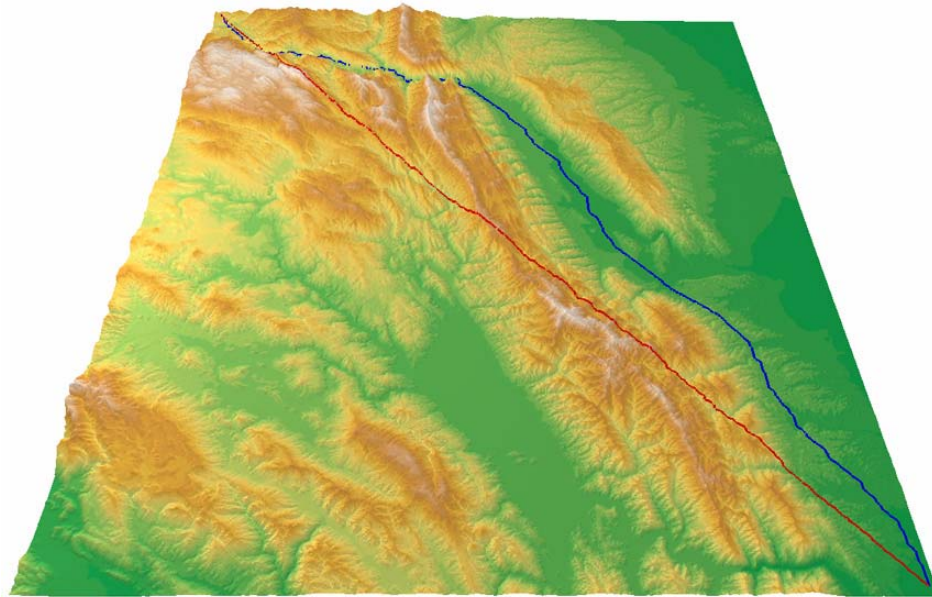# Energetically Optimal Travel across Terrain: Visualizations and a New Metric of Geographic Distance with Archaeological Applications

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- Figure 1. Terrain with path comparisons. The shortest path is shown in red while the energetically least cost path is shown in blue. This visualization shows how least cost paths often follow natural features of the landscape, avoiding unnecessary elevation gains. The elevation profiles of these two paths further illustrate this fact. See figure 2. The overall caloric saving for the least cost path is 21%.

ABSTRACT

We present a visualization and computation tool for modeling the caloric cost of pedestrian travel across three dimensional terrains. This tool is being used in ongoing archaeological research that analyzes how costs of locomotion affect the spatial distribution of trails and artifacts across archaeological landscapes. Throughout human history, traveling by foot has been the most common form of transportation, and therefore analyses of pedestrian travel costs are important for understanding prehistoric patterns of resource acquisition, migration, trade, and political interaction. Traditionally, archaeologists have measured geographic proximity based on "as the crow flies" distance. We propose new methods for terrain visualization and analysis based on measuring paths of least caloric expense, calculated using well established metabolic equations. Our approach provides a human centered metric of geographic closeness, and overcomes significant limitations of all available Geographic Information System (GIS) software. We demonstrate such path computations and visualizations applied to archaeological research questions.

Our system includes tools to visualize: energetic cost surfaces, comparisons of the elevation profiles of shortest paths versus least cost paths, and the display of paths of least caloric effort on Digital Elevation Models (DEMs). These analysis tools can be applied to calculate and visualize 1) likely locations of prehistoric trails and 2) expected ratios of raw material types to be recovered at archaeological sites.

CR Categories and Subject Descriptors: I.3.8 [Computer Graphics]: Applications; J.2 [Physical Sciences and Engineering]: Archaeology.

Additional Keywords: Energy, optimization, travel, prehistory, least cost path.

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1 INTRODUCTION

If you were faced with the task of reaching a water source, would you choose the shortest path, which took you directly over a hill, or would you choose a slightly longer route which took you around the hill but required much less energy? Most humans are concerned with conserving their energy and would choose the less strenuous path around the hill; however, this essential human characteristic is typically overlooked in geographic and archaeological models of pedestrian travel.

