

Remote Sensing Multitemporal Data for Geomorphological Analysis of the Murghab Alluvial Fan in Turkmenistan

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Abstract: Archaeological studies are ever more landscape-oriented, in order to study archaeological evidences in relation with their territorial contexts. In such a framework, reconstruction and understanding of ancient landscapes assume a crucial role for archaeological research. This study proposes a first morphological analysis of the whole Murghab alluvial fan in Turkmenistan, by means of the SRTM-DEM datum, and then the reconstruction of the ancient hydrography in the northeastern fringe of the fan, based on medium-high geometric resolution satellite data, and in continuity with previous studies. The importance to know historical fluvial network is due to the strict relationship between fresh water availability and human settlement distribution. SRTM-DEM, Corona, Soyuz KFA, Landsat, and Aster data were used, overlaying them in a GIS, and digitizing palaeochannels through photo-interpretation were done. Today, this is an almost desert area of the fan, and that is why it is easier to recognize buried forms by means of photo-interpretation, even though sometimes in a doubtful way. Despite the uncertainties, this model provided a useful tool for next and focused archaeological field surveys and excavations, aimed to find out human settlement evidences in correlation with ancient waterways.

Key words: Remote sensing, digital elevation model, satellite multitemporal data, Murghab alluvial fan, geoarcheology.

1. Introduction

Over the last decades, the increasing development of ground, aerial, and space based remote sensing have progressively focused on the use of this technique for supporting cultural heritage applications, management, and valorisation processes, as well as monitoring and preservation of cultural resources, especially in the archaeological research [1-5]. In this field, main challenges for researches were related to the crucial importance of integrating remote sensing data and analysis with other traditional archaeological data and methods, such as aerial photos, field surveys, trials, excavations, and historical documentation [6-9].

By the sixties, researchers began to be increasingly interested in the relationships between historical sites and their physical context, rather than in the archaeological site as an isolated object, in accordance with the *New Archaeology* movement. This underlined the importance to understand ancient history from social and economic points of view, evoking principles also from the anthropological theory [10-12]. As a consequence, a geo-archaeological method of investigation, with an increasing focus on the environment as a container of past evidences, its evolution over time, and its influence on population and settlements models, became central [13-19]. Remote sensing data were particularly used to “rebuild” palaeoenvironmental contexts through identification of palaeoforms and, more generally, by means of geomorphological features analysis, which was originated from natural or artificial phenomena,

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such as fluvial and marine action, aeolian morphogenesis, or human activities [20, 21].

Multiscale and multitemporal data allow analysis and understanding at different levels, from a synoptic to a more detailed view, both studying specifics and relationships in the morphological context during time [22, 23].

In this framework and in continuity with a long tradition of such studies in the Murghab alluvial fan [19, 24-30], this work firstly aims to recall the general morphology of the fan, and secondly to outline the palaeohydrography of the Murghab fan, in a circumscribed area in the northeastern part of it, by means of photo-interpretation and using multitemporal and medium-high geometric resolution data: Corona 1972, Landsat 1972, 1988 and 2010, Soyuz KFA 1988, and Aster 2001. The importance to know ancient waterways, in this area of the fan is due to the probability to discover ancient settlements in their proximity, as in the case of previous accomplished works in an adjacent area [31]. The final model could be therefore used as a first work plan for further field surveys.

2. The Murghab Alluvial Fan

2.1 Geographical and Geomorphological Context

The alluvial plan, formed by the Murghab River, extends for about 20,000 km² in the southern Turkmenistan (Central Asia) between the Amu Darya River, which defines the northeastern fringe of the plain, and the mountain chain of KopetDagh, in the southwest. The sources of the Murghab River are located in the northwestern Afghanistan, in the mountain chain of Paropamisus (Fig. 1). The river flows towards northwest up to the Turkmenistan Country, where it spreads its waters in the Karakum desert, forming a vast alluvial fan. Southern Turkmenistan is characterized by a continental climate, characteristic of sub-tropical desert zones, in which dry climate is predominant [32, 33] with an average annual temperature of about 14.5 °C and low levels of

precipitation between 139 and 249 mm per year [31].

The Karakum desert is located inside a large tectonic depression located at an average altitude of 200 m above sea level, and it is largely sprinkled with barcanoids systems (isolated sand hills, sometimes related each other), and *takyr* areas (flat and salty clayey floors).

The Murghab River flows in a canyon excavated in loess sediments, which covers the southern part of the Country, and then it spreads its waters in the alluvial plain with a meandering pattern, due to the very slight slope of land, which ranges from 200 to 20 m above sea level.

When the Murghab River flows into the plain, it forms a characteristic fan-shaped structure, defined as alluvial fan, due to the accumulation of fluvial sediments (gravels, sands, clays etc.). The fan thus shows the shape of a conic structure (about 75 km × 85 km), with a concave profile, in which coarser sediments lie in the apical part of the fan, and the thinnest ones lie in the distal part, where the alluvial fan smoothly drains into the plain.

Inside the fan a prevalence of depositional phenomena is recorded, due to the lower energy of flowing waters in this flat area; in the surrounding area, there is a combination of erosive and depositional phenomena, mostly due to winds action, which continuously raises and redeposits the Karakum sands [34, 35]. Since depositional actions are conservative phenomena, they tend to cover the existing sedimentary deposits, thus ensuring its preservation. That is why areas inside the fan could also be suitable to outpoint to the occurrence of buried structures, but in a difficult with uncertain results, due to the intensive anthropogenic activities over the fan, which have destroyed or covered ancient signs. Conversely, areas around the fan appear to be more suitable for surveys, thanks to the absence of present-day human activities, even though the scattered presence of high and mobile dunes, or other sediments could however impede archaeological works.

