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Integrated remote sensing investigations of ancient quarries and road systems in the Greater Dayr al-Barshā Region, Middle Egypt: a study of logistics

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ABSTRACT

Although the study of stone quarries is gaining increasing importance in Egyptian archaeology, quarry logistics, particularly as concerns transport facilities, has hitherto hardly been investigated. In the case of the quarry roads in the greater Dayr al-Barshā region (Middle Egypt), distinguishing between roads related to quarry exploitation from those resulting from other periods of use (in this case mainly related to funerary cult and Late Antique–Early Islamic Period monastic communities) poses another methodological problem. In this paper the use of very high spatial resolution satellite (VHSRS) technology is combined with archaeological methods to investigate the interplay between limestone quarries and roads in the study region. Remote sensing affords significant advantages over traditional survey techniques by visualizing the spatial context, whereas the spectral information content of the imagery adds information on road characteristics.

Results indicate that spectral content is of less importance for road detection in desert-like conditions than the spatial resolution of the imagery. Filtering techniques have an additional value, but in general enhancement techniques such as histogram equalization are most important for mapping road networks in the greater Dayr al-Barshā region. Based on spectral and morphological characteristics, six road types could be identified, a seventh being located using traditional techniques. Ground verification in conjunction with archaeological evidence clarified the spatial context and functions of the routes in the pharaonic and later periods, serving cemetery, quarry and settlement logistics.

Apart from one Middle Kingdom processional road, most roads have their origin in New Kingdom quarry activities. The road pattern we discovered provides important indications on how the stone transport was organized in a practical way. Many quarries in Dayr Abū Ḥinnis were not connected to harbours along the Nile, but to a long desert road that facilitated talatat transport to an area in northern Amarna. When the abandoned quarry complexes were turned into settlements in the Late Antique–Early Islamic Period, the resident communities selected parts of the existing road system for inter-site transport and transport from and to the Nile Valley. New paths were only rarely developed.

These observations demonstrate that remote sensing techniques hold great potential for surveying road patterns over large distance in desert-like conditions.

1. Introduction

Known ancient quarry areas in Egypt range in date from the Early Dynastic (c. 3000 B.C.) to the beginning of the Islamic Period (c. A.D. 641) and are located on the flanks of the Nile Valley, in large parts of the Eastern and Western Deserts, in Nubia, and in the Sinai. The Nile Valley quarries supplied nearly all building stones (limestone, sandstone, granite and granodiorite), with limestone being

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the dominant material for stone masonry between the Nile Delta and Idfū (Harrell and Storemyr, 2009: 9, 17; Harrell, 2012: 1–4). Despite the obvious importance of this material for ancient Egyptian society and economy, the study of exploitation, social organization, and logistics of stone quarries is still in its infancy. Written and pictorial records left behind in quarries were for a long time almost the only source of information on ancient quarrying deemed worthy of publication.

Although the gypsum quarry at Umm al-Sawwān (Northern Fayyūm) had already been studied as an archaeological source in 1934 (Caton-Thompson and Gardner, 1934), research of Egyptian quarries and mines only made a real start in the 1980s. Research topics varied: Shaw (1986, 2010), Harrell (1989), and Arnold (1991) concentrated on the archaeological potential of quarry sites; Klemm and Klemm (2008) studied the petrography and provenance of rock, while Isler (2001) and Stocks (2003) focused on the experimental replication of the extracting technology. Between 2005 and 2008 the interdisciplinary QuarryScapes project studied eleven quarry landscapes in Turkey, Jordan and Egypt in order to develop a general methodology of documentation and evaluation of quarry sites (QuarryScapes 2005–2008, Harrell and Storemyr, 2009). None of these studies, however, has paid much attention to a further essential aspect of the logistics of stone quarrying: the transport infrastructure. Circulation within quarry areas, or transport of stone from a quarry to the next point in the transport system, often related to waterways, have hardly been investigated (Klemm and Klemm, 2008: 52; Coli et al., 2011). Such studies as do exist mostly concern particularly long roads, such as those at Widān al-Faras (Northern Fayyūm), Hatnub (Eastern Desert, c. 15 km south-east of Amarna) and Tūshka (Harrell and Bown, 1995; Shaw, 2010: 117; Shaw, 2006: 257–258) or are mainly focused on the logistics of the quarry system and not on the road system itself (Bloxam, 2003, 2010: 6–7).

This paper addresses the interplay between quarries and roads in the surroundings of Dayr-al Barshā, Middle Egypt, from Pharaonic to Early Christian times. An innovative aspect of our approach is the combination of very high spatial resolution satellite (VHSRS) technology with archaeological methods. Remote sensing not only affords significant advantages over traditional surveying techniques by providing spatial context, the spectral information content of the imagery also adds information on road characteristics and typology. To investigate this interrelation, emphasis is placed on the detection and mapping of ancient roads and quarry remains using remote sensing data.

2. Study area

The study area lies on the eastern Nile bank opposite the town of Mallawī, in the archaeological concession of Leuven University, which extends from al-Shaykh Saʿīd in the south to Dayr Abū Ḥinnis in the north (Fig. 1). Because of the archaeological core site, we designate this area as the greater Dayr al-Barshā region. Although in this entire area limestone quarries and shallow pit workings for extracting other minerals (mines) were exploited in the front of the Eastern Desert plateau fringing the floodplain, this article will primarily address the dense zone stretching from Dayr al-Barshā to Dayr Abū Ḥinnis.

The calcareous rock formation of the desert front belongs to the Banī Hasan Member of the Minia Formation (Middle Eocene). From the base to the top of the plateau Klemm and Klemm (2009) identified 17 sedimentological cycles in the Wādī Nakhla. Each cycle consists of two to three layers. The topmost layer 1 of each cycle consists of concretions of hard, typically ellipse-shaped, crystalline limestone boulders within a softer matrix. These concretions are so hard that they remain at the surface where the softer, surrounding limestone has eroded (Klemm and Klemm, 2008: 89). At Dayr al-Barshā, layers 2 and 3 of the 12th cycle consist of two superimposed layers of which the topmost one (2) is harder than the lower one (3) (Willems et al., 2004: 271–272; Klemm and Klemm, 2008: 89–94; Klemm and Klemm 2009: 211–216). Layer 3 was clearly of high quality, for it was in this stratum that in the Middle Kingdom the tombs of the provincial governors were carved out. When the area was later turned into a quarry site, both layer 2 and the lower layer 3 of cycle 12 were exploited.

Hitherto, the distinction between layers 2 and 3 has only been positively observed in Dayr al-Barshā. The difference is mostly one of hardness. Visually, it is difficult to distinguish the layers. Therefore we will from now on consider layers 2–3 as one stratigraphic unit. All the way from Dayr al-Barshā to Dayr Abū Ḥinnis, this unit is clearly recognizable from afar as a white stratum in the rock face. It was exploited intensively almost everywhere in the region. Sporadically, small scale quarrying also took place in other cycles although often not beyond the stage of testing the lithology for potential new quarries. South of the Wādī Nakhla, the higher cycles have increasingly eroded away. There are still some quarries immediately to the south of the wadi, but further south cycle 12 soon disappears. This explains the relative rarity of limestone quarries in the southern half of the greater Dayr al-Barshā region.

Apart from limestone quarries, there are at least two mining zones for other minerals on the desert plateaus south and north of the Wādī Nakhla (zones 6 and 12 respectively, Figs. 1 and 9), and two quarry areas for calcite alabaster or travertine (Maghāra Abū ʿAzīz and Wādī Barshāwī, Fig. 1. For a discussion on the terminology see Harrell, 1990 and Klemm and Klemm, 1991).

3. Patterns of occupation

Human activity in this region spans most of the pharaonic to Early Christian periods. East of al-Shaykh Saʿīd quarrying began as early as the Old Kingdom (Willems et al., 2009). Mining at Dayr al-Barshā started in the same period in zone 12. Between the Early Old Kingdom (c. 2700 B.C.) and the Early New Kingdom (c. 1500 B.C.) many parts of the low and higher deserts, and in some cases the wadi floors, were used as cemeteries. After the abandonment of the rock-cut cemetery of Dayr al-Barshā in the early New Kingdom, extensive quarry exploitation began (Klemm and Klemm, 2008: 83–95). Exploitation received a strong impetus by the explosive growth in demand for building material when pharaoh Akhenaten (1346–1336 B.C.) created Egypt's new capital at Amarna, immediately south of the area dealt with here. It is generally assumed that the quarries supplying the limestone for constructing the monuments in this vast city were located immediately north of Amarna (survey of pertinent literature in Willems and Demarée, 2009). However, there is unmistakable evidence of limestone quarries of the same period in Dayr al-Barshā, and from here, Amarna period quarries continue uninterruptedly towards Dayr Abū Ḥinnis where by far the largest concentration exists (Gasse, 1983; Willems and Demarée, 2009: 223).

