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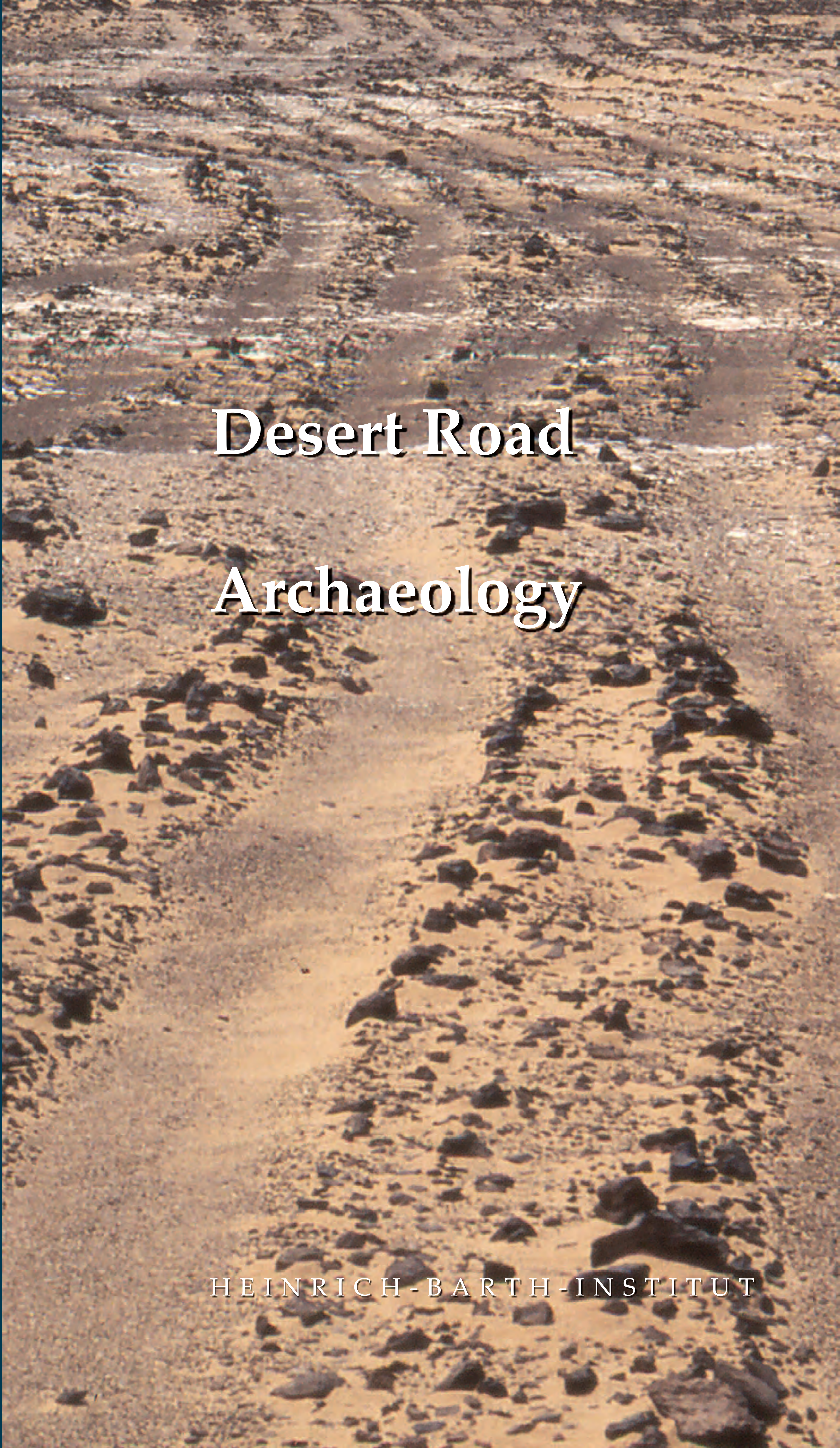

Desert Road Archaeology

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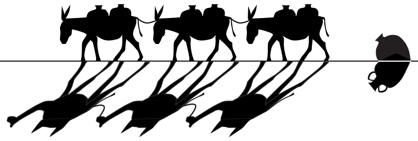
Desert Road Archaeology in Ancient Egypt and Beyond

Edited by Frank Förster & Heiko Riemer



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Olaf Bubenzer & Andreas Bolten

Top down: New satellite data and ground-truth data as base for a reconstruction of ancient caravan routes. Examples from the Western Desert of Egypt

Abstract

Thanks to new satellite data, it is possible to examine deserts area-wide for linear structures. Additionally, digital elevation models can be use to evaluate the geomorphological situation. In conjunction with historical sources and ground-truth data, these data allow us, for the first time, to reconstruct the position of the caravan routes with reasonable accuracy, here exemplified for the extremely arid Western Desert of Egypt. On the central Egyyptian Limestone Plateau where stony ground (*hamada, serir*) prevails, most of the routes can be precisely seen from space. Their special natural preservation conditions are also described in this chapter. In contrast, surfaces with thick sandy layers, with a few exceptions, do not allow a localization of routes in the used satellite image.

Due to the recent demographic development and the growth of desert tourism, the old caravan routes are being increasingly destroyed together with important archaeological finds. This gives good reason for further satellite based analyses in combination with geoarchaeological field investigations.

Keywords: digital elevation model, geomorphology, landscape, satellite imagery, path, track, Darb el-Tawil

1. Introduction

The ancient caravan routes of the Sahara are legendary. The introduction of the camel most probably from Asia in the 7th century BC (Wilson 1984) laid the foundations for regular trade links over great distances so that the trading centres of Central Africa became accessible for the coastal cities of North Africa. Exotic luxury goods such as ivory, ostrich feathers, gold dust and slaves were traded, as well as articles of everyday use supplied to the inhabitants of the oases. The ancient desert roads had to conquer the inhospitable desert landscape between the places where people could live on the natural resources. The most important aspect for road construction and travelling was to find the shortest route between the starting point and the destination of the road in order to reduce logistical and caretaking measures. However, the shortest route is not consequently the easiest to take, and that ultimately refers to the landscape to be covered. To minimize the amount of effort that had to be spent on the crossing of various landscapes, desert roads virtually represent compromises between the shortest distance and the difficulties in overcoming specific obstacles. The primary constrains of landscape features are topography and surface cover (Förster et al. 2010).

