# Least-Cost Pathways, Exchange Routes, and Settlement Patterns
## In Late Prehistoric East-Central New Mexico

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## Abstract

The research presented here employs topographically determined Least-Cost Pathways (LCPs) to investigate the role of trade in the settlement structure of east-central New Mexico. The research evaluates the importance of trade in choosing locations of 1) architectural sites in a main drainage leading west from the Pecos River, 2) large sites in the Estancia Basin, or 3) large sites in the Galisteo Basin. If trade were important, sites would be located directly on travel routes. By extension, if LCPs accurately predict the location of travel routes, sites would be located directly on LCPs. The procedure revealed no association of LCPs with drainages of the Pecos River system. Intermediate sites in the Estancia Basin were not clearly associated with LCPs. However, at least three important sites were located very close to LCPs between other important sites in the Galisteo Basin. The validity and usefulness of the procedure are discussed.

## 1 Introduction

The theme of this year's conference emphasizes new frontiers and discovery. This paper follows that theme in that it examines settlement patterns in east-central New Mexico during the protohistoric and early historic periods. Here was a frontier between Spain and the Pueblo world. But it was more than that. The most eastern pueblos lie on the frontier between the Great Plains and the Southwest, and between the differently organized peoples that used those two geographic provinces. There is evidence of growing trade between the two groups, as bison meat was transported west to the growing Puebloan communities in exchange for maize, cotton blankets and clothing, and other goods (Spielmann 1991). At the same time, trade was thriving among the Puebloan population centers along and adjacent to the northern Rio Grande.

The research presented here explores the use of Geographic Information Systems and Least-Cost Pathways (LCPs) to investigate exchange routes and the role of trade in the settlement structure of east-central New Mexico. LCPs are approximations of logical routes for human travel between and among site clusters. For this paper, I assume that the method used does return a reasonably accurate approximation of the routes that humans would choose, although my results allow a few observations about that assumption (see below).

Basic to the underlying theoretical position of this paper is the concept of a mature exchange system. I define such a system as one in which trade is important and inclusive. That is, its value to the livelihoods of the people in the system is not negligible. Further, a non-negligible portion of the population or settlement system engages in this trade. These are relative terms: the more important and inclusive the trade, the more mature the system. Here, then, is the theoretical proposition: the more mature the exchange system, the greater will be the influence of exchange routes on site location. For archaeological situations, then, the greater

the trade, the more likely that some sites will be directly located on transportation routes between two other sites. In more general terms, trade may explain the locations and the sequence of settlement in a region.

Modeling greatest efficiency routes has a great deal of promise for archaeological investigation of economic landscapes, but has not yet been widely applied. Most archaeological applications have examined the closeness of fit of LCPs to archaeologically or historically documented roads or paths (Aubuchon 2003; Gorenflo and Bell 1991; Kantner 1997; Whitley and Hicks 2001). In other studies, LCPs have been used to explain the location of monumental art (Jensen 2003), to predict prehistoric economic boundaries around central places (Hare 2004), and to provide insight into the routes taken during the Paleoindian expansion into and around the Americas (Anderson and Gillam 2000). They have also been used to evaluate the economic interconnectedness of sites in a small region of Italy (Bell et al. 2002). The present research follows the latter focus of evaluating the interconnectedness of sites. I evaluate the use of LCPs to explore the role of trade and communication links in structuring settlement systems.

The setting is east central New Mexico, from the southern tip of the Rocky Mountains in the north and the central mountain chain in the west, to the 34th parallel of latitude in the south and the Pecos River in the east (Figure 1). Three very different clusters of settlement are used for this study. All are late prehistoric, but not necessarily contemporaneous. The regions were selected because site density and distribution suggest three different levels of internal economic integration, and thus three different levels of intensity of trade. To make this assessment, I used the following considerations. Large sites that are more clustered likely represent a more mature and inclusive economy. Sites that are spread out, in contrast, are likely to be not as closely linked within an economic system or network. Sites that are very widely

dispersed are even more independent of the constraints and opportunities of an economic system. Of course, direct archaeological or historical evidence of trade and/or specialization will complement the evidence from settlement patterns. These three areas, then, would provide interesting comparative cases for the use of LCPs to analyze the effect of trade on the distribution of settlements. I used large, named sites for this research, although many more sites are documented.

The first group is an aggregated cluster of communities in dissected terrain (Figure 2). The Galisteo Basin, just southeast of Santa Fe, is an area of heavy site density, with some of the largest architectural sites in New Mexico. Most date to Pueblo IV, the last Puebloan phase prior to the arrival of the Spanish. An unknown number were occupied at the time of contact, and it is difficult to positively connect colonial names with the sites. The Galisteo Basin was the early focus of archaeological research, in the days of Nelson and Kidder, but little professional work has been done since then, until the recent survey at Burnt Corn Pueblo by Snead and excavations at San Marcos by Thomas and by Ramenofsky (Pierce and Ramenofsky 2000; Snead 2004).

