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GIS modeling of lithic procurement in highlands: Archaeological and actualistic approach in the Andes

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ABSTRACT

The purpose of this work is to model human movements and lithic procurement costs in high-altitude environments on the basis of geographical aspects. Using GIS we analyzed movement costs that can be applied as of early occupation times in the Southern Andes. We compared curves used to analyze pedestrian movements and contrasted actualistic and ethnographic information in the Andes. We adapted the Tobler Offpath Hiking algorithm to GIS and estimated movement costs in the process of exploiting lithic resources that can be considered within local, non-local and extra-regional categories in Andean topographies as a function of isochrons or times of movement. We propose "local" to be the range of space which can be accessed in one 8-hour movement day. On this scale we establish a ranking regarding the costs of accessing the sources of raw material. The resulting movement scales can be useful for works in comparable environments and in different stages of occupation of high-altitude spaces.

1. Introduction

The patterns of human use of the Andean highlands have been a central topic in the archaeology of western South America for decades, from the earliest records up to those linked to settlements connecting one slope to another (Aldenderfer, 1998; Capriles et al., 2016; Cortegoso, 2014; Durán et al., 2006; Murra, 1972; Rademaker et al., 2014). These environments have structures of heterogeneous landscapes which presented major challenges to the human groups that began to occupy them more than twelve thousand years ago. Some of these challenges are related to topographical and environmental differences in relation to the surrounding landscapes during the initial exploration stage (Borrero, 1989–1990). The Andes mountain range is one of the key physiographic features of South America, extending 7500 km along the western margin of the continent, from 10° N in Colombia to 53° S in Tierra del Fuego Island (Clapperton, 1993). The Southern Andes have extreme elevations of this geological structure with heights above than 6000 masl.

The purpose of this work is to present a spatial model of human movements in high-altitude spaces, their means of procurement and use of lithic sources through a GIS model based on the cost of movement as a function of the topography. The model makes it possible to suggest how these movements took place in one of the most challenging barriers for human groups. This work is based on archaeological studies in an Andean area on the border of Argentina and Chile, which was occupied since the beginning of the Holocene (Cortegoso et al., 2012). The area remained occupied almost continually throughout the Holocene except for a brief regional hiatus during the hyper-arid mid-Holocene period (Méndez et al., 2015).

In the Southern Andes of Central West Argentina systematic studies of procurement and sources of raw materials only during in the past two decades, fundamentally in the northwest of Mendoza and San Juan (Castro et al., 2014, 2020; Cortegoso, 2004; Cortegoso et al., 2017; among others). The creation of a methodological tool to evaluate movement costs as a function of topography is still an ongoing task. Importantly, this approach can be applied to other highland contexts, thus allowing to build a comparative geographic framework.

We discuss the relevance of applying to the classic proposals that discriminate between local and non-local resources as a function of distance in the Andes. We also explore the tools developed for the cost of movement in different types of environments and confront them with those that are considered most appropriate for studies of high-altitude environments, based on novel actualistic records for environments

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higher than 3000 masl. Into account this information in addition to ethnographic data, the precision of the usually applied Tobler's Offpath Hiking algorithm (1993) is evaluated.

On the basis of a case study in the northwest of San Juan (Argentina, 29°20′S) (Fig. 1), the GIS methodology was tested on a local scale, evaluating the effects of distance, altitude and slope on source accessibility costs. Finally, it is considered that the resulting model could be useful to predict the relative location of sources to lower cost routes that could link the area with peripheral settlement nodes registered in the upper and intermediate valleys of both mountain ranges.

2. Background

The use of GIS to interpret spatial data and the creation of models has caused great impact on anthropology and archaeology (Ebert, 2004). Archaeological data are spatial and temporal in nature and therefore adjust to the basic principles that promote the dynamics and use of GIS.

In the Southern Andes of CWA an increase in the use of GIS has been observed in research projects including different latitudinal segments between 29° and 34° latitude South (Fig. 1). In these regions, GIS has been used to address different archaeological issues in high-altitude environments through the application of analytical techniques such as geomorphometry and terrain analysis, geoprocessing of spatial data and geographic models in different scales and latitudes.

At latitude 29°S (NW of San Juan) GIS has been used in the analysis and modeling of lithic resource exploitation, intensity of site use and human interactions between mountain divides slopes, as well as possible circulation/contact routes between high and lowlands (Castro et al., 2014, 2020; Lucero, 2015; Lucero et al., 2016, 2014). At 32°S (NW of Mendoza) it was applied to model lower-cost routes, evaluate accessibility and possible connection routes between different locations with archaeological history and high-quality sources of siliceous rock (Cortegoso et al., 2017). Between 34° S and 36° S (Andean area of central Mendoza and north of Neuquén) a model was tested to calculate the distribution of obsidian sources by means of spatial clusters and to evaluate the anisotropic cost and relative distribution of sites containing obsidian from minority sources (Cortegoso et al., 2016).

In all these projects, GIS has played a key role in the treatment of data and the interpretation of spatial and temporal phenomena, making it possible to combine different sources of environmental, geographical, geological and stratigraphic data, as well as to process information issuing from different lines of evidence, improve the data layout and conduct the best possible comparative analysis.

3. Provenance studies in archaeology (raw materials and their sources)

The sources of raw material are key to understand the manner in which human groups used lithic resources and technology (Ericson, 1984). One of the frequent proposals in technology research is linked to the origin of lithic materials in sites (Odell, 2004). Information regarding the availability of rocks for knapping makes it possible to assess hypotheses and inferences linked to the relations between geographic localities, accessibility, ranges of action and degree of mobility of the groups, as well as systems of lithic production, procurement strategies and interaction among populations (Bamforth, 1986; Binford, 1979; Kuhn, 1995; Meltzer, 1989; among others).

The availability, dispersion and spheres of interaction between groups have been assessed through the analysis of sources from different perspectives (Kuhn, 2004; Lhomme et al., 2004; Meltzer, 1989; Odell, 1989; Renfrew, 1977; Turq et al., 1999). The presence of foreign elements can also be linked to the social value attached to the resources (Brose, 1994; Martínez and Mackie, 2004; Sassaman, 1993; among others).

In ethnographically-based provenance studies, Gould (1980) and Gould and Saggers (1985) proposed a radius of 40 km to distinguish