In history, some caravan routes became too dangerous because of attacks and had to be given up or changed. Some of them also disappeared because of wars or, if longer distances had to challenged, after pivotal watering places along the route had dried up (Skriwanek 2007). Whereas the routes of the western and central part of this biggest desert on earth are well documented, in the Eastern Sahara only the major routes, e.g. the famous Darb el-Arbain, are well-known and described (Shaw 1929). For centuries, the caravan routes of the Western Desert of Egypt had been the trade and communication routes in one of the most inhospitable regions of the world. Maps of these routes were published mainly after initial scientific expeditions during the time span between the end of the 18th century and 1940. Thus these maps probably provide an incomplete and, from a geodetical point of view, inaccurate picture. Investigations after the Second World War, for example, of the Geological Survey of Egypt (e.g. Klitzsch et al. 1987) or of different scientific groups had other objectives. However, these researchers documented a lot of observation with more or less exact coordinates.

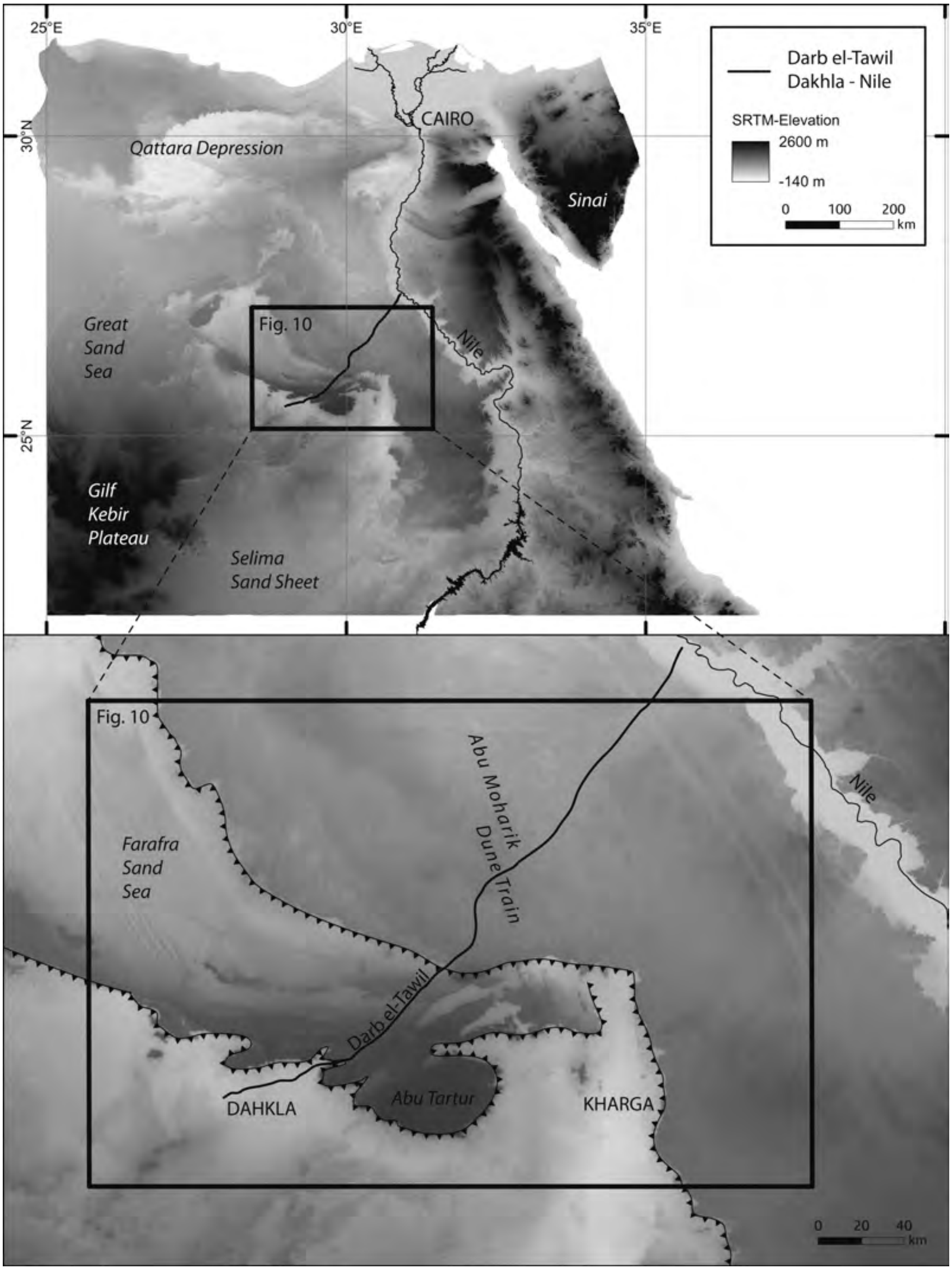
Thanks to the satellite data provided by the high-resolution ASTER sensor (Terra-Satellite), which has been freely available in the subproject E1 of the Cologne Collaborative Research Centre "Arid Climate, Adaptation and Cultural Innovation in Africa" (ACACIA) for scientific purposes, since 2000 there has been the possibility to examine the Western Desert of Egypt area-wide and in sufficient detail for a reconstruction of visible routes. Additionally, the stereoscopic ASTER data allows us to calculate digital elevation models and therefore to evaluate the geomorphological situation in the surrounding area of these routes. Today, a worldwide elevation model derived from ASTER data is available for free (ASTER GDEM 2009). In conjunction with historical sources and ground-truth information (e.g. GPS-points of route markers, documented in the logbooks of the ACACIA subproject A1), these data have made it possible, for the first time, to document and reconstruct the position of caravan routes in the Western Desert almost completely and with reasonable accuracy. The ASTER satellite images provided a huge increase in information with the result that it was possible to correct and extend the known network of caravan routes or to propose further specific investigations by (submeter) high-resolution satellite imagery and fieldwork. This showed that on the stony ground of the central Egyptian Limestone Plateau special natural aeolian processes provided a preservation of the camel tracks and their visibility. In contrast, surfaces with thick sandy layers, with a few exceptions, do not allow to locate routes in the ASTER satellite images. However, examples of the Farafra–Abu Minqar–Kufra caravan route, which had to surmount the natural barrier in the shape of the Great Sand Sea, and the Abu Ballas Trail (Förster, this volume), show that there were links to the south and west despite the inhospitable conditions prevailing in this part of the Western Desert.