After the Amarna period, quarry exploitation dropped markedly in the whole region, only to be resumed in the Late Period. Inscriptions date the vast quarries of Wādī Nakhla to the reign of king Nektanebo I (380–362 B.C.), whose large-scale building operations throughout Egypt are well known (Depraetere and Depauw, 2009). There is also sporadic evidence for Late Period quarrying and substantial evidence for Roman/Early Christian quarrying in Dayr Abū Ḥinnis.

In the Christian period, the function of the quarries changed. When organized exploitation had ceased, monks and hermits began to occupy the quarries and adapted them into living and

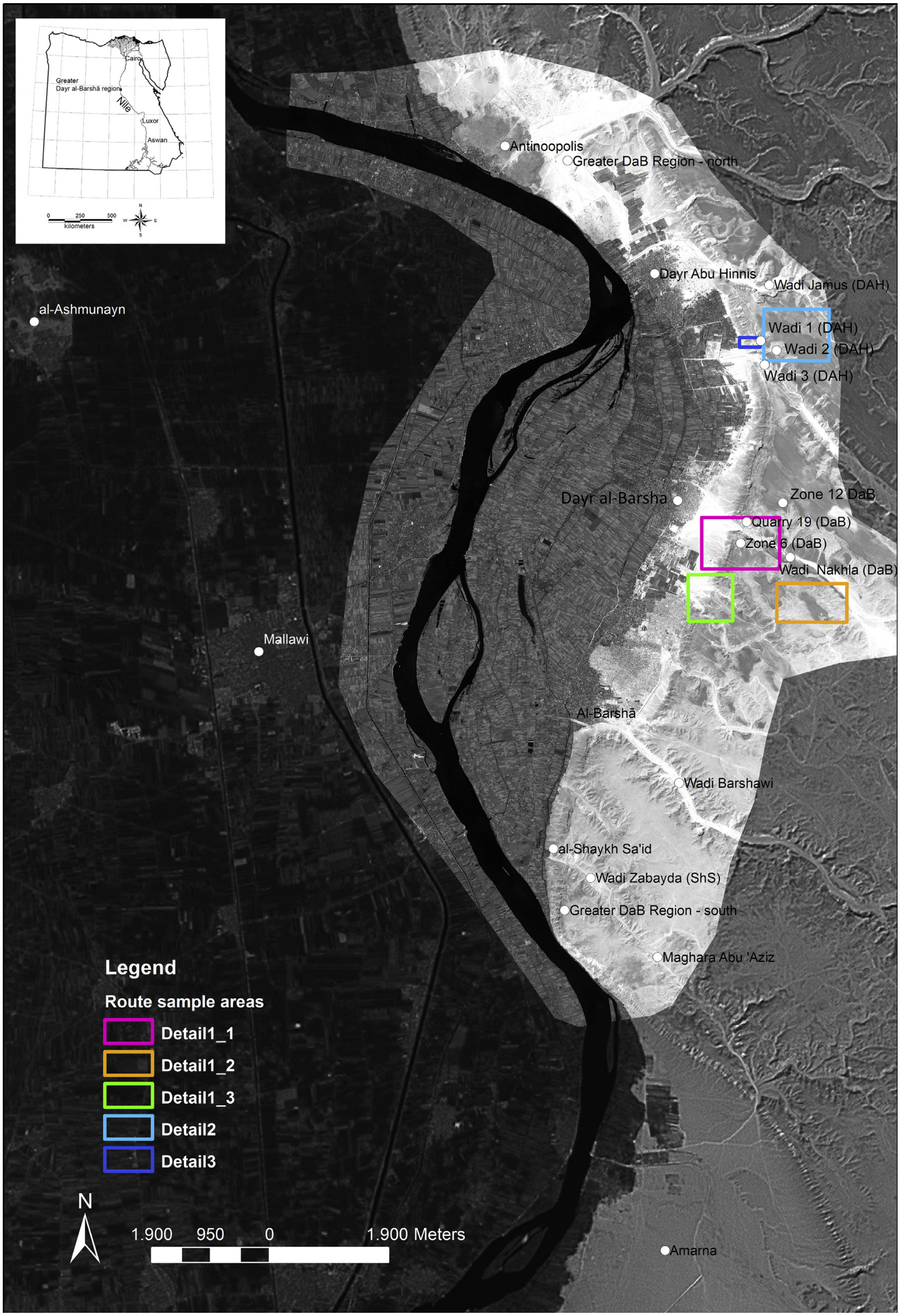

Fig. 1. The study area.

working quarters. Tombs were reused in the same way. Withdrawn from the world, yet close enough for contact and trade, these sites were perfectly suited to the monastic ideal. Extensive settlements known as *laurae* emerged in Dayr Abū Ḥinnis and Dayr al-Barshā (Van Loon and Delattre, 2004, 2005, 2006; Van Loon, in press; Van Loon and De Laet, in press, all with earlier literature).

Each occupation phase changed the functional organization of the landscape and thus the transport system. Existing roads and paths could be adapted to new functions, or new road networks could be developed, tailored to the specific needs of economic activities, (funerary) cult and habitation. The next section will explore methods to define types of such routes that were created to meet these requirements.

4. Remote sensing for studying quarries and roads

4.1. Remote sensing for studying roads: a state of the art

Roads, tracks or paths usually have some degree of permanence, formal recognition or distinct physical characteristics, including paved surfaces or simply wear associated with frequent use (Gaffney and Gaffney, 2010). For the definition of various types of roads and paths, we base our definitions on Heldal and Bloxam (2008, fact sheet 9).

A “road” involves construction and has a durable surface of, for example, stones or stone slabs. In case of a “non-paved road” there is frequently a cleared or smoothened surface (the natural soil or desert), often lined with cairns. When the trajectory is cut into the bedrock, it is called a “rock cut road.” A “path” or “track” results from repeated use by people and/or animals. It follows the least cost trajectory by going along natural contours in the landscape. Built-up structures connecting various levels of topography are called terrain ramps.

The identification of ancient roads and quarries has in the past generally been accomplished through pedestrian archaeological survey using global positioning system (GPS) receivers (for Egypt, see, for example, Darnell and Darnell, 2002). However, problems arise when trails extend beyond a research area or are part of a more complex network (Dore and McElroy, 2011). Remote sensing may offer a solution to this problem: it allows large areas to be surveyed in significantly less time and it enables studying the spatial linkage of phenomena like roads and quarries. Until now, the use of remote sensing techniques for road mapping has largely been limited to the visual identification of hollow roads (Van Liere and Lauffray, 1954–55; Wilkinson, 1993; Altaweel, 2005; Ur, 2003), local radial trail patterns (Ur, 2003) and the detection of trails over very large distances in a sandy desert environment (Blom et al., 2007; for an overview, see Riemer and Förster, 2013). Recently, remote sensing was applied in tracing caravan routes (Bubenzer and Bolten, 2013) but publications applying remote sensing techniques to the study of ancient quarries do not exist.

In continuation of the work of Dore and McElroy (2011), this study first evaluates the detection potential of ancient road tracks on desert pavements. Secondly, it aims to construct a road typology for the region of Dayr al-Barshā. Results will subsequently be correlated with the location of ancient quarries and the settlement pattern in the region.

One approach to differentiating ancient road tracks by means of remote sensing methodologies is to look for textural differences caused by use alterations that may provide distinguishable characteristics in specific areas of the electromagnetic spectrum. Removal of the thin desert pavement may cause the sediment composition of road tracks to differ from the surroundings and as such induce greater overall reflectance. This aspect is enhanced by the morphology of ancient tracks as they often continue over great distances (Dore and McElroy, 2011). Previous research on the RS identification of archaeological features shows that a spatial resolution of c. 1 m is required (De Laet et al., 2007). For larger features such as roads and ancient quarries a minimal spatial resolution of c. 2 m is required, as in, for example Spot-5 or Corona imagery (Fig. 2b–c). The development of a road typology, however, is only possible using imagery with a higher spatial resolution similar to Quickbird (0.61 m), as is depicted in Fig. 2d. While in Spot-5 and Corona one can identify the location of road stretches, Quickbird allows for a more detailed investigation of the roads themselves.

4.2. Remote sensing methodology and results

In this study, road identification is largely based on visual inspection of a digitally enhanced Quickbird-2 image. The image was first georeferenced using Ground Control Points (GCPs) collected in the field. Currently no ortho-rectification is carried out as no high resolution digital surface model (DSM) is yet available. The coregistered panchromatic (PAN) and multispectral (MS) information was subsequently fused using Gram-Schmidt (GS) spectral sharpening (Aiazzi et al., 2006; Laben and Brower, 2000) (as implemented in the ENVI 4.8® software), such that the resulting fused MS data (PANSHARP) exhibits a higher sharpness and spectral quality. In order to assess the added value of the MS information and the image sharpening process respectively, the number of roads that could be identified within the different sample areas (Fig. 1) was counted, regardless of their typology (Fig. 3). The sample areas were selected on the basis of a representative amount of roads in order to generate a reliable basis for statistical analysis.

