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Finding Byzantine junctions with Steiner trees

1 Introduction

In archaeology, computational approaches to the study of movement practices have become more and more popular in recent years, especially when applied to prehistoric contexts (Bell / Lock 2000; Llobera 2000; De Silva / Pizziolo 2001; van Leusen 2002; Fábrega Álvarez / Parcero Oubiña 2007; Snead *et al.* 2009; Llobera *et al.* 2011). The main aim of these methods is not just to reconstruct paths and road systems, but to use these models to understand the establishment and transformation of a hierarchical network of settlement nodes, also including a focus on off-site land use practices.

In this paper, we will introduce an example of the use of GIS-based modelling techniques for the study of the Roman-Byzantine communication system in the Roman Province of Cappadocia, in modern Turkey. We will argue that adopting a landscape archaeology approach to the analysis of an historic road system contributes to a deeper understanding of settlement dynamics (Bell *et al.* 2002). A GIS-based, spatial approach allows us to study settlements and pathways in a more formal manner and, by doing so, to address questions about ancient cognitive geography and past decision-making processes (Rockman / Steele 2003). By systematically analysing the structure and phenomenology of the Roman provincial landscape, indicators of power and social order can be extracted from agricultural centuriation and communication systems (Witcher 1998; Laurence 1999). In the cultural context of Roman and Byzantine communication systems, GIS methods are usually employed to reconstruct ancient routes in the landscape. These reconstructions are constrained by the possibilities of testing the model with material evidence of roads (remains, milestones, bridges; see Graßhoff / Mittenhuber 2009). A further limitation concerns the integration of path models created at a micro-regional scale with a macro-regional approach that considers the road system as a coherent planned network of connections.

We therefore aim here to combine path models constructed on the basis of topographic and environmental constraints at the micro-regional level – like slope, distance to natural resources, and visibility – with a model of macro-regional movement in a strategic network composed of nodes and junctions. In this network, movement is structured and affected by "cultural" constraints, like site density and distribution, and the position of strategic administrative, economic, religious and/or military centres.

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The integration of these two approaches is realized by combining a GIS approach for modelling segments of the system (paths), based on the environmental context, with a Steiner tree vector-based approach that takes into account the nodes and edges of the system. As an example, we use the documented inter-regional road system of Cappadocia that was established in the Roman period. It follows the previous pattern of macro- (Persian Royal Road)[1] and micro-regional (tribal villages) movement axes (Mitford 2000). Written sources and archaeological remains document this pattern of communication routes, consisting of strategic connections along a set of way stations. It can still be recognized in the pattern of Seljuk caravanserais in historical times (Hild 1977).

2 The Roman and Byzantine road system in Cappadocia

For this case study we focus on the methodological aspects of reconstructing and analysing the inter-regional road system of the Roman/Byzantine province of Cappadocia in Asia Minor (current Kapadokya in Turkey). The road system of Roman/Byzantine Cappadocia is an inter-regional communication system, from which we will analyse only one segment and we will focus on path modelling at the micro-regional scale. For this, we will integrate path modelling and network modelling approaches, and take into account topography-based constraints (Llobera 2000; 2001), as well as the structure of the macro-regional network.

The study region (Fig. 1) is dominated by mountains and characterized by a continental climate with snow from November to April in the area above the tree line. The area studied is a high plateau, enclosed to the south by the Taurus mountain range and cut transversely by the Antitaurus massif. The regional settlement pattern and the road system of Cappadocia are strongly structured and defined by topography. From the Bronze Age onward, the river plains were the main areas of settlement and acted as the primary axes of communication. Assyrians, Hittites, Phrygians, Lydians and Persians successively occupied the territory of Cappadocia, and were later followed by Seleucid, Roman, Byzantine, Seljuk and Ottoman rulers. The region has been subject to a centralized administration since the Persian period, and this clearly influenced the strategic construction and long-term use of the road systems. A strong relationship is evident, for example, between the Roman road system and the Seljuk caravanserais.

During the Roman Empire, strategic routes were set up from the provincial capital of Caesarea (currently Kayseri; Greek: Kaisarea) to connect it to Melitene (currently Malatya), over a total distance of approximately 250 km.[2] Caesarea, the starting point, was a central

1 Herodotus 5.52–54; French (1998). On the Cappadocian pathways cf. Herodotus 52.2.2, French (1998, 18) and Hild (1977, 99 and Abb. 68) on the route from Elbistan to Melitene. For a localization of the route on modern topography cf. French (1998, 28: Kayseri sheet: Kayseri-(Aydinlar)-Kamber-Akmescit).