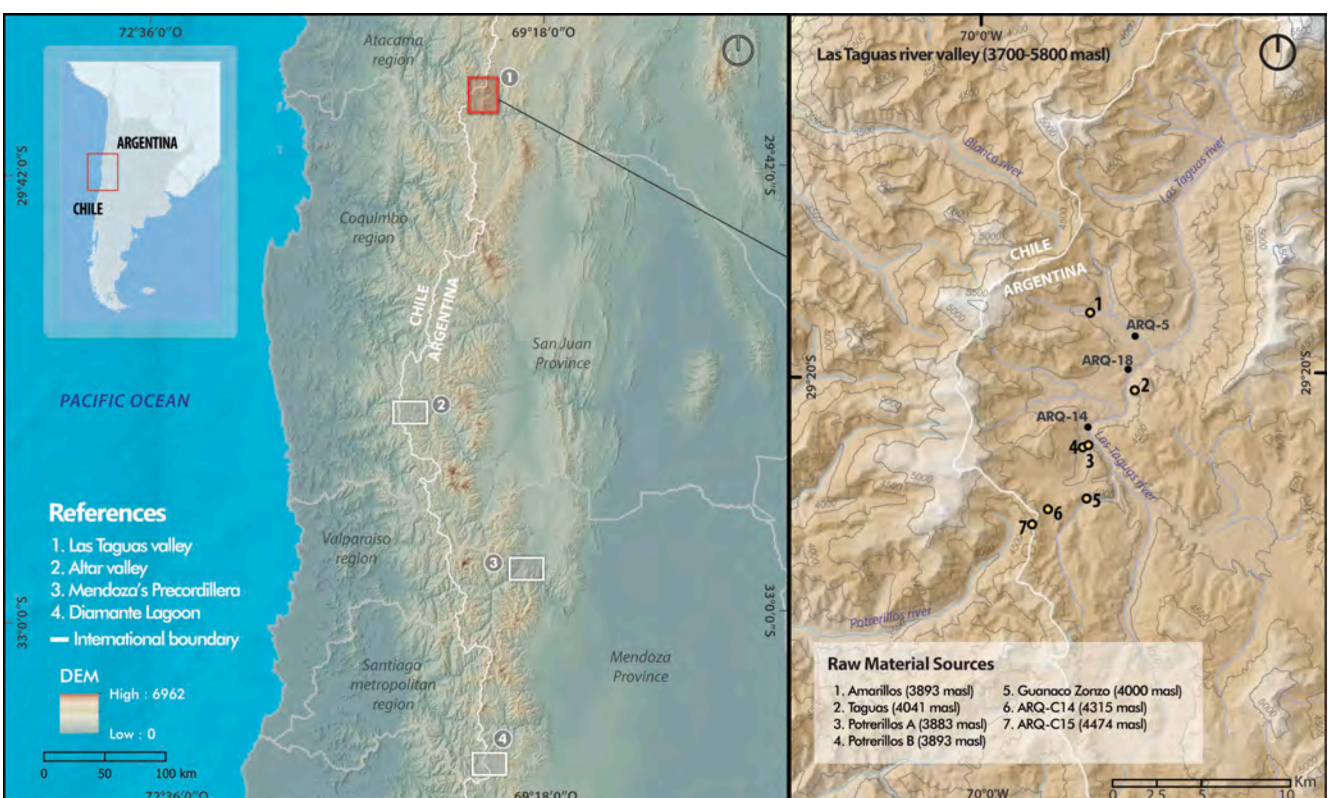

Fig. 1. Area of study.

between local and non-local resources. Meltzer (1989), in an archaeological study on Paleo-Indians in the east of USA, applies this proposal but includes within the local category resources issuing from the immediate neighborhood, i.e., rocks available near to the place of use and/or discarding.

In Argentina many criteria have been considered. Ethnographically-based works have been widely used for studies in plains and lowland environments (Bayón and Flegenheimer, 2004; Civalero and Franco, 2003; Hermo et al., 2015; Salgán, 2012; among others). When comparing these works, modifications are observed tending to adjust Meltzer's proposal to the spatial scales of each project. For example, Civalero and Franco (2003) maintain the proposal of 40 km for local rocks but discriminate between immediately available rocks located within 5 km from the site and rocks close to the site located at a distance of less than 10 km. In another example, Bayón and Flegenheimer (2004) extend the local range to 60 km, within which the immediately available rocks are those located at 10 km from the site. They refer to resources originating from a middle distance when the sources are located between 60 and 100 km away, and to long distances when they exceed 100 km.

Geographic criteria are frequently used in Andean environments of Argentina; the range assigned to local provenance is usually lower than Meltzer's proposed. Aschero (1988) introduces the term micro-region and considers local sources to be those resembling a specific geographical feature (e.g ravines) in hunter-gatherer contexts. This proposal has been applied in different Andean regions to discriminate between local and non-local provenance (Cortegoso, 2004; Pintar, 1995; Yacobaccio, 1991). In the grasslands (Puna) of Argentina (3500–4500 masl), the methodological options used to determine the provenance of lithic resources are varied. In Catamarca, Ratto (2003) considers local sources to be those located within a range of 5 km within the same sub-basin, regional those located indistinctly within one of the sub-basins of the region, and extra-regional those located outside the region of study. In Antofagasta de la Sierra, in addition to the mentioned works that follow the micro-region criterion, some works have applied the proposals of Meltzer (1989) and Civalero and Franco (2003), while in others the radius estimated to be local has been reduced to a maximum of 25–30 km (Escola, 2000; Hocsman, 2006).

The reduction of the distance estimated to determine whether a resource is local or non-local is linked to the greater costs (in time and energy) required to move around in high-altitude environments. For this reason, in order to evaluate the provisioning costs of lithic resources in Andean environments it is fundamental to consider, in addition to distance, the slope and its relationship with speed of movement (Aldenderfer, 1998; Tripcevich, 2007, 2008a).

4. Materials and methodology

We examine how movement costs in the landscape can be modeled, in order to apply a least-cost analysis (Surface-Evans and White, 2012; White, 2015; Whitley, 2017). Spatial analyses using GIS occupy a predominant place in the construction of a model, and actualistic information provides it with greater substance (Binford, 1967).

The model is based on a cost function that makes it possible to calculate the cost of movement from one raster cell to another neighboring cell. Isotropic and anisotropic curves have been applied to different studies on pedestrian routes (Ericson and Goldstein, 1980; Langmuir, 1984; Naismith, 1892; Rees, 2003; Tobler, 1993). These curves take into account different variables such as slope degree, topography, meteorological conditions and even physical and psychological conditions (Márquez Pérez, Vallejo Villalta and Álvarez Francoso, 2015). To evaluate the cost of human movements in high-altitude environments we selected the Tobler hiking function (1993), which recognizes the effects of slope on ascending and descending movements. This function is expressed as follows:

$$w = 6exp^{\{-3.5*abs(S+0.05)\}}$$

Where W is the speed of movement on foot represented in km/h and S is the tangent of the slope in radians. Tobler indicates that the function is devised thinking of movements walking along footpaths. If the movements occur offpath, the function is multiplied by 3/5 (0,6), and the formula is expressed as follows:

$$w = 0.6exp^{\{-3.5*abs(S+0.05)\}}$$

Thus, movement costs will be evaluated according to Tobler's off-path (OP) curve, because it shows slower movement speeds than the footpath curve (Fig. 2a), which assumes the presence of clearly marked out pathways in the analysis.

The OP algorithm (Fig. 2a) is based on an anisotropic method in which the direction of the movement (ascending or descending) affects the cost in time, which is very important in Andean environments where there are notable topographic differences. As a general principle, moving along a terrain with slope fluctuations is considered to be anisotropic, involving greater effort when moving along a cell with positive slope and lesser costs when dealing with a negative slope (Herzog, 2014). Tobler's hiking function has been widely used in archaeological studies that evaluate the cost of human movements (Aldenderfer, 1998; Jennings and Craig, 2001; Lucero et al., 2014; Magee, 2015; Tripcevich, 2008b; among others), due to its continuous values and its ease of application using the ArcGIS program to calculate optimal routes (Jennings and Craig, 2001; Tripcevich, 2008a, 2008b).

We believe that OP considers standard values similar to curves commonly used in the calculation of pedestrian locomotion[1] (Fig. 2b). In almost all these curves a reduction of speed is recorded as the positive slope increases (Márquez Pérez et al., 2015). If we compare the Tobler curve with those of Ericson and Goldstein (1980), Naismith (1892) and Rees (2003) and take as an example a slope of 10°, it is observed that in positive slopes the average speed is 2.1 km/h and in negative slopes it is 2.3 km/h. In positive slopes, the curve of Tobler shows a difference of 1.5 km with the Rees curve, which has the least cost. In turn, in negative slopes it maintains a difference of 0.5 km/h with regard to the least cost curve developed by Ericson and Goldstein. The greatest differences are observed on surfaces with no slope, where they can reach 1.5 km/h, which when added up in wide spatial scales can result in relevant cost differences.