Along with the Galisteo Basin sites, I included the sites of Tunque, in the Rio Grande Valley to the west, and Pecos, on the upper Pecos River, a major center of trade with the peoples of the plains (Spielmann 1991). A lively trade among these sites is documented historically, and there is archaeological and historical evidence of community specialization. San Marcos is thought to have exploited and perhaps controlled turquoise mines in the Cerrillos Hills, while Tunque is thought to have specialized in pottery production (Barrett 2002; Morales 1997). These archaeological and historical indicators distinguish the Galisteo Basin as the most economically well-integrated of the three areas. While there is some information about colonial routes of travel among these sites, roadways have not been detected.

Second is another well-established population cluster partly in flat terrain, and partly strung out along the base of the mountains in the Estancia Basin (Figure 3). These include the Salinas and Jumanos Pueblos, so named by the Spanish.

Trade is again well attested, again without much detail. Salt was a major item of trade for at least some of these communities—note the extensive playa system. The salt trade would probably have been directed mostly to the west over Abo Pass to the pueblos of the southern Albuquerque communities. Gran Quivira, the largest community in the area, was noted for its trade with Plains peoples (Spielmann 1991). Note that the Estancia Basin communities are not clustered as tightly as the communities of the Galisteo Basin, and there is a linear distribution of sites to the north along the base of the mountains. Thus, I estimate the Estancia Basin to be a less mature economic system.

Third is a rather linear distribution of poorly-known sites in Pintada Arroyo, a major drainage of more than 60 miles descending from the edge of the Estancia Basin down to the Pecos River (Figure 4). These are frontier settlements in the sense that they are very low density, and well distant from any centers of population in the eastern Pueblo world.

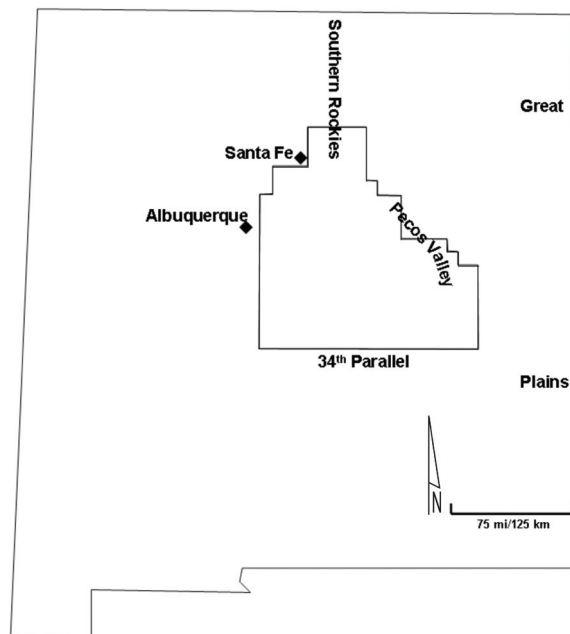There are at least four large sites in two clusters of two in



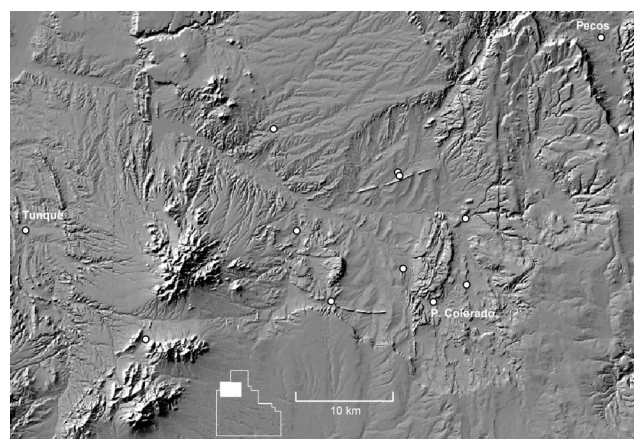Figure 1. Location of the study area within New Mexico.