2 The modern road connection measures 339 km.

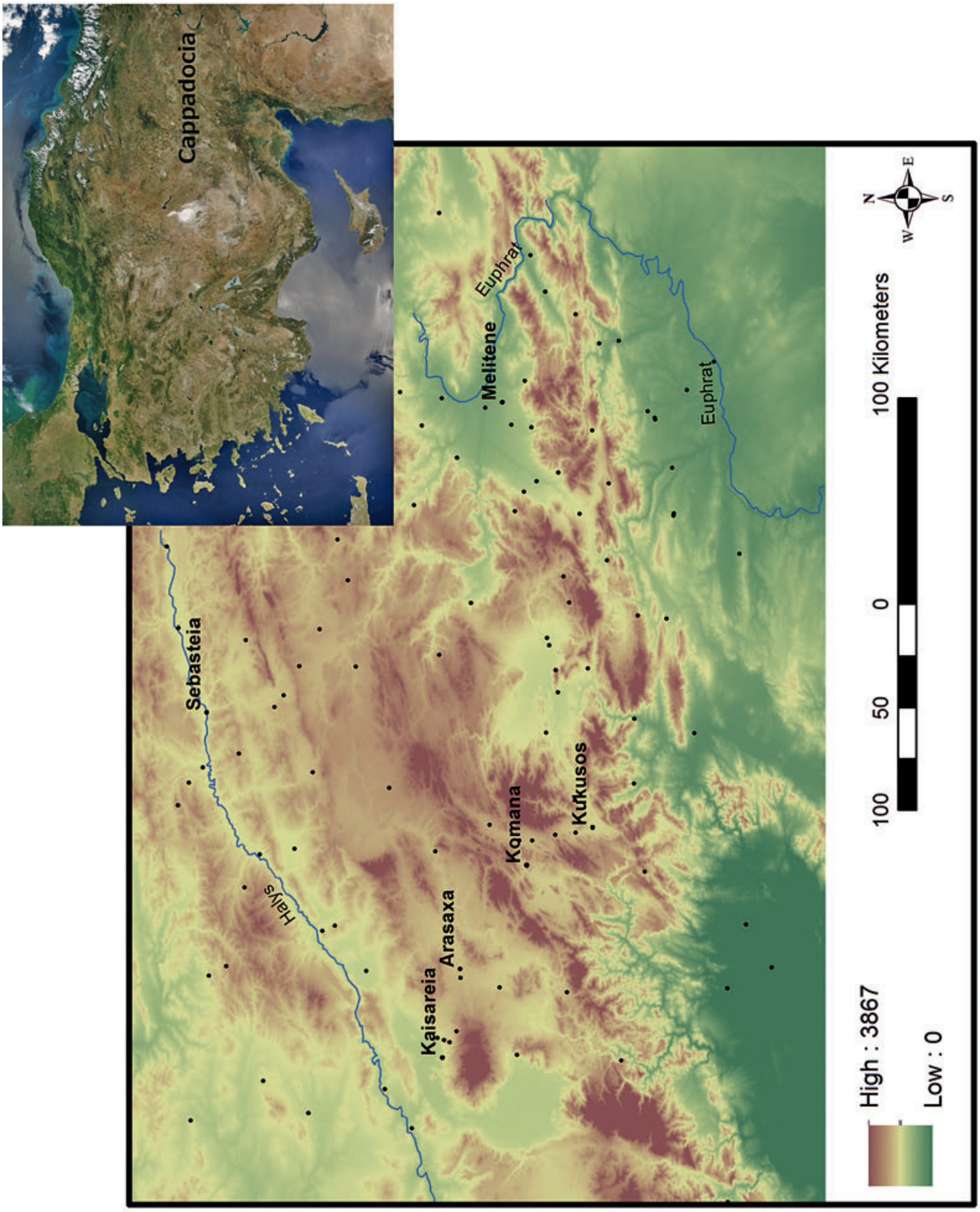

Fig. 1 | Overview map of Cappadocia and the considered region. Source: http://visibleearth.nasa.gov/view_rec.php?id=8139.

place from Assyrian times. It became a Hellenistic polis and then capital of the Roman province of Cappadocia and it was a central node of the road system in central Asia Minor during both Roman and Byzantine times. The connection we are studying was the southern alternative to reach Melitene, via Comana (Caesarea – Arasaxa – Comana – Kokousos – Melitene; Hild 1977, 85; Mitford 2000, 991). Along the route, way stations were built at distances of approximately 40 km. A number of milestones, some of them found *in situ*, are attested along the route to Comana (Hild 1977, 85; French 1988 and 2012), and trace the corridor used by the Roman road. The so-called Roman *Itineraria* list the distances between the stations along the roads. For this area, the Itinerarium Antonini *(ItAnt)* and the Tabula Peutingeriana (*TabPeut)* provide geographical information about the paths used.

The pathway to Melitene passing by Comana seems to have been in use only until the Early Byzantine period (4th – 7th century AD; Hild 1977, 84). In the 7th century, an alternative northern route passed via the fortress of Taranta to Melitene (for documentation and sources see Hild 1977, 84 n. 73). According to the sources, the area of the Antitaurus mountains, made desolate by the Byzantine campaigns against the Arabs, was re-organized during the 8th century. The eastern frontiers of the Byzantine Empire were restructured and the road system changed. In the Middle Byzantine period (9th – 11th century AD) a new alternative route diverged from Arasaxa – the first node of the Roman road and maintained as a Byzantine junction – to the north, passing via Tzamandos and Ariaratheia to Arabissos (as documented by Arab itinerary sources: Hild 1977, 90 and n. 108). This last connection is an alternative route that passes via Arabissos. Arasaxa still seems to have been used as a way station during the Mamluk campaign against Caesarea in 1277. The northern variant via Taranta was re-established in the Seljuk period and still serves today as the main route from Kayseri to Malatya (Hild 1977, 84, note 75). The southern variant is no longer used for modern traffic (Hild 1977, 88).

3 Case study

For this paper, we only consider the first stretch of the route, from Caesarea to Arasaxa, the first way station on the route listed in the *ItAnt*. It was still in use as a caravanserai in Ottoman times. The straight-line distance between these sites is 34.87 km. In order to reach Arasaxa from Caesarea, the route has to move uphill and pass between the high Argaeos mountain to the south,[3] and a lower mountain range to the north. On this stretch, the road has to cross several river valleys that are dry most of the year. As far as we know, no other settlements were connected by the road in Roman times.[4] In Byzantine times, however,

3 The extinct volcano of Erciyes Dağı, the highest mountain in central Anatolia, with its summit reaching 4013 m.
4 The *TabPeut* links Caesarea first to Sinispora (?) (35.52 km) and then to Arasaxa (19.24 km; cf. Mitford 2000, 990). The name Sinispora is corrupt, however (it mixes two other toponyms), and should be eliminated (Ramsey 2010 [1890], 272). For an approach comparing Itinerary sources to reconstructed roads see French (1974).

Fig. 2 | Reconstruction of the stretch between Caesarea and Arasaxa (Hild 1977, map 6).

a new military and religious settlement pattern developed along the road and probably redefined it.

The reconstruction of the stretch by Hild (1977, 85 and map 6; Fig. 2) shows a route that passes through the sites of Moutalaske (currently Talas; a Byzantine 6th – 13th century hermitage site with religious buildings), Sari Han (a Seljuk caravanserai dating from the 13th century, partly built from Byzantine *spolia*) and Meşkiran Kalesi (currently Meskuan; a Byzantine castle). The sites of Iskokson (a small Byzantine site with a church) and Sakaltutan (a possible Byzantine castle where a Roman milestone was found, not *in situ*) are indicated as additional waypoints (Hild 1977, map 6). About 4 km west of Sakaltutan, the route passes north of the excavated rock-cut monastic complex at Kepez (Hild / Restle 1981, map; Decker 2007, 242). Obviously, these are all post-Roman sites, and the reconstruction is therefore only pertinent for the Byzantine period.[5] The sources attest to the changing pattern of communication routes in this region. The Byzantine and Medieval phases show a restructuring of the road from Caesarea to Arasaxa along a new settlement pattern constituted by religious (Moutalaske is a birthplace of saints) and military landmarks (Sari Han is a caravanserai; Meşkiran Kalesi a Medieval fortress).

5 According to Hild / Restle 1981 the settlements in this area date from the 4th – 13th centuries AD.

The existing information about the diachronic settlement pattern, roads and communication system in this macro-region offers a convenient dataset for exploratory purposes. However, no comprehensive archaeological survey at the micro-regional scale has been undertaken across eastern Cappadocia.[6] Only some isolated surveys have been done, focusing on churches and Byzantine paintings, and almost all physical remains from the ancient world have been destroyed or re-used. Apart from the displaced Roman milestone at Sakaltutan, the only known traces of the Byzantine road have been discovered near Meşkiran Kalesi (Hild 1977, 85). Modern travel journals from the 19th century (see Mitford 2000, 985–986) provide some additional descriptions locating places and roads (Ramsey 2010 [1890]). However, these are not always reliable.