2. Study area: The Egyptian Limestone Plateau

2.1. Geological and geomorphical conditions

The Egyptian Limestone Plateau (also named Abu Muhariq Plateau) is situated between the curve of the oases of the Western Desert and the Nile Valley **[Fig. 1]**. Covering an area of approximately 200,000 km^2, it has been a hyper-arid desert for about 7,000 years (Kuper & Kröpelin 2006; Bubenzer & Riemer 2007). The plateau´s surface varies from about 500 m above sea level in the south (Abu Tartur subplateau between the oases of Dakhla and Kharga) to 200 m above sea level in the north and towards the Nile Valley. Whereas the oasis floors consist mainly of Cretaceous sedimentary rocks (limestone, shale, sandstone), the plateau surface consists of Paleocene and Eocene limestones of marin origin (Klitzsch et al. 1987). A prominent relief feature is the steep escarpment at the eastern and northern edges of the oases with altitudinal differences of up to 350 m within a few kilometres. The relief of the plateau documents a karstic landscape with plains or rounded hill tops which are intercepted by minor escarpments and flat depressions. Flat draining channels resulting from former wetter climate phases (El Aref et al. 1987; Kröpelin 1993; Moeyersons et al. 2002; Bubenzer & Hilgers 2003; Kindermann et al. 2006). The Pleistocene and modern hyperaridity led and leads to partly strong wind abrasion. Whereas *serir* and *hamada* surfaces (for definitions of these terms, see footnotes 3 and 4 in **Fig. 3**) predominate, there are also some depressions covered by aeolian sands and the Abu Muhariq dune belt. The depressions and wadi channels are currently covered with sparse vegetation such as shrubs and a few tufts of grass and small herbs, which are independent of available ground water. The *serir* and *hamada* surface are completely bereft of vegetation.

Fig. 1 Map of Egypt. The different morphological structures are clearly visible by the relief energy. The marked route shows the course of the Darb el-Tawil caravan route from the Dakhla Oasis to the Nile.



But why are caravan roads partly visible in the field and even from space more than 100 years after their last use? Mason (1936: 27) wrote: "Where the route [Derb al Arba´in] passes between two adjacent cliffs the Derb narrows to a single track; where it crosses broad, flat stretches of stony desert a hundred tracks spread carelessly apart – as the beasts spread – rejoining and separating aimlessly, but all roughly parallel. Countless thousands of padded feet have pushed the small stones aside, here, and made them smooth. Time will not alter them; it only blows sand to fill them, so they become yellow ribbons amid the darker scoria." He continued (op.cit.: 29): "The result is that the broader stretches of the Derb are just

Fig. 2 The descent into the Kharga Oasis on the Darb el-Arbain (Beadnell 1909). On the left the serpentine track of the caravan route is visible.

a series of wiggly, vacillating, haphazard, characterless lines, like a hank of hair from a poodle's coat, illustrating the 'I'll-go-as-I-damn-please-and-you-can't-hurry-me' nature of the camel." (The special geomophological preservation conditions are described in section 4.1.).

2.2. The course of the Darb el-Tawil caravan route

The main trunk of the Darb el-Tawil connects the eastern part of the Dakhla Oasis (Teneida) with Beni Adi in the Nile-valley. The passage has a distance of 266 kilometre **[Fig. 1]** and was heavily frequented until around the late 19th century (Shaw 1929). On the whole route, evidence of wells or other freshwater sources is lacking. After climbing the Dakhla escarpment, the course continues across the Egyptian Limestone Plateau which is predominantly dominated by *hamada* surface, in shallow channels by *serir* in parts and by sandcover surface as well **[cf. Fig. 9]**. Unfavourable sections for caravans with profound loose sand are located along the escarpment edges and the area of the Abu Muhariq traverse. Here, the route does not follow the direct course. Besides the steep pass east of Teneida (Dakhla), an additional escarpment, of only 75 m in height, has to be transcended at Abu Gerara. As an example of such a climb through an esarpment **Fig. 2** shows a historic photo, indicating the descent to the Kharga Oasis on the Darb el-Arbain.

Several authors describe the average day performance of caravans. Dependent on the number of animals, load, overall length, relief and surface, a daily performance of between 30 and 70 km is indicated **[Tab. 1]**. Initially, the maximum value seems very high. However, Meerpohl (2007) who participated in a modern caravan travelling from Chad to Libya reported a day performance of up to 80 kilometres. The caravan generally needs 16 days for that 1,000 kilometre distance, which equates to a mean daily reach of more than 60 kilometres. However, in contrast to the classical caravans, the modern (meat-)camels carry no load and are supported with feed and water by off-road trucks.

For the Darb el-Tawil travel times of 62.5 hours (Beadnell 1909) and 63 hours (Edmonstone 1822) are reported to cross the waterless Egyptian Limestone Plateau. These times apparently denote the absolute walking time without breaks. Cailliaud (1822) indicates five days travel time, which matches a day performance of more than 53 kilometres (including rest periods) **[Tab. 2]**. Assuming an average day performance of 48 kilometres (average in **Tab. 1**) the pure walking time is 66.5 hours. This matches a realistic walking speed of 4 km/h with a daily walking time of 12 hours.

3. Methods and data

Within the interdisciplinary subproject A1 "Climatic Change and Human Settlement between the Nile Valley and the Central Sahara" as part of the Cologne Collaborative Research Centre 389 ACACIA, a wide range of geoscientific, (archaeo-)botanical and archaeological methods were used all over the funding period (1995 to 2007) (Bubenzer et al., eds., 2007). Alongside the analysis of satellite data, point information was recorded in field-work expeditions.

3.1. Groundcheck

During surveys and excavation campaigns, every crossing of the caravan routes or historic landmarks was recorded by GPS-measurement and documentation in the logbook. These ground-truth data represent a unique archive and merit a direct countercheck of the satellite data interpretation. Thus, different strategies concerning the placing of route markers (*alamat*) could be investigated (see **Fig. 6** and Förster et al. 2010; Riemer 2007; Riemer, this volume). A particular form was used to record the different landscape situations (see **Fig. 3** and Bubenzer 2009). The detailed measuring and describing of the surface condition provide the mentioned approach to the study and conservation of caravan tracks.

3.2. Satellite images, satellite data, data evaluation, and data processing

The use of satellite data has become more and more important during the last 30 years. Even in less accessible regions of arid Africa, satellite data can answer many types of questions. In addition, they can be used as a map substitute in regions which are barely covered with cartographic data. For these regions, maps with scales of up to 1:50,000 with additional information layers (e.g. waypoints or tracks) are now feasible on demand e.g. by use of ASTER satellite data. One of the most important advances in satellite sensor technique is the enhancement of the resolution. The first Landsat satellites reached spatial resolutions of about 80 m per pixel. New commercial satellites reach pixel resolutions of better than 0.5 m for each pixel, like the WorldView 1 imager (DigitalGlobe 2009). Therefore, the resolution reaches the scale of aerial photos and enables this good quality to be used for inaccessible regions as well. However, at the same time the amount of storage space quadrupled for each bisection of the pixel size. Consequently, more and more data storage and processing power is needed to handle the data quantity. In addition, the visual inspection of the data takes more and more time, so the current research tries to use automatic object filtering to enhance and accelerate the use of high-resolution satellite data (de Jong & van der Meer 2006). The second development in satellite technique is the enhancement of the spectral resolution and number of different bands used with the satellite systems. However, for the detecting of linear structures the spatial resolution is essential.