We evaluated the precision and relevance of OP for Andean environments on the basis of comparative values set forth in a novel actualistic study in 2012 in the San Juan Andean range (Fig. 3). In this test two individuals[2] went on a cross-country walk plotting out a track with the use of a GPS navigator. The walk began at the confluence of rivers Casa de Piedra and La Pantanosa at 3200 masl and culminated at the international boundary between Argentina and Chile at 3800 masl. The outbound trip was on an average ascending slope of 10°, and 6.5 km were traversed in 4.5 h at an estimated average speed of 1.4 km/h. The return trip had a descending slope of −10° and 7 km were covered in 3 h at an estimated average speed of 2.3 km/h. A comparison of these results with those estimated by Tobler's OP showed coincidences, with a barely higher cost in actualistic tracking of 0.5 h in the ascending movement stage. We thus reached the conclusion that the application of Tobler's curve to evaluate the cost of movement in spaces with abrupt topography is relevant.

The spatial modeling involved the use of a geo-referenced mosaic with 34 digital elevation model scenes (DEM) obtained from an ASTER Global DEM source. We used the ArcGIS 10.4.1 software and the

[1] For a more in-depth analysis of the characteristics of each curve see Herzog 2014; Márquez Pérez et al. 2015.

[2] Both individuals were acclimatized to this type of high-altitude space, having worked at that height for the past 10 years.

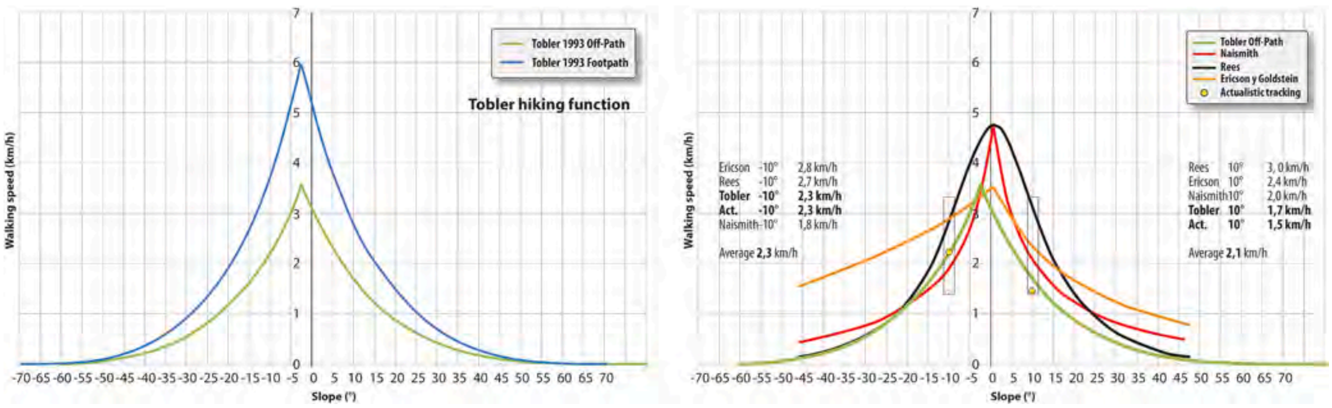

Fig. 2. a) Tobler offpath and footpath curves (1993). b) Comparison of curves used in pedestrian locomotion calculations.

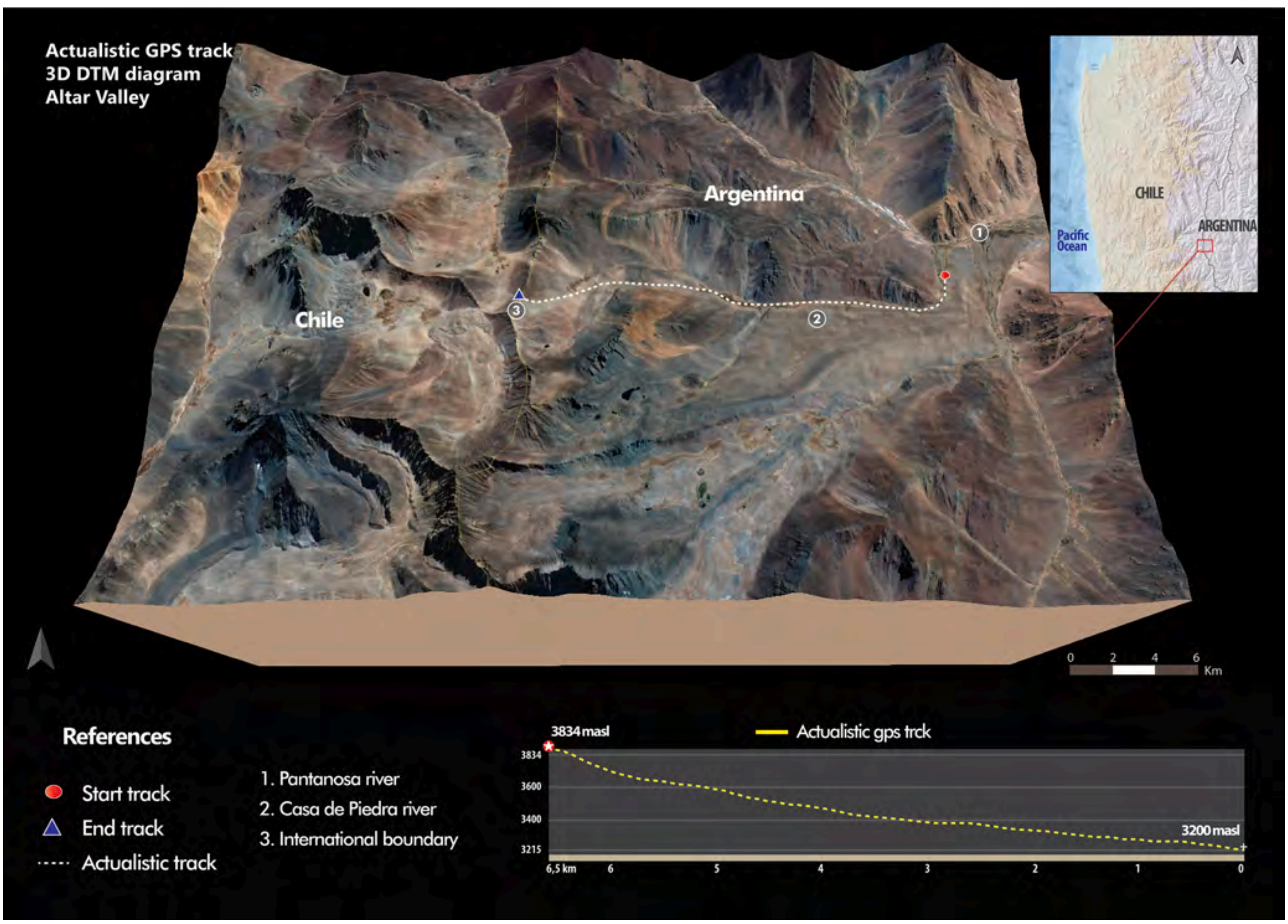

Fig. 3. Digital 3D actualistic tracking model, valley of the Casa de Piedra river, SW of San Juan, Argentina.

adjustment of Tobler's algorithm to the ArcGIS as posited by Tripcevich (2007-2008) but with a modification of the offpath function. Using the *Path Distance* tool, friction surfaces were generated representing variations in the surface distance due to the slope (Gietl et al., 2007; Whitley, 2017). The result of the GIS analysis is a DTM with values expressed over time, divided into isochronal entities of 2 h each and of 8 h equivalent to a pedestrian movement day starting from a centroid (Fig. 4).