In order to analyse the course of the paths, and their stability or possible change over time in relation to the documented pattern of settlements, we have used the following dataset including topography, historical geography, archaeological and epigraphic sources:

- Digital elevation model: Aster DEM at 30 m resolution;
- GUGK (Glawnoe Uprawlenie Geodesii i Kartografi) Maps (scale 1 : 200,000)
- Sites, bridges, road remains:
    - Google Earth-based localizations of ancient sites on the basis of the modern names;
    - Hild / Restle (1981);
- Milestones: French (1988, 2012);
- Road system description: Hild (1977);
- General information: Map 64 Caesarea-Melitene (Mitford 2000) in the *Barrington Atlas of the Greek and Roman World* (Talbert 2000).
- Itinerary Sources:
    - *Itinerarium Antonini* (Cuntz 1990);
    - *Tabula Peutingeriana* (Miller 1988).

The ancient geographical dataset of the Roman *Itineraria* contains explicit information about settlements and distances as well as implicit information about the regional road network as a coherent infrastructure, connecting central places and a pattern of secondary settlements or stations. Archaeological information about the nature and typology of the secondary settlements related to the road system is not available for the region. Stations indicated in the Itinerary sources cannot always be located on the ground.

4 Roman road building and least cost path modelling

In the current case study we are dealing with the construction and maintenance of the roads that were administered by the Roman and Byzantine Empire. The archetypical

6 For an archaeological survey focusing on roads and paths in Cappadocia in the Sivas region, see Tuba Ökse (2007).

image of a Roman road is that of a straight route, paved with slabs of stone. The Roman administration indeed placed special emphasis on the efficiency of connections. The emperor Vespasian, for example, when advancing into Galilee in AD 67, records that he straightened and levelled existing tracks (Hucker 2009). All over the Roman Empire we find evidence that the construction of the major roads was aimed at creating speedy and reliable connections that could also be easily maintained. Even though constructing a Roman road must have been an expensive venture, once the roads were built they proved to be highly persistent, as is witnessed all around the former Roman Empire, where many Roman routes are still in use. However, in many instances the landscape offered challenges to Roman engineers, like steep slopes or wet areas that made the construction of straight stretches difficult (Quilici 1995). The Romans therefore adopted a flexible approach to road construction. Evidence for complex engineering solutions can be found in many places, in particular bridges, dikes and switchbacks, and sometimes even tunnels. All in all, the Roman road system is more variable than is often thought.

Where to put the roads must have been dictated by military, political and economic factors, for which the speed, reliability and comprehensiveness of the connections between administrative centres must have been of primary importance. Two aspects of Roman road building make it somewhat different in terms of route (least cost path) modelling than most other cases considered in archaeology. These are connected to the primarily military function of the roads. In fact, most major roads in the Roman provinces were initially built to accommodate the army advancing into enemy territory, and were only later fixed in place as "imperial highways."[7] The roads had to accommodate not just the soldiers and horses, but also the supply trains of wagons and carts.[8]

From a modelling perspective, this poses a challenge: while extensive (experimental) research has been done to define equations that adequately model speed and energy expenditure for travel on foot (see e.g. Herzog 2013), similar data are not available for wheeled transport using transport animals. One of the few authors who has made an effort to collect this information is Raepsaet (2002). He produced an equation that gives the traction force needed to get a cart moving, depending on the weight of the cart, the paving used, and the slope.[9] If we use this equation with the figures for a typical Roman cart, the *carpentum*,

7 On the organization and infrastructure of the *cursus publicus* see Kolb (2000).

8 For a short introduction to Roman land transport based on literary, epigraphic and legal sources see Meijer / van Nijf (1992, 136–140).

9 $T = kP + Pi$
where
T = traction force needed for movement
P = weight of loaded cart in kg
k = rolling coefficient
i = slope in m/m
The rolling coefficient k is composed of a pavement friction factor and an axle friction factor.

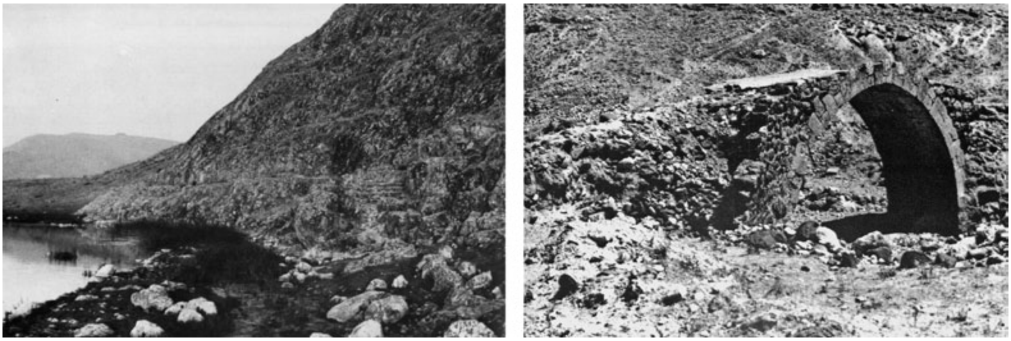

Fig. 3 | Ancient road remains in Cappadocia (Hild 1977, Abb. 62: road remains west of Elbistan; Abb. 68: Byzantine bridge west of Akçadağ).

drawn by 2 mules with a supposed maximum load of 500 kg (Roth 1998, 208–212), it indicates that it would be impossible to get these carts moving up a slope of more than 9 %. While we can assume that in the case of steeper slopes wagonloads would be reduced, most Roman roads never take slopes > 15 % (Hucker 2009; Quilici 1995). "Normal" least cost path calculations using hiking functions, like those defined by Tobler (1993) or Minetti *et al.* (2002) are therefore not best suited for Roman road modelling.

Secondly, the positioning of Roman roads in various parts of the empire seems to indicate that visibility was an important consideration as well. In Britain for example, Roman roads consistently follow ridges and plateaus instead of valleys when given the choice (Hucker 2009). This may only partly have been for reasons of preventing ambush: when setting out the road, Roman engineers (*gromatici*) would have had to set up survey stations and sighting points on the route that should be intervisible. Typical distances between survey points would be in the order of 2–3 km, but if braziers were used longer distances could be measured as well (Hucker 2009). The Roman road system in our study area was probably constructed in the same way.

Much less is known about the construction and maintenance of the Byzantine road system. The major waypoints were still maintained as traffic nodes, but instead of emphasizing speedy connections between the major administrative centres, the Byzantine road system constitutes a more fine-grained transport network that also connected the minor religious and military centres in the area. In eastern Cappadocia we have several archaeological remains that relate to the Byzantine road system (Hild 1977; Hild / Restle 1981): in the area of interest a bridge on the road from Kayseri to Malatya is documented (Hild 1977, Abb. 68). From the material remains it is also clear that difficult topography was sometimes preferred over wetlands (Hild 1977, 95 and Abb. 62, 68; Fig. 3).