This remote sensing analysis shows that the number of roads identified in the MS band combination (MS) is very limited compared to the panchromatic (PAN) and sharpened MS (PANSHARP) band combination, an aspect that should largely be attributed to the lower spatial resolution of the MS bands. Surprisingly, the number of roads detected in the sharpened MS band combination (PANSHARP) is somewhat lower than the amount identified in the panchromatic (PAN) band. This observation suggests that spectral content is of minor importance for road detection compared to the spatial resolution of the imagery. Since the identification of tracks in the MS image and to a much lesser extend in the PANSHARP image did not provide accurate results, evaluation of the added value of applying different enhancement and convolution filtering techniques has been limited to the panchromatic (PAN) band.

Image enhancement assumes that the digital image values span a limited segment of the radiometric resolution range available. It improves image contrast by manipulating the range of Digital Numbers (DNs), using histogram characteristics (Mather, 2004). The process is simply one of looking at the histogram of the DNs and resampling them after stretching the values which made up the bulk of the variation over the full range of possible values. As such, it improves the visual interpretation and understanding of imagery. For this particular research, histogram equalization and Gaussian stretching have been applied (Fig. 4c and b), as implemented in the ENVI 4.8® software.

These techniques were chosen because they appeared to be the most informative for detecting roads and quarries and have opposite effects (Mather, 2004). Gaussian stretch emphasizes contrast in the tails of the distribution while histogram equalization reduces contrast in this region because of the unimodal shape of most image histograms (Schowengerdt, 2007). Using histogram equalization, contrast is reduced in very light (high spectral values) or dark (low spectral values) parts of the image (Fig. 4c). During histogram equalization, the histogram of spectral values present in the image or image section is transformed into a cumulative

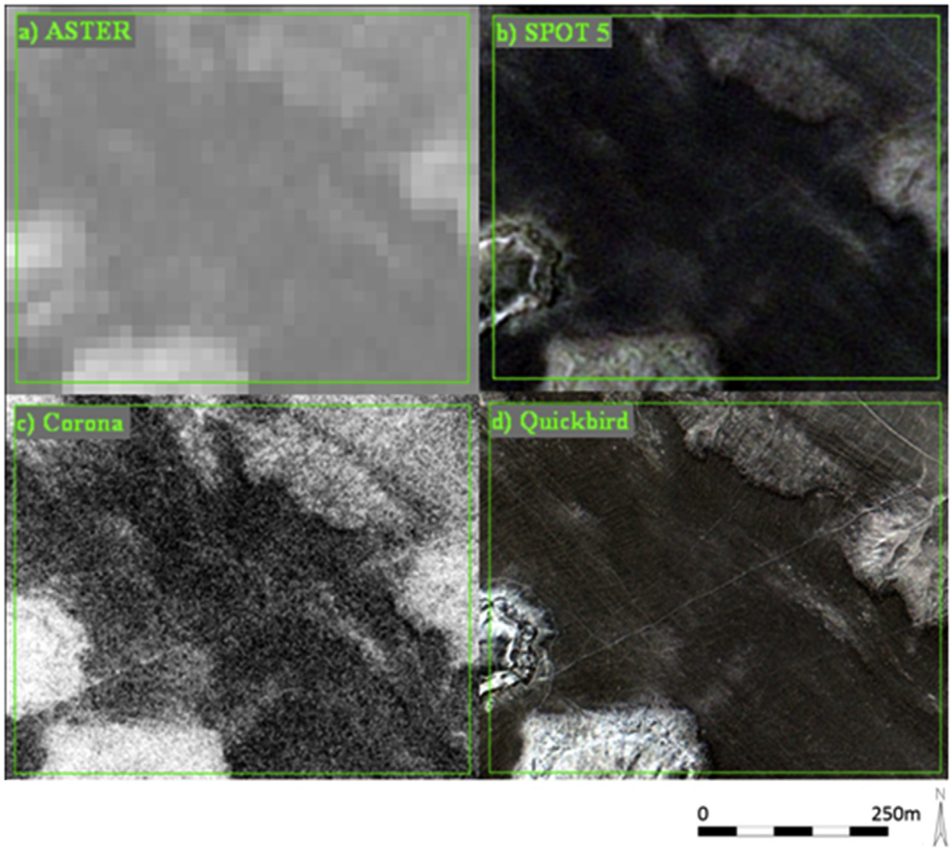

Fig. 2. Identification of routes in various imageries.

histogram (Cumulative Distribution Function, CDF) and is subsequently divided into segments of equal proportions of pixel values (Gonzalez and Wintz, 1977). In this way the shape as well as the extent of the histogram is taken into consideration (Mather, 2004). By using histogram equalization, the entropy or information content of the image is increased (Mather, 2004). Where the CDF increases rapidly, the contrast gain also increases. Since the highest gain therefore occurs at DNs with the most pixels (Schowengerdt, 2007), this technique works best in small parts of the overall satellite image. Gaussian stretching is somewhat similar to a linear stretching technique. While for linear stretching the highest recorded value is transformed into the highest value possible and

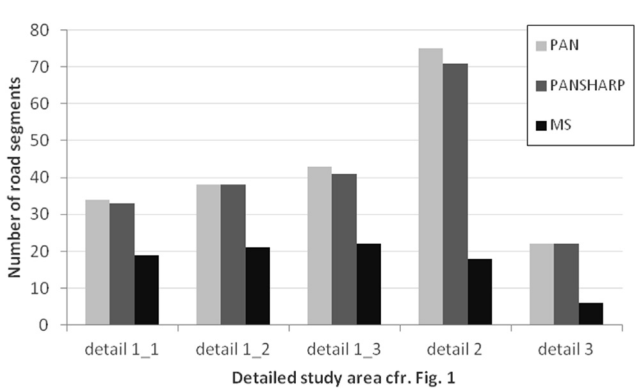

Fig. 3. Distribution of the number of road segments for the different detailed study areas indicated in Fig. 1, depending on the image type (pan = panchromatic image, pansharp = panchromatic sharpened image, MS = false colour composite).

the lowest values recorded transformed into the lowest value possible and everything in between is adjusted in a linear fashion, Gaussian stretching assumes that the digital values should have a bell-shaped curve or normal distribution (Mather, 2004). As such it takes the mean and standard deviation of the DNs present in the image into consideration. Since Gaussian stretching and histogram equalization have opposite effects they were treated as one group in the statistical analysis outlined in Table 2 and Fig. 5.

Convolution filtering emphasizes or deemphasizes image data of various spatial frequencies. Spatial frequency in this case refers to the "roughness" of the tonal variation occurring in an image (Lillesand et al., 2004). Spatial filtering is a "local" operation: Pixel values in the original image are modified on the basis of the grey values of the neighbouring pixels using a moving window with a specified kernel size. For this study the following filtering techniques, mostly using a 5×5 kernel, have been evaluated: Laplacian, Sobel Edge, adaptive Wallis, Roberts and High pass filtering (Fig. 4d–h), as implemented in the ENVI 4.8® software.

A high pass filter (Fig. 4h) removes the low frequency (background) components of an image while retaining the high frequency (local variations). It can be used to enhance edges between different regions as well as to sharpen an image. This is accomplished using a kernel with a high central value (i.e. 24) surrounded by negative weights (i.e. −1) (Lillesand et al., 2004). Laplacian non-directional filtering (Fig. 4d) emphasizes maximum values within the image by using a kernel with a high central value (i.e. 4), typically surrounded by negative weights (i.e. −1) in the north–south and east–west directions and zero values at the kernel corners (Haralick et al., 1987). The Sobel Edge filter (Fig. 4e) is a non-linear edge enhancement, special case filter that uses an approximation of the true Sobel function and a 3×3 kernel. The