The energetic cost of locomotion has been the focus of considerable research in anthropology. This research has identified many unique muscular and skeletal adaptations that allow humans to travel efficiently [for example, refs 1-4]. Efficiently moving was crucial throughout human evolution, and continues to be among traditional societies. The !Kung San hunter-gatherers, for instance, have been estimated to walk on foot 2400 km per year [5].

Because efficiently traveling is essential for survival, archaeologists often perform geographic analyses that are guided by the principal of energetic optimization. Such analyses have been used to define which resources are locally available to a given camp or village, or the likelihood of interaction and political associations between villages [6-8]. Valid measures of travel costs are essential for these studies. The traditional measure of geographic closeness employed is "as the crow flies" distance [9, 10]. We propose a more human-centered metric of geographic closeness: the energetic expense of travel.

There are well- established methods for calculating the caloric cost of travel based on path distance, slope, traveler weight, speed of travel, and type of terrain [11, 12]. We employ these equations to model the costs of traveling over terrain, using DEMs that are available from a variety of sources, such as the National Geophysical Data Center [13] and the United States Geological Survey [14].

In this ongoing research project, we are building tools for scientists and recreational users to compute and visualize paths of least energetic effort using actual terrain data. The software currently includes methods to compute and visualize geometric shortest paths as well as paths of least caloric cost between given sources and destinations. See Figure 1 for an example. Additional visualizations include comparing elevation profiles of paths between given locations. See Figure 2 for an elevation profile comparison of the least cost path and the shortest geometric path. The system also includes the ability to visualize the minimum caloric costs that are required to travel from a source to all other points in the terrain, which we call the energetic terrain. This visualization allows the user to have a quick understanding of the energetic- proximity of a given landscape (see figure 3). Building on these routing techniques, our system is able to predict ratios of different types of stone-tool raw materials that would be expected to be found at archaeological sites based on the locations of their geologic sources (see figure 6).

2 PREVIOUS WORK

Traditionally, archaeologists have used "as the crow flies" distance to approximate travel costs. In recent years, the use of GIS has allowed archaeologists to progressively build more sophisticated models of travel cost that incorporate the effects of three-dimensional terrain in various ways [8, 16-18].

Unfortunately these efforts have been hampered by two major problems:

1. Limitations of currently available GIS software.
2. Incomplete and unverified measures of travel cost.

All published research in this area has employed raster-based models using two forms of commercial GIS software: ArcView [17, 18] and ArcInfo [15] both manufactured by Environmental Systems Research Institute (ESRI Corp, Redlands, CA). The manner in which these systems calculate slope of terrain is extremely problematic for studies of pedestrian travel. These systems assign a single slope value to every surface location, calculated by taking the maximum possible slope value that can be achieved by traversing through a cell from its four cardinal neighbors [19]. This maximum-value approach eliminates all negative slopes, and hence any evidence that downhill travel is possible. In these models, because there are no downhill slopes, it really is possible to walk to school uphill both ways! By assigning a single slope value to all locations, previous models disregard the fact that in the real world, a single location could potentially have a range of significantly different slopes, e.g. -25%, 0%, or +25%, depending on the direction of travel through the location. Slope is critically important in determining travel costs [11, 20, 21], and for this reason we have built our system using a directed graph network model that calculates slope and maintains travel cost information between terrain locations and their 8 potential neighbors.

While hindered by the limitations of currently available systems, archaeologists are making progress in their modeling of pedestrian travel costs, although no system currently available makes use of a network data structure or metabolic equations to derive paths of least caloric effort. Limp [22] developed a function whereby the cost of travel increases as the square of the slope of terrain. Christopherson et al [18] developed travel cost estimates based on arbitrary categories of slope. Other researchers have employed a formula developed by Tobler [23] to derive estimates of travel time based on path slope and distance [8, 15-17]. This equation has not been empirically verified under a range of controlled conditions, as is the case with the metabolic formula that our system employs [11]. In addition, Tobler's equation does not incorporate impedance factors for a variety of travel surface types, nor does it incorporate the effect of traveler body weight or load carriage, as does Pandolf's equation.

In the archaeological research cited above, terrains are invariably viewed with an orthographic projection and with limited attention to visualization details. Our system creates visualizations which employ color and three-dimensional perspective viewing.