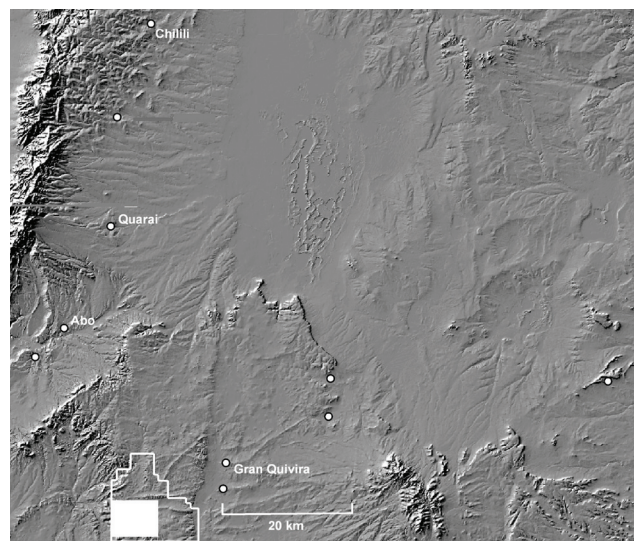Figure 2. Major sites of the Galisteo Basin, plus Pecos and Tunque.
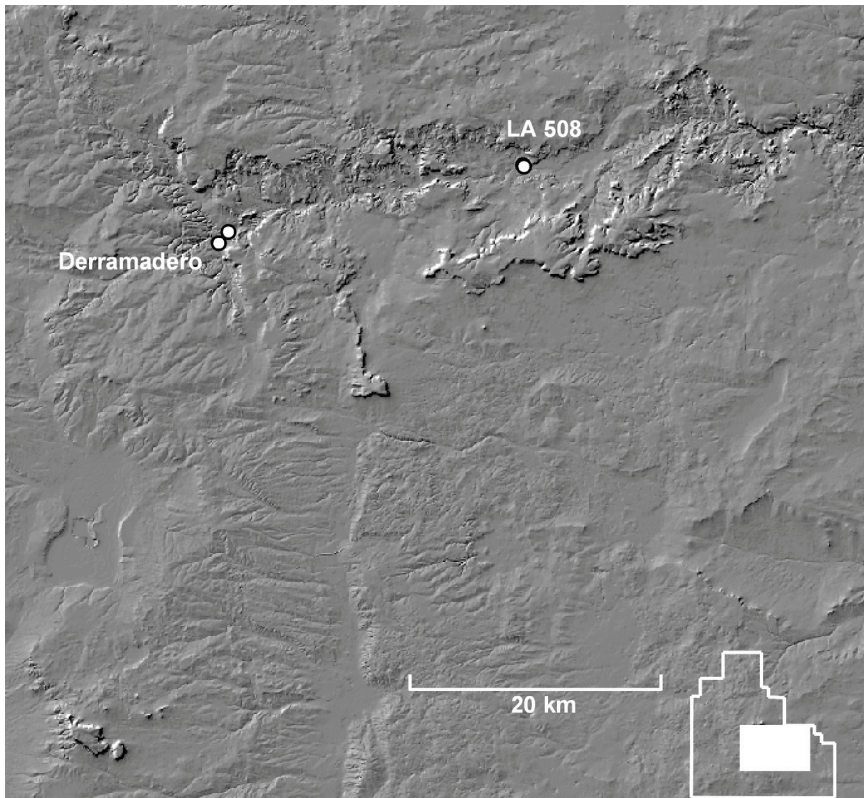


Figure 3. Major sites of the Estancia Basin.

*Figure 4. Major sites of Pintada Arroyo.*

is far from any population clusters, and there could be many reasons for a canyon setting to be chosen for these remote settlements. Three that come easily to mind are, first, that canyons collect and channel runoff, thus concentrating sparse rainfall at parcels of land that may be of sufficient size to support a settlement. Second, canyons are sheltered and provide such benefits as piñon, wild game, and protection from enemies. Third, canyons may provide natural travel routes. If trade were to explain the location of these settlements, then I would expect this last reason to be the case.

In areas remote from major population concentrations, however, the influence of trade on location choice can be inferred only if there is a major or at least a logical trade route between two other places passing near to a settlement. I suggest that if the Pintada Arroyo sites were formed or grew to take advantage of the growing trade between the Southwest and the Plains, then they will be located along an important route for that trade. If the route does not exist, then it is not likely that trade played a major role in determining site location. In this area, the LCPs would have to model routes from diffuse origin points (the Plains) to a single settlement cluster (the Salinas Pueblos). If Pintada Arroyo formed a topographically superior route from the plains to Quarai (for example), then LCPs originating at scattered and arbitrary points along the Pecos River should coalesce and funnel right past the Pintada Arroyo sites.

That leaves the Estancia Basin cluster. My expectation here was that trade between the Rio Grande Pueblos and the Salinas and Jumanos Pueblos took a dendritic form. That is, the trade was externally oriented: trade goods from the Plains and salt from the playas were passed on to the populous communities along the Rio Grande. The Estancia Basin pueblos, according to this line of thought, were not so much a part of a network as outliers of a network. Goods were concentrated and transported to the consumer communities in the Rio Grande Valley. Because of this, and because sites are spread out rather than clustered, I did not expect clear evidence from the LCPs of a maturing network in which sites were located to take advantage of trade routes between other sites.

this broad canyon. They are not documented in the historical record, and were probably already abandoned before the arrival of the Spanish. Some were apparently founded and abandoned between about AD 1000 and 1350, while others survived into the PIV period. All on private land, none has been professionally excavated or mapped. The extent to which these communities participated in trade can only be guessed at, but it seems likely that this was economically the least mature of the three areas.