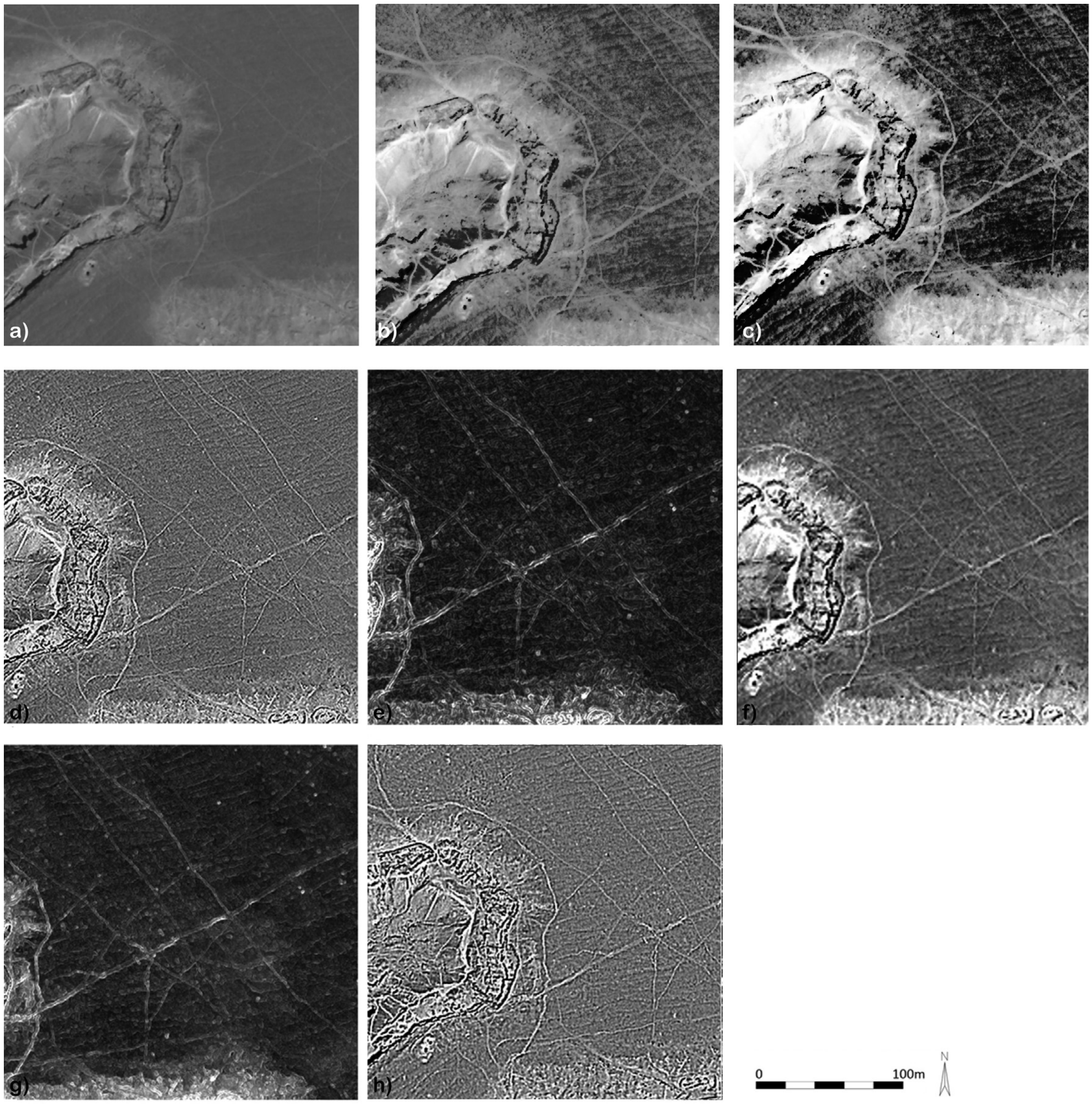

Fig. 4. Filtering techniques: a) linear stretch; b) Gaussian, c) histo; d) Laplacian; e) Sobel edge; f) adaptive Wallis filtering; g) Roberts; h) High pass.

Roberts filter (Fig. 4g) is a non-linear edge detector filter, similar to the Sobel filter. This special case filter uses a preset 2×2 approximation of the true Roberts function, a simple, 2D differencing method for edge-sharpening and isolation (Haralick et al., 1987). Finally, the Wallis filtering process (Fig. 4f) applies a locally-adaptive (spatially varying) contrast enhancement to a grayscale raster. The image is separated into high and low frequency component images. The low frequency image is considered to represent the overall scene luminance. These two components are then recombined in various relative amounts using multipliers derived from lookup tables which are driven by the overall scene luminance. This filter is designed for grayscale images in which there are significant areas of bright and dark tones (Fahnestock and Schowengerdt, 1983), as is the case in our study area. This enhancement produces good local contrast throughout the image, while reducing the overall contrast between bright and dark areas.

In order to examine the reliability of the remotely sensed road extraction analysis, different sample areas have been selected (Fig. 1 – details 1_1, 1_2, 1_3, 2, and 3) for which on a 95% significance level and using a using a Chi-square analysis no significant difference could be detected in the distribution of road segments for the various enhancement or filtering techniques (Table 1). Therefore these areas can be used to test the added value of

Table 1
Chi-square statistical analysis of the distribution of road segments in the different detailed sample areas represented in Fig. 1.

Study area		Detail 1_1	Detail 1_2	Detail 1_3	Detail 2
Detail 1_2	Chi square	2.7719			
	P-value	0.7351			
	Cramers V	0.096			
Detail 1_3	Chi square	3.3491	0.5171		
	P-value	0.6463	0.9915		
	Cramers V	0.1021	0.0376		
Detail 2	Chi square	6.8846	0.7908	1.1203	
	P-value	0.2294	0.9776	0.9523	
	Cramers V	0.1185	0.0384	0.0449	
Detail 3	Chi square	4.4385	1.5647	1.6794	1.8512
	P-value	0.4882	0.9055	0.8915	0.8693
	Cramers V	0.136	0.0741	0.0742	0.0625

different filtering/enhancement techniques (Fig. 5 and Table 2) using a non-parametric analysis of variance.

The analysis shows that Gaussian stretching and histogram equalization enhancement and Wallis filtering techniques yield significantly different results from both the Sobel and the Roberts filters on a 95% and 90% significance level, respectively. As a result three filter/enhancement pairs are defined. Enhancement and Wallis filtering provide the best results, followed by Laplacian and High pass filtering and finally Sobel and Roberts filtering. Even though enhancement and Wallis filtering are statistically equivalent, enhancement is preferred since the visible contrast is higher, facilitating the visual mapping of road segments. To conclude, filtering techniques do have an additional value, but in general enhancement techniques (a combination of Gaussian and histogram equalization) are most important for mapping road networks in the greater Dayr al-Barshā region.

Table 2
Nonparametric statistical variance analysis of the number of road segments per type of filtering/enhancement technique in the different detailed study areas represented in Fig. 1.

Image enhancement/ filtering techniques		High pass	Laplacian	Sobel	Roberts	Wallis
Laplacian	Z-value	−0.7334				
	P-value	0.2579				
Sobel	Z-value	0.8356	1.0574			
	P-value	0.2103	0.1508			
Roberts	Z-value	0.5238	1.0574	−0.3143		
	P-value	0.2937	0.1508	0.3651		
Wallis	Z-value	−1.0445	−0.7425	−1.3619	−1.3619	
	P-value	0.1548	0.2302	0.0833	0.0833	
Enhancement	Z-value	−1.1524	−1.0476	−1.6711	−1.781	−0.5238
	P-value	0.127	0.1429	0.0476	0.0317	0.2976

5. Route typology

The study of different types of routes (roads and paths) has led to the construction of a typology primarily based on the particular spectral response, supplemented by morphology, slope gradient, topographic location and spatial context of tracks in the study area. Taking into account these spectral (RS) and morphological (field observations) considerations, seven types of routes were identified (Table 3, Fig. 6). Routes are defined as pronounced linear features continuing over long distances and having distinct spectral and morphological characteristics. In this typology no reference has been made to routes which most likely have a modern origin.

Roads of Type 1 appear in the imagery as two narrow parallel linear features (Fig. 8) with very low border spectral values (an average digital number, DN, of 504 – Fig. 7). Border and surface spectral values refer to the borders and the tread surface of the transect. Dark grey to black tones in Fig. 6 can be correlated with silicified limestone boulders bounding this type of route. These linear features are separated by higher surface spectral values with an average DN of 695 (Fig. 7). The light grey to white tones in Fig. 6 are related to erosion of the desert pavement because of the use as walking surface. The width of the eroded surface amounts to 1–2 m (Figs. 6 and 8).

Paths of Type 2 are at most 1 m wide (characterized by a very low average surface spectral value of 618 DN), bounded by very low intermediate border spectral values (an average DN of 551) (Figs. 6 and 7). Very low surface spectral values are most likely due to the limited use of these routes in modern times. The cross-profile of this type of route shows a less pronounced dip because they are not delimited by boulders (Figs. 6 and 8), in contrast to Type 3 roads where a pronounced dip in the cross-profile is expected because of boulder edgings. Most likely, the average border spectral values of Type 2 paths are lower (551) than those of Type 3 roads (577) because of the spectral similarity between the border zone and the surrounding substrate (which also consists of boulders) and the fact that the boulder zone is very narrow (i.e. less than 1 pixel).