3 OVERVIEW

We present a visualization system that allows for the computation and visualization of paths of least caloric effort. The applications of these computations and visualizations are numerous. In this ongoing research we have focused on archeological applications of computing a human centered measure of geographic proximity using least cost caloric path computations. Our initial application is a computation and analysis of predicted travel paths throughout the Sierra Nevada mountain range. This study area was selected because it encompasses difficult mountain passages and demonstrates unique features of our model. In Section 5 we use our model of energetically optimal travel to predict paths of travel from a single starting point to 16 destinations in the eastern Sierra. We also use our model to predict ratios of types of obsidian (a volcanic glass

used to fashion tools) likely to be deposited in archaeological sites across the Sierran landscape.

When initializing our system, the user first selects a Digital Elevation Model (DEM) that represents the area of interest. Our system renders and displays this terrain in a three-dimensional perspective view. A gradient of colors, ranging from green at lower elevations, to tan/orange at mid elevations, to white at highest elevations, is used to help visualize variation in elevation. After the terrain is initially displayed, several types of analyses are made available to the user. These include:

1. Creating a terrain network,
2. Calculating a shortest path,
3. Calculating a least cost path,
4. Calculating an energetic terrain,
5. Predicting raw material ratios,
6. Viewing previously saved paths,
7. Viewing elevation profiles of paths,
8. Viewing predicted raw material ratios

Creating a terrain network file (feature 1) is essential for all other analyses and visualizations. In this step, the software reads and transforms a raster DEM file into a network data structure in which each elevation point is linked to its 8 neighbors. Once constructed, terrain network files can be saved to disk as a simple ASCII file. In order to perform least cost routing, the user is prompted to input traveler body weight, age, height, sex, speed of travel, and load carried. Default values are provided as a convenience for analyses of prehistoric travel.

For creating shortest paths or least cost paths, our system prompts the user to input a terrain network file, as well as the starting point and destination (in decimal degrees) of travel. When a path is generated by our system, it is saved to disk in a format that allows for later viewing.

When calculating an energetic terrain, the user must input a specific terrain network file, as well as the starting point of travel. Energetic terrains are built using the entire extent of a given terrain network file. For the calculation of raw material ratios, an energetic terrain file must be built which encompasses all the prospective sources. The user must then input the decimal degree coordinates of each raw material source.

In Figures 1, 2 and 4, it can be seen that energetically least cost paths typically avoid traveling unnecessarily over peaks and ridges, and take advantage of terrain features such as valleys and passes that circumvent dramatic elevation gains. Shortest paths take more direct routes and often include traveling over peaks and ridges. Based on the computed paths, we can calculate the caloric cost of traveling from a particular archaeological site to another site of interest. Such calculations in the Sierra Nevada region show that least cost caloric paths can provide significant energetic savings over the shortest path (see section 5). Terrain ruggedness appears to positively predict the energetic savings of least cost paths. Figure 2 shows a side by side comparison of the elevations of a shortest path and a least cost caloric path between the same locations. As the graph clearly demonstrates, a least cost caloric path appears much better suited for pedestrian travel.
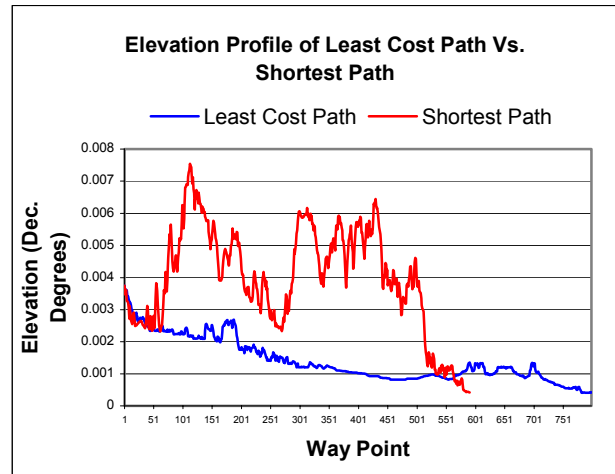
- Figure 2. An elevation graph comparing two types of paths between the same source and destination for the terrain shown in Figure 1. Note that the shortest path includes substantial elevation gains, while the least cost caloric path takes a much more level path.