For this work we considered other spatial studies carried out in the northwest of San Juan (Lucero et al., 2014; Lucero, 2015) and also contrasted ethnographic data at a regional level and from other Andean areas (Erazo and Garay-Flühmann, 2011; Gasco et al., 2015; Opazo, 1917; Tripcevich, 2008a; among others) which provide contextual information to the model. Even with this analogy-derived information available, there is no reason to consider that a person or group may not have walked for a longer time per day to obtain the resources or extended the search for more hours. In summer seasons, when these spaces were occupied, no extreme conditions are expected normally when walking during daytime hours. Taking this into account and our own experience interpreted in the actualistic work, an 8-hour day seems to be a realistically balanced average value.

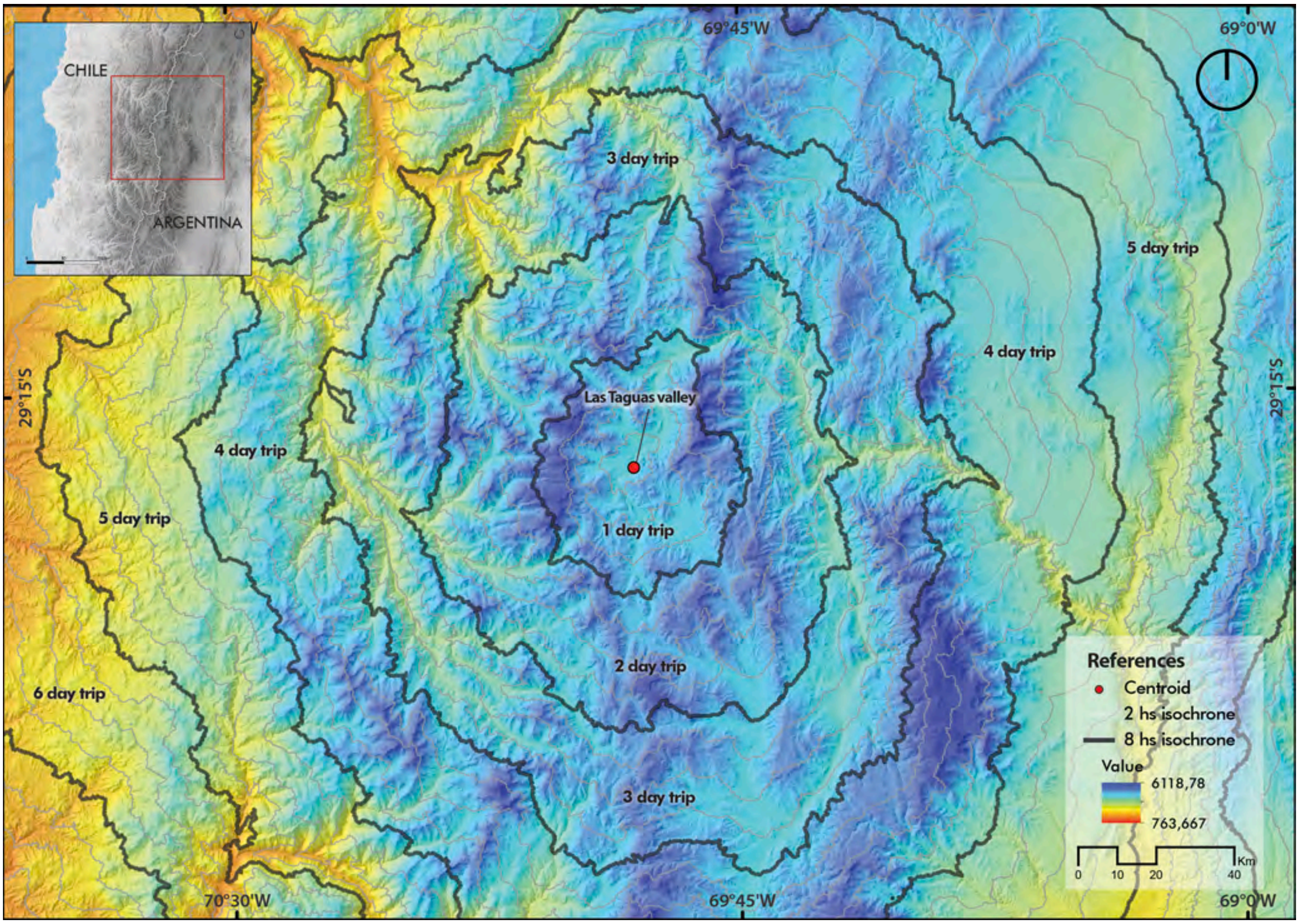

Fig. 4. Generation of a digital terrain model (DTM) on the basis of a friction surface as a function of the slope.

As observed, the procurement models that have been used in Patagonia or Pampa consider only ethnographic data from other comparable environments to estimate procurement costs. In this study we have provided the ethnographic data of movements in high altitude environments with an unpublished actualistic study as a suitable input for modeling with GIS and that improves the previous equations that are not thought for highland topographies.

5. Results

5.1. Local provenance: ranges of distance as a function of cost in time

We first evaluated how the OP algorithm works to compare speed of movement (km/h) in flat surfaces and reliefs with slopes of 15° (Lucero, 2015). The results indicate that in flat reliefs the speed is 3 km/h while in slopes of 15° the speed drops to 1.18 km/h uphill and 1.67 km/h downhill (Table 1). Getting back to the classic ethnographic models that propose 40 km as the limit for local provenance, we assess how much would it cost to cover 40 km in reliefs with abrupt topographies. For terrains without slopes –such as the Australian desert– walking that distance has a cost of 13 h, whereas in reliefs with slopes of + 15° the cost is 34 h and with slopes of −15° the cost is 24 h (Table 1). It is observed that the costs in reliefs with abrupt topographies are higher than those on flat reliefs and widely exceed any potential daily time of movement.

On the basis of OP we contrasted the movement costs of the classic model (Gould and Saggers, 1985; Meltzer, 1989) for neutral and abruptly-sloped terrains with the actualistic study for abrupt slopes.

As of a distance of 10 km the cost diminishes considerably (Table 1) and adjusts to what a person can walk on average per day in high-altitude environments: 8.5 h in ascending movements and 6 h in descending movements. Given that neither the slopes in these spaces nor the direction of movement are constant, we evaluated how the cost of movement in a space with these characteristics varies. The spatial analysis allowed us to observe that the distance traveled and the cost of movement co-vary depending on the direction toward which the movement is oriented. Fig. 4 shows that the direction of movement involves variations in the slopes and even in the use of natural corridors such as watercourses and ravines. The comparative information between the cost values of OP and the actualistic tracking extends to surfaces between slopes of 10° and −10° (Table 1).

Table 1
Comparison of values between slopes based on Tobler's OP and actualistic tracking.