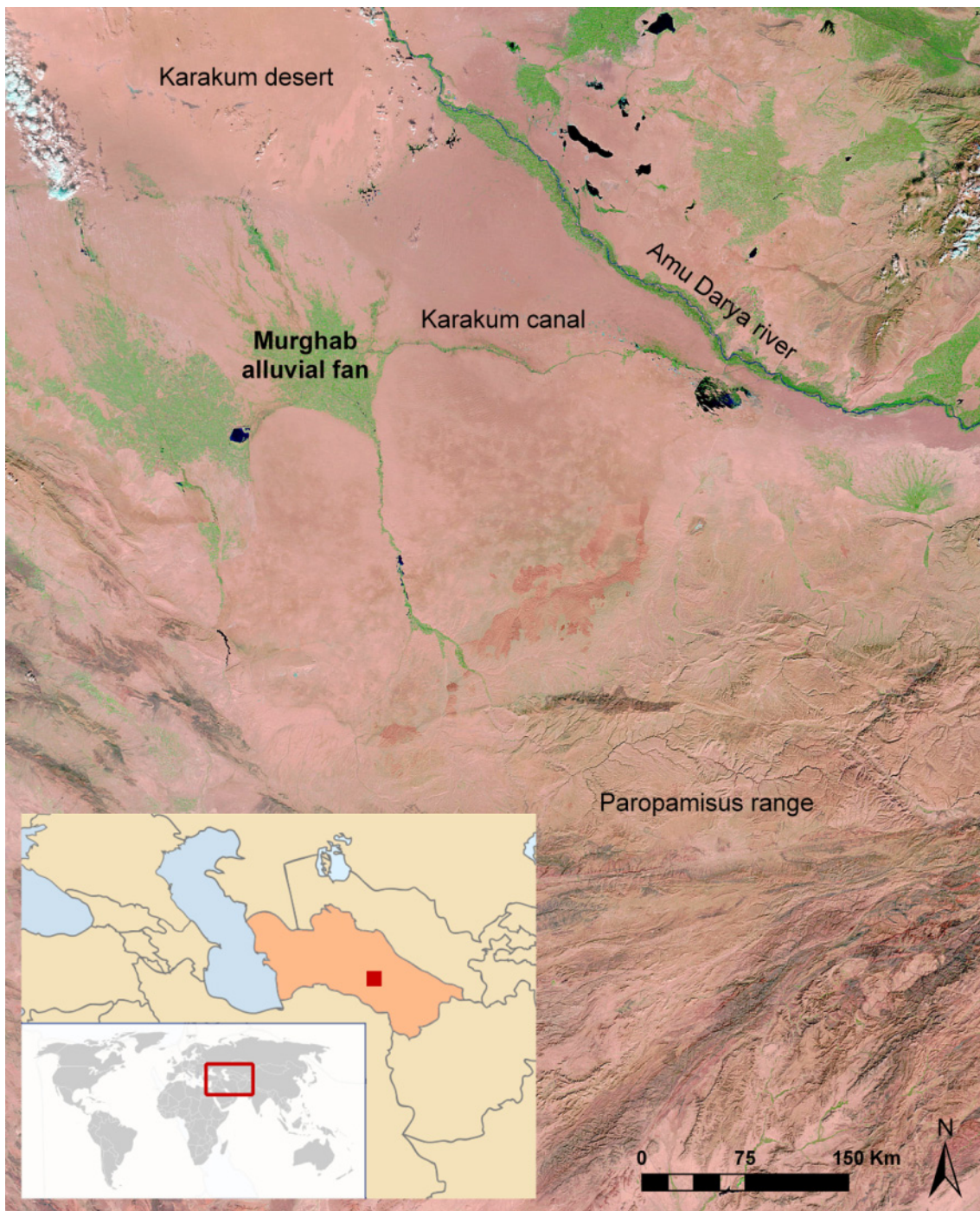


Fig. 1 Geographical area of the Murghab alluvial fan (in green) with main morphological elements highlighted (base Modis).

Marcolongo and Mozzi [24, 36] who studied Turkmenistan's tectonics, pointed out to the presence of a tectonic plate, the Amu Darya plate, which eastern border, approximately alongside the Amu Darya River (Fig. 1), is raised above the Murghab

plain. The Murghab is located in a fault block, with a southwest sloping. For this reason, the whole fluvial system may have undergone a conversion towards west, dated in the Late-Quaternary age [24, 37]. This movement could be partly responsible for the

present-day lack of river branches in the northeast area of the fan.

Cremaschi [31] suggests to consider the neo-tectonic movement as a complementary factor, since the general construction of the fan seems to be related to a general loss in water availability, due to a drier climate after the 4th-3rd millennium BP, which caused a regression in water supply, and forced ancient population to move towards south.

In the north-northeastern part of the Murghab fan, Mauro Cremaschi's research group identified an inactive fluvial network, by means of historic cartography, satellite data, and field surveys [25]. This present-day inactive fluvial network was used to optimize archaeologists' fieldwork, directing their digs' locations. It was indeed proved (Fig. 7, light blue channels and coloured dots) that correlation exists between ancient waterways mapped by Cremaschi group, and archaeological remains, on which also this paper is based.

2.2 Historical and Archaeological Context

The alluvial plain formed by the Murghab River has been inhabited since the protohistoric period: the first evidence of human settlement dates back to the 5th millennium BP. The success of this region is due to its intrinsic natural features, since it is within a desert area made fertile by the Murghab River.

As a consequence of such an ancient population, this is a highly interesting area for its archaeological wealth: within the alluvial fan of the Murghab River, and its surroundings, a large number of sites from the Bronze Age (5th-4th millennium BP), until the recent past, have been found. Particularly, in the northeastern part of the fan, important relics from the Bronze to the Iron Age (4th-3rd millennium BP) were discovered [25, 27, 29] and here reported in Fig. 7. Currently, this specific area is an arid or semi-desert land, but it had to be well watered in the past, since life of ancient populations was strictly related to the availability of fresh water, especially in the distal part of the fan,

where water flow is slower, offering a more suitable environmental for living. In the past, the water supply of the Murghab River was higher than today [31]. That is why many studies have been performed in this area, thanks to the first scientific cooperation signed in 1989 by the Institute of Archaeology of the Soviet Academy of Sciences in Moscow, the State University of Turkmenistan, and the Italian Institute for the Middle and Far East of Rome [26]. After this first agreement, a series of studies and field surveys were made, at first on annual or biannual basis.

Key purpose of these works was the reconstruction of the ancient settlement system in the Murghab area, from earliest attestations, dating back to the 6th millennium BP—Chalcolithic period—until to the 13th century—Islamic period—within the project *The Archaeological Map of the Murghab Delta* [25]. The project aimed at creating an archaeological map of the Murghab area, in which all discovered sites had a georeferenced location. It would have also provided a dynamic working environment as a base for further excavations and surveys, according to principles delineated by the *New Archaeology* movement. Knowledge of territories is indeed fundamental in order to identify areas of potential archaeological interest, as in the case of the Murghab fan, which is rich in archaeological remains, and which could host other buried sites under desert sands or covered by modern settlements, built on the ancient ones [27, 29].

Field survey thus represents the most important tool for acquiring data in small parts of a territory, while remote sensing data and their analysis in a GIS (geographic information system), are very useful for managing large amounts of data in such a vast area as the Murghab alluvial fan (about 20,000 km²). This is the reason why their combined application is the best way for archaeological researches in vast areas, starting from general surveys of the whole territory, and continuing with a more detailed analysis of its parts, as a standard method adopted in a growing number of archaeological projects [19, 23, 25, 28, 38].

3. Tools and Methodologies

3.1 Available Data Sources

This work benefited from satellite data analysis only, and we deliberately decided to not use historical maps, since they were used in previous works [26] for recreating the ancient irrigation system of the Murghab fan before influence due to human activities, especially after the construction of the Karakum Canal in 1954 [39]: for this aspect, we directly refer to those works. Furthermore, historical maps do not provide useful data for the northeastern fringe of the fan—which is the area of our main interest—since it is mostly represented as a desert, with only main active branches outlined.

In accordance with our purpose of acquiring the palaeohydrography of the fan, with particular focus on the northeast part of it, satellite data are the more suitable for preparing a work plan for next field surveys.

Satellite data at our disposal were: SRTM-DEM, Landsat MSS (1976), CORONA KH-4B (1972), Soyuz KFA 1000 (1988), ASTER (2001), and Landsat TM (2010). We also benefited from the support of the more recent maps from Google Earth for a further check, since they have a high geometric resolution, and they are available for free. Characteristics of satellite data are listed below.

A DEM (digital elevation model) was acquired from the SRTM mission (<http://srtm.usgs.gov/index.php>) with a ground resolution of 90 m, in order to have information on general morphology of the alluvial plain, its altimetry and hydrographic network.