4 IMPLEMENTATION

Our system is written in C++ using standard libraries, OpenGL, and glut. For elevation data, our system relies on the ASCII DEM file format originally developed by ESRI that is widely supported among GIS software vendors. For the present study, the elevation data is taken from GEODAS software produced by the National Geophysical Data Center. We build an internal network representation of the terrain to facilitate shortest path, least cost path, and caloric terrain computations. More specifically, we create a weighted, directed graph in which each elevation point on the terrain is modeled as a node that is linked outwardly with directed edges to its 8 cardinal and diagonal neighbors. The weights that are ascribed to each edge are either geometric distance (for shortest path analysis) or caloric cost (for least cost path analysis). To ascribe a caloric cost to an edge, we employ metabolic equations that require inputting the traveler's sex, weight, height, age, walking speed, load carried, and terrain factor. Helper functions that calculate the geometric length of an edge, its slope, and the time required to traverse the edge are also used. With this information, we first calculate the metabolic rate, in watts, that would be experienced when walking between two terrain locations. Based on the time required to traverse the edge, we then convert our metabolic rate into a total energetic cost in kcal. Two metabolic formulae are necessary: one for downhill travel, and one for level and positive slopes [11, 21].

For downhill slopes, metabolic rate in watts (MR) is calculated as:

$MR = M - C$, where
$M = 1.5w + 2.0(w + l)(l/w)^2 + \eta(w + l)[1.5v^2 + 0.35vg]$
$C = \eta[(g(w+l)v)/3.5 - (((w + l)(g+6)^2)/w) + (25 - v^2)]$

For level or positive slopes, $MR = M$, where
MR is metabolic rate in watts;
w is subject weight in kilograms;
l is load carried in kilograms;
v is walking speed in meters per second;
g is grade in percentage,
η is terrain factor (e.g., 1 for treadmill walking).

One limitation of the metabolic equations is that they can under-predict the cost of traveling at slow speeds on downhill grades [24]. For this purpose, we check that the travel cost of an edge is not lower than what would be incurred based on standing metabolic rate (SMR). We calculate SMR as $1.2*$ Basal Metabolic Rate (BMR) as calculated by the Harris-Benedict [25] equations:

BMR, males $= 66 + (13.7*w) + (5*h) - (6.8*a)$
BMR, females $= 655 + (9.6*w) + (1.8*h) - (4.7*a)$

Where w = weight in kg;
h = height in cm.
a = subject age in years

We are able to perform optimal path analyses after creating a network representation of the terrain. This analysis is implemented using Dijkstra's shortest path algorithm [26]. Our algorithm choice was guided by a recent review of shortest path computations that found implementations of Dijkstra's algorithm to typically outperform all other shortest path algorithms [27].

The performance of our system is contingent upon the size and sampling density of the terrain of interest, and the corresponding size of its network representation. Of course the memory resources of the executing system also constrain performance. We have performed limited testing of our system using a Dell Inspiron 8500 laptop with a 2.6 Ghz Pentium 4-M processor, 512 MB DDR-SD RAM, and 768 MB of virtual memory. Under these conditions, tests indicate that graph construction, which includes the time to iterate through the DEM file and construct its internal network representation, as well as writing the graph representation out to an ASCII file, increases linearly with the number of vertices in the graph. Optimal path execution time using our system appears to increase at around the theoretical time complexity of Dijkstra's algorithm, $O((V+E)\log V)$, until terrain sizes reach about 650 x 650 in size. At this point, performance significantly degrades. This is due to the system running out of RAM and needing to heavily rely on virtual memory. In this study, we have used DEM files that have elevation values sampled every 1-arc second, or approximately every 90 meters. In this context, a terrain that is 650 X 650 has a geographic extent of 58.5 Km X 58.5 Km, or approximately 3,400 square kilometers.

5 RESULTS

In this ongoing research, we have experimented with applying our model of energetically optimal travel in the Sierra Nevada mountain range of California and Nevada.