Average daily reach		Reference
32 km	(20 miles)	Rennel (1802)
60–70 km		Beadnell (1909)
40 km		Hassanein Bey (1926)
40 km	(25 miles)	Harding King (1930)
56 km	(35 miles)	Ball (1928) *

* "on long waterless distances"

Tab. 1 Average daily reach of a transport camel.

Traveler (Reference)	Travel time	Route length	
Edmonstone (Edmonstone 1822)	63 hours	285 km	(178 miles)
Drovretti (Cailliaud 1822)	5 days	n/a	
Beadnell (Beadnell 1909)	62.5 hours	250 km	
This study	Average daily reach of 48 km (cf. **Tab. 1**): 5.5 days or 66.5 walking hours with a speed of 4 km/h	266 km (calculated by ArcGIS)	

Tab. 2 Travel time by camel on the Darb el-Tawil from Dakhla Oasis to Beni Adi (Nile Valley).

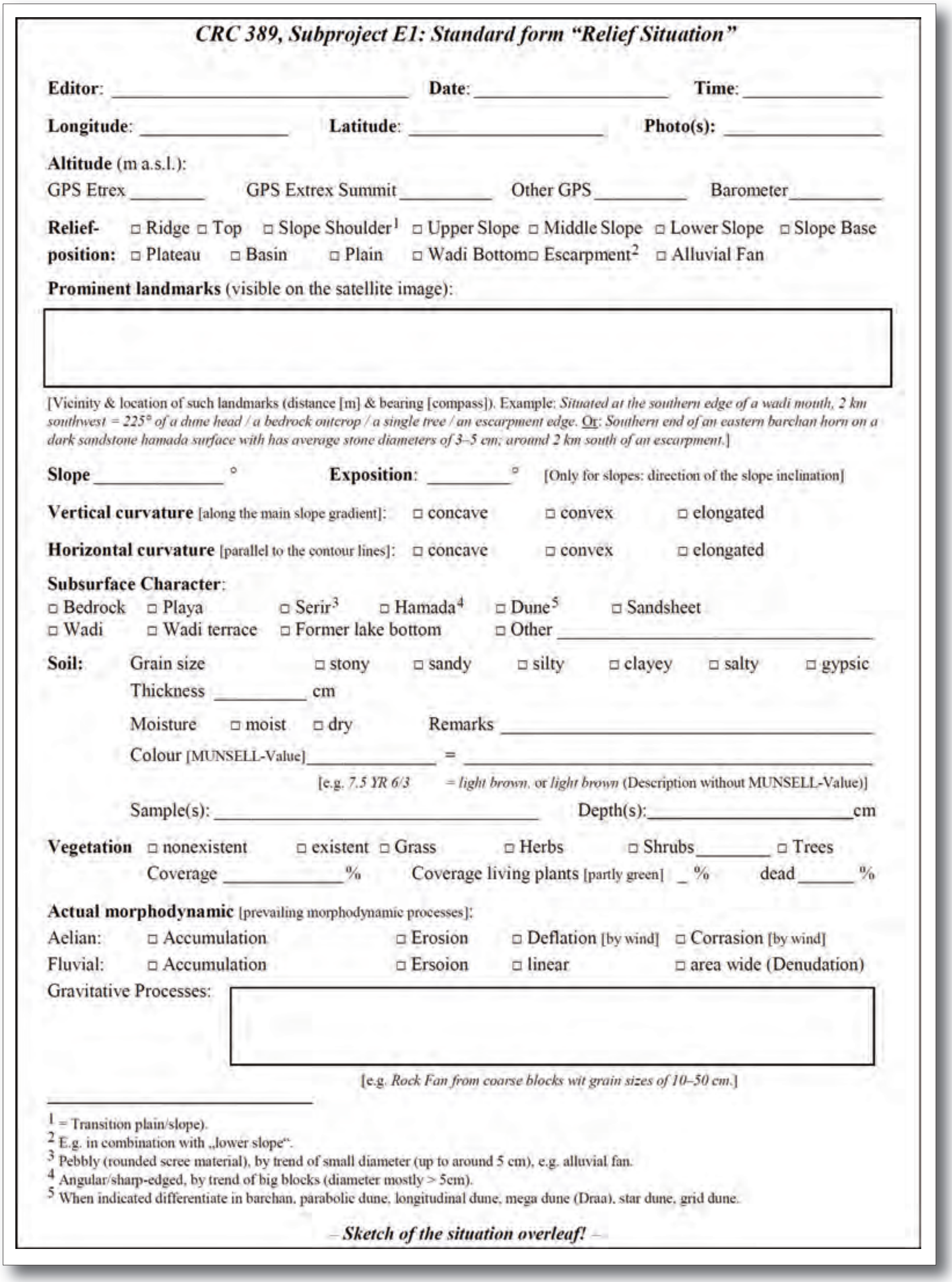


Fig. 3 Standard form: Acquisition of the relief situation.

CRC 389, Subproject E1: Standard form "Relief Situation"

Editor: ____________ **Date**: ____________ **Time**: ____________

Longitude: ____________ **Latitude**: ____________ **Photo(s)**: ____________

Altitude (m a.s.l.):

GPS Etrex ________ GPS Extrex Summit ________ Other GPS ________ Barometer ________

Relief-position: ☐ Ridge ☐ Top ☐ Slope Shoulder[1] ☐ Upper Slope ☐ Middle Slope ☐ Lower Slope ☐ Slope Base ☐ Plateau ☐ Basin ☐ Plain ☐ Wadi Bottom☐ Escarpment[2] ☐ Alluvial Fan

Prominent landmarks (visible on the satellite image):

[Vicinity & location of such landmarks (distance [m] & bearing [compass]). Example: *Situated at the southern edge of a wadi mouth, 2 km southwest = 225° of a dune head / a bedrock outcrop / a single tree / an escarpment edge.* Or: *Southern end of an eastern barchan horn on a dark sandstone hamada surface with has average stone diameters of 3–5 cm; around 2 km south of an escarpment.*]

Slope ____________ ° **Exposition**: ________ ° [Only for slopes: direction of the slope inclination]

Vertical curvature [along the main slope gradient]: ☐ concave ☐ convex ☐ elongated

Horizontal curvature [parallel to the contour lines]: ☐ concave ☐ convex ☐ elongated

Subsurface Character:

☐ Bedrock ☐ Playa ☐ Serir[3] ☐ Hamada[4] ☐ Dune[5] ☐ Sandsheet

☐ Wadi ☐ Wadi terrace ☐ Former lake bottom ☐ Other ____________

Soil: Grain size ☐ stony ☐ sandy ☐ silty ☐ clayey ☐ salty ☐ gypsic

Thickness ________ cm

Moisture ☐ moist ☐ dry Remarks ____________

Colour [MUNSELL-Value]____________ = ____________

[e.g. *7.5 YR 6/3* = *light brown*, or *light brown* (Description without MUNSELL-Value)]

Sample(s): ____________ Depth(s):____________cm

Vegetation ☐ nonexistent ☐ existent ☐ Grass ☐ Herbs ☐ Shrubs________ ☐ Trees

Coverage ____________% Coverage living plants [partly green] _ % dead ______ %

Actual morphodynamic [prevailing morphodynamic processes]:

Aelian: ☐ Accumulation ☐ Erosion ☐ Deflation [by wind] ☐ Corrasion [by wind]

Fluvial: ☐ Accumulation ☐ Ersoion ☐ linear ☐ area wide (Denudation)

Gravitative Processes:

[e.g. *Rock Fan from coarse blocks wit grain sizes of 10–50 cm.*]

---

[1] = Transition plain/slope).