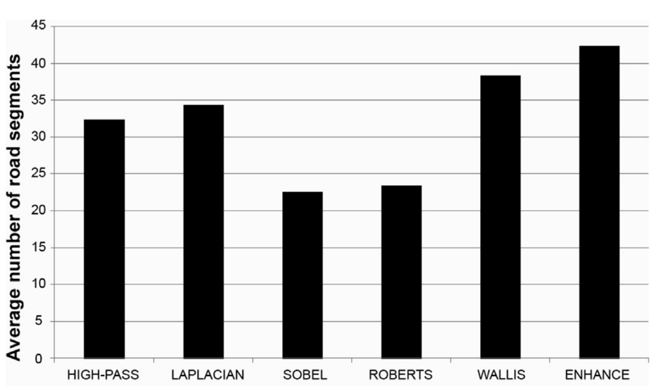

Fig. 5. Average number of road segments per filter type across the different detailed study areas represented in Fig. 1.

The walking surface of Type 3 roads is up to 6 m wide (Fig. 8). Similar to paths of Type 2, intermediate surface spectral values with an average DN of 664 can be related to the limited use of these types of routes in modern times.

Type 4 ramps are unique in the sample. Like Type 3 roads, their walking surface is about 6 m wide, but the total width of these features is about 14 m because of the very wide boulder edges (Figs. 6 and 8). This boulder zone causes a very pronounced dip in the spectral transect on both sides of the tread surface (Fig. 8). Consequently, their border spectral values are the lowest of all route types (i.e. an average DN of 4580) (Fig. 7). Even though these kinds of routes are no longer in use, they were most likely heavily used in the past, which causes their surface spectral values to be higher than those of Type 2 (i.e. an average DN of 62 for Type 4 versus c. 618) (Fig. 7). The plateau in the spectral cross-profile indicates that the surface has been artificially levelled, as otherwise a more diverse range of spectral values would be present (Fig. 8).

Like roads of Type 1, the walking surface of Type 5 roads is 1–2 m wide. These roads show clear indications of artificial levelling as they have hand-made rock cut surfaces delimiting the walking surface (Fig. 6). This artificial levelling causes the pronounced plateau in the spectral transect (Fig. 8). Because of this artificial levelling, a fresh limestone surface is outcropping, which causes the spectral surface values to be the highest of all types of routes, i.e. an average DN of c. 848 (Fig. 7). Since these routes are not bordered by crystalline limestone boulders, their border spectral values are the highest from all types of routes, i.e. an average DN of c. 648 (Fig. 7).

Like paths of Type 2, those of Type 6 are at most 1 m wide. Similar to roads of Type 5, these routes do not show a dip in the spectral profile, since they are not bordered by crystalline limestone boulders. Many of these routes are still in use. As a result, their surface is very fresh, causing the surface spectral values to be rather high (an average DN of 734).

Type 7 roads were known through field surveys. RS analysis yielded no results because they are currently hidden below a thin layer of desert sand. Nevertheless, substantial parts of these roads could be retrieved by opening trial trenches. In most places, they were built directly on top of the original desert surface. Where necessary, hollows were filled with stones and the track was everywhere covered with alluvial mud to serve as a slipway. At

Table 3
Typological characteristics of route types (DAH = Dayr Abū Ḥinnis; DaB = Dayr al-Barshā).

Type of route	Width (m)	Morphology			Slope gradient (%)	Geomorphological position	Spatial context (connection between)	Transport		Period of first use	Geographic location
		Weathered desert pavement due to longterm use (high spectr. Values)	Artificially levelled surface	Bordered by dark limestone boulders (low spectr. Values)				Goods	Means		
1. (road)	1–2	X	X	X	C. 15–30	45° parallel to the front of the plateau	Settlement and floodplain	Goods related to settlements	Man & animals	Early Christian Period	DaB
2. (path)	Max. 1	X			C. 0	On the plateau	Quarry – settlement Cemetery – settlement Quarry–quarry	Goods related to settlements	Man & animals	Pharaonic Period–Early Christian Period?	DaB DAH
3. (road)	6	X	X	X	C. 0	On the plateau	Quarry and floodplain	Quarried blocks	Sledge, wheeled or donkey transport	Pharaonic Period	DaB DAH
4. (ramp)	5–6	X	X	X	>50 at steepest section	Perpendicular to front of the plateau	Quarry and floodplain	Quarried blocks	Sledge?	Pharaonic Period (mainly New Kingdom)	DaB DAH
5. (road)	1–2		X		C. 20–30	0–45° to the steep front of the plateau	Quarries and floodplain Quarry–quarry	Quarried blocks, provisions etc.	Man & animals	Pharaonic Period till Early Christian Period	DaB DAH
6. (path)	Max. 1	X			C. 15–30	In front of the quarries	Connection within the quarries	Quarried blocks	Man & animals	Pharaonic Period (mainly New Kingdom) till Early Christian Period	DAH
7. (road)	2.5–4		X (with mud)	X (sometimes)	C. 0	60–90° to desert front	Low desert zone connecting quarry area/ cemetery area with floodplain	Funerary equipment and quarried blocks	Man, animals, and sledge transport	Pharaonic Period (Middle to New Kingdom)	DaB

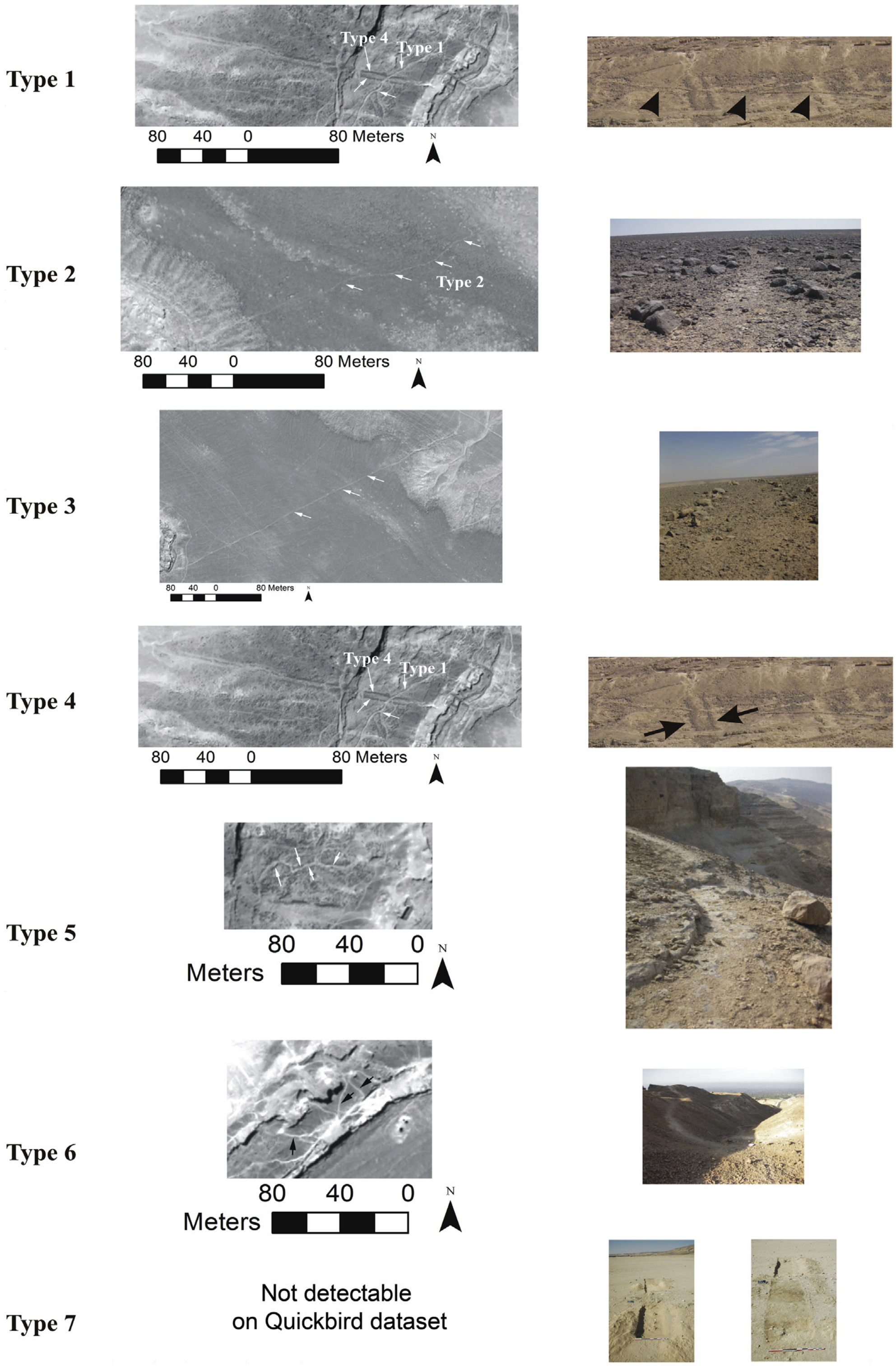

Fig. 6. Representation of the different types of routes on the Quickbird image and in the field.

present, these roads are only found in the protected archaeological area of Dayr al-Barshā where the desert surface is not disturbed.