Our first analysis is an investigation into the differences between energetically optimal and shortest paths between the same locations, in areas of varying terrain ruggedness. In figure 4, 16 travel destinations have been selected, to which both shortest paths and least cost paths have been calculated. These length and caloric cost of each path calculated is presented in Table 1. The summary of these data (Table 2) shows that least cost paths on average offer a 5% energetic savings compared to shortest paths, but that in mountainous areas, the benefit increases to 11%. These calculations also show that least cost paths are 3% longer on average than shortest paths, but that in mountainous areas they are 6% longer. These results show that ruggedness of terrain positively predicts 1) the energetic benefit of least cost paths, and 2) the difference in length between least cost and shortest paths.

The path computation procedures used in this demonstration could be used to predict the likely locations of trails connecting prehistoric villages and resource locations. We plan to carry out these analyses in the American southwest, in which numerous Anasazi trails have been identified.

Other path calculations that we have performed show that the routes of energetically optimal paths between varieties of different locations tend to converge. These convergences are not surprising because least cost paths trend toward natural drainages and level regions of the terrain. This suggests that energetically optimal path computations could lead to finding common paths that would be followed by people traveling throughout a landscape.

Our second demonstration shows how our model can be used to predict landscape-wide spatial distributions of artifacts derived from different stone raw material source locations. The study of how people select resources, and how spatial patterns in artifact types can be used to infer prehistoric behavior, has been the focus of considerable research in archaeology [for example, refs. 6, 28-36]. So-called "gravity decay models" are analyses based on the idea that the source location of given resource strongly influences where that resource will be used and by whom, and ultimately what archaeological sites will contain evidence of that resource [37]. As such, gravity models are one way to predict variation in archaeological assemblages based simply on locations of resource origins. Our tool extends this simple reasoning in a way that incorporates the natural form of the landscape and its energetic consequences.

Our software uses the origin locations of two resources to predict ratios of those resources in archaeological sites. For this analysis, the assumption is that at a given archaeology site, the abundance of artifacts derived from a particular resource will inversely correlate with the energetic distance from the origin of that resource.

In the example presented here, the resource locations in question are obsidian quarries. Using these analyses, a ratio of obsidian types can be predicted for every location on a terrain. In practical terms, this means that archaeological sites very close to a certain quarry should exclusively contain material from that quarry, while sites of equal caloric distance from two obsidian quarries should have a 50/50 breakdown in toolstone ratios.

In the eastern Sierra Nevada, at least 8 sources of obsidian were available for tool making and use throughout prehistory. Volcanic glass degrades quickly through use, and was discarded frequently and is now recovered in great abundance by archaeologists. Figure 6 shows the location of two major obsidian sources, Casa Diablo and Queen. Applying our model, we can visualize for each location on the landscape a ratio of raw material types predicted by our behavioral model. The predicted ratios are shown in figure 6.

An important advantage of our model in comparison to "as the crow flies" models is evident in figure 6. In much of the western portion of the image (i.e. the left hand side), ratios of obsidian types are predicted to be roughly equal. A traditional approach that used only airline distance would predict a much greater abundance of the western-most source, Casa Diablo. Using our model, however, the great energetic cost of traversing the Sierra Nevada mountain range is incorporated into the analysis, and as our visualization shows, this great energetic cost reduces the real benefit of Casa Diablo's westernmost location.

We plan to test these predictions with actual artifact collections recovered from sites excavated in California and Nevada. Like any simple model, ours is likely to explain only a portion of the observed variation in artifact assemblages. Its value will come not only in predicting observed ratios, but also in identifying cases in which the archaeological data suggest more complex social or behavioral processes (e.g. trade, territorialism, obsidian preferences) contributing to artifact assemblages.