The SRTM (Shuttle Radar Topography Mission) is a joint project between the NIMA (National Imagery and Mapping Agency), and the NASA (National Aeronautics and Space Administration). The objective of this project is to produce digital topographic data for 80% of the Earth's land surface. This radar system will gather data that result the most accurate and

complete topographic map of the Earth's surface that has ever been assembled. Any project that requires a rather accurate knowledge of shape and height of terrain can benefit from it. Some examples of main uses of this type of datum are flood control, soil conservation, reforestation, monitoring of volcano and movement of glaciers, earthquake research. SRTM elevation data were processed from raw C-band radar signals spaced at intervals of 1 arc-second (approximately 30 meters) at NASA's JPL (Jet Propulsion Laboratory). This version was then edited or finished by the NGA (National Geospatial-Intelligence Agency) to delineate and flatten water bodies, define coastlines, remove spikes and wells, and fill small voids. Data for regions outside the United States were sampled at 3 arc-seconds (approximately 90 meters) using a cubic convolution resampling technique for open distribution.

The SRTM-90 DEM has a 90 m resolution at the Equator, and it is available in both ArcInfo ASCII and GeoTiff format to facilitate their use in a range of image processing and GIS applications. Data can be downloaded from the ftp site <http://www.cgiar-csi.org/>.

CORONA images (https://lta.cr.usgs.gov/declass_1) come from the American CORONA platform and they were designed and used, during the sixties and seventies of the last century, for military purposes primarily. Recently, they were subject to a declassification which allowed the access to even non-military purposes and to the users. Their ground resolution vary from 12.20 m (the first mission, Corona KH-1, 1959-1960) to 1.80 m (the last mission, Corona KH-4B, 1967-1972, used in this work). The recovery of aerial and satellite images of the past is of great interest to a broad spectrum of applications, from the analysis of urban development at regional or even local to specific inquiries relating to sites of industrial, environmental, and archaeological interest, as in this study.

KFA-1000 camera is placed on Russian civilian satellite Resurs-F1 (<http://ngeocomp.ru/en/>). Main tasks solved by these satellites are agriculture, forestry, and water monitoring, and emergency forecast. KFA-1000 camera collected imagery in a time range from 1974 to 1999. Image specifications are: 5 m of spatial resolution, image size 30×30 cm, covered area 75×75 km, spectral Range 570-680 micrometers (panchromatic) or 680-810 m. Images are originally collected on film in panchromatic or spectrozonal band; digital copies are made from the original films by means of scanning, using high precision photogrammetric scanners.

The ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) is an imaging instrument onboard Terra satellite, the flagship satellite of NASA's EOS (Earth Observing System), launched in December 1999 (<http://asterweb.jpl.nasa.gov/>). The goal of the NASA Earth Science project is to develop a scientific understanding of the Earth as an integrated system, and to better predict variability and trends in climate, weather, and natural hazards. ASTER provided the next generation in remote sensing capabilities, when compared to the older Landsat Thematic Mapper and to the Japan's JERS-1 OPS scanner. ASTER captures high spatial resolution data in 14 bands, from visible to thermal infrared wavelengths, and provides stereo viewing capability for digital elevation model creation. ASTER instrument consists of three separate subsystems: VNIR (Visible and Near Infrared), the SWIR (Shortwave Infrared), and the TIR (Thermal Infrared). Its resolution on ground is 15 m.

Landsat images come from the Landsat Project (<http://landsat.usgs.gov/>), started in 1972, as a joint initiative of the USGS (U.S. Geological Survey) and the NASA (National Aeronautics and Space Administration). Landsat Global Survey Mission is to establish and execute a data acquisition strategy that ensures repetitive acquisition of observations over the Earth's land, coastal boundaries, and marine environment.

The MSS (MultiSpectral Scanner) is one of the original Landsat imaging sensors and has flown on Landsat satellites. The MSS stopped acquiring images in 1992 because of improved data available through the Thematic Mapper sensor. Landsat Thematic Mapper is a multispectral scanning radiometer that was carried on board Landsats 4 and 5; TM sensors have provided nearly continuous coverage from July 1982 to present. The Landsat ETM (Enhanced Thematic Mapper) was introduced with Landsat 7. Landsat satellites were designed to be used for a variety of fields like forestry, agriculture, geology, and land-use planning. The choice of spectral bands was especially geared towards the discrimination of different types and amounts of vegetation. Their spatial resolution vary from 60 m (Landsat MSS) to 30 m (Landsat TM).

In multispectral satellite images the use of different bands, which spanning different regions of the electromagnetic spectrum, allows the observation of the Earth's surface in "true" and "false" colours. Using combination of false colours, it can be possible to obtain several information on land cover, and on properties of the objects' surface, such as nature of rocks and soils, density and condition of vegetation, ancient networks, patterns, structures and/or alignments [37, 40, 41]. Spectral bands of the near and medium infrared, for example, allow the identification of grey tones, which are not visible to human eye, highlighting potential buried structures through anomalies in the distribution of moisture, and vegetation, in soils. These bands are extensively used in historical and archaeological research.

Main geo-archaeological information, which are deductible from aerial and spatial images, can be synthesized into three basic categories. The first category is based on the description of different palaeo-environmental features, and their evolution, in relation to spatial distribution and types of ancient settlements. The second type is based on the identification and direct description of large structures,

even if partially buried (e.g. Roman agrarian pattern, called *Centuriatione*, ancient irrigation systems, large urban complexes, and others), whose identification depends from resolution of remote sensing spatial and spectral data [42]. The last one concerns the prediction models, which provide the probability of archaeological existence in a given area, based on favourable paleo-environmental situations, on direct links between natural resources and human needs, and similar pattern and settlements already known.

3.2 The Digital Elevation Model for a Morphological Characterisation of the Fan

Valued the importance to first have a synoptic view of a territory, especially when it is not previously known, we first present an overview of the morphology and hydrology of the whole fan, using the Digital Elevation Model. We also refer to the existing bibliography on this area for further information on this subject.

A DEM (digital elevation model) is the representation of the surface altimetry distribution in digital format. DEM is normally produced in raster format by associating each pixel to its absolute height value.

The main advantage of the SRTM-DEM is the use of a radar sensor, which is better than a passive one over the atmospheric noise, allowing a higher discrimination in non-optimal weather conditions, as in the presence of clouds and fogs [43-46]. Furthermore, it allows penetration into the thick vegetation, and other structures inside the fan, which cover ancient morphology and hydrography, thus allowing the study of previous fluvial systems.

On the other hand, due to its low geometric resolution (90 m), the SRTM is not suitable for a detailed slopes analysis in a minimum height differences area, such as the Murghab plain, which values range from 250 m above sea level, where the river flows into the plain, to 20 m in correspondence of the most distant ramifications of the fan (about 100

km far away). According to its distribution in altimetry, the plain shows a general sloping towards northwest.