The mapping of these seven different types of roads, paths, and ramps (Fig. 9) indicates that Type 1 roads mainly occur on slopes with gradients between 15 and 30%, i.e. at slope angles of about 45° parallel to the front of the plateau. They connect settlements dating to the Early Christian period that are located in the upper section of the front of the plateau towards the floodplain. This type of roads has, within the research area, until now, only been found in the immediate surroundings of Dayr al-Barshā. Since they are bordered by crystalline limestone boulders, they show evidence of construction and are therefore classified as roads.

Paths of Type 2 are evenly distributed across the study area, only occur on flat surfaces, i.e. on the plateau, and either link a quarry

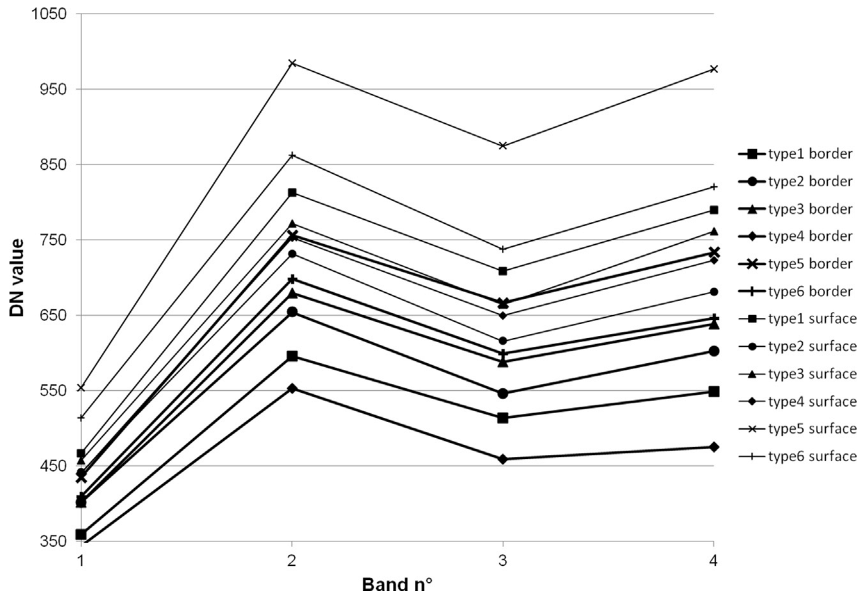

Fig. 7. Spectral signature of both the border (suffix border) as well as the walking surface (suffix surface) of the different types of routes.

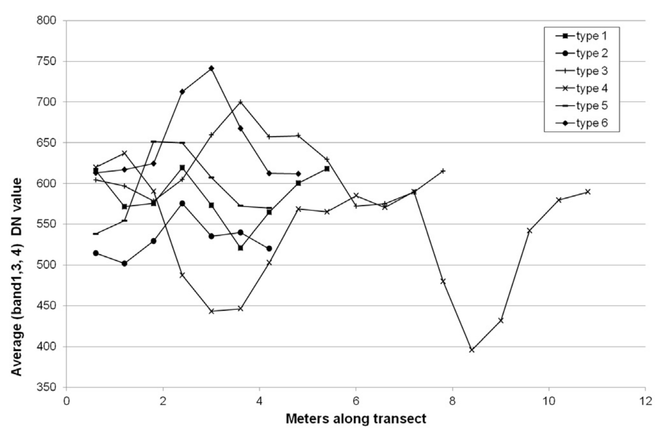

Fig. 8. Spectral transect profile across different types of routes.

area with a settlement nearby, form the connection between a settlement and the nearby cemetery, or link different quarry areas. These paths do not show any trace of construction, only evidence of erosion due to frequent use in the past. As such these kinds of routes are called paths.

Like Type 2, Type 3 roads are part of circulation systems linking the plateau to the floodplain, but they characteristically reach their end where the slope into the Nile Valley begins. They are bordered by small boulders and their surface is often cleared.

Type 4 ramps only run perpendicular to the limestone front, so that on the steepest sections the slope gradient is higher than 50%. They link Type 3 roads with the floodplain or directly connect quarries and floodplain, sometimes ending in Type 7 roads. The combination of Type 3 roads and Type 4 ramps occurs at regular intervals along the limestone front.

Similar to Type 1, Type 5 roads only occur on slopes with gradients between 20 and 30% and at slope angles of up to 45° parallel to the front of the plateau. As these rock-cut routes show clear evidence of construction, they are classified as roads. In almost all cases, these cut stretches are part of a longer route (mainly Type 6 paths). They were constructed to level outcrops or bridge heights and these routes link quarries to the floodplain or connect different quarry zones.

Type 5 roads occur both in Day ral-Barshā and in Dayr Abū Ḥinnis. A similar road stretch has been documented in the quarry zone of Dayr al-Sumbāt, c. 6.5 km north of Dayr Abū Ḥinnis (Coli et al., 2011, 2704–2705, fig. 13).

Type 6 paths, with an eroded surface due to frequent use, have only been found on slopes with slope gradients between 15 and 30%. On top of the plateau, they connect quarry entrances within larger quarry areas.

Type 7 roads have thus far only been discovered in the flat desert area at Dayr al-Barshā, where they form the continuation of Type 4 ramps descending from the quarries higher up the slope. They lead into the Nile Valley, probably to collecting points near harbours, where the stones could be loaded onto ships.

6. Archaeological evidence of quarry routes

Archaeological investigation of the transport facilities in the greater Dayr al-Barshā region complements the road typology defined by remote sensing analysis supplemented with field observations. The outline and structure of the roads, which is directly related to their function, will be discussed in chronological order. The particular aspects of the various geographical sub-regions will be taken into account.

6.1. Old and Middle Kingdom

Evidence for forms of Old kingdom exploitation in the desert was found in zone 12 at Dayr al-Barshā, the flat desert on top of the plateau northeast of the Wādī Nakhla. On the plateau, there are three still unexplored groups of rectangular, longitudinal, and circular structures built of field stones. Several of these may be huts (Fig. 9), but the form of some raises doubts over whether all were used for habitation. Surrounding these structures are large numbers of shallow pits, showing that some mineral was dug up here, which has not been determined yet. The date range of the pottery found here suggests that the site was used from the Old Kingdom until the Late Period and very possibly later. The size of the extraction pits, coupled with the long period of use, implies