6 CONCLUSION

The results of our path computations and visualizations are promising. In a demonstration of possible archaeological

applications, we have been able to quantify the minimum caloric costs that traveling to different destinations would have incurred on prehistoric people. We believe that these measures are a valid and straightforward way to make predictions about the locations of prehistoric trails, as well as economic behavior that involves travel. These predictions will be tested in future archaeological research. In the Sierra Nevada study area, least cost paths were on average 5% less costly that shortest paths. In mountainous areas, least cost paths offer an energetic saving of as much as 24% over shortest paths. These results demonstrate that ruggedness of terrain determines the energetic benefit of least cost paths over shortest paths. In an entirely flat terrain, least cost paths would be identical to shortest paths, while in more varied terrain, the energetic savings of following least cost paths increases on average. The visualizations produced by our system allow the user to quickly see and compare paths overlaid on actual terrain (see Figures 1 and 4). In addition, our system offers tools to further analyze geographic proximity by creating an energetic terrain for a specific site (see Figure 3). By using well established equations for calculating the caloric costs of travel based on path distance, slope, traveler weight, load carried, speed of travel, and type of terrain combined with accurate Digital Elevation Models our system provides a human centered metric to measure geographic closeness with archeological applications.

7 FUTURE WORK

In this ongoing research we plan to pursue examining geographic closeness for various archeological applications. Such applications include predicting the location of foot paths used throughout prehistory in the American southwest. We are also interested in testing our spatial model of obsidian distributions with archaeological data recovered throughout the Sierra Nevada region.

Additionally, we would like to continue to improve the current system by improving memory management including looking into multi-resolution data structures for larger scale terrain evaluation. We would also like to continue to develop the user interface for the system and provide additional methods for user interaction and caloric cost computations. We would also like to explore the use of a continuous Dijkstra's search in order to allow paths to traverse the faces of the three-dimensional terrain. Finally, we would also like to allow for input of fine-grained overlays of terrain factors or other impedance information, to further develop the human centered nature of our geographic closeness computations.
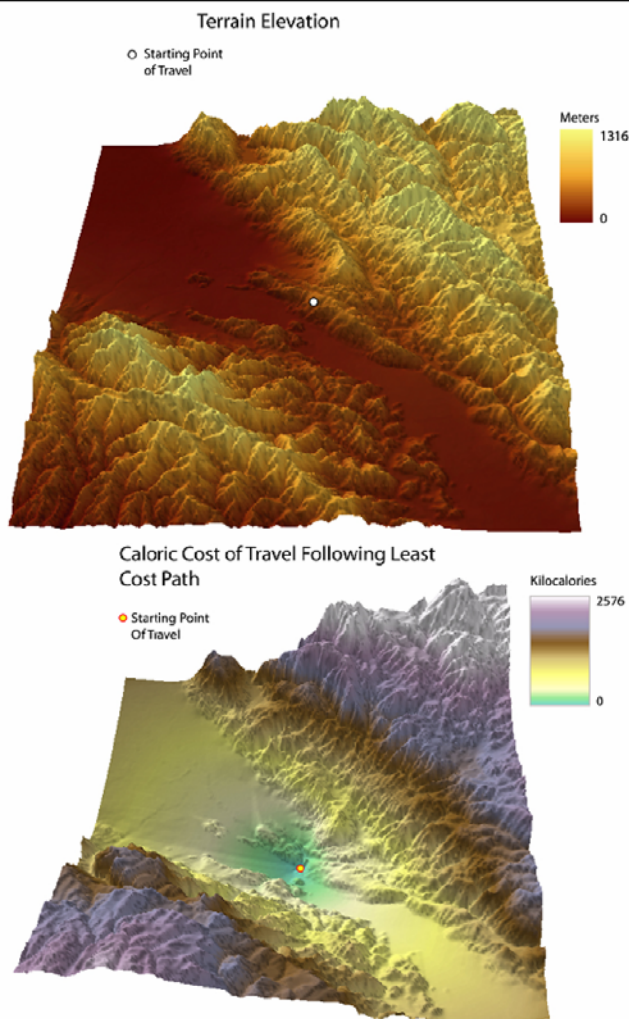
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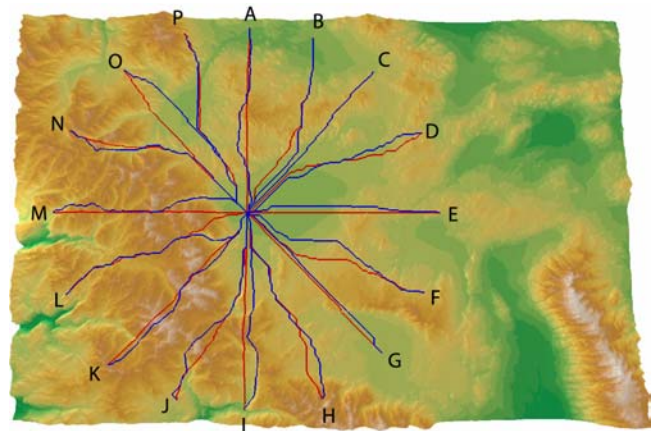
- Figure 4. A view of the eastern Sierra Nevada, showing shortest paths (in red) and energetically optimal paths (in blue) from the same source to 16 destinations.