[2] E.g. in combination with „lower slope".

[3] Pebbly (rounded scree material), by trend of small diameter (up to around 5 cm), e.g. alluvial fan.

[4] Angular/sharp-edged, by trend of big blocks (diameter mostly > 5cm).

[5] When indicated differentiate in barchan, parabolic dune, longitudinal dune, mega dune (Draa), star dune, grid dune.

– ***Sketch of the situation overleaf!*** –

Man-made linear structures in the Western Desert of Egypt can be sorted into two main groups. Firstly, structures concerning motorcars, and secondly structures from ancient roads, mainly from camel or donkey tracks **[cf. Fig. 4]**. In scales smaller than 1:50,000 the difference is hard to distinguish, due to the fact that both appear as one linear structure. Only the comparison with other sources (e.g. ground control or other mapping work) can give more information. Greater scales like 1:10,000 sometimes show the splitting up in several small tracks **[Fig. 4d]**, which gives a good hint for a camel track.

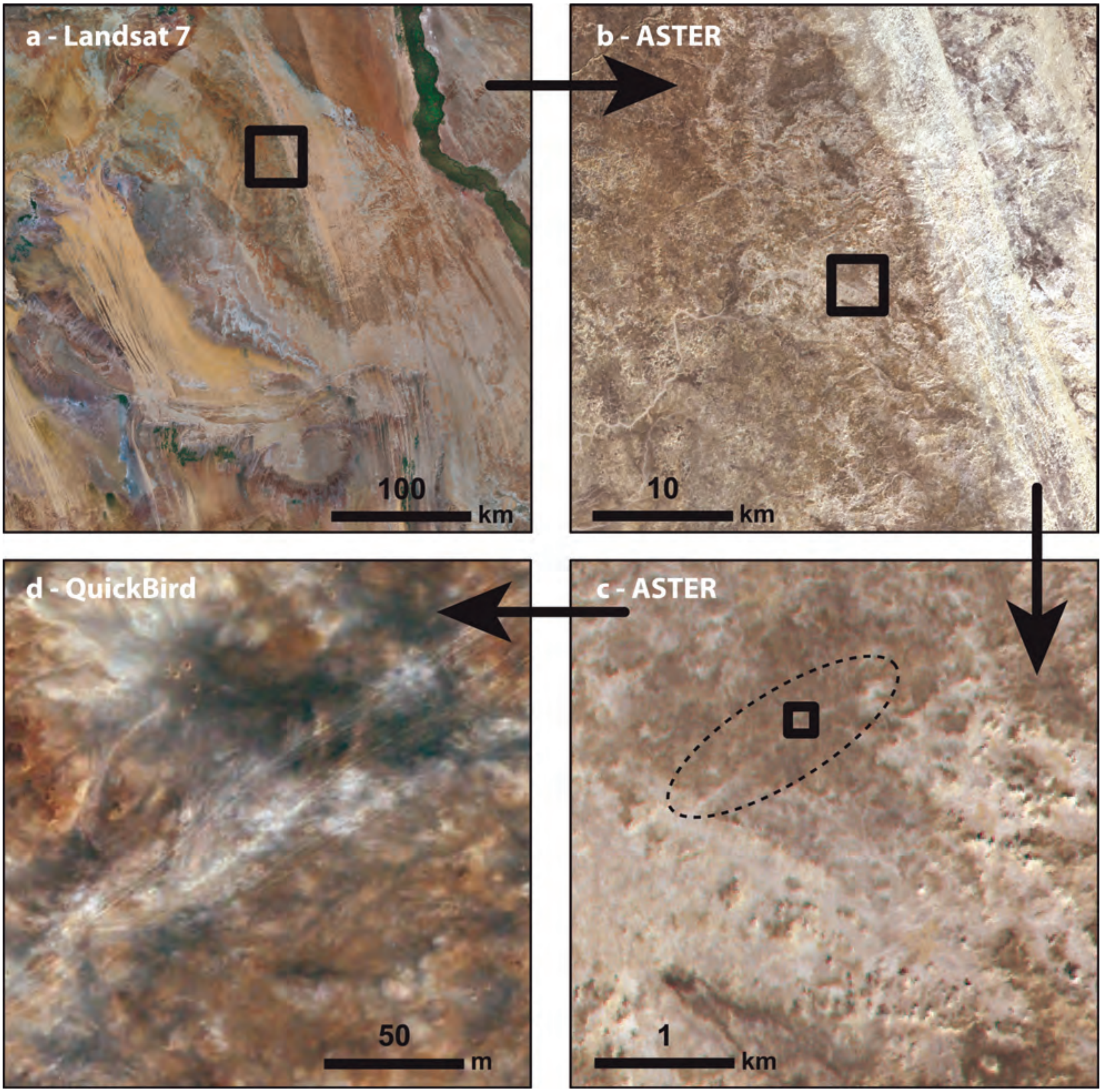


Fig. 4 Resolutions in different satellite sources. Zoom in clockwise from upper left: **a** Landsat 7; **b** ASTER; **c** ASTER; **d** QuickBird. The inset shows the map detail to be enlarged in the following figure. It becomes clear that linear structures like caravan routes are only visible from a specific scale (starting at 1:50,000). Figure **c** (ASTER) shows a faint linear structure in front of the dark background (marked by ellipse). The higher spatial resolution (smaller pixel size) of the QuickBird satellite data in **d** reveals the splitting of the linear structure into several individual camel tracks.

Unfortunately, satellite data feasible in the scales are very expensive and only available for small areas.