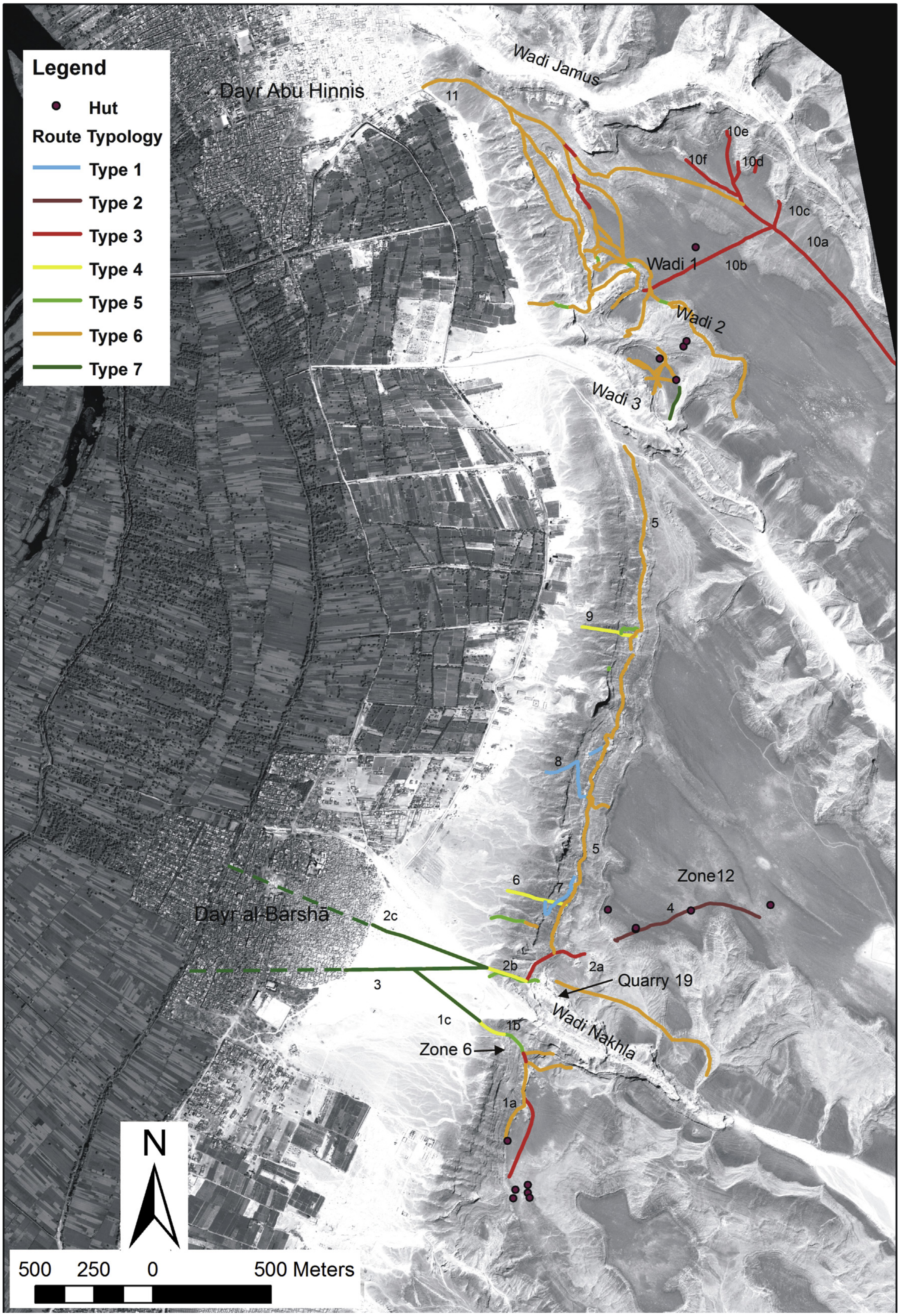

Fig. 9. Distribution of the different types of routes in the wider surroundings of Dayr-al Barshā (Road stretch 2b consists of a Type 4 New Kingdom road superimposed upon a Type 5 Middle Kingdom road).

that, while the use continued over very long periods of time, the output must have been rather restricted. This is supported by the simple form of the path (Type 2), which can only have facilitated manual transportation, or at best transportation by donkey. This path can be easily followed on top of the plateau, but is lost close to the desert edge, which makes an interpretation of the destination impossible (Path 4 in Fig. 9).

Although it has been suggested that some quarries in Dayr al-Barshā date back to the Middle Kingdom (Klemm and Klemm, 2008: 90), evidence to this effect is inconclusive (Depraetere and Depauw in Willems et al., 2004: 272–282). There is however strong evidence that the mine in zone 12 remained in use in the Middle Kingdom and Second Intermediate Period, as sherds of Marl C water jars were found there. This ware was not of local origin, but was produced in the Memphite region and is likely to have been distributed from the capital in al-Lisht. This suggests that this exploitation stood under the supervision of some central authority (Bader, 2001: 30–36). Even so, the exploitation must have been on a fairly small scale. The Type 2 path (number 4) may have been in use in this period.

Since evidence for Middle Kingdom quarries is lacking, there is *a priori* no reason to associate any extant road traces with quarry activity in that period. However, there is evidence for other categories of Middle Kingdom roads. Given that economic activity took place in the same region at a later date, a proper understanding of road development in the Middle Kingdom may help to understand the form and trajectory of later road networks.

In the Middle Kingdom, Dayr al-Barshā was the cemetery of al-Ashmūnayn, the capital of the Hare *nome* (province). Burial ceremonies and the subsequent mortuary cult required regular movement of people and goods from the capital in the west to the cemetery on the east bank of the Nile. Since the Nile had to be crossed on these occasions, there must have been a harbour on the Eastern side of the Nile. The processions to the cemetery would have started from there. A road stretch located on a straight line connecting al-Ashmūnayn with Dayr al-Barshā was found in the flat desert plain at the foot of the Eastern Desert hills (Herbich and Peeters, 2006; Willems et al., 2004, 2005). Since it was not detected using remote sensing techniques, it is not included in Figs. 7–8. In order to provide a complete overview of roads in the region, the location of this stretch of road is represented on Fig. 9 (2c) and its characteristics are described in Table 3 as a road of Type 7. Formally, it can be characterized as an intentional deposition of Nile alluvium on the desert surface. It has a width of 2–3 m. After being humidified, this road could be used as a slipway for transporting heavy loads. During recent excavations, traces probably left by coffin sledges could still be observed (Willems, 2008: 104). As this was not a quarry road, but a processional road, it is likely to have been used for transportation only when tomb equipment had to be dragged to the large elite tombs in the east. The sacred nature of this road may explain why, unlike in the New Kingdom Type 7 quarry roads to be discussed later, no stones were observed anywhere under or near the road surface of Road 2c. This suggests the surface of this processional road may have been more carefully cleaned.

By contrast, the Middle Kingdom road leading from Hatnub into the Nile Valley (located c. 15 km south-east of Amarna), that definitely served to transport quarried stone, is of our Type 3 (personal observation; Shaw, 2010, 109–115). This suggests that the functional requirements of the Dayr al-Barshā ritual road could be met by a much simpler kind of structure than was needed for a heavy-duty quarry road. The eastward extension uphill to the tombs probably followed the trajectory of the New Kingdom Type 4 Ramp 2b. In 2013, a mud road cover probably representing this Type 5 Middle Kingdom phase of use was found below this New Kingdom road.

6.2. *New Kingdom*

During the New Kingdom, the quarry areas of both Dayr al-Barshā and Dayr Abū Ḥinnis were in use. From production site to destination, two stages of transport can be distinguished: 1) internal transport, including transport from quarry to collecting point (stock pile); and 2) transport from stock pile to quays, harbours and waterways, and subsequently to the final destination.

The type of stones produced had an impact on the kind of roads required for transport. Throughout most of Egypt's history, almost all stone construction involved ashlars and paving slabs of substantial size, with individual blocks weighing between several hundreds of kilos and many tons, requiring heavy duty roads. In the Amarna period, however, the basic construction unit was the talatat block of $1 \times 0.5 \times 0.5$ cubit (= c. $52 \times 26 \times 26$ cm). This module, as we know from scenes on temple walls, could be transported manually (Vergnieux, 1999: 8–11). Over longer distances, however, blocks were most probably carried by donkeys, or arguably transported on sledges. It stands to reason that the simpler transport requirements of talatat blocks made it possible to use less elaborate types of roads, an aspect not addressed before in literature.

Internal transport can be defined as displacement between the various production areas within a quarry zone. It involves traffic of workmen from one quarry to another, movement inside a quarry, and transport of blocks from the extraction point to the place where they will be semi-finished. The discovery of semi-finished talatat blocks inside various quarries in the entire region between Dayr Abū Ḥinnis and Dayr al-Barshā implies that the finishing happened in the direct vicinity of the quarries and not near the stock pile or at the construction site.

6.2.1. *Dayr al-Barshā*

Until 2013, only Type 4 transport ramps leading down the south and the north slopes of the Wādī Nakhla (Fig. 9: Roads 1b and 2b) were known, as indicated already in Griffith and Newberry (1895: pl. II). However, the destination of these roads was not clear. Occasional concentrations of boulders cropping out of the sandy desert plain suggested a N-W extension of Road 1b (called Road 1c). Trial trenches excavated in 2013 confirmed this hypothesis and showed that the construction of 1b and 1c was similar. They were both built of boulders of crystalline limestone, topped with alluvial mud serving as a slipway. In most places, Road 1c had been washed away, but on higher 'islands' in the plain, it turned out still to be well preserved. In trial trenches further west, fewer boulders were used for road construction, and in some trenches none at all. However, a clay layer was usually still in place and stones had been swept aside to construct a regular surface creating the picture of a mud-topped track flanked by heaps of stones.

Road 3 lies on a straight W–E line leading directly to Ramp 2b on the northern slope. This road system leads to an area with a large amount of New Kingdom quarries, including Quarry 19, which contains a stela dated to the reign of pharaoh Thutmosis III (c. 1446 B.C.; Willems et al., 2004: 274). This is probably the earliest New Kingdom quarry road system.

Road System 1a–b–c (see Fig. 9) descends from the southern wadi slope and because it links up to the Thutmosis III road, it is likely to be of later date. One of the quarries on the south slope holds a stela dated to the reign of Amenhotep III (c. 1390–1352 B.C.), while another contains evidence for talatat quarrying, suggesting quarry exploitation under Akhenaten (1352–1336 B.C. (Amarna period); Willems et al., 2004: 274–275). Accordingly, the new Road System 1a–c seems to have been created in the latter period, linking up to the already existing Road System 2b and 3. Both sides of the wadi show the same pattern: Type 4 ramps continuing into Type 7 roads. Within the hilltop quarry areas, Type 6 paths branched off from the main arteries.