## 2  Expectations

What can Least Cost Pathways tell us about the relationships between and among settlements in these three clusters? The issue to be evaluated is whether exchange was a factor in decisions about community location. It seems likely that economic activity along a trade route invites new communities to establish themselves along that route. This is the premise behind Christaller's K=4 central place system, in which communities are founded and grow on the transport routes between other centers (Smith 1974). In a developing settlement system with flourishing commerce, routes connecting certain points in the system would likely stimulate the founding of new communities to take advantage of commercial traffic. It is clear that commerce thrived in the northern Rio Grande and adjacent Galisteo Basin, as noted above. Thus, as the site cluster with the greatest apparent economic maturity, we might expect LCPs between two sites to run very near to another site.

At the other extreme, one would not expect an area with low site densities to have the same structure. Pintada Arroyo

## 3  Methods

Least cost pathways begin with a cost surface: a raster map where the z-dimension is the least accumulated travel cost of each cell from a specific source point. GIS programs are capable of incorporating diverse variables into a cost surface, from a slope-based value, to vegetation, water, and

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other environmental or social variables that may affect the cost of travel through a landscape.

There are two basic approaches to the problem of creating cost surfaces for archaeological landscapes. One prefers simple solutions with only one variable, and the other prefers to get closer to reality by adding more complex sets of variables. I belong to the former group. In my view, we do not know enough about prehistoric values to know how to weight the multiplicity of possible variables. In the Southwest, these include reliable water, shelter from the wind, good fuel sources, and defensible locations. Creating a cost surface that accounts for all of these variables would require considerable guesswork about the relative importance of each of these factors. Tweaking the model could eventually make the routes go where we want them to, but that does not make them more realistic. Such an approach would be most valuable where the routes were already known. Where they are not known, a simple model is preferred. Deviations from the model then stimulate further investigation.

## 3.1 Derivation of the Method

Algorithms to use computing power to estimate most efficient routes through a topographical landscape are described by Tobler (1993). Using data collected by the Swiss Army (Imhof 1950, cited in Tobler 1993), he devised the so-called Hiking Function, which relates walking speed to terrain of varying steepness:

$$V = 6(-3.5 \times |S+0.05|), \qquad (1)$$

where V is the walking velocity and S is the percent slope. This formula allows slope values to be converted into the time required to traverse a cell of the raster. Thus, for a 10-meter cell with no slope, it takes about 7 seconds to cross it. Different individuals will walk at a different pace, but the changes in time with increasing steepness should be relatively proportional for all people. The function is symmetrical, but predicts a peak speed at a slope of about 5% downhill (Figure 5). Taking this slight difference into account would complicate the model considerably, but neglecting it should not seriously affect the quality (Aubuchon 2003; Van Leusen 2002; but see Baelstrom 2000, Bell et al. 2002). Therefore, I chose not to distinguish between upslopes and downslopes.

Least cost pathways were created using ESRI's ARCView 3.2 and ARCMap 8.3 GIS packages. I knit together about 215 7.5-minute DEMs into one large relief map of east-central New Mexico at 10 by 10-meter resolution, a resolution that only recently has become available. Elevation values were converted to slope values, and using the Hiking Function, converted to the cost of crossing each cell. Cost surface rasters were generated for each major site, along with cost-direction rasters to point the way to the neighboring cell with the least accumulated cost. LCPs then trace the most efficient way back to each source site from a given destination point. These might be important sites in the cluster, or arbitrary points along a line, such as the Pecos River.
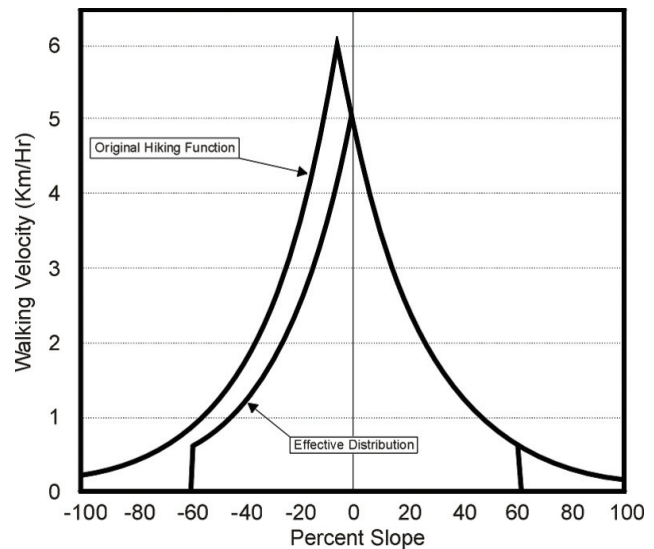


Figure 5. The hiking function distribution. Note the maximum speed at about 5% downhill. Drafted by Jesse Fuhrman (after Aubuchon 2003).

## 4 Results and Discussion

Figure 6 shows some of the LCPs between sites in the Galisteo Basin. Note that at least three important sites were located very close to LCPs between other important sites. The three routes from Pecos, Tunque, and Pueblo Colorado, coincide nearly exactly with shorter segments; note San Marcos, Pueblo Blanco, and San Cristobal.