In this study, ASTER satellite images were used for an area-wide detection of caravan routes. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is a high-spatial-resolution, multispectral global imager on the NASA spacecraft TERRA. TERRA was launched in December 1999 and provides several passive sensors that are able to receive both the reflected sun energy, as for visible wavelengths, and the absorbed and re-emitted sun energy, as for thermal infrared

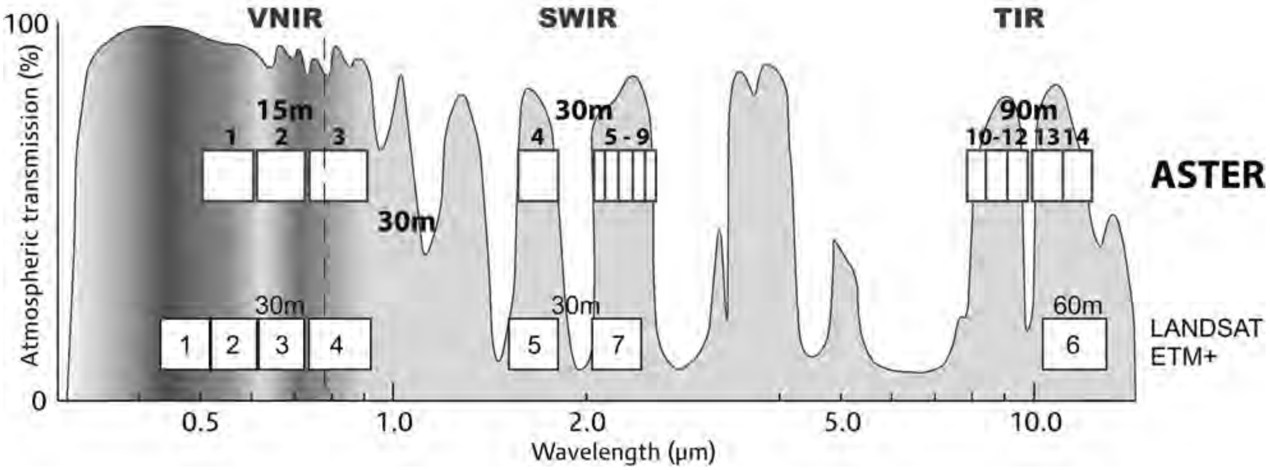


Fig. 5 ASTER spectral bands (top) compared to Landsat ETM+ (bottom). The rectangular boxes indicate the sensor channel with the respective spatial resolution on the top of the boxes (modified after Kääb et al. 2002).

Abbreviations: VNIR (visible and near infrared), SWIR (short-wave infrared) and TIR (thermal infrared).

wavelengths (cf., e.g., Lillesand & Kiefer 2004). Therefore, the sensor can only be used to detect energy when the naturally occurring sun energy is available. Reflected sun energy is only measurable during the day. Energy that is naturally emitted, e.g. thermal infrared, is detectable by day and at night, provided that the amount of energy is large enough to be recorded. The sensor provides along-track digital stereo data at 15 m resolution in contrast, e.g., Spot satellite data with across-track stereo images. Yamaguchi et al. (1998) give an overview of the configuration features and performance. ASTER's spectral and geometric capabilities include 14 bands in different wavelengths **[Fig. 5]**, three bands in VNIR (visible and near infrared) with 15 m resolution, six bands in the SWIR (short-wave infrared) with 30 m and five bands in the TIR (thermal infrared) with 90 m, and a 15 m along-track stereo-band looking backward with the same wavelength as band 3 (nadir). A comparison of ASTER and the well-known LANDSAT ETM+ spectral bands is given in **Fig. 5** (modified after Kääb et al. 2003). Other prominent imagers with variable operations are present on the TERRA platform like the MODIS sensor system.There are several processing steps before using the satellite images:

(1) Selection of suitable satellite scenes with no cloud cover
(2) Processing of a colour image (Red/Green/Blue) from three compatible satellite bands;
(3) Colour and contrast enhancement
(4) Registration of the image

After these steps the image is completed for the visual inspection to find linear structures concerning with caravan tracks. As a cross-check, several other evidences can be used. On the one hand, the ACACIA missions gathered point information on every field-trip, so information about crossing a caravan route exists. On the other hand, several maps contain information about caravan routes. However, the sources of the data come mostly from the same old colonial maps. For this reason the data is spatially inaccurate and sometimes even wrong. However, the famous Darb el-Tawil is precisely depicted on many maps. Indeed, the track is also well represented in the ASTER satellite data, especially where the subsurface colour is different from the that of the surface and the track-visibility becomes more obvious.

3.3. Digital map based on SRTM-DEM data

Fig. 6 A route marker (*alam*) on the Darb el-Tawil (photo: Rudolph Kuper).

Since the early 1990s worldwide elevation models become more and more usable for research questions. The main problems or limitations are the resolution of each digital pixel and the quality of the data. The first near global elevation model, the GTOPO 30 data (Gesch & Larson 1996) provides one elevation value for each square of one by one kilometre. Composed of several primary data of partly low or unknown quality the feasibility of the data is spatially restricted. From around 2002, data from the year 2000 Shuttle Radar Topography Mission (SRTM) became available in multi-temporal quality releases. These data provides 90 m resolution elevation data, so it is nearly a hundred times as precise than the GTOPO 30 model.

Data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) enable a resolution of 30 m for each elevation value and provides another step in low cost or freely available elevation data. Further increased resolution is very cost-intensive and currently not available worldwide. **Fig. 1** shows the SRTM data for Egypt and clearly reflects the morphologic structures of the region with several depressions, the Nile Valley, the mountainous regions of Sinai, the Eastern Desert, the Gilf Kebir – Oueinat region in the southwestern part of Egypt, and the oasis belt along the great escarpment in the central part of Egypt.

Since 2009, Japan's Ministry of Economy, Trade and Industry (METI) and NASA announced the release of the ASTER Global Digital Elevation Model (GDEM) (ASTER GDEM 2009). Now the earth's surface (between 83°N and 83°S) is covered by a 30 m resolution elevation model created by 1.3 million ASTER scenes. Hence, for the first time 99 % of the earth's surface is area-wide covered with a high resolution elevation model. After the TerraSAR-X mission, we expect a 10 m elevation model within the next few years (Krieger et al. 2010).

4. Results

The results of the fieldwork and the satellite data study compliment each other extremely well. On the one hand, the satellite data enables us to locate in advance identified linear structures in the field. On the other hand, the GPS-data in the logbooks enables us to verify unclear satellite data interpretation. Furthermore, the conservation conditions of caravan routes in rocky deserts with extreme aridity could be investigated. From the archaeological

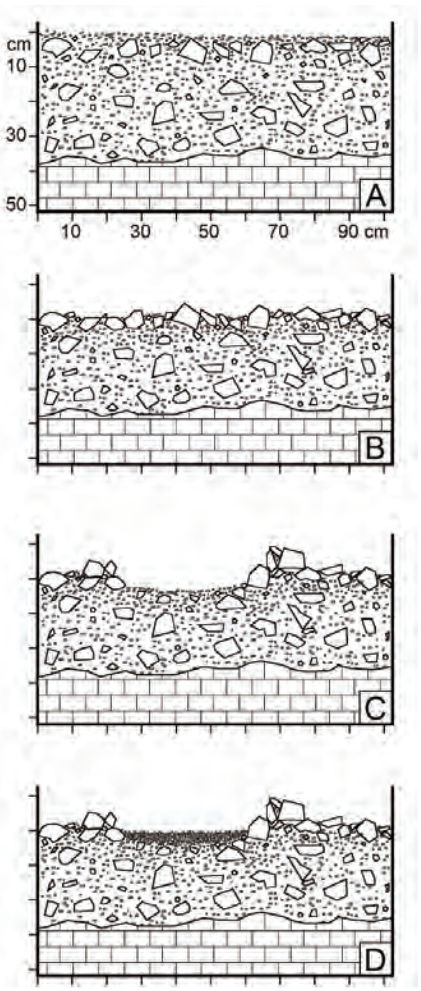


Fig. 7 Generation and conservation of a *hamada* surface and a caravan track (schematic).