5 Modelling the Roman route with least cost paths

Because of the lack of applicable cost functions that take into account wheeled transport, we have compared the two most commonly used hiking functions (Tobler's and Minetti's) and a least cost function avoiding all slopes over 9% (which might have been prohibitive for wheeled transport). We have calculated least cost paths between Caesarea and Arasaxa based on these functions using a slope map derived from the Aster DEM.[10] The modelled paths between Caesarea and Arasaxa all show similar routes, passing north of all the Byzantine sites mentioned as waypoints by Hild (Fig. 4). The distance of the Tobler and Minetti paths is 37.26 and 37.5 km respectively, and both routes are relatively straight, with a sinuosity[11] of 1.07 and 1.08 respectively. According to the *ItAnt* (Cuntz 1990) and *TabPeut* (Miller 1988), the length of the route from Caesarea to Arasaxa measures 35.52 km (24 Roman miles (mp); 1 mp = 1.48 km (French 1998, 146, fig. 2). The walking time needed to follow the shortest (Tobler) route is approximately 9 hours and 15 minutes,[12] and would therefore fit well within a day's travel. The route avoiding all steep slopes is 39.69 km long (sinuosity 1.14, approximately 10 hours walking).

These figures are in line with the available information on travel speeds in the Roman Empire. For pedestrian movement, Kolb (2000, 310, tab. 1 and note 1; *ibid.* 311) gives an average of 20–25 mp (30–37 km) per day. Similar figures are supplied for transport using pack animals like mules, donkeys, horses and in some regions even camels and dromedaries (on average 24 mp or 35 km per day; Kolb 2000, 312, tab. 2). Higher speeds could of course be achieved by riders on horseback or carts, especially with a regular change of animals.

The sources are less clear about travel speeds of heavy transport with wagons and carts. For ox-carts, a speed of 8 mp (12 km) per day is given by Kolb (2000, 316, Tab. 5). This, however, seems to be on the low end of the scale. For the Early Medieval period Bachrach (1993, 717) estimates a maximum speed of 9 mp (15 km) per day. Roth (1998, 211), however, reports that 19th-century American ox-carts could cover 19 to 24 km (12 to 15 mp) per day. Mule-carts are faster and could easily cover 19 mp (30 km) per day (Bachrach 1993, 717). Since there are no equations that specify the relationships between slope and travel speeds for various kinds of animals and carts, it is impossible to be more specific about the efficiency of the modelled paths with regard to the various modes of transport. In either case, it seems impossible for ox-carts to cover the whole distance between Caesarea and Arasaxa in one day, and even for mule carts it seems improbable.

10 The paths were calculated in ArcGIS 9.2, using the *Path Distance* module in order to account for the effect of anisotropic slope (see Herzog 2013).

11 The sinuosity index (Mueller 1968) is a measure of the directness of a route, it calculates the deviation from a straight line by dividing the route's length by the straight-line distance.

12 The walking time calculations are based on Tobler's hiking equation.

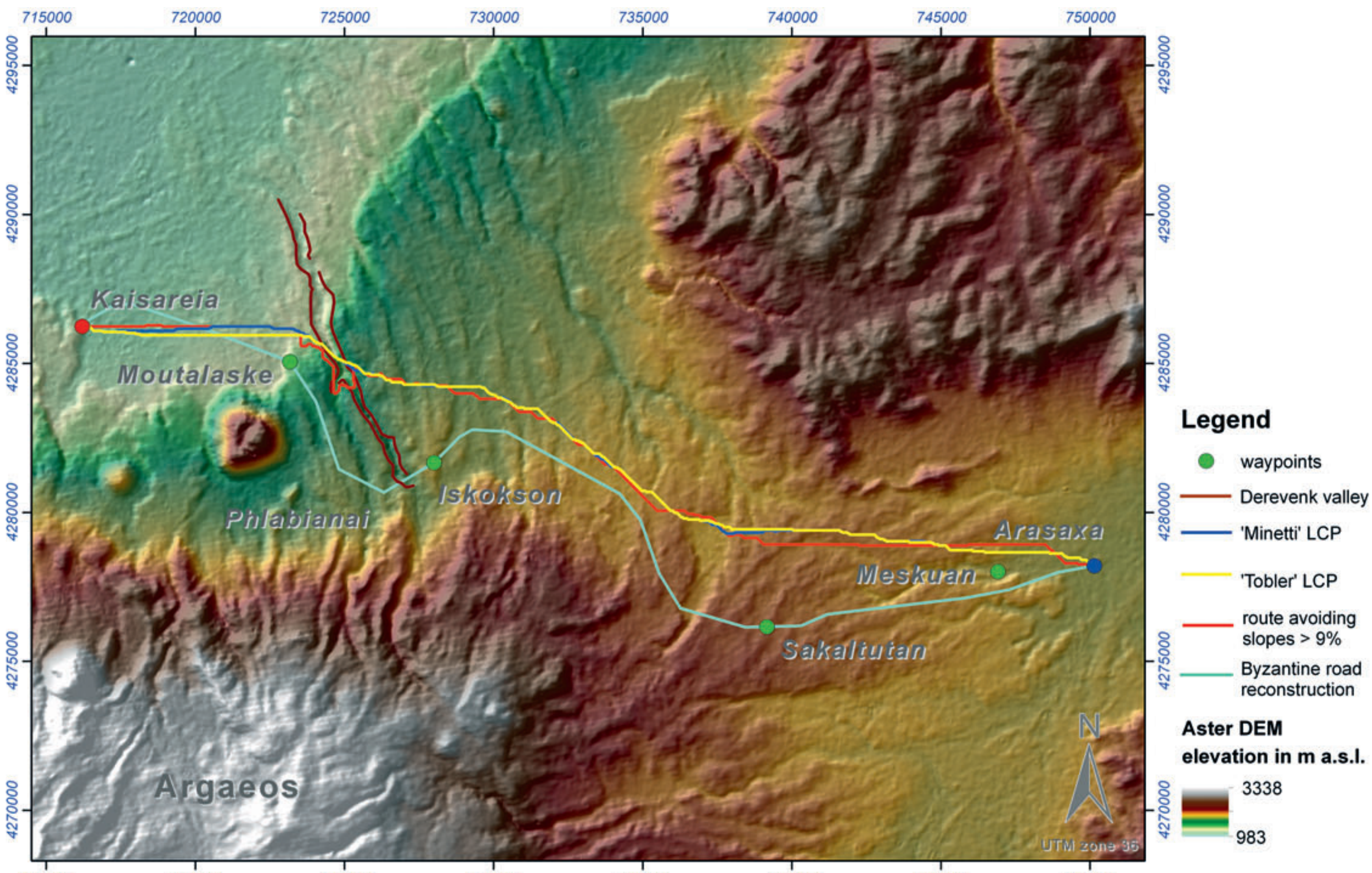

Fig. 4 | Least cost paths between Caesarea and Arasaxa, based on Tobler's and Minetti's hiking equations respectively, and least cost path only avoiding slopes over 9 %.