The center point for San Cristobal is only 18 meters from the LCP between P. Colorado and Pecos. Pueblo Blanco is about 50 meters from the LCP between P. Colorado and Tunque. San Marcos is much more distant, at 360 meters, but still close considering the total distance of the route. This is the most intriguing of the results of this study.

The location of sites along routes between two other sites implies that the midpoint sites were founded later than the endpoints. This is testable. Was San Cristobal founded later than P. Colorado and Pecos? Was P. Blanco founded after P. Colorado and Tunque? What about San Marcos? Considerable study is required before we can answer these questions, but for now, at least, the Galisteo Basin resembles the K=4 Central Place System described by Christaller (Smith 1974). This is noteworthy, because it suggests that an incipient market system was in place prehistorically in the Galisteo Basin.

In the Estancia Basin, LCPs do not form a network (Figure 7). However, the LCP between Abo and Snodgrass, over mostly flat ground, passes very close to the location of Pueblo Blanco (South).

In addition, the LCP between Tenabo and Snodgrass bypasses P. Blanco by only about 1400 meters. It is difficult to interpret this distance over such a long route in gentle terrain. Still, however we interpret this particular LCP, the linear relationships between sites are consistent with the expectations of a dendritic trading system.

What is the difference between these two basins? Is it safe to say on the basis of least-cost path analysis that one was a more integrated, market-based trading network while
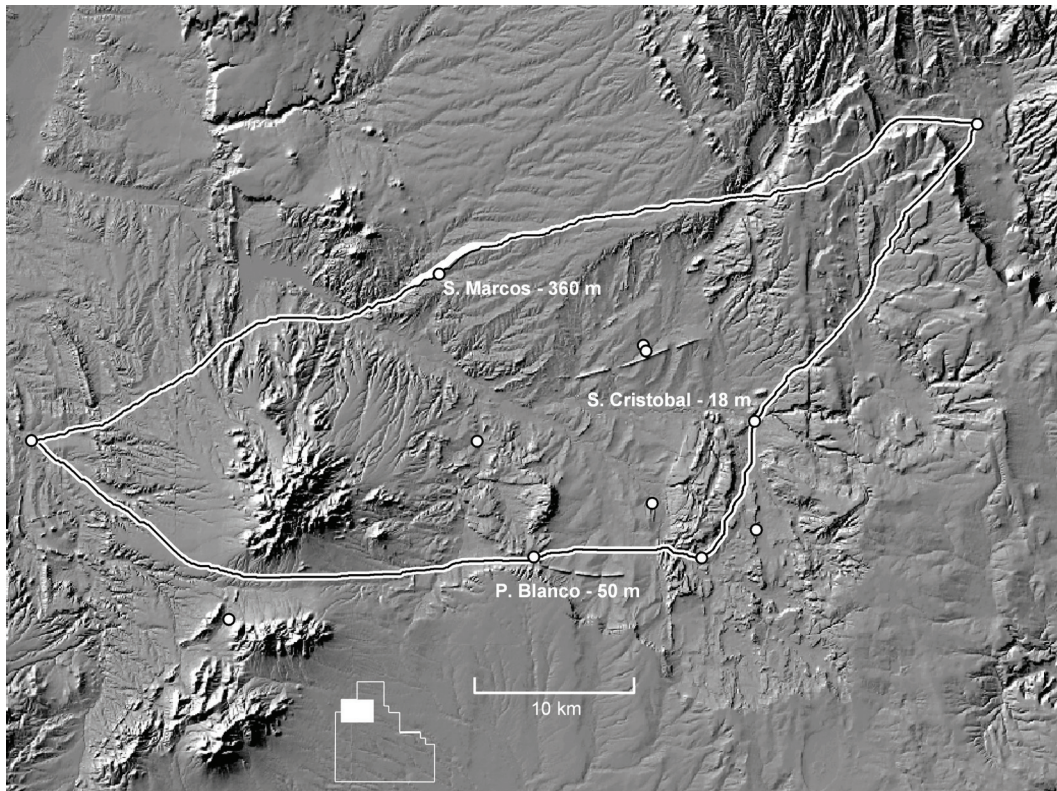
*Figure 6. Coincident least-cost pathways in the Galisteo Basin. Through-going LCPs are broad white lines, thin black lines stop at the intermediate sites. Numbers represent the distance of the through-going LCP from the center of the site (e.g. the LCP from Tunque to Pecos passes San Marcos at a distance of about 360 meters.*
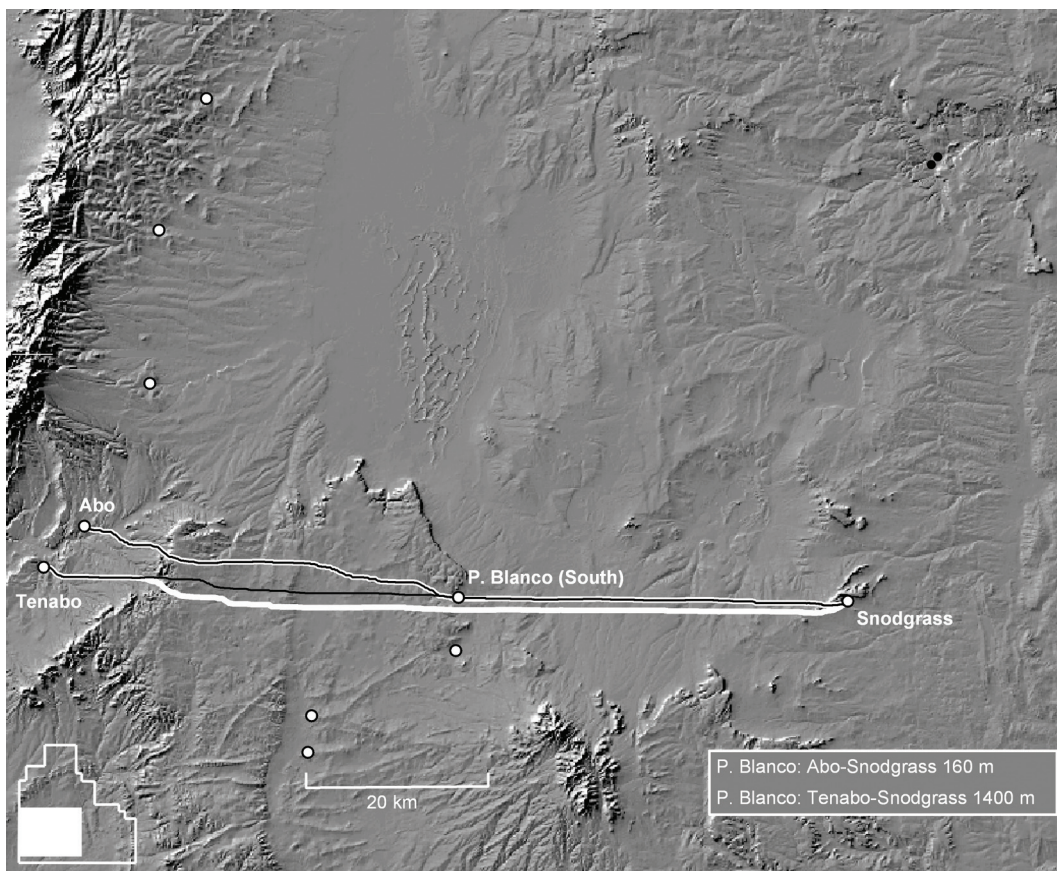