It would be obviously desirable using images with a better spatial resolution, in order to identify minimum variations in height, and therefore better studying micro-reliefs, of fundamental importance in understanding the micromorphology and hydrology of the alluvial plain, but we did not have additional remote sensing data for this area. Despite these limitations, the use of SRTM images allowed the recognition of important morphological structures, and fundamental hydrological features, around and into the fan, such as different wind action in the two lobes at the western and eastern sides of the river, formed due to progressive accumulation of sediments (Fig. 2). They are characterized by morphologies organized in two different directions: the first one (left hydrographic side of the river) with a prevailing NW-SE direction, the second one (right side) with E-W direction. In the strip of land between the Murghab and the Amu Darya rivers it is possible to detect two major types of dunes, with linear morphology, and arranged predominantly in north-south direction. These are typical landforms in arid environments and their formation is due to winds that blows in an almost unidirectional way. Farther south, it is possible to observe circular structures, which appear to have been shaped by soil erosion. They probably are deflation basins, which cannot be defined in a more detailed way, without prior confirmation “in situ”.

With the aim to accentuate the hydrographic model of the fan, filters were applied on the original DEM. In satellite imagery, it is indeed possible to emphasize certain bands through mathematical algorithms, called “filters”, which function is to de-emphasize certain types of frequencies, or to emphasize others. Filters which pass high frequencies, and emphasize fine details and edges, are called *high pass* filters. *Low pass* filters, which suppress high frequencies, are

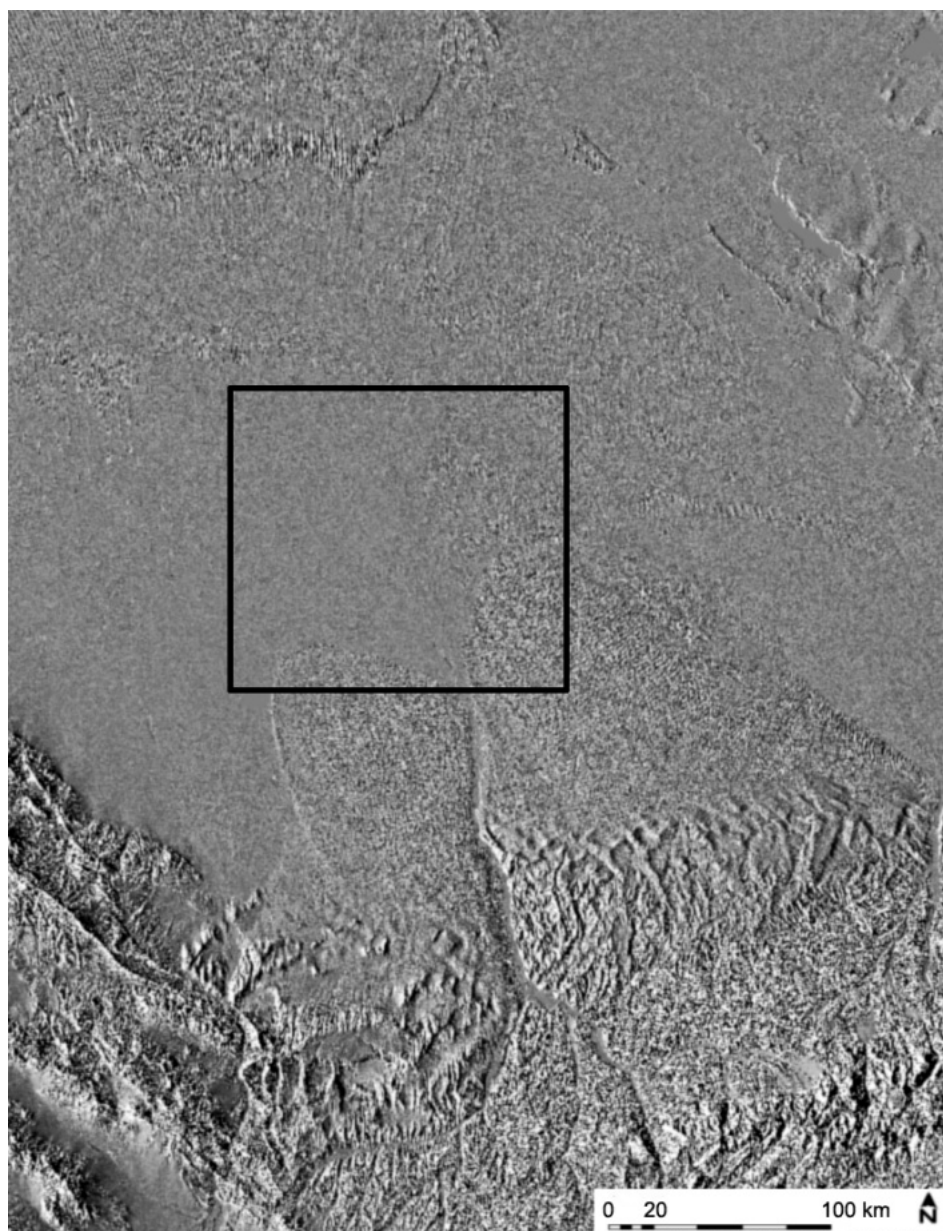


Fig. 2 Territory of the Murghab alluvial fan on shaded SRTM-DEM.

instead useful in smoothing, reducing or eliminate lines, borders, and “salt and pepper” noise [43]. Edges and lines are examples of high frequency data; in contrast, gradual changes of brightness, according with the position, associated with smoother tonal variations, account for the low frequency content in the band spectrum [47].

This technique explores the distribution of pixels with varying brightness in an image, and especially detects and sharpens the boundary discontinuities.

Convolution filtering is a common mathematical method for implementing spatial filters; in this way, each pixel value is replaced with an average value over a square area centered on that pixel (normally, square sizes are 3×3 , 5×5 , or 9×9). Generally, spatially filtered images must be contrast stretched before, in order to use the full range of image display.

In this study, in order to highlight the Murghab waterways, a high pass filter has been applied on the

SRTM-DEM original image (kernel 3×3 , direction 90°). The use of this type of filter allowed the better understanding of the natural hydrographic fan network (Fig. 3). The original fluvial system was indeed diverse, if compared to the modern one, which is deeply transformed by recent human activities, especially after the construction of the Karakum canal, during the last phase of the Soviet period (1954-1988). Many present-day branches inside the fan are indeed

rectified for agricultural purposes [25].

Model obtained by shaded and filtered SRTM-DEM (Fig. 3) shows a meandering pattern, oriented towards northwest, in accordance with themorphology of the area, and it displays a dense fluvial network features in the apical part of the fan, and a sparse structure in the distal part of it. Such structure shows an intense fluvial activity in the southern part, with a large amount of water and sediments. Conversely, in the