Fig. 5 | The Derevenk valley (http://static.panoramio.com/photos/original/20000398.jpg; copyright: Efkan Sinan).

The least cost path models do not adequately account for the crossing of the Derevenk valley, which has very steep sides (Fig. 5). The Aster DEM allows a relatively easy crossing just east of the site of Moutalaske, which seems a highly unlikely solution given the steep descent. The vertical accuracy and horizontal resolution of the DEM is probably not good enough to reflect the actual topography of the Derevenk valley. Obviously, by taking the route further up- or downstream, the building of an expensive bridge may have been avoided. Forcing the least cost path model to avoid crossing the Derevenk valley creates a more southerly variant (Fig. 6). However, it still does not pass through any of the sites mentioned by Hild. We can therefore conclude that Hild's reconstructed route, even when we force the least cost path to avoid the Derevenk valley, is not the most efficient option to reach Arasaxa from Caesarea. Hild's route has a length of 40.97 km (approx. 11.5 hours walking, sinuosity 1.17).

This is also true when we take into account the Byzantine waypoints. Making the least cost path model pass through the Byzantine sites involves creating paths from site to site, rather than modelling a single route from Caesarea to Arasaxa. This results in a path with a total length of 39.17 km (approx. 10 hours walking, sinuosity 1.12). Avoiding the Derevenk valley takes 40.39 km (approx. 10.25 hours walking, sinuosity 1.16). Following Hild's route

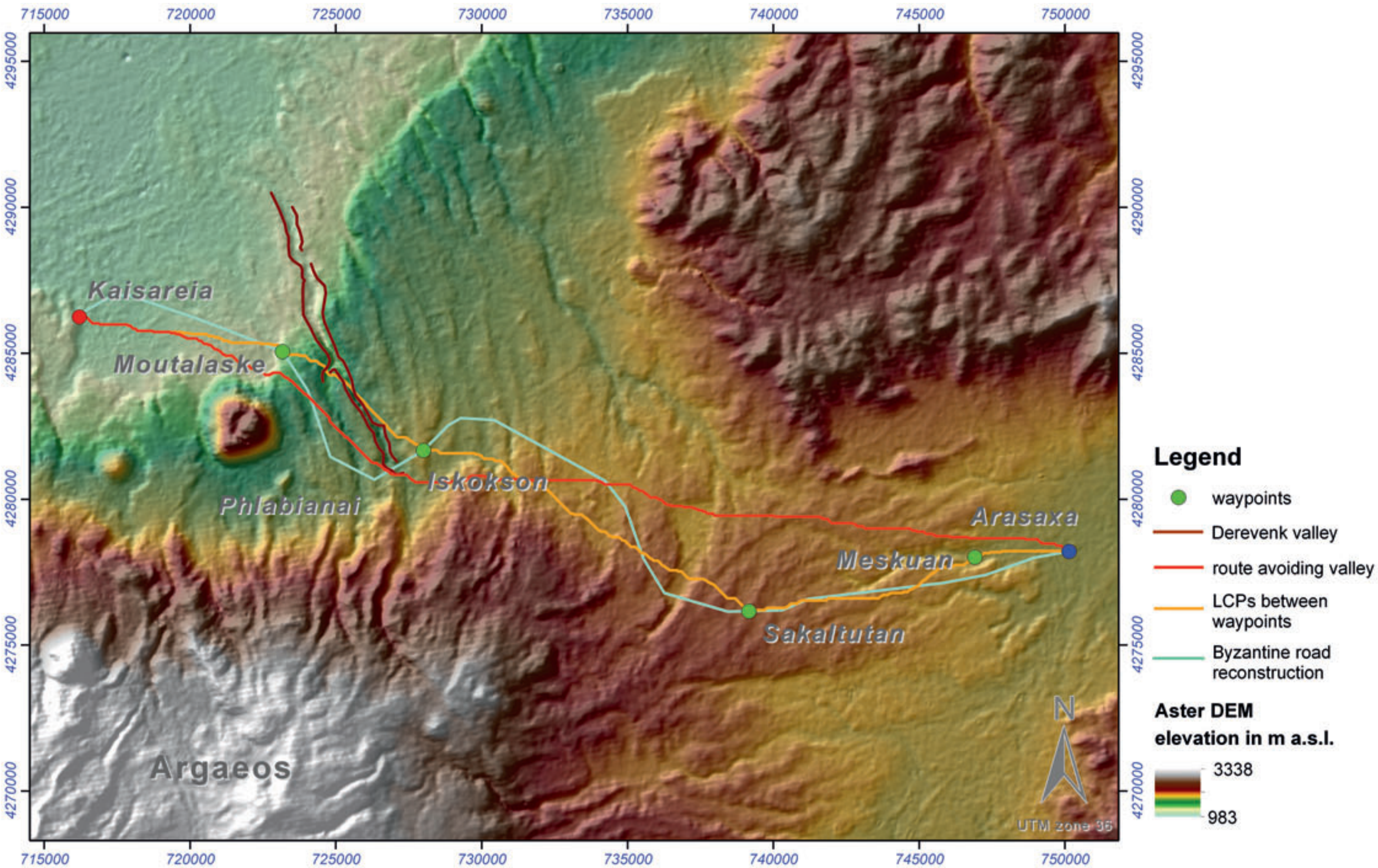

Fig. 6 | Least cost paths between Caesarea and Arasaxa (based on Tobler's hiking equation), avoiding the Derevenk valley, and passing through the waypoints.

from Caesarea to Arasaxa would therefore add at least one hour extra walking. But since his reconstruction is plotted on 1:800,000 scale topographic maps, it is probably not very accurate.

By comparing different sources we can conclude that the use of least cost path methods for road reconstruction conflicts with the unpredictability of past decision-making processes as a result of non-optimal environmental and/or cultural choices. However, we can gain a better understanding of these processes using a model based on formal criteria that involve quantitative and qualitative aspects related to environment and settlement history.

For example, if we include visibility into the model, by calculating a total viewshed of the area and letting this progressively weigh as a cost factor, the modelling results indicate that the routes with best visibility are found further to the north (Fig. 7). This suggests that Roman road building in the area was probably not dictated by optimal visibility. It also prompts the question if there was something like "good enough" visibility for the Roman *gromatici*, and whether using a total viewshed would be the best way to model this (see also Verhagen / Jeneson 2012).

6 Junctions and Steiner trees

Hild's reconstruction shows a junction that is located approximately halfway between the sites of Phlabianai (a Byzantine church site, 4th – 13th century AD) and Iskokson. Here, a second route branches off to the southeast, leading to the Byzantine settlements of Cebir and Tomarza and onwards to the Late Roman/Early Byzantine site of Kiskisos (Hild / Restle 1981, 206).