Both systems reach the floodplain at the southern edge of the modern village of Dayr al-Barshā, just south of the proposed location of the pharaonic village of Tjerty (Willems, 2013) (Fig. 9). Still unpublished core drillings by G. Verstraeten have revealed the existence of ancient Nile beds in the close vicinity of the village, and one of these produced New Kingdom pottery. Therefore, Tjerty is likely to have been a docking station for the transport of locally quarried limestone. Given that the quarries on the southern wadi slope were still operational in the Amarna period, some of its production must have reached the town of Amarna.

North of the Wādī Nakhla, the range of limestone cliffs continues uninterruptedly as far as Dayr Abū Ḥinnis. Here, stone was transported directly from the quarry to the nearest ramp (Type 4), using Type 6 paths situated on top of the quarry debris. Little evidence is available on the communication lines within this quarry zone. Two further Type 4 ramps can be seen (numbers 6 and 9 on Fig. 9), which lead down to the floodplain, where, further west, two docking stations must have been located. Considering the presence of talatat in the quarries above, these roads are likely to date to, or at least to have been still used, in the Amarna period. The quarries continue to Dayr Abū Ḥinnis where the path along the quarries (5) descends to the entrance of Wadi 3.

6.2.2. Dayr Abū Ḥinnis

At Dayr Abū Ḥinnis, almost all quarries produced talatat blocks and they are therefore datable to the Amarna period. The majority of the routes inside the quarry area are of Type 6, suggesting donkey transport. This is valid for all quarry sites in our study area, but most pronounced in the Dayr Abū Ḥinnis region. Here, several individual wadi systems are present with a prominent topographical variation, which requires an extensive system of interconnected paths.

In the northern part of Dayr Abū Ḥinnis, a whole series of Type 6 paths converge in a wider Type 6 road (number 11) descending into the floodplain. Another road probably led from Wadi 3 into the floodplain. However, recent disturbances west of the wadi mouth have so thoroughly destroyed the surface that no remains can now be detected. The latter roads most likely were transport roads to a harbour located near or under the modern village. A visitor's inscription in one of the Wadi 3 quarries written by an Amarna period “scribe of a contingent of boatmen” is highly suggestive of the presence of a harbour (Willems and Demarée, 2009: 224). Since the steep quarry debris slopes inside Wadi 3 acted as an ideal sliding surface, ramp construction was not required.

Not all talatat were transported to the river. On top of the plateau several routes connect Wadi 1 and Wadi 2. At the junction of these routes, Type 3 Road 10b (Fig. 9) provides a transport connection to Road 10a. The northern part of this road splits into Roads 10c–f, which branch off to a series of quarries on the southern slope of the Wādī Jamūs. Based on the similarity of quarry graffiti to those elsewhere in Dayr Abū Ḥinnis, these quarries can be dated to the Amarna period. Although this range of quarries is close, there are no quarry roads leading down to Road 11, nor are there roads descending into the wadi. Instead, all transport routes starting at this group of quarries ascend to the plateau above the quarries and join Road 10a, which runs in southeasterly direction (Fig. 9). We have followed this road on foot for about 5 km, and it turns out to be a comfortable, almost level road that must have constituted a very easy transport road for donkeys. Since the road starts at a group of Amarna quarries without evidence for subsequent exploitation, the road is likely to date to the Amarna period. Although we have lost this path under the sand of the higher ranges of the Wādī Jamūs the only possible destination was the city of Amarna. In fact, on a map published by Timme (1917: Blatt 6) a road can be seen entering Amarna from the northeast. This is likely to be the southern end of the road we discovered.

6.3. Late Period

While quarrying was extensive in Dayr al-Barshā during the Late Period, remains of this phase are almost non-existent in the Dayr Abū Ḥinnis region. In Dayr al-Barshā, the Late Period exploitation tends to be located at a lower level than the New Kingdom quarries, thus using a partly different road system. The existing main roads from the quarry area to the Nile may again have been used, although there is no positive evidence in this direction. However, the methods of stone transport had probably changed by this time. Depictions in the Wādī Nakhla and dated to the reign of Nektanebo I (Thirtieth Dynasty, 380–362 B.C.) depict a high-wheeled cart used for this purpose (Depraetere and Depauw, 2009: 56–57).

At Dayr Abū Ḥinnis, quarry exploitation was resumed in the Roman Period. Again, the later quarries are located at a lower level than the New Kingdom exploitation and may have partially obliterated remains of the earlier road system. Quarrying in these periods is likely to have served building projects in Antinoopolis and in al-Ashmūnayn/Hermopolis Magna (Fig. 1).

In the Early Christian Period, the function of the quarries changed. For some time, organized exploitation had ceased and a layer of sand and debris had accumulated in the ancient quarries and on the plateau in front. At least from the fourth century onwards, monks and hermits occupied the quarries and turned them into living and working quarters. Paths connected the hermitages to each other and, if available, to communal buildings, like churches, a community oratory, a bakery, or an administrative building (Wipszycka, 2009: 288–290). These communities used the already available road system when convenient and, when deemed necessary, developed new paths. The only evidence for the latter type of path was found in Dayr al-Barshā, where a bordered foot path of Type 1 connecting hermitages crosses a transport ramp (For an analysis of the habitation pattern of the quarries in Dayr Abū Ḥinnis, see Van Loon and Delattre, in press and Van Loon and De Laet, in press).

7. Conclusions

This paper demonstrates that remote sensing techniques hold great potential for surveying road patterns over large distances in desert-like conditions. It affords significant advantages over traditional survey techniques by visualizing the spatial context, whereas the spectral information content of the imagery adds information on road characteristics.

Results indicate that spectral content is of lesser importance for road detection in this type of landscape than the spatial resolution of the imagery. Filtering techniques (such as Wallis filtering) do have an additional value, but in general enhancement techniques, such as histogram equalization, are more important for mapping road networks in the Greater Dayr al-Barshā Region. Based on spectral and morphological characteristics, six road types could be identified. Ground verification in conjunction with archaeological evidence clarified the spatial context and functions of the routes in the pharaonic and later periods, serving cemetery, quarry and settlement logistics.

As far as is currently known, the only funerary route is located at Dayr al-Barshā. Road systems 2b and 2c presumably formed part of a more extensive road system connecting the *nome* capital at al-Ashmūnayn with the tombs of the provincial governors at Dayr al-Barshā.

This study concentrates on the routes that emerged in connection with quarry exploitation (calcite alabaster and limestone) and mining of other minerals. Archaeological evidence indicates that the various quarry and mining sites in the Greater Dayr al-Barshā Region were in use from the Old Kingdom till the Early Christian Period. However, exploitation was not continuous. It overwhelmingly dates to the Amarna period. Our research shows that a stretch of land of c. 15 km to the north of the town of Amarna was turned into a vast production area for calcite alabaster and (most importantly) limestone. These findings completely change the current picture, according to which quarrying was limited to a small desert area to the north of the town. The road pattern we discovered provides important indications on how the stone transport was organized in a practical way. On the one hand at least five road systems are in evidence (or strongly implied) in the archaeological record, connecting quarry areas with the Nile Valley (at al-Shaykh Saʿīd, Dayr al-Barshā, Dayr al-Barshā north, in front of Wadi 3 at Dayr Abū Ḥinnis and at Dayr Abū Ḥinnis north). If the New Kingdom calcite alabaster quarry in the Wādī Barshāwī was already in use in the Amarna period, this (very smooth) wadi must have served as a further transport road (Klemm and Klemm, 2008: 158–161). The same holds true for the Wādī Zabayda, which must have served as a transport road for calcite alabaster from the Maghāra Abū ʿAzīz to a stone workers' settlement of the (pre-)Amarna period (Willems et al., 2009: 326.). It is likely that all these roads led to harbours with temporary storage areas for quarried talatat. Clearly, large parts of the eastern Nile bank must have been converted into an industrial area in this period.

When the abandoned quarry complexes were turned into settlements in the Late Antique–Early Islamic Period, the resident communities selected, according to their requirements, parts of the existing road system for inter-site transport and transport from and to the Nile Valley. New paths were only rarely developed.

The picture of the eastern Nile bank to the north of Amarna as a vast production area gives illuminating insights into quarry exploitation and organization in the New Kingdom. However, the most unexpected outcome of this research is the discovery of a land transportation route. Many quarries in Dayr Abū Ḥinnis were not connected to harbours along the Nile, but to a long desert road that facilitated talatat transport to an area in north-eastern Amarna. Taken together, the new evidence significantly alters our conceptions of the size and nature of the townscape of Amarna. According to current interpretations, the town was linked to a vast stretch of the Nile floodplain to the west (e.g. Kemp, 2012: 32). To this can now be added a very significant area further north. Conceivably, the network of harbours implied by the road pattern here disclosed, may have been linked to a whole series of workmen's settlements (perhaps near already existing villages?), adding another new window on what the outskirts of Egypt's capital may have looked like.

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