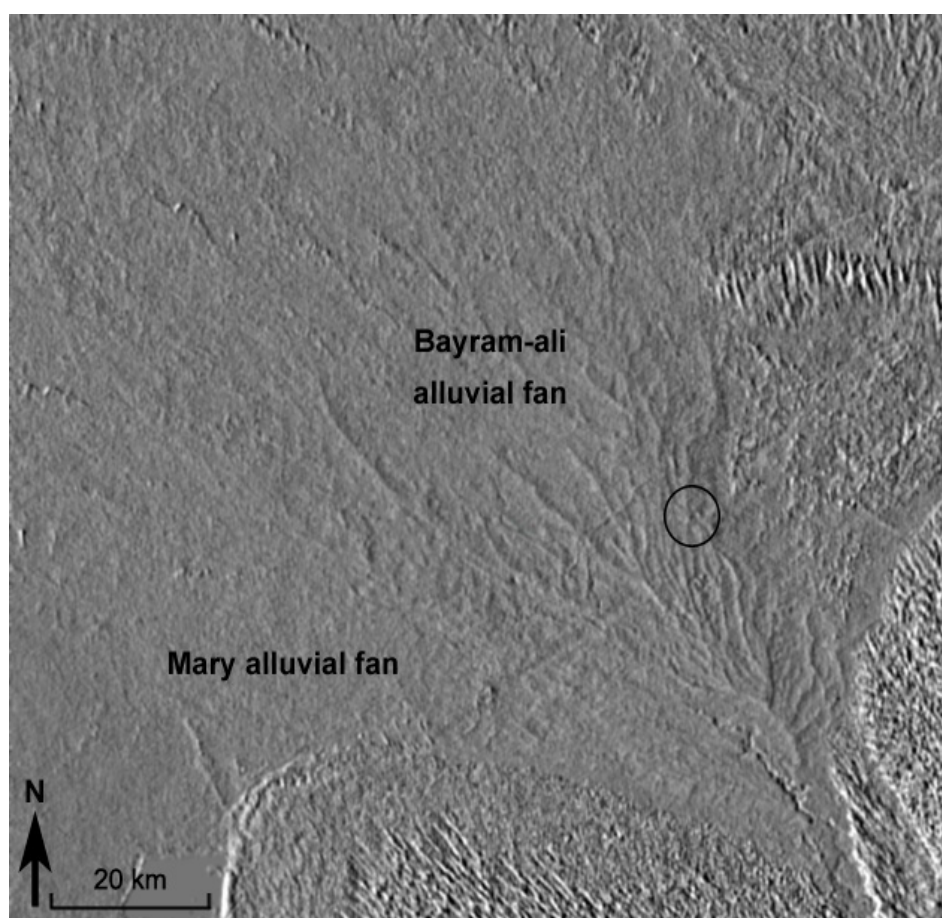


Fig. 3 Effect of a *high pass* filter on the original SRTM-DEM. Use of this type of filter highlights the natural hydrographic network, and in this case, in which a directional filter of 90° was used, it was especially pointed out the Bayram-Ali sub-fan (since it has an N-S prevalent direction) rather than the Mary sub-fan (direction SE-NW). Black circle stresses the overlapping of some branches of the river.

Table 1 List of satellite datasets that have been used for the ancient fluvial network interpretation.

Satellite data	Acquisition date	Ground resolution
LANDSAT MSS (1-2-3-4 band)	1976	60 m
CORONA KH-4B	1972	1.80-7.60 m
SOYUZ KFA 1000	1988	5 m
ASTER	2001	15 m
LANDSAT TM (1-2-3-4-5-7 band)	1988; 2010	30 m

distal part of the fan, river activity is today lower, so it could be easier to find ancient sites not covered by sediments, despite obstacles from sandy dunes that are quite numerous here.

The filter we used mainly highlights the sub-fan of Bayram-Ali, since it has a prevailing north-south direction, while Mary sub-fan is faintly recognizable, since it flows in a different direction, from east-southeast to west-northwest. Bayram-Ali and Mary are the two parts that form the alluvial fan of the Murghab River, they slightly differ in height, and they are both characterized by a shift towards west [24, 37]. An evidence for the shift is also recognizable due to an overlap of some branches of the river with different directions, towards S-N and towards SE-NW (Fig. 3, black circle also compare [31]). It is not possible to establish the exact date of the shift using remote sensing data only, but it is evident that the shift took place at some time subsequent to the formation of a previous fluvial structure, which had a prevailing direction towards north.

The northeastern fringe of the fan is difficult to identify by this datum, since it mainly shows absence of water activity and scattered aeolian formations, indicating that the area is shaped both by aeolian and ancient fluvial processes. For this reason, we used all the other data for studying this area, as explained below.

3.3 The Ancient Fluvial Network in the Northeastern Fringe of the Murghab Fan

After the foregoing overview of the whole fan, we focused on a circumscribed area in the northeastern part of it, for a more detailed investigation of ancient hydrography. Interest for the hydrographic pattern is due to the strict relationship between fresh water supply and human settlements in historical time.

A list of all available remote sensing data, that we used and compared in a GIS project, is reported in Table 1, in accordance with their main characteristics.

All data were already georeferenced and we inserted them in a GIS project, using the Geodetic System UTM-WGS 84.

It was chosen a study area of approximately 3,400 km² (55×62 km, red square, Fig. 4) as large as the previously investigated area (Fig. 7, light blue channels) and beside it, with a partial overlay zone as a control (Fig. 6).

Palaeochannels traced in previous studies were highlighted (Fig. 7, light blue channels), as well as the archaeological sites until now discovered. Particular attention has been reserved to settlements from the Bronze to the Iron Age, since they are located in the distal part of the fan (Fig. 4). Recession of human settlements toward south, from the Late Bronze Age (4000-3500 BP), and the Andronovo Period (3500-3400 BP), to the First Iron Age (3400-2900 BP) is evident. The move is explained by a shift, and a regression in water supply, of the Murghab River branches in historical period [18]. Such modification of the fan could have forced ancient populations to leave their previous settlements and move southward, looking for fresh water, as explained in previous paragraphs.

Ancient palaeohydrography was traced by vector editing in a GIS system, through photo-interpretation, trying to recognize inactive channels only, which have left a marked sign on territory (Fig. 5).

Active meanders in irrigated areas, were not acquired in our work, since they were digitized before [25] and the aim of this work was the identification of the disappeared fluvial system.

Tracks of ancient channels are pretty recognizable on satellite data, in scattered ways, since they left “morphological evidences” up to 30-40 m in width in the present-day desert. Their size is due to their condition in the past, since during the Bronze Age, and the Iron Age, they were not “ephemeral streams penetrating a desert area but branches of the Murghab delta system meandering over a true flood plain” [18].

In many cases, there were indeed more adjacent

channels, probably due to ancient flooding, favoured by flat lands and the large amount of water in historical time. We marked the most visible tracks, considering faintly visible adjacent diversions as part of the same waterway.

However, this part of the fan is not always easily deductible by photo-interpretation, principally due to the obstruction from aeolian sand and dunes, which

are in high number in this area, as it is possible to check in Fig. 7. Additionally, quality of data is not always and everywhere high, especially for the Corona images. The possibility to refer to more satellite data, sometimes even basemaps from the web, directly available in GIS system, revealed its usefulness for comparisons and decisions in all questionable cases.