Additionally to slope, which influences the feasibility and stability of the paths, a structuring role in movement is played by nodes and junctions (Gibson 2007). Junctions are important elements in a coherent road system, but have been neglected in many case studies, in part because few applications of GIS in the field of Roman and Medieval archaeology are available (Witcher 1998; Bell *et al.* 2002; Fiz/Orengo 2008; Bellavia 2006; Gaffney 2006; de Soto / Carreras 2008; de Soto 2010). A GIS-based path modelling procedure using only archaeological sites as waypoints does not allow for the creation of junctions that optimize movement along the whole strategic network. From a mathematical point of view, the problem of finding the optimal interconnection of a set of points is covered by the Steiner Tree Problem, a generalization of the Minimal Spanning Tree Problem. Given a set of nodes (points) with edges (connecting lines) that connect various pairs of points and have associated costs, the minimal spanning tree seeks the least cost tree (i.e. a collection of edges having no loops, and the points they connect) containing each of the given points. In a Steiner Tree Problem, additional points (Steiner points) may be utilized if they can help lower the cost of the tree (Fig. 8). To avoid confusion, the original points that must be connected are

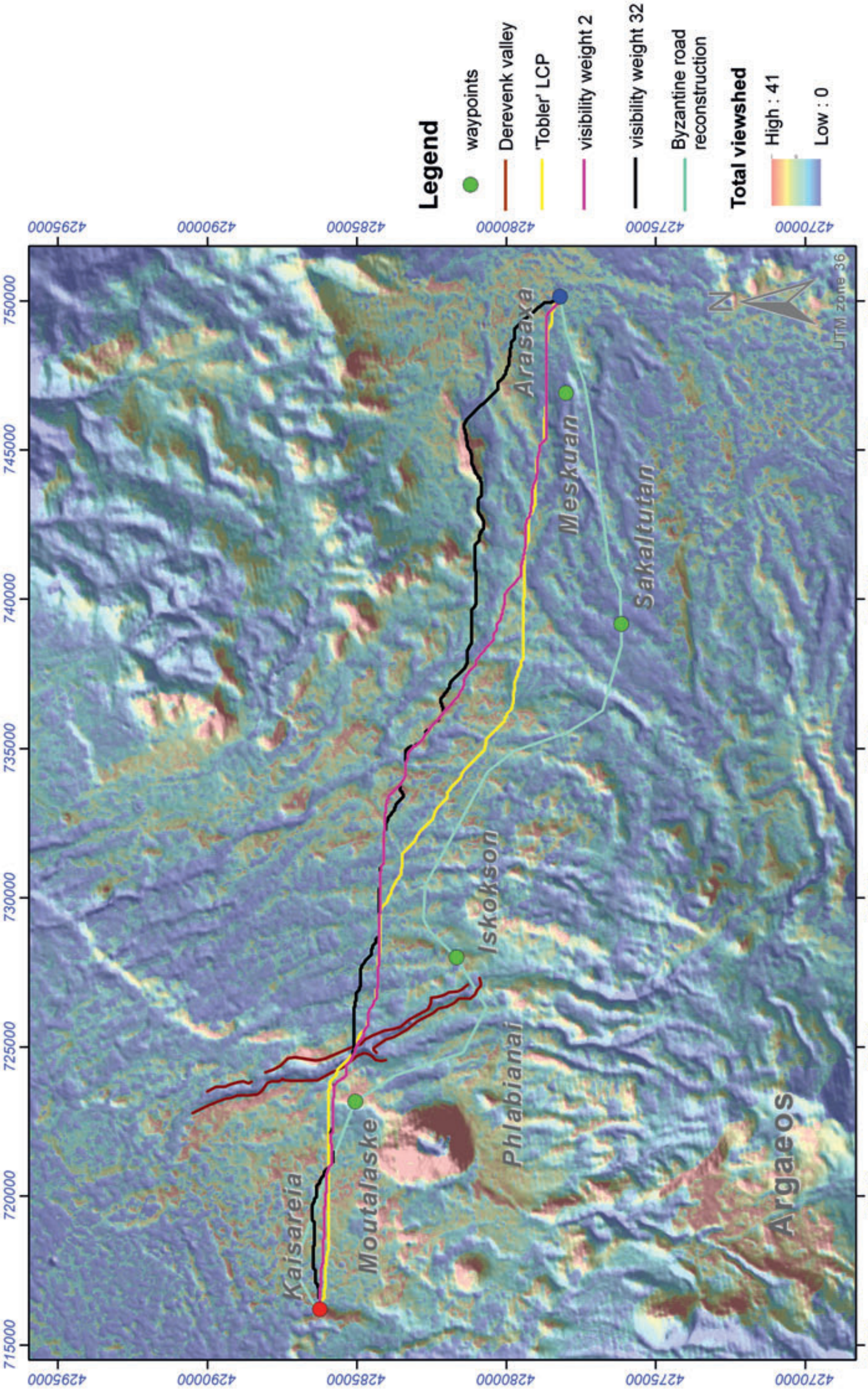

Fig. 7 | Least cost paths between Caesarea and Arasaxa, based on Tobler's hiking equation and different weights for visibility.

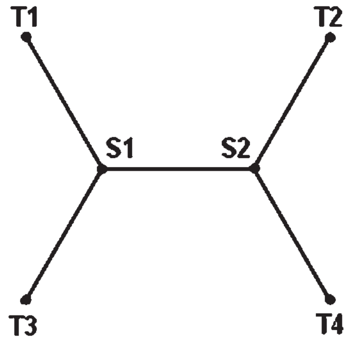

Fig. 8 | Steiner tree connecting points T1, T2, T3, and T4 by using Steiner points S1 and S2. The four terminal points could be connected without using S1 and S2, but the cost (i.e., length of the tree in this case) would be higher.

referred to as "terminal nodes." These problems are often situated in the Euclidean plane, in which case costs are the Euclidean distances. Since distances between settlements in real landscapes should not be measured as Euclidean distances, but as (non-uniform) cost distances, an additional complication is found in creating the optimal network connections. The Euclidean Non-Uniform Steiner Tree Problem, described by Frommer / Golden (2007a), aims to efficiently solve the Steiner Tree Problem for a network of points using non-uniform distances. In the Euclidean Non-Uniform Steiner Tree Problem, each location in the Euclidean plane has an associated cost. An edge connecting two points will have a cost that depends on the cost of the locations through which it passes (a least cost path). Devising a network of paths connecting sites in a rugged mountainous landscape can be formulated as a Euclidean Non-Uniform Steiner Tree Problem, with location costs dependent on land use, slope, elevation and other factors.