	Slope	Speed	Distance	Cost
Tobler's OP	0°	3 km/h	40 km	13 h
	15°	1.18 km/h	40 km	34 h
	−15	1.67 km/h	40 km	24 h
	15°	1.18 km/h	10 km	8,5h
	−15	1.67 km/h	10 km	6 h
	10°	1.63 km/h	6,5 km	4 h
	−10	2.31 km/h	7 km	3 h
Actualistic tracking	10°	1.4 km/h	6,5 km	4,5h
	−10	2.3 km/h	7 km	3 h

5.2. Case study: exploitation of lithic resources on a local scale. Valle de Las Taguas (San Juan)

Based on a case study in the Las Taguas river area (NW of San Juan, Argentina) we tested the GIS model at a local scale, evaluating the effect of distance and other key factors on high-altitude environments such as altitude and slope on the accessibility to sources. On a local scale, we combine the variable cost of exploitation of the resource (model) with the variable quality of the source. It is important to note that the quality of resources is not an extrapolated data as it is unique to each region.

The upper basin of Las Taguas river is situated at 3700 masl, surrounded by mountain chains higher than 5500 masl. The area records occupations between 9980 cal yr BP and 510 cal yr BP. A study has been made of all productive systems and technological changes from a spatial and temporal perspective (Lucero et al., 2017). The analysis of reduction sequences in lithic quarries and multiple activity sites evidenced that sequential lithic production systems were maintained (Ericson, 1984), although a variability was observed in the exploitation of the resources in terms of procurement costs and type of subsistence strategy (Castro et al., 2014; Lucero et al., 2017). The sequence include subsistence systems change from hunters and gatherers to herders recorded in ca. 3000 years BP (Castro et al., 2014).

Seven lithic sources were detected (Fig. 1) situated in three altitudinal segments (Castro et al., 2014). In the highest range (≥4000 masl) sources ARQ-C15 and ARQ-C14 have regular quality rocks for cutting[3]. In the intermediate range (4000–3800 masl) sources Potrerillos A, Potrerillos B, Guanaco Zonzo[4] and Amarillos present very high quality rocks. In the lowest altitude range (<3800 masl) the Taguas source has good quality rocks. Local resources include a subcategory called unpositioned sources (hereinafter Local NP) to refer rocks whose specific source locations remains unknown (they are located outside the 380 km^2 surveyed area) but whose geological and petrographic features are similar to resources recorded in the sources systematically studied. Additionally, their relative high representation could reinforce the estimation of their availability in proximate area[5]. In addition, excellent quality rocks from indeterminate provenance are recorded, the sources of which could potentially be found in the Chilean semi-arid north.

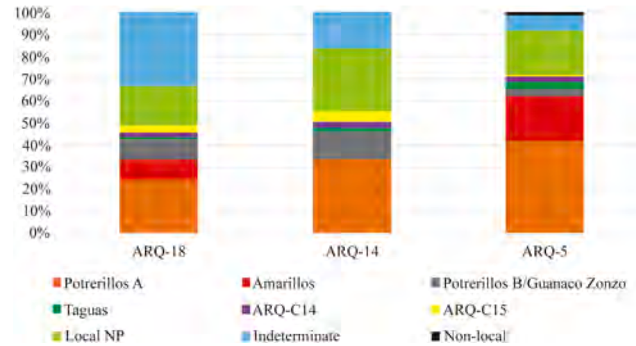

Fig. 5. Provenance of lithic resources per site.

An analysis was made of the record (N = 15617)[6] of archaeological sites ARQ-5 (510 cal BP), ARQ-14 (3050 cal BP) and ARQ-18 (3080 cal BP – 1380 cal BP). The bone, lithic and botanical record of the rock shelter ARQ-18 allow us to evaluate the recurrent use of the area by groups with diversified economies from ca. 3080 years cal BP (Castro, 2015; Gasco, 2014; Llano y Fernández, 2014). Lithic technology and associated walls and structures made of stacked stones studies at the ARQ-5 and ARQ-14 surface sites provide information that strengthens this proposal (Lucero, 2015). Based on the size, complexity of the conditioned facilities and abundant lithic records, it has been proposed that these sites could function as semi-temporary summer camps, implying in broad behavioral terms a greater intensity of occupation and an increase in redundancy of the occupations (Lucero et al., 2017). In addition, in all of them the settlement was associated with safer places, on relatively stable slopes and with the presence of critical resources for subsistence (Lucero, 2015).

From a spatial perspective considering an average of the records (Borrero, 1995), a differential exploitation of the mentioned sources was observed (Figs. 1 and 5). The Potrerillos A source is the most represented in all cases (42% in ARQ-5, 33% in ARQ-14 and 24% in ARQ-18). The Amarillos source appears in second place in ARQ-5 and ARQ-18 (20% and 10%, respectively), while there is practically no record of exploitation in ARQ-14 (<0%). Sources Potrerillos B/Guanaco Zonzo occupy second place in ARQ-14 (13%) and third in ARQ-18 (9%) and ARQ-5 (4%). The Taguas sources, ARQ-C14 and ARQ-C15, are the least represented in all cases.

We suggest that the differences in the exploitation of lithic resources are directly linked to the cost of access to the source and the quality of the rocks. To inquire about how they could operate these variables on human decisions we propose: 1) calculate the cost of access from each archaeological site to each source using hiking off path function (Fig. 6); 2) rank the quality of the rocks for knapping using the very good (3), good (2) and regular (1) ordinal scale and; 3) evaluate the degree of statistical association between these two variables using the following tests: a) Analysis of variance (ANOVA) to evaluate if there are differences between the means of the cost of access associated with the

[3] The area is characterized by the high availability of good quality resources with a lithology of hydrothermal aggregates, quartz veins and crystalline rhyolitic tuffs, all of them with a high degree of silicification (Castro et al., 2014). The regional lithic resource base involved the detection of raw material sources and lithic workshops through archaeological and geological surveys, the elaboration of a geological map in archaeological scale and a petrographic analysis to learn about the origin of the lithic resources (Castro et al., 2014; Lucero, 2015). It is understood that the best rocks for knapping are those with a homogeneous microcrystalline structure without joints, inclusions or other types of irregularities which give them a conchoidal fractures (Nami, 1992; Andrefsky, 1998). We also consider the mechanical and thermal processes that affect rock quality due to the periglacial environment. In order to these data and considering the resources that the area presents three quality categories are used: 1- Very Good (the rocks dońt show weathering and/or crust), 2- Good (the rocks appear in veins) and 3- Fair (high presence of crust and the degree of fracturing and weathering). The quality category also considers how resources are presented in nature (eg in the form of pebbles, nodules, veins) to give an idea of the cost of extracting those particular resources.

[4] Geological prospections in Potrerillos B and Guanaco Zonzo sources have indicated availability in both locations of siliceous rocks with similar macroscopic characteristics, and therefore these sources are presented jointly in the provenance analysis.

[5] In relation to the different geological location and the recurrence of exploitation, we can classify sources as "localized": defined quarries and specific localities where the rock is found, which can be visited repeatedly; or "non-localized": rocks collected on the surface of the ground or near the place where they are needed (Gould, 1978).

[6] It is based on the certainty that the understanding of the technological organization and the reconstruction of lithic production systems implemented by prehistoric groups requires the study of the entire lithic group (Ericson 1984; Kelly 1988). Consequently, the entire lithic record of the sites is analyzed, including nodules, cores, instruments and debris (Lucero et al. 2017).