Path	Distance (meters)		Cost (kcal)	
	Least cost	Shortest	Least cost	Shortest
A	55423	51693	4640	4823
B	56083	55883	4392	4423
C	52883	52883	4156	4157
D	55620	55617	4318	4334
E	52939	51518	4183	4333
F	55589	55459	4511	4534
G	52540	51691	4185	4318
H	56142	55627	4913	5016
I*	55605	51956	4764	5920
J*	58045	55840	5305	5410
K*	55763	53238	5991	6706
L*	58597	55670	5155	5341
M*	58048	52461	5614	6769
N*	57744	55766	5543	5744
O	55446	52917	4631	4762
P	56460	55856	4941	4979

- Table 1. The distance and energetic cost of the 32 paths shown in figure 4. Those paths labeled with an asterisk are considered mountainous in discussion.

LCP Energetic benefit (mountains)	11%
LCP Energetic benefit (overall)	5%
LCP Maximum energetic benefit	24%
LCP Average additional distance (overall)	3%
LCP Average additional distance (mountains)	6%

- Table 2. A summary of the costs and benefits of energetically optimal versus shortest paths detailed in Table 1.

Terrain Elevation

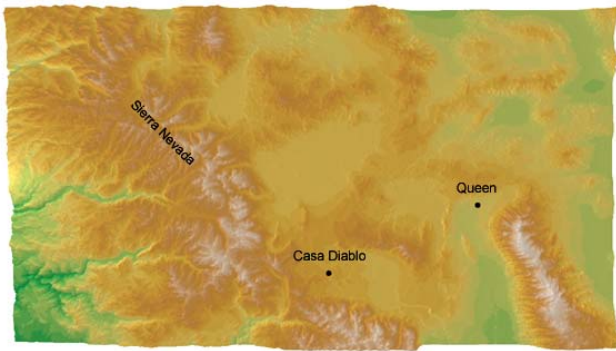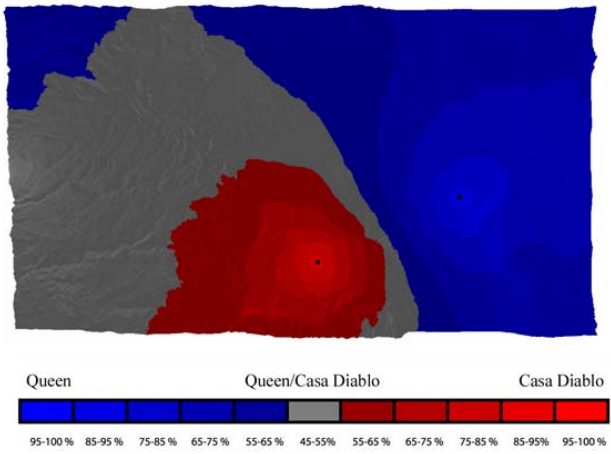## Caloric Cost of Travel Following Least Cost Path

- Figure 3. On the top we see a normal terrain rendering of an area in Northern California (near Gilroy). On the bottom we see a caloric cost terrain from the highlighted source point. Notice the progressive cost of travel into the hilly region to the East.

- Figure 5. An overview of the eastern Sierra Nevada terrain encompassing the Casa Diablo and Queen obsidian sources.

| Queen | | | | | Queen/Casa Diablo | | | | Casa Diablo | |
| 95-100 % | 85-95 % | 75-85 % | 65-75 % | 55-65 % | 45-55% | 55-65 % | 65-75 % | 75-85 % | 85-95% | 95-100 % |

- Figure 6. The predicted ratios of obsidians to be recovered at archaeology sites throughout the region based on a behavioral model of energetically optimal travel.