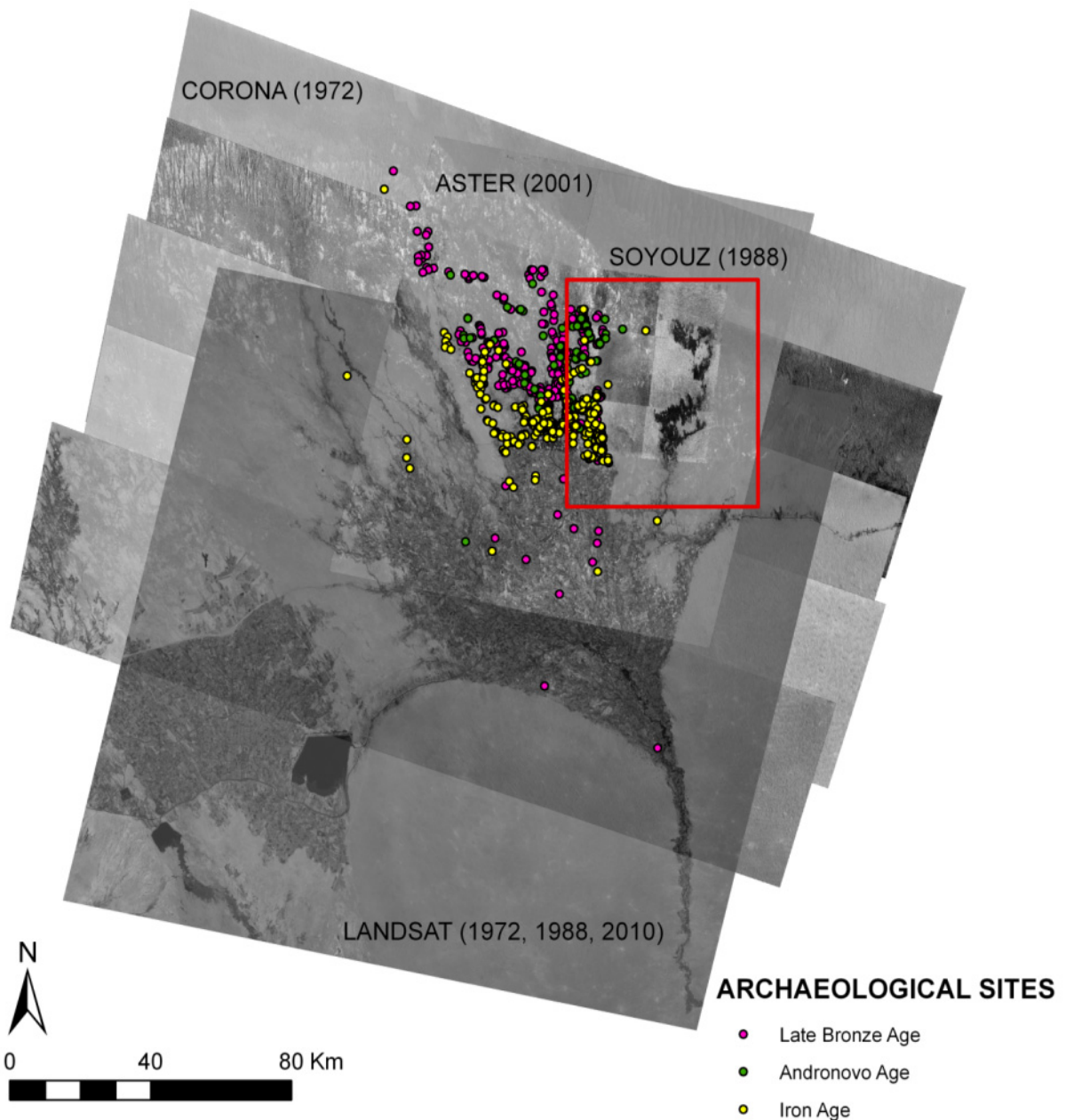


Fig. 4 GIS project with all satellite data used and shapefiles of archaeological sites from the Late Bronze Age to the Iron Age. Study area (in red).

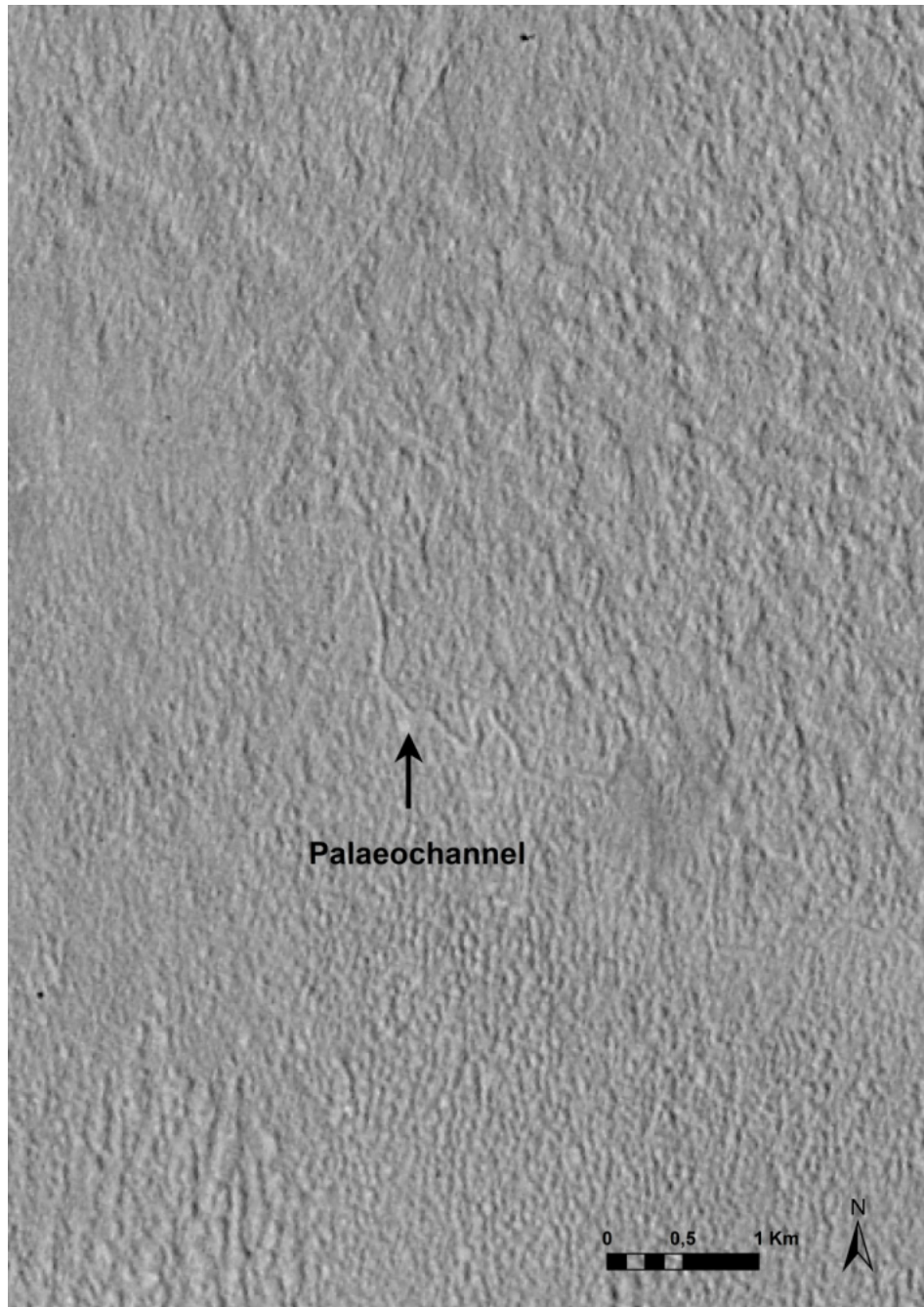


Fig. 5 Palaeochannel's track in the extreme northeastern fringe of the study area. Above it, the longitudinal strip of dunes impedes other eventual understanding of ancient hydrography (base Corona).