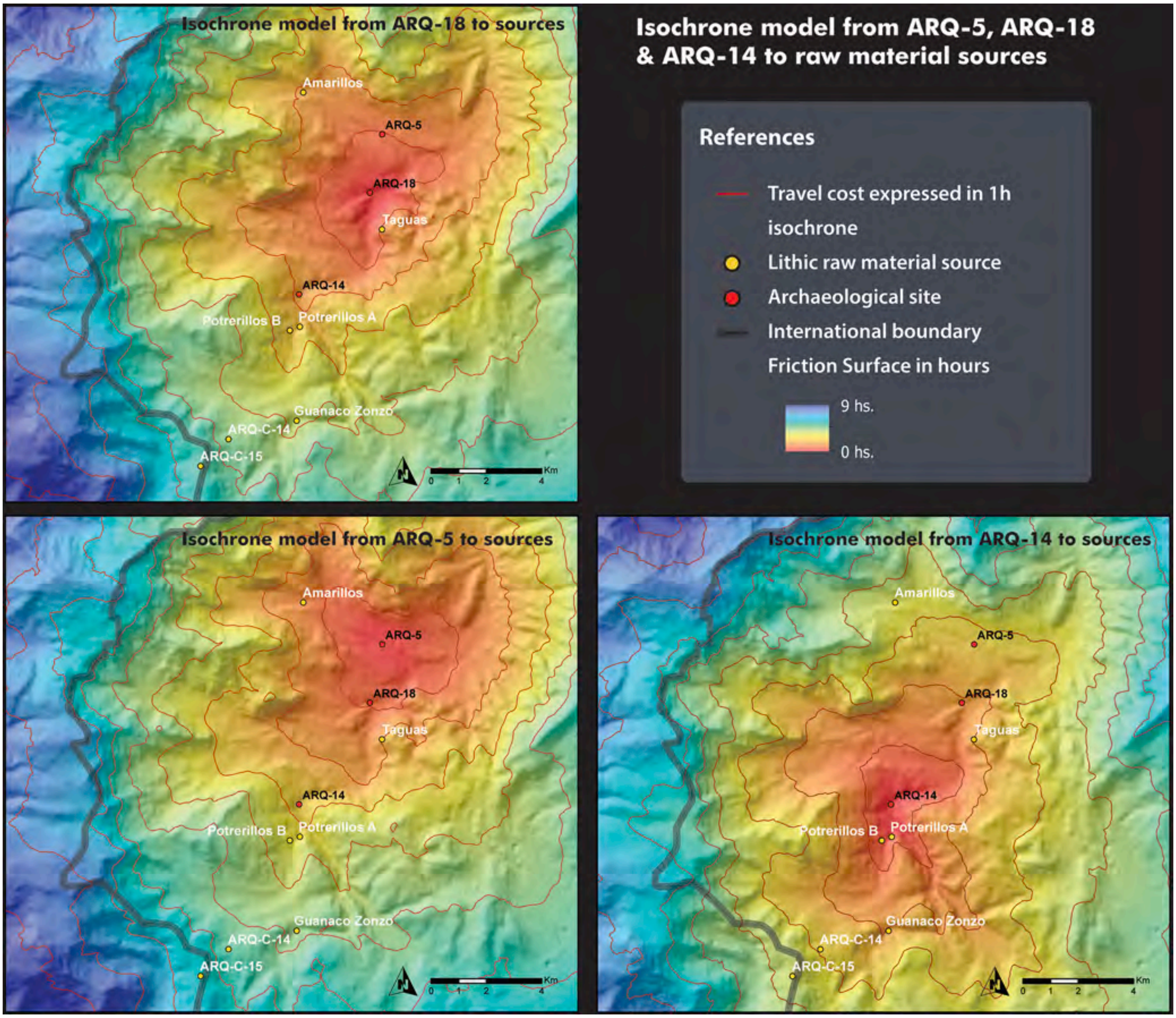

Fig. 6. Costs of accessibility to sources of lithic raw material from sites ARQ-5, ARQ-18 and ARQ-14.

Table 2
Quality/Cost Ratio relationship and qualitative criterion of relation from highest to lowest between the cost of access and quality of resources.

Site	Source	Distance (km)	Access cost (hours, minutes)	Raw material quality	Ratio = Q/C	Normalized (0 a 1)	Qualitative criterion
ARQ-14	Potrerillos A	1,2	0,32	3	9,38	1,000	Excellent
ARQ-14	Potrerillos B	1,5	0,39	2	5,13	0,539	Very Good
ARQ-5	Amarillos	3,4	1,2	3	2,50	0,254	Very Good
ARQ-18	Taguas	1,5	1,16	2	1,72	0,170	Good
ARQ-18	Amarillos	4,7	2	3	1,50	0,146	Good
ARQ-18	Potrerillos A	6,1	2,27	3	1,32	0,126	Good
ARQ-5	Taguas	4	2,05	2	0,98	0,089	Regular
ARQ-14	Guanaco Zonzo	4,8	2,07	2	0,97	0,088	Regular
ARQ-14	Taguas	4,5	2,13	2	0,94	0,085	Regular
ARQ-5	Potrerillos A	8	3,24	3	0,93	0,083	Regular
ARQ-14	Amarillos	7,3	3,35	3	0,90	0,080	Regular
ARQ-18	Potrerillos B	6,4	2,35	2	0,85	0,075	Regular
ARQ-14	ARQ-C14	6,3	2,57	2	0,78	0,067	Regular
ARQ-5	Potrerillos B	8,4	3,32	2	0,60	0,048	Regular
ARQ-18	Guanaco Zonzo	9,6	4,02	2	0,50	0,037	Regular
ARQ-18	ARQ-C14	11,2	4,55	2	0,44	0,031	Regular
ARQ-5	Guanaco Zonzo	11,7	5	2	0,40	0,026	Regular
ARQ-5	ARQ-C14	13,2	5,5	2	0,36	0,022	Regular
ARQ-14	ARQ-C15	7,7	3,44	1	0,29	0,014	Bad
ARQ-18	ARQ-C15	12,7	5,39	1	0,19	0,003	Bad
ARQ-5	ARQ-C15	14,6	6,36	1	0,16	0,000	Bad

different qualities of the rocks, b) Post-hoc analysis to determine where the differences are between the groups, c) The Spearman's correlation to assess whether there are relationships between the variables and d) "Quality/cost ratio". In this quotient the results were ordered from highest to lowest. They were normalized in order to obtain an indicator ranging from 0 to 1, where values close to 0 indicate a "lower" quality/cost relationship and results close to 1 indicate a better quality/cost relationship.

From the statistical point of view ANOVA results showed statistically significant differences there between quality and cost variables (0.031) (Table 4 Annex). The Tukey B post-hoc test shows that qualities 3 and 2 are homogeneous subgroups or, in other words, from a statistical point of view there are no differences between these subgroups. On the other hand, quality 1 (regular) is very different from the rest of the qualities, moving away in its average values (Table 5 Annex). The Spearman's correlation shows results similar to the graph of means. A significant negative correlation of −0.518 (significance of 0.016) was observed. The test suggests that as the quality of raw materials increases the cost of access costs decreases its weight in the sourcing decision. Considering that in our case the samples are unequal (3 = regular, 12 = good and 6 = very good) we carry out another test eliminating the regular qualities. Spearman's result is that there is no statistically significant correlation −0.273 (sig = 0.274). This implies that in the sphere of good-very good qualities the cost is not relevant but the quality.

There is a high association between the quality/cost variables. In the particular case of the Valle de Las Taguas sources most represented in the sets are the closest/less expensive and better quality for knapping. However, in the subgroup good/very good the relationship is not direct with the cost and we believe that in human decisions on this scale quality had a higher weight than the cost.

The results of the quality/cost ratio show a normalized theoretical graduation between the variables quality of raw materials and cost of obtaining (Table 2). Values closer to 1 indicate a better quality/cost ratio, in other words, more attractive sources for their exploitation, that is, more accessible and with higher quality resources. On the other hand, values close to 0 indicate a lower quality/cost ratio, or less attractive sources, in other words, more expensive to access and with less optimal quality resources.