*Figure 7. Some LCPs in the Estancia Basin. The route from Abo to Snodgrass comes closest to passing through an intermediate site (Pueblo Blanco South)*

the other was a resource extraction and foreign trade area dendritically linked with the more integrated pueblos of the Rio Grande area? No. There are other constraints on settlement location that may be more powerful than economic communication routes. A look at settlement patterns in the area clearly shows the influence of other physical factors on settlement in the Estancia Basin (Figure 8). Although some of the information on missing settlement in the center of the basin could merely be missing information—most of the land is private—it is also likely that the need for reliable water and fertile (not saline) farmland constrained permanent settlement. A next step would be to overlay information on water sources, prehistoric rainfall patterns, and soil types in the two areas, and to learn as much as we can from excavation and survey. Still, the LCPs clearly reveal differences between these two areas that may be linked to trade.

The procedure revealed no association of LCPs with drainages linking the east mountain communities to the Pecos River (Figure 9). It is apparent that to a computer, drainages were impediments to travel that were generally exited as soon as possible. From a purely topographic point of view, it is easier to avoid arroyos than to follow them. There are many potential impediments to travel, including meanders, constrictions, and drop-offs. It makes sense to get up and out of the arroyos onto the gentle plain. Note that the lack of fit of the LCPs with the Pintada Arroyo sites does not absolutely prove that trade was not a factor. The simple algorithm that I elected to use does not consider other cultural benefits of the major drainages: water, fuel wood, shelter from the ubiquitous plains winds, or places to hide. In this case, introducing additional variables into the cost surface would be useful.

This last result may tell us more about the process than it does about the prehistoric economy of our locale. It should be noted that the accuracy of LCPs depends on the terrain under investigation. LCPs in the southern area, where slopes are not necessarily flat but much more uniform, are less likely to be able to trace actual routes than LCPs in the more rugged northern area. In a flat landscape resembling Christaller's featureless plain, routes are restricted only by social and economic issues. In rugged terrain, the constraints of the physical environment are more likely to dominate. The following example demonstrates this.