Along these lines, the problem of trying to find possible routes between archaeological sites given known waypoints can be formulated as a Euclidean Non-Uniform Steiner Tree Problem. The existing sites can be thought of as the terminal points in the tree that must be connected in a reconstruction of an ancient network of paths or roads. Steiner points help to lower the cost of the overall tree, i.e., they result in more efficient pathways. Furthermore, Steiner points always have at least three edges leading to/from them, and hence may function as junctions in a (road) network. Generating Steiner trees for larger sets of points is computationally intensive, however. Furthermore, no implementations of algorithms that generate Steiner trees from point data are available in GIS.[13]

13 The *v.net.steiner* module in GRASS (grass.osgeo.org) only finds the optimal connection between a subset of points in an existing network (i.e. with predefined edges); it will not create a new network.

7 A genetic algorithm to solve the Euclidean non-uniform Steiner tree problem

Frommer and Golden (2007a) developed a genetic algorithm to solve the Euclidean Non-Uniform Steiner Tree Problem, and applied this to sample problems with structured landscapes (e.g. hills, rings, etc.). The algorithm was later combined with GIS data in an exercise aimed at connecting recreational sites in Stowe, Vermont (Frommer / Golden 2007b). A weighted combination of layers of GIS data (elevation, land use and slope) was used to specify the underlying cost structure.

The problem is situated on a hexagonal grid. Each hexagonal cell on the grid may contain at most one point, and has a cost associated with it. Given two points, the edge connecting them is defined as the shortest path between them, which is not necessarily the straight line segment connecting the points. The cost of the edge equals the sum of the costs of the cells through which the edge passes plus one half the costs of the two end points' cells. Using a grid reduces the size of the solution search space from infinite to finite, though it is still potentially very large. It also allows the problem to be represented in network (or weighted graph) form. A genetic algorithm is only one possible solution, and some of the trade-offs between the genetic algorithm and other approaches are discussed in Frommer / Golden 2007a. What is important for this work is that the genetic algorithm finds good (and in some cases optimal) solutions for reasonably sized problems relatively quickly. It may not necessarily be the fastest or best performing algorithm, but it is quite flexible to changes in problem formulation.

Genetic algorithms are based on biological evolution and natural selection. They typically consist of a population of individuals representing solutions that change over time through the application of crossover and mutation operators. A fitness function assigns a value to each individual in the solution with regard to how well it meets the problem goal. In the genetic algorithm we employ, each individual in the genetic algorithm population is defined by a set of potential Steiner points. The fitness function is the cost of the minimal cost tree connecting the terminal points and possibly using some of the Steiner points. Lower cost solutions are chosen with higher probability than higher cost solutions, and are then used to generate new individuals through the use of crossover and mutation. This genetic algorithm is discussed more fully in Frommer / Golden 2007a.

8 Application

The genetic algorithm was applied to find the minimal spanning tree that connects the waypoints on the route from Caesarea to Arasaxa and those on the route branching off to the southeast towards Cebir via Phlabianai, as specified by Hild (1977). The results are shown in Fig. 9. The genetic algorithm solution does an effective job of connecting the terminal points, while avoiding high cost regions wherever possible. The deviations from the Tobler

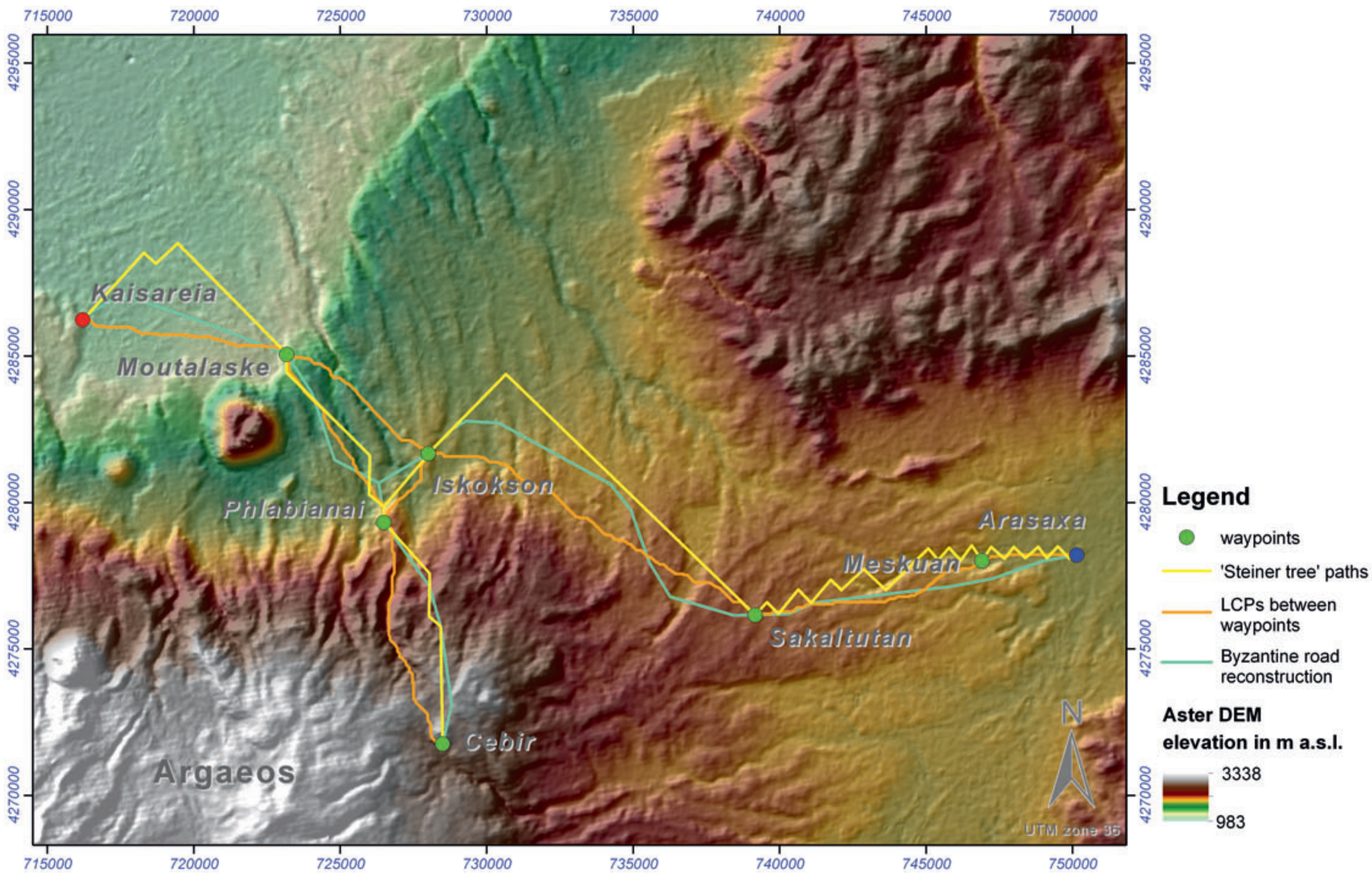

Fig. 9 | Optimal paths between Caesarea, Arasaxa and Cebir based on the genetic algorithm described in Frommer / Golden 2007a.

least cost paths calculated between the way points are clear. The two detours to the north (right from the start in Caesarea, and between Iskokson and Sakaltutan) are more in line with Hild's reconstruction than with the least cost path. The junction near Phlabianai is close to where Hild hypothesized it. Note that the genetic algorithm finds a detour in the upper left that is not found in the other models. This solution uses a narrow low-cost path of approach to Moutalaske that yields a cost approximately 3% less than the next best route. A question to consider is how likely people would be to find the less intuitive detour when it only provides relatively small savings. Such considerations can be incorporated in the algorithm, as described below.