Following is a description of the variable exploitation of each source and its relationship with availability in terms of accessibility and resource quality.

1) Potrerillos A, the most exploited source in the three sites, is always among the two most attractive with values of 0.083 to 1 of the cost/quality ratio. This is due to 1) low accessibility costs, not only of the distance between the sites and the source, but also of its location in the intermediate altitudinal sector (4000–3800 masl), and 2) the very good quality of its resources with very large blocks and scant cortex.

2) Amarillos, has been highly exploited in sites ARQ-18 and ARQ-5, and is the most attractive. It has a qualitative criterion of fair to good cost/quality ratio (r = 0.080–0.254). This position would be linked to the low accessibility costs from those sites and the very good quality of the resources.

3) Sources Potrerillos B/Guanaco Zonzo are ranked in intermediate positions because their access costs are differential. Potrerillos B has a qualitative criterion from fair to good (r = 0.048 to 0.539). Guanaco Zonzo B has a regular cost/quality criterion (r = 0.026 to 0.088). We can infer that the resources from the record of the three archaeological sites possibly come from Potrerillos B, since it is more attractive than Guanaco Zonzo due to its lower accessibility costs.

4) The Taguas source has a good cost-quality relation from the ARQ-18 site (r = 0.170) and fair from the ARQ-5 and ARQ-14 sites (r = 0.085–0.089) but it has been scarcely exploited. This could be due to high extraction costs because the rock appears in the form of veins.

5) The ARQ-C14 source has a fair cost-quality ratio for all three sites (r = 0.022–0.067) and the ARQ-C15 source has a poor cost-quality relationship (r = 0.000–0.014). These are the least attractive sources from the three sites, both due to their higher accessibility costs and the lower quality of the resources in terms of suitability for knapping, which explains their low representation in the sites.

6. Discussion

Integration of spatial, and cost resource exploitation analyses, provide the basis for constructing a model of human movements and source use for Andean environments. This model adopts some assumptions and proposes possible scenarios taking into account the topographic variability of the Andes: 1) in high-altitude environments, occupation by human groups is seasonal, concentrated and relatively stable during the summer season (Lucero, 2015); 2) straying from the seasonal residential or semi-permanent bases in an environment with low climatic predictability involves risks; 3) The natural lower resistance routes provide the adequate geographical setting for human circulation (Herzog, 2013, Borrero, 1989–1990), and basically in the Andes (Tripcevich, 2007; Lucero, 2015).

Other factors considered are the range in terms of distance (km) over a very variable amount of time depending on the topographical features of each region, the presence of natural access and circulation routes (e.g. ravines, rivers and streams) and the direction in which the movement is oriented. We propose that a one 8-hour traveling day covering an average distance of 15.5 km is the standard to configure the scale of access to local sources using a predominantly direct procurement strategy (Binford, 1979; Meltzer, 1989) (Table 3). On this local scale, exploitation can be variable depending on the relation between accessibility cost and rock quality.

Between the second (32 km average) and third day (49 km average) of movement, a non-local resource environment is structured, where human groups had access to other types and varieties of raw materials using direct and indirect procurement strategies. The fourth day marks the beginning of the extra-regional sources, where evidence of exchanges usually appears.

In the case of the Las Taguas river, groups had access to a variety of different quality resources with differential costs as a function of their altitudinal and topographic location. In the first range of movement the predominant procurement strategies may have been direct (Lucero et al., 2017). In accordance with the proposed model, the sources of the mesoregion of study are "local", and within this category siliceous rocks and rhyolitic tuff are found (Fig. 5). The landscape structure is made up of natural connectivity corridors given by their topographic features and the presence of resources for subsistence purposes (Lucero, 2015).

In two days it was possible to travel an average of 32 km and in three days an average of 49 km in a radial manner. The movements were transversal, using the valley bottoms and routes of lower resistance. In the western sector of the range these features would encompass circulation along the tributaries and upper basins of the Elqui and Huasco rivers, which have been proposed as connectivity routes between both mountain slopes (see Lucero et al., 2014). In the eastern section, circulation is more feasible in a north to south direction because of the presence of mountain chains with altitudes higher than 5000 masl toward the west of the area of study. In the north it would be along the upper basin of the Las Taguas river and the longitudinal corridors of the

Table 3
Model of human movements and resource exploitation for Andean environments.

	First day	Second day	Third day	Fourth day
Time	8 h	16 h	32 h	64 h
Type of provenance	Local	Non-local	Non-local	Extra-regional
Average distance	15 km	32 km	49 km	63 km
Procurement strategy	Direct	Direct and indirect	Direct and indirect	Indirect

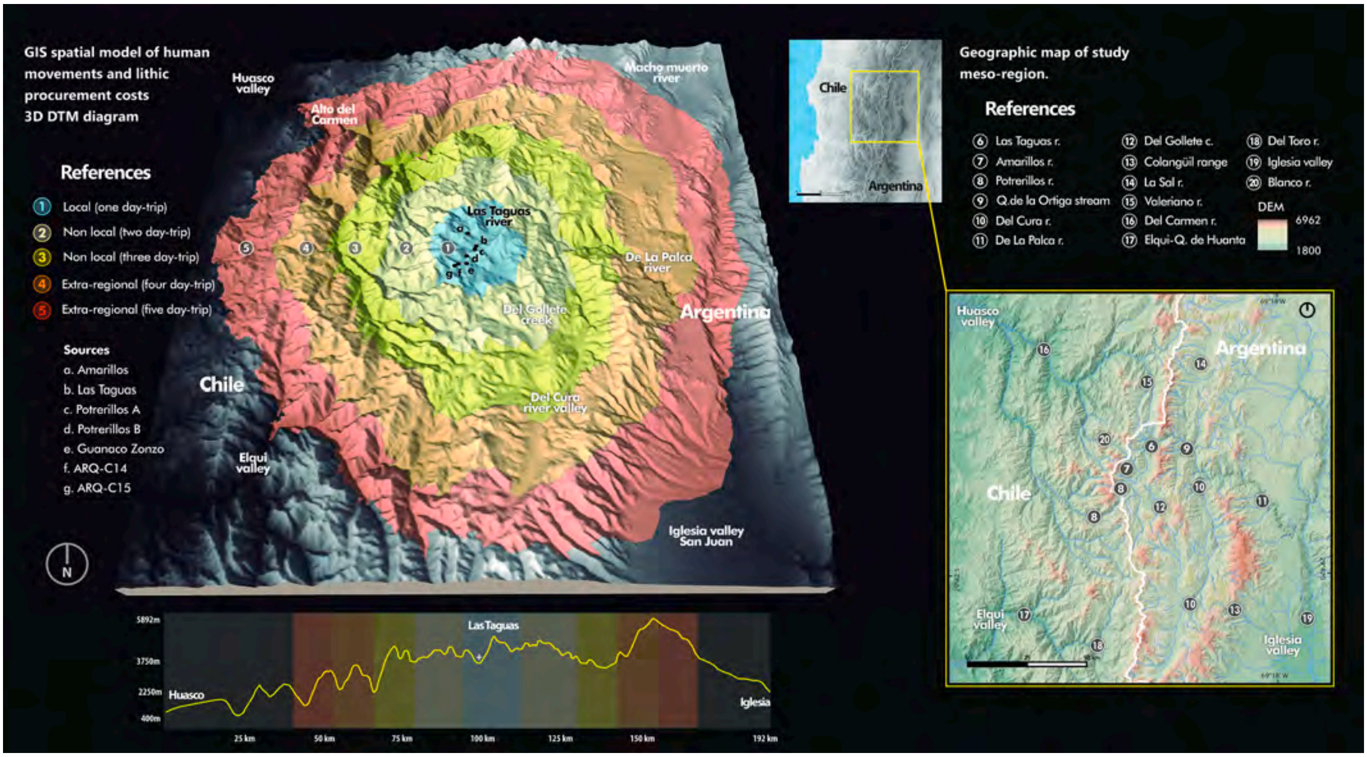

Fig. 7. Anisotropic model and geographic map of the upper basin of the Las Taguas river.