To test the algorithm, I turned to Bandelier National Monument, where prehistoric trail segments were identified on archaeological survey (Snead 2002). I ran LCPs between some of the larger sites to see whether they would pass through a known trail segment. The Frijoles Staircase is a set of steps carved into the bedrock leading down into Frijoles Canyon, the main prehistoric population center of the park. Note that all paths leaving the site of Tyuonyi on the Frijoles Canyon floor to sites to the east, south, or west exited via this stairway (Figure 10). The LCPs leading to all five different sites pass within one meter of the center point of the stairway! This is apparently the only reasonable way out of the canyon. In this extremely rugged region, one can be confident that a computer generated path can closely predict the locations of real communication routes.

This may not be the only way out of the canyon, however. It may simply be the least cost route. One might experiment to see whether artificially plugging up the route past the Frijoles Staircase would result in other routes appearing. There is an interesting behavioral issue here. Frijoles Staircase improvements were clearly made on an existing
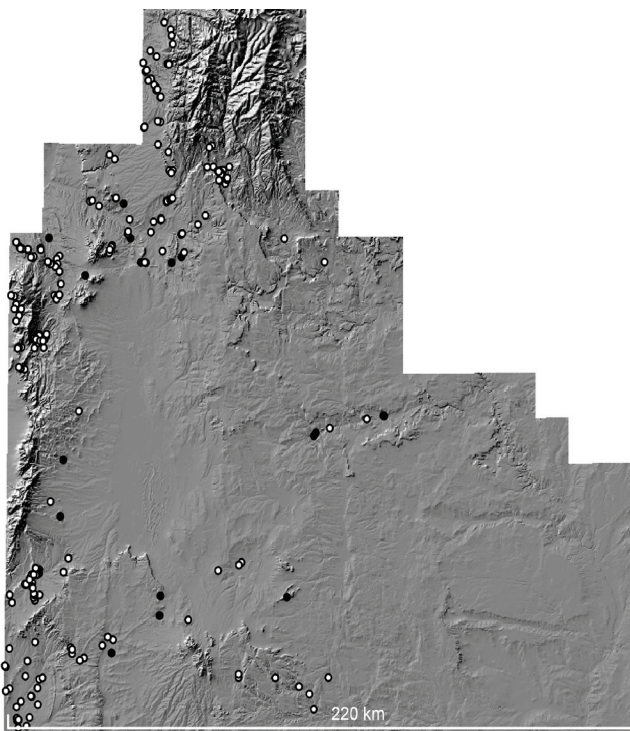


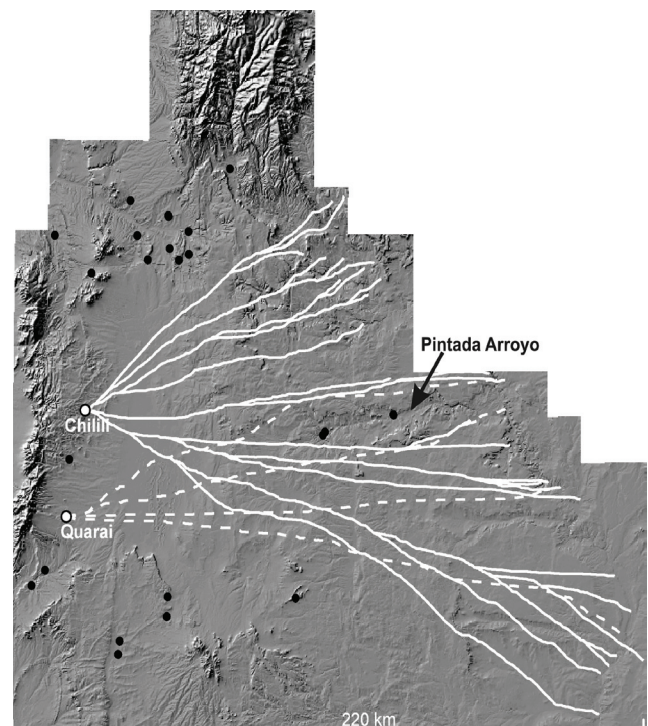Figure 8. Distribution of architectural sites around the study area.



Figure 9. LCPs from scattered locations along the Pecos River to the Estancia Basin sites of Chilili and Quarai. Note how the computer-generated routes avoid Pintada Arroyo, even those beginning right at the mouth of the arroyo.

route, one that was already in the most logical place for foot traffic. A trail that would have developed informally over many years was improved to expedite traffic, but not in such a way as to short-cut the existing route. Another scenario might involve modifications to obstacles that would be invisible to a computer because the slope would not be changed. A small change of accessibility of one or a small cluster of cells in the DEM could drastically alter the cumulative cost of travel to those cells, thus altering the LCP. This brings up some important questions. How do people build trails? Is there a pattern to trail-making behavior? In what situations do people make improvements on existing trails, and when do they make shortcuts by adding features to make steep slopes passable? These are questions that arise from least-cost path analysis, and that can be answered with carefully designed fieldwork, computer modeling, experimentation, and ethnographic research.

