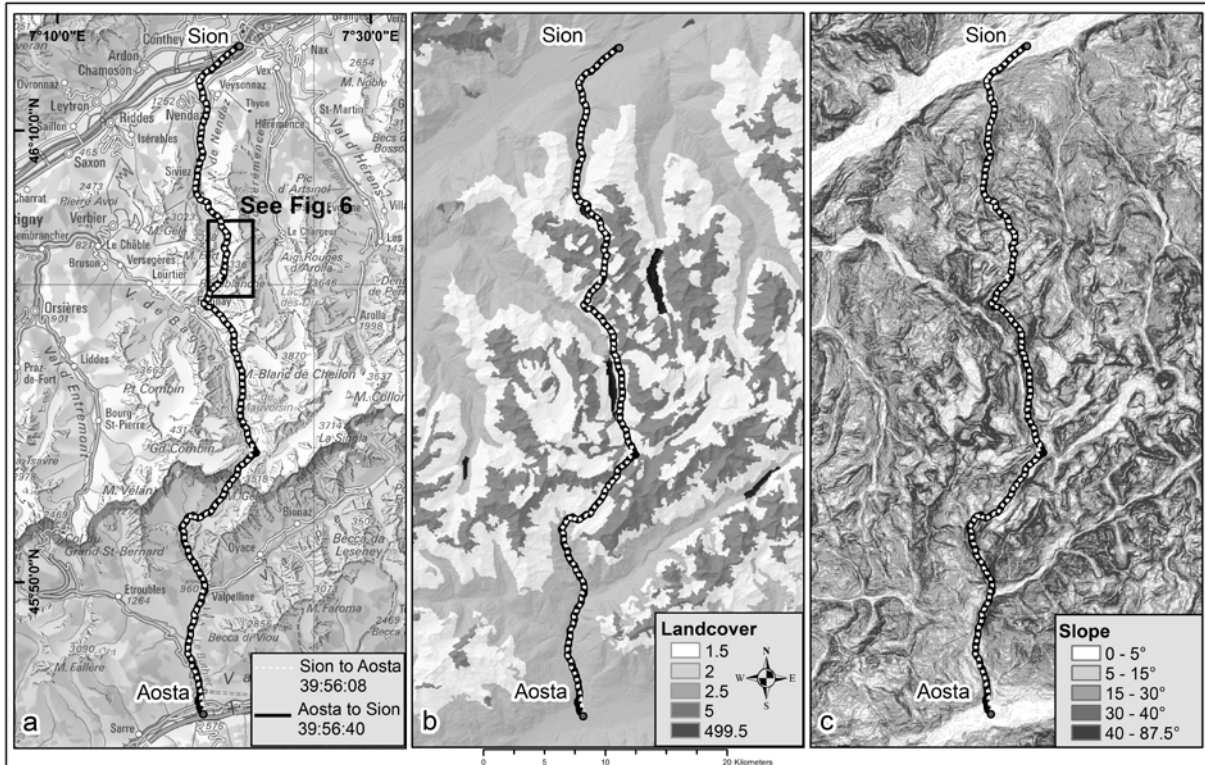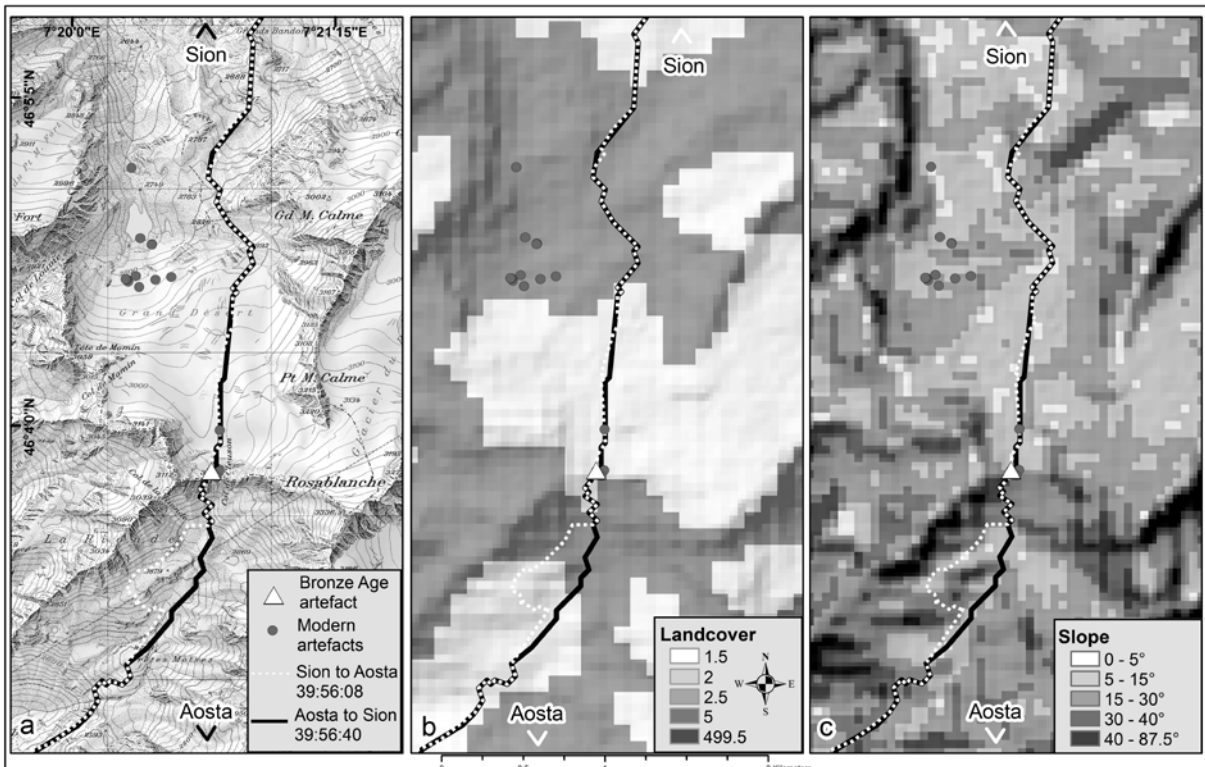
Figure 5. Least cost paths from Sion to Aosta and vice versa on 1:500,000 topographic map with travel times (a), second weighted prehistoric landcover cost raster (b), and DEM-derived slope (c) backgrounds. Landcover values correspond to the reclassification categories in Table 3

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

terrains. Another algorithm which calculates walking times is the *r.walk* function from GRASS (Neteler and Mitasova, 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 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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