Since the algorithm works on a hexagonal grid, the number of directions of edges is limited to six. So solutions sometimes exhibit staggered (zigzag) paths when they need to move in a direction other than one of the six. Because of this, the efficiency of the calculated route appears to be very low. The connection created between Caesarea and Arasaxa has a length of 50.84 km (approx. 13.5 hours walking, sinuosity 1.46). The zigzags could be replaced by the lines they are attempting to follow in a post-processing routine. Given that this work represents only an initial exploration, the post-processing has not been implemented. Alternatively, the current set-up could be replaced with a rectilinear grid and edges allowed to take on any direction. Cost would be calculated using numerical line integrals. Steiner point locations would still need to be restricted, possibly to the centre of each cell. In addition, the grid could have multiple resolutions, with a finer grid used in areas of highly variable cost structure.

9 Concluding remarks

We have shown that the traditional application of least cost path algorithms will only calculate optimal pathways between pairs of points, and are not effective for finding intermediate waypoints, like those hypothesized in Hild's reconstruction of the Byzantine route between Caesarea and Arasaxa. The only way in which least cost paths will approach the location of the supposed route is by progressively including known waypoints and calculating least cost paths between them. Even then, the resulting path network will not be the optimal solution to connect a set of known points. It also deviates substantially from the route suggested by Hild. We applied the Euclidean Non-Uniform Steiner Tree Problem using the genetic algorithm developed by Frommer and Golden (2007a, 2007b) to the issue of finding the optimal connection between the waypoints on the route. This resulted in a modelled route network that, while not perfectly fitting the reconstruction, shares important characteristics with it, especially the presence of a junction outside the set of known points, as well as deviations from the least cost paths that are more in line with the reconstructed route. From this we can (cautiously) conclude that the Byzantine road system was constructed with the aim of creating optimal connections for the whole micro-regional network. This clearly contrasts with the system of macro-regional connections that characterizes the Roman road network as described by the itinerary sources. The results fit with what we already know about the Byzantine road system. The new religious[14] and military geography of the area restructured the micro-regional communication and transport network, using the Roman way stations as points of departure. Both the Byzantine settlement pattern and the modelled reconstructions suggest that the Roman road itself was not in use anymore.

As alluded to above, the actual paths used in the Byzantine period may not have been optimal with regard to the cost landscape, since their creators would obviously not have had access to the full range of cost information, nor to any sophisticated algorithms. An optimal topography-based model may be inappropriate and unsuitable for reconstructing past decision-making processes (see e.g. Whitley 2002). These, on the one hand, involve a certain degree of environmental knowledge (Rockman 2003), and on the other hand concern the dynamics of changing land use, settlement pattern and functional or symbolic landmarks (military and religious sites; the caravanserai system), which influence the structure of a communication system. Depending on the function and aims of the paths and roads, spatial models can provide multiple optimal paths corresponding to the minimization or maximization of specific environmental or cultural criteria, as we did in the case of the visibility criterion (see also Howey 2011). However, the choice of which costs to use in the model, their values and their respective weights are all subjective, and so results will vary depending on these decisions. Furthermore, least cost path modelling will not easily allow us to analyse alternative options. The least cost path routines in GIS will give a single optimal solution, not the second best or nth-best. Even though k-shortest path algorithms, designed to find less optimal solutions, are described in various computer science publications (e.g. Yen 1971; Eppstein 1998; Hershberger *et al.* 2007), they are very difficult to achieve with computational efficiency, and have not been implemented in GIS.

The genetic algorithm described by Frommer and Golden (2007a, 2007b) is in fact well suited to address these issues. First of all, the algorithm generates an entire population of solutions, not just one. Furthermore, because it has an element of randomness, it may not return the same "best" solution each time. Uncertainty in costs and their weightings can be reflected in multiple runs of the algorithm. One potentially useful approach would be to run the genetic algorithm numerous times with different cost settings and count how often a given location is found in the least cost solution (or within a set of the top solutions). The results of this simulation across various cost value settings would be to assign a probability that a path passed through a particular location for each location on the map.

The study of the development of settlement distribution, density and hierarchy has recently been carried out using GIS-based techniques that support the interpretation or re-interpretation of the dynamic relationship between supra-regional roads, regional pathways, sites and off-site land use over time (cf. Bell *et al.* 2002; Fairén Jiménez 2004; Zakšek

14 For churches as proxies for settlements in the area around Caesarea see Decker (2007, 241).

et al. 2008). Other (landscape) theoretical questions still need to be explored, like the influence of different environmental costs and sociocultural factors, and landmarks that attract movement over the long term (Murrieta Flores 2010), especially where they concern the coherence of road networks, their function and the articulation and use by the local population of primary (i.e., *viae publicae*) and secondary networks (regional paths) in the Roman period.

Did the local population of the Cappadocian upland, a territory at the eastern frontier of the Roman and then Byzantine Empire, use the structured Roman and Byzantine road system? To what extent is the strategic network connecting central places and stations a product of the previous regional pattern of sites and infrastructures, and/or related to land use and resource exploitation, like mixed farming, agropastoralism and a mining economy?[15] In this respect we also consider it a relevant issue to examine the location and function of junctions unifying and subdividing the movement (Gibson 2007) along a diachronic network.

The feasibility of exploring these issues is for this case study restricted by the availability of archaeological survey data and fine-grained chronology. However, even for relatively well-known regions it is still very much limited by the availability of software solutions. Even when using off-the-shelf GIS packages, setting up and executing a multitude of different least cost path variants and comparing these is a complex task. The current implementation of the genetic algorithm for the Euclidean Non-Uniform Steiner Tree Problem is suitable for the experimental purpose for which it was applied here, but still needs to be substantially improved in speed, flexibility and accessibility to other users before it can be used to effect in landscape archaeology.

Acknowledgements

The writing of this paper was made possible partly by a VENI research grant from NWO (the Netherlands Organization for Scientific Research) awarded to Philip Verhagen.

The dataset on Cappadocia was collected by Silvia Polla within the framework of the "Ancient Cartography" Project (2006–2008) at The Karman Center for Advanced Studies in the Humanities (University of Bern).

15 On agropastoralism see Decker 2007, 256; on the Hittites control of markets and over regional routes for metal exploitation see Yakar (1976); Kaptan 1990, 78.

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