Quebrada de la Ortiga stream and the Valle del Cura and La Palca rivers. And from the southeast, along the headwaters of the Las Taguas river, El Gollete stream and the mid-course of the Valle del Cura river (see Lucero et al., 2014). The procurement strategies in these ranges may have been direct or indirect (Fig. 7).

The limits for non-local provenance would be the Colangüil range to the east, the intermediate basins of the La Sal and Valeriano rivers to the north, the El Cura stream to the south and up to the La Punilla range, comprising the mid-basin of the Del Carmen river to the northwest and the Elqui-Quebrada de Huanta and Del Toro rivers to the southwest. As of the fourth day the extra-regional environment encompasses the major part of the western interfluvial valleys and the Iglesia valley in the eastern sector. In the area of study we have not yet recorded rocks that could have been used as prestigious, exotic or exchange goods. There is, however, evidence of exchange in the peripheral valleys from both off-mountain sectors (Gambier, 1988; Niemeyer et al., 1989).

The model presented show the remarkable differences in traveling 40 km in plain environments than in Andean environments with abrupt and variable topography. In the case of regions of Puntutjarpa Australia (Gould and Saggers, 1985) traveling 40 km at the local level implies a cost between 13 and 15 h; similar situation occurs in the Pampas or in Patagonia. On the other hand, in the case of the Las Taguas Valley, the incidence of topography in the cost of movements and access to sources was clearly observed, where traveling 40 km implies a variable cost of 24–34 h in the scope of the non-local sources. In other words, a linear movement of 40 km in the Andes could imply crossing an entire mountain range, whereby the range of the local is diluted.

We consider that the GIS tool allows us to better think about spatial models to interpret mobility ranges of different types of societies. In hunter-gatherer groups, access to these sources and their exploitation could imply broad scales of movement and in transhumant groups with mixed economies it could imply specific rounds on a smaller scale. Therefore, the tools to calculate costs are useful in the analyzes that consider different geographical scales based on the movements of the human groups studied.

7. Conclusions

In this work we presented a GIS spatial model of human movements and lithic procurement costs in high-altitude environments based on geographical aspects. We examine how these movements can be modeled as a function of the effect of topographical and altitude variables, which are also key in the position, distribution and availability of resources that are critical for subsistence and the costs of obtaining lithic resources.

We discuss the relevance of applying the classic proposals that discriminate between local and non-local resources based solely on the distance factor to Andean studies on lithic resource exploitation. We compared Tobler's Offpath curve to other functions of pedestrian locomotion and, on the basis of ethnographic information and a novel actualistic study, we contrasted these values and concluded that it is the one that best fits the models and analyses of human movement in Andean contexts. We adapted this algorithm to a GIS and from an Andean enclave we conducted an analysis, the result of which made it possible to segment the resulting friction surface into isochrons of 2 and 8 h of movement toward the different sources situated in the landscape. The result is a model of analytical spatial scales of procurement which can be useful for other comparable works in Andean environments and that involve local (one 8-hour day), non-local (2–3 days) and extra-regional (4 or more days) contexts.

Finally, on a local scale, we present a case study where we apply the spatial model interacting with the variable quality of raw materials, which cannot be extrapolated and which is typical of this geographical space. The sources were characterized geologically, chemically and by the way in which resources are presented in nature. These variables were statistically tested to find a certain degree of correlation and then a qualitative criterion was sought to explain which sources could be more attractive based on the degree of association between cost/quality variables and how those resources are presented in each archaeological site, where the lower values indicate less attractive lithic resources, and the higher values indicate more attractive lithic resources. After the first day's journey, the non-local resource area begins, where the topography is considered together with the position of the resources in order to devise lower cost routes.

This type of analysis seeks to contribute to identify direct or indirect access modalities to strategic resources located in high-altitude environments by means of isochrons entailing days of movement. The days can be measured in distance, although this variable is relative, depending on the relationship between topographic complexity and time. In this sense, the proposed model is neutral because it is based on the topographical factor. In addition to considering movement costs, it allows a hierarchy to be made of relative positions of the resources in relation to the dominant circulation vectors and/or articulation of mountain divides. It is useful as a tool for formulating hypotheses and testing the access modes to strategic resources in high-altitude spaces, and can also be applied to other types of static resources in the landscape (wood, clay, for example). The modes of circulation in this type of topography are limited to natural courses of lower resistance, and therefore the model can be useful for the study and interpretation of initial exploration movements in these Andean spaces.

For a more in-depth analysis of the characteristics of each curve see Herzog, 2014; Márquez Pérez et al., 2015.

Both individuals were acclimatized to this type of high-altitude space, having worked at that height for the past 10 years.

The area is characterized by the high availability of good quality resources with a lithology of hydrothermal aggregates, quartz veins and crystalline rhyolitic tuffs, all of them with a high degree of silicification (Castro et al., 2014). The regional lithic resource base involved the detection of raw material sources and lithic workshops through archaeological and geological surveys, the elaboration of a geological map in archaeological scale and a petrographic analysis to learn about the origin of the lithic resources (Castro et al., 2014; Lucero, 2015). It is understood that the best rocks for knapping are those with a homogeneous microcrystalline structure without joints, inclusions or other types of irregularities which give them a conchoidal fractures (Andrefsky, 1998; Nami, 1992). We also consider the mechanical and thermal processes that affect rock quality due to the periglacial environment. In order to these data and considering the resources that the area presents three quality categories are used: 1- Very Good (the rocks don't show weathering and/or crust), 2- Good (the rocks appear in veins) and 3- Fair (high presence of crust and the degree of fracturing and weathering). The quality category also considers how resources are presented in nature (eg in the form of pebbles, nodules, veins) to give an idea of the cost of extracting those particular resources.

Geological prospections in Potrerillos B and Guanaco Zonzo sources have indicated availability in both locations of siliceous rocks with similar macroscopic characteristics, and therefore these sources are presented jointly in the provenance analysis.

In relation to the different geological location and the recurrence of exploitation, we can classify sources as "localized": defined quarries and specific localities where the rock is found, which can be visited repeatedly; or "non-localized": rocks collected on the surface of the ground or near the place where they are needed (Gould, 1978; Borrero, 1990; Capriles et al., 2016; Cortegoso, 2014; Durán et al., 2006; Lucero et al., 2016; Martínez and Mackie, 2004; Murra, 1972; Opazo, 1917; Rademaker et al., 2014).

It is based on the certainty that the understanding of the technological organization and the reconstruction of lithic production systems implemented by prehistoric groups requires the study of the entire lithic group (Ericson, 1984; Kelly, 1988). Consequently, the entire lithic record of the sites is analyzed, including nodules, cores, instruments and debris (Lucero et al., 2017).

This don't imply the occurrence of other economic, symbolic or phenomenological factors that have not been addressed in this analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2021.103026.

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