## 5   Conclusions

Although gratifying that it appears to work rather well in rugged terrain, the value of this kind of research does not necessarily depend on the degree to which the Hiking Function reflects reality. Despite or perhaps because of the simplifying assumptions, a number of important insights

and testable predictions came out of this study: arroyos don't make the best sidewalks, residents of Tyuonyi modified an existing trail rather than constructing a new one, the Estancia Basin looks like a dendritic trading system, and the Galisteo Basin looks like a K=4 central place network. There are also important leads to be followed, including ground-truthing of likely pathways, spatial analysis of site distributions about LCPs, assessing the relationship of LCPs with rock art, and refining the algorithm with additional environmental or social variables.

This use of GIS least-cost pathway analysis was exploratory, and it more than lived up to my expectations. As a discovery technique, it has provided considerable insight into the locations of trails, questions of trail-making behavior, and the economic structure of prehistoric settlement clusters in east-central New Mexico. If the value of a procedure is measured by the directions of further research it can point to, then least-cost path analysis is a powerful method indeed.
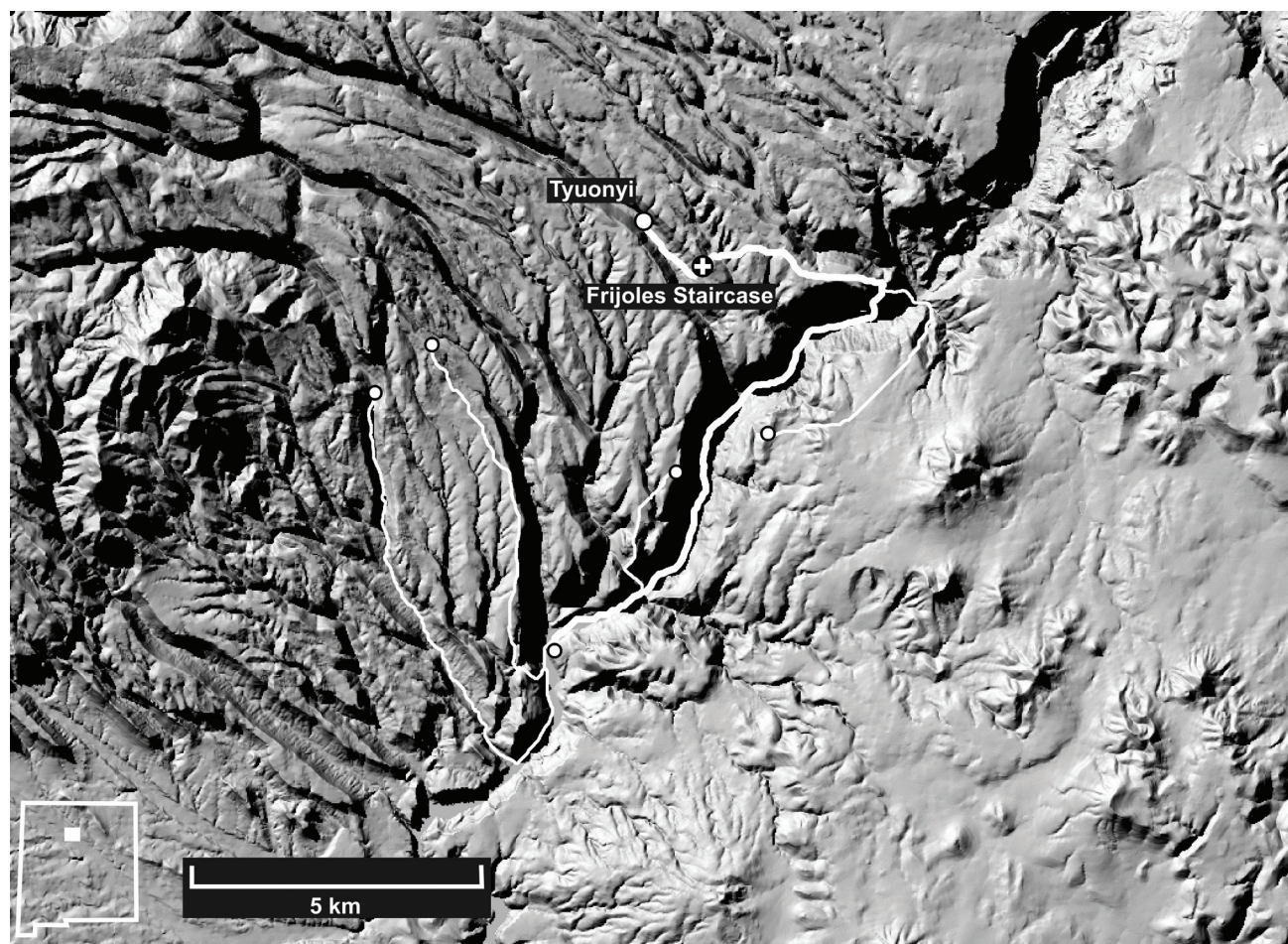
*Figure 10. Bandelier National Monument area, showing routes from Tyuonyi to five other sites, all passing through the Frijoles Staircase (indicated by a cross in a circle).*

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