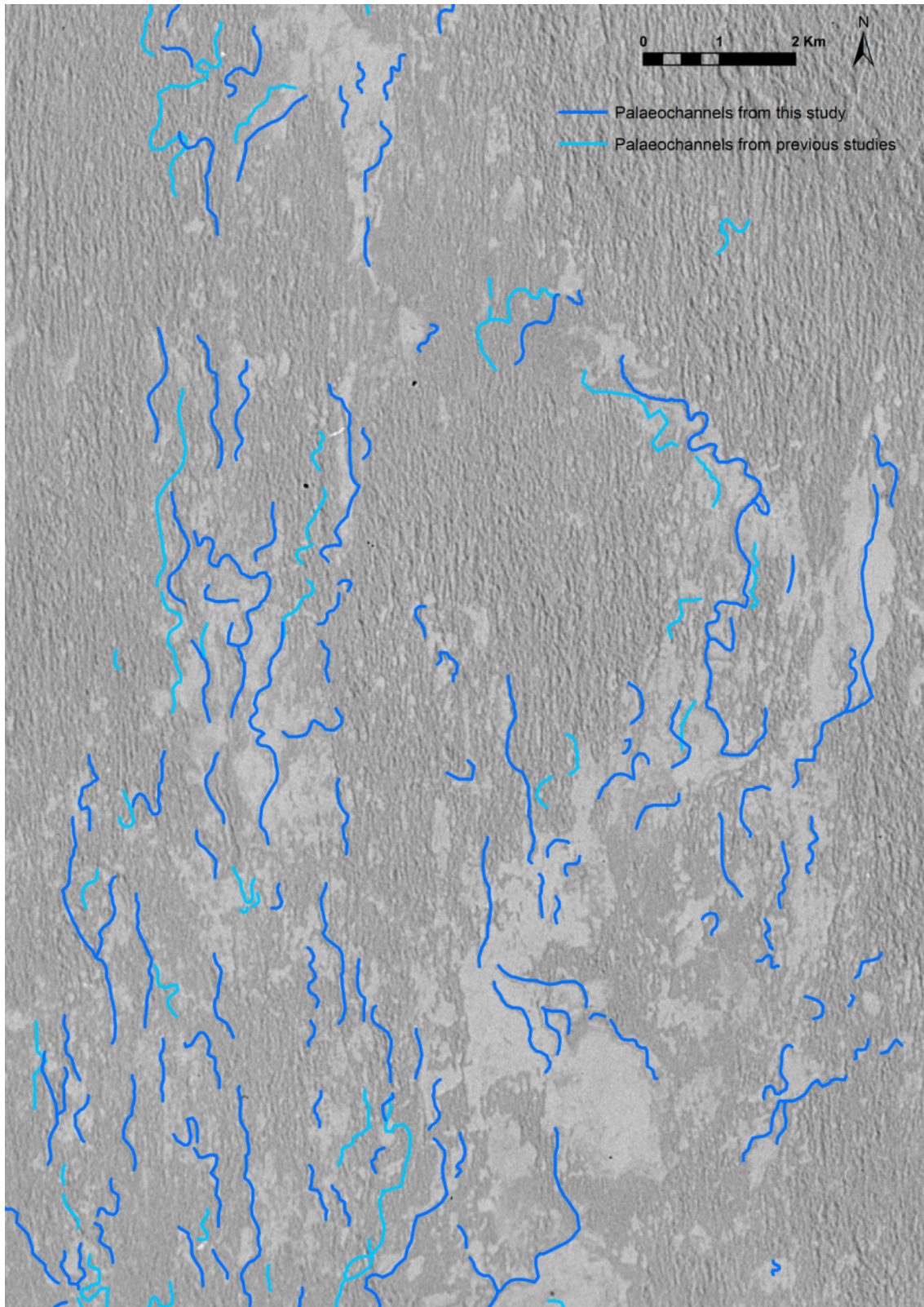


Fig. 6 The overlapping area between the previous study (light blue channels) and this work (dark blue channels) that has been used as a check. Image shows the good correspondence between the two works in the recognition and digitization of palaeochannels (base Corona).

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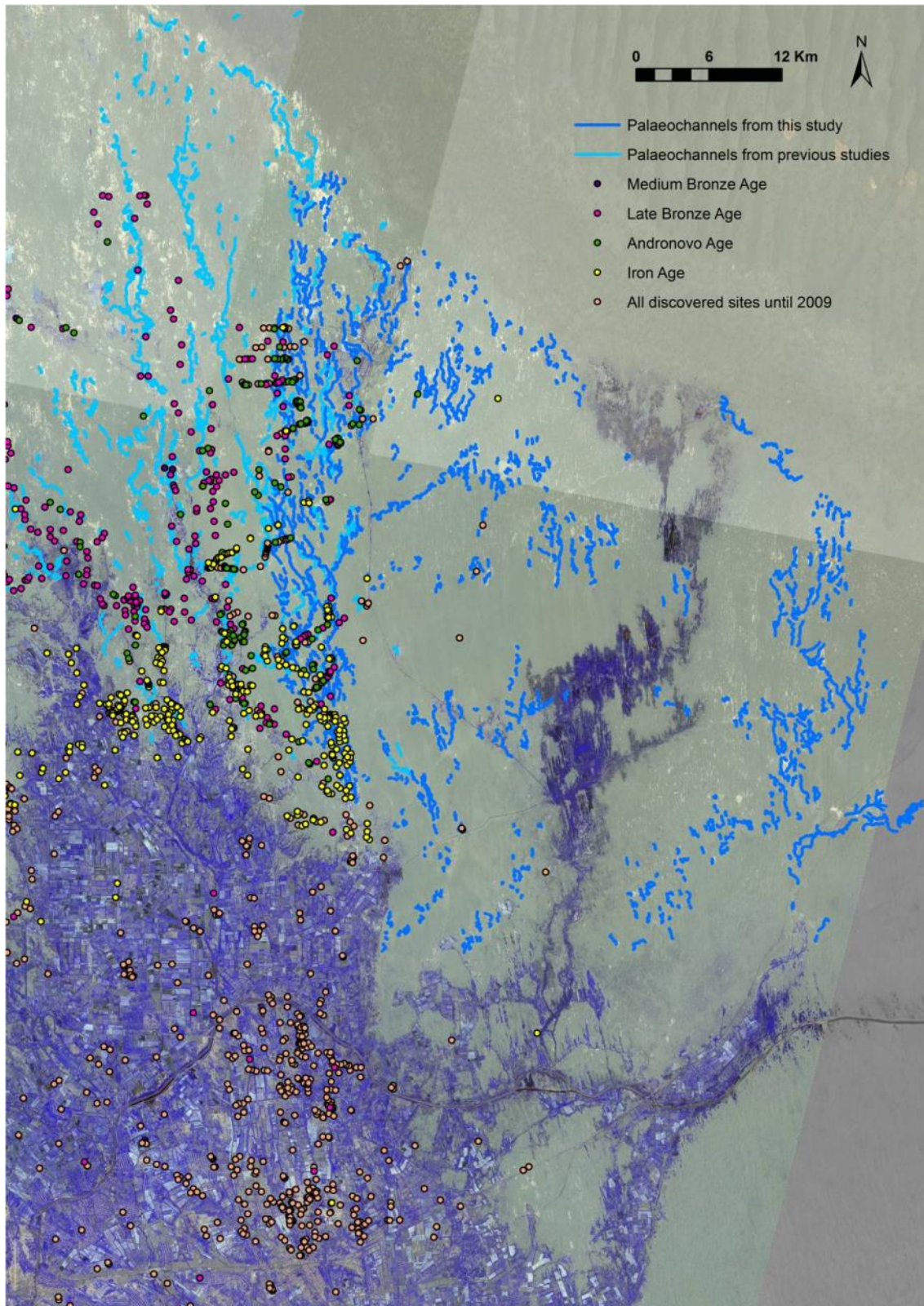


Fig. 7 Study area in the northeastern fringe of the Murghab alluvial fan. In dark blue the palaeochannels edited in this work, and in light blue the previously digitized palaeochannels (base Aster).