A Initial situation. Bedrock builds the basis (here mainly limestone). Above, salt-, freeze-, and insolation-weathering loose and crushed bedrock material plus deposited (fluvial and aeolian) sediments (mainly quartz sand and calcite dust) are situated.

B Further development to a *hamada* surface. Long-lasting aridity and wind deflation causes the transportation of the possible wind transportable fraction (up to sand fraction) and results in a relative accumulation of the coarser fractions at the surface. This process and rarely fluvial events after episodically precipitation generates a so-called 'desert pavement', which protects the underlying finer fraction from additional deflation. Afterwards, the stable morphodynamic conditions lead to the development of a brown to black coloured desert varnish which is composed of clay along with iron and manganese oxides, organic matter, and trace elements (Perry & Adams 1978).

C Generation of a camel track. Camels kick the larger stones to both sides or in the underground and generate a track after long lasting repeated use **[cf. Figs. 8–9]**.

D After forsaking the camel routes, the wind accumulates sand in the slightly deepened and covered tracks. This process conserves the camel tracks and causes the excellent visibility in the field and from space. Hence, several dozens to hundreds of camels in each caravan generate the displayed track-bundle **[Fig. 9]**, which is, dependent on the pixel resolution, visible in the satellite images as discrete lines or in sum as one linear structure.

Fig. 8 A beaten track still in use by donkeys, Deir el Haggar, Dakhla Oasis (photo: Peter Schönfeld).

Fig. 9 Bundles of animal tracks:

A Darb el-Tawil, developed in a *hamada* surface (photo: Olaf Bubenzer) **[cf. Fig. 7]**.

B Darb el-Tawil, developed in a *serir* surface. The rounded stones (gravel) at the surface are the result of ancient fluvial processes which can be reconstructed by the palaeodrainage systems (Bolten & Bubenzer 2008, Bolten et al. 2009). Due to the long-lasting dryness they are also coated by a dark desert varnish **[cf. Fig. 7]**. In the background, the Abu Muhariq dune belt is visible. Here, it shows several gaps in the transition zone from longitudinal dunes to barchans. Hence, the caravans were not forced to cross longer distances in profound loose sand (photo: Olaf Bubenzer).

point of view multiple findings could be gathered along the caravan routes (lost load, remains of perished camels, etc.).

4.1. Groundcheck

As mentioned in section 1, the primary constrains to cross the waterless desert are the topography and the surface cover. Therefore, from a geoscientific perspective, we mapped and measured the geomorphological situation **[cf. Fig. 3]** (Bubenzer 2009) and studied the sedimentological conditions. The found routed markers (*alamat*) were mapped and their exact location were recorded by GPS **[Fig. 10]**. They are made of artificially built stone cairns, stone slabs set upright or impressive stones that have been placed on the ground **[Fig. 6]**. Intervisibility is the principle of the *alamat* that were continuously set in a line along the pathway. The setting of the road signs, in turn, depends on the configuration of the landscape (Förster et al. 2010; Riemer, this volume). However, even on high-resolution satellite data, they cannot be clearly identified.

With regard to the caravan tracks we can conclude that visibility and conservation is mainly dependent on the surface character. Tracks originally imprinted in loose sand become invisible shortly after covered by wind-blown sand.

In part, they can be identified in the landscape by light traces or aforementioned archaeological findings, but not from space. Hence, an accurate localization needs extensive fieldwork (such as the investigation of the Abu Ballas Trail, cf. Förster, this volume). The situation is different depending on whether the surface is dominantly built up by stones, like on the Egyptian Limestone Plateau. This is based by the special building and conservation conditions of the *serir* and *hamada* surfaces and the line-like disturbance of the surface based on the caravan activity **[Fig. 7]**. The resultinc bundles of tracks **[Fig. 9]** are still well preserved after decades to centuries after forsaking the caravan routes.

4.2. Analyses of satellite data

This section presents results of the visual analyses of the satellite images. **Fig. 10** shows the region between the Dakhla Oasis and the Nile and the evidences of possible caravan tracks. In addition, the map gives the information regarding other sources of caravan tracks and the information from ACACIA field trips. Most of the caravan tracks can be seen precisely on the stony ground of the vast *serir* and *hamada* regions of the central limestone plateau because the finer particles in the tracks (see section 4.1.) clearly reflect light in the ASTER satellite image. Thus the main links between the Nile Valley and the oases and between the oases themselves can usually be clearly recognised.

Links between the largest caravan routes of the Western Desert, the Darb el-Tawil and the famous Darb el-Arbain were pinpointed on the satellite image. It was also possible to identify the location of the hitherto hardly known route through the great depression north of the Abu Tartur Plateau which lies between the two great oases of Kharga and Dakhla. A number of sections which were traced by the British explorer Harding King (1912) at the beginning of the last century could be identified in the well rectified ASTER images. Therefore, in conjunction with the ground-truth data, these data allow for the first time the reconstruction of the position of the caravan routes with reasonable accuracy. In addition, the ASTER Global Digital Elevation Model data allow the calculation and analyses of realistic topographical caravan route profiles **[Fig. 10]**. The analysed elevation profile of the Darb el-Tawil shows the Abu Muhariq dune belt and the two escarpments **[cf. Fig. 1]** which had to be overcome by the caravans, as well as the general slope on the plateau. However, due to the high data quality, the elevation data can also be used to identify minor escarpments and therefore to find more difficult passages or wind-protected positions as possible caravan camp sites.

5. Discussion und conclusions

In combination with the ground-truth data and the knowledge about the preservation conditions of tracks, the ASTER satellite images provide a huge increase in information with the result that it was possible to correct and extend the known network of caravan routes. These results are transferable to other deserts in general. The fact that significantly more caravan routes were not found on the Egyptian Limestone Plateau may be because the existing routes, which had been known for centuries, were the fastest and easiest links between the oases and the Nile Valley.

The caravans had to cross long distances on routes through the desert with neither water nor vegetation. This was an extremely arduous enterprise as the journey often took longer than a week. Thus, the lengths of the existing caravan routes calculated within the framework of this research suggest that due to the distances and the consequently greater duration of journeys, alternative routes were probably not considered. The indicators revealed in the satellite image do not allow any clear conclusions to be drawn about the frequency of use or the age of individual caravan routes.

Beyond the area of the limestone plateau it was, with a few exceptions, not possible to locate caravan routes in the ASTER satellite image. The edge of the Nubian Sandstone Formation and the associated layer of sand on the surface south of the Dakhla–Kharga line have quite obviously had a negative effect on natural preservation and the visibility of caravan routes on the satellite image. Field observation showed that they are hardly even recognizable by ground checks. Thus the question of routes in the southern and southwestern part of the Western Desert cannot be accurately answered. One exception is the most famous caravan route of the Western Desert, the Darb el-Arbain. This is to be explained by the fact that it is well documented and, unfortunately, that it is today mainly covered by a modern asphalt road, which can be clearly seen on

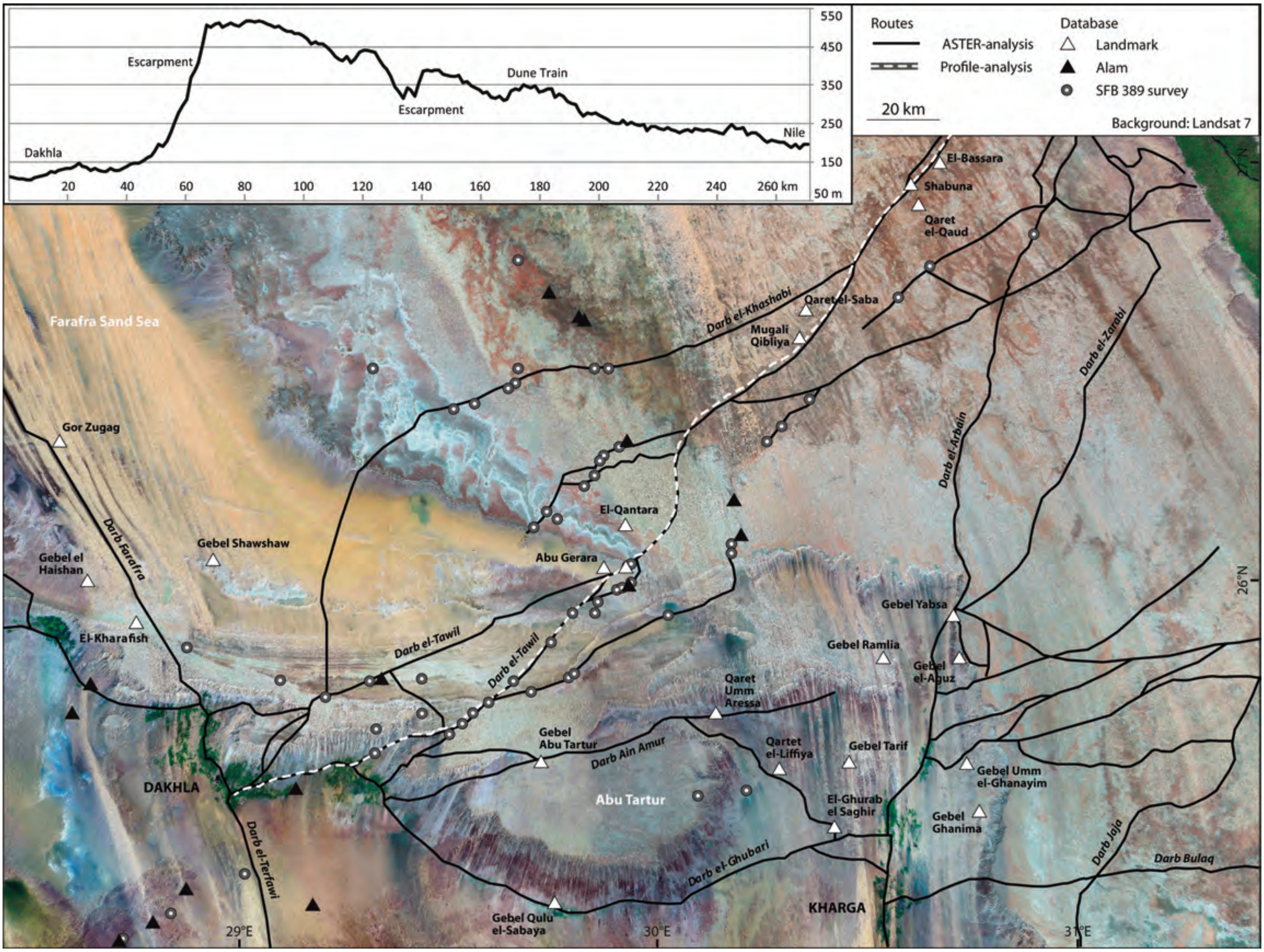


Fig. 10 Cartographic compilation of satellite-based data, ground-truth data from ACACIA field surveys, and historic sources on the Darb el-Tawil and related Western Desert caravan routes (generalised compilation after Skriwanek 2007). The elevation profile shows the vertical situation of the Darb el-Tawil from Dakhla to the Nile Valley. Note the clearly visible escarpments, and the yellow dune sands of the the Abu Muhariq dune train.

the satellite image (cf. Riemer & Förster, this volume: fig. 17). There are also Egyptian plans to connect the Nile Valley and the oases by an asphalt road along the route of the Darb el-Tawil. Following this, the on-the-spot observations made by the ACACIA expeditions are the only reliable indicators to caravan routes in the southern and southwestern area of the Western Desert (cf. Förster, this volume). However, the Abu Ballas Trail for example, shows that there were links to the south and west despite the inhospitable conditions prevailing in this part of the Western Desert. For future remote sensing analyses, probably using optical, multispectral, and radar satellite data with higher resolutions, old caravan routes that were used for the transport of goods and people between the central Sahara and the Nile Valley could be discovered.

A recent and future problem is the demographic growth and the increase of desert tourism. Due to the fact that the old caravan routes were built as the best and easiest transitions between populated places, they have always been guidelines for later travellers (e.g. Harding-King 1912). The first motorized expeditions also followed these tracks (cf., e.g., Bagnold 1931; Goudie 2006). Consequently, it can be assumed that the old routes are increasingly endangered to be destroyed in the future together with valuable archaeological finds and features. This vital information on the history of the utilisation of the Western Desert is then irretrievably lost. Deserts are not only unique archives of cultural and natural heritage and human history; they are also unique archives of geological evolution, biodiversity, and climate change (<http://www.uni-koeln.de/hbi/Texte/respect_desert.pdf>). For the sake of protection it is therefore urgent and essential to aim at a thorough documentation of these ancient trade routes by combining advanced remote sensing techniques and fieldwork as an example for further interdisciplinary desert road archaeology.

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