Main channels were however easily recognizable, while the thinnest ones remained often doubtful, but they have been digitized, even though in a more fragmented way. Main doubts that emerge during the photo-interpretation process are due to faintly visible tracks, often also related to incoherent ways of channels; in other cases, uncertainty are due to shapes that seem to be similar to palaeochannel tracks, but that could be something else, and mostly linked to aeolian processes, such as borders between sand dunes, or other cracks in the soil, which are active in the whole studied area.

More visible channels were often located into or beside *takyr* areas (Fig. 7, bright soils), sometimes they also were in the sandy desert (e.g. Fig. 5), while sand dunes completely obstructed eventual remains and the possibility to identify buried structures. Beside these areas, tracks that were possible to detect were often very short and fragmented, nonetheless they returned fairly coherent ways, if studied as a whole.

On the top of the study area, longitudinal strips of dunes seem to represent the extreme northern limit of the ancient fan, since it is not possible to recognize channels tracks beyond them, and they seem to be a sort of “barrier” covering eventual palaeochannels and directing the others towards west (Fig. 7).

At the end, we marked three main types of palaeochannels:

- (1) highly visible palaeochannels;
- (2) faintly visible palaeochannels, but recognizable in two different data, at least;
- (3) faintly visible palaeochannels with a position or direction coherent with other more recognizable tracks.

4. Results and Assessments

The adopted methodology allowed a first general morphological characterization of the Murghab area, by means of SRTM-DEM analysis, and a more specific understanding of the hydrographic network in the northeastern fringe of the alluvial fan using

medium-high resolution data (Landsat MSS and TM, CORONA KH-4B, Soyuz KFA 1000, ASTER).

Through the application of a shaded effect on the original Digital Elevation Model, main morphologies have been identified: high reliefs in the south, and active aeolian processes around the alluvial plain of the Murghab River. The Murghab fan slopes towards northwest, with values ranging from 200 to 20 m asl.

Use of *high pass* filters, on the original SRTM-DEM, allowed the better identification of natural hydrographic network of the fan, which is dense in the apical part of the fan—index of intense activity of the river—while it has sparse channels in the distal part—index of a present-day low gradient of activity.

In order to better understand the distal part of the fan, today an arid area, medium-high resolution data were used, with the aim to identify present-day inactive channels, but that were previously actives, since life of ancient populations was strictly related to water availability.

Final map (Fig. 7) shows a complex and fragmented network of palaeochannels, in which it is possible to recognize at least three main clusters of palaeochannels, with a prevailing vertical alignment, from south towards north, but also towards northeast and northwest.

The first cluster corresponds to the overlapping area between previous works and this study. This area was used as a check for this work. The hydrographical network here digitized (Fig. 7, dark blue palaeochannels) reveals a satisfying correspondence with the previously digitized network (Fig. 7, light blue palaeochannels). This is a first proof of good quality of our photo-interpretation, since the previous model had been also verified on field. It is also possible to note that palaeochannels' tracks actually follow the direction of ancient already known settlements, thus demonstrating the close correlation between hydrography and settlement choice in the past. Slight gap between the two models is probably

due to different Geodetic Systems used (here the UTM-WGS 84, 41 N zone).

The second cluster of palaeochannels highlights more fragmented waterways in the central part of the study area, between the previously investigated area and the present-day irrigated branch of the Murghab fan.

This region could be a further area of investigation, since other archaeological evidences could be found. Until 2009, only few sites have been found [13] (Fig. 7) and more recent field surveys did not generate further findings. This area could therefore represent the oriental border of human settlement in the Murghab area, or reveal other discoveries along some palaeochannels' tracks, not yet examined.

In such a framework, it could be more interesting to analyze the more eastern branches of the fan, in the east side of the present-day irrigated branch, which represent the third cluster of palaeochannels digitized.

The opportunity to study this peripheral area of the fan could give important information about historical settlement choice, which could have spread in a higher number of areas than those until now verified, extended up to this eastern borderline. Eventual findings could also be used to date river branches.

The most significant data, for their quality and suitable covering, were Corona and Aster data, mostly due to their geometric resolution on ground, which was suitable for the analysis of palaeoforms up to 30-40 metres in size.

Aster images were particularly significant for their good geometric resolution on the ground, and their legibility, due to the capability of this sensor to acquire in 14 bands, from visible to the thermal infrared wavelengths. Also Corona images allowed a good discrimination of natural drainage pattern of the Murghab River, revealing their usefulness for geomorphological and geohistorical purposes. Basemaps in GIS were also used for additional checks only, considering their good geometric resolution on ground and their availability for free.

Also Soyuz images could have been a good support for this research, due to their suitable ground resolution, but they can be used up to the central part of the study area only, since the eastern one was not covered by this dataset (see Fig. 4).

Conversely, Landsat data proved to be immediately unfit for work purposes, principally because of their insufficient ground resolution.

Preference for studying arid zones rather than irrigated ones, gave the double advantage to obtain a clearer restitution of inactive palaeochannels and a greater possibility to do following field surveys.

Finally, despite the presence of *takyr* areas is not in itself indicative of palaeochannels' existence [31] it is evident, in this study, the close correspondence between ancient riverbeds and presence of *takyr* areas, as already pointed out in the previous study [25]. They also are flat areas, in which it is easier to find ancient forms and evidences. For these reasons they can be considered areas of interest for this kind of researches.

5. Conclusions

This work continued previous researches aimed at understanding the ancient environment of the Murghab alluvial fan with archaeological purposes, with focus on the acquisition of the ancient hydrography, since it was strictly related to human life and settlements.

The adopted methodology firstly provided a broad understanding of the fan morphology, and its surroundings, by means of the SRTM-DEM analysis; secondly, it described a circumscribed area in the northeastern part of the fan, by means of medium-high ground resolution data, with particular focus on ancient hydrography, whose tracks are in a present-day arid area.

Corona and Aster data were particularly valuable, since they allowed the identification of a high number of palaeochannels, even though in a fragmented and sometimes very doubtful way. Final map indeed shows a meandering and fragmented network.

The most significant area for further archaeological studies can be considered the more eastern part of the study area, since it could be an additional belt of ancient settlement, due to a series of ancient branches of the Murghab River, which could have provided some historical sites not yet discovered. For this purpose this area could be taken into consideration for further studies and surveys.

It is actually worth to point out that this research does not presume to have traced “sure” paleochannels, but rather “possible” tracks, sometimes very doubtful because of natural obstacles, such as dunes, or uncertainty in the data; the SAR (synthetic aperture radar) data analysis may be used to identify in detail such channels in future research.

It is therefore possible that new field surveys, or other types of researches, could falsify the hypothesis presented here, which has to be confirmed on field for eventual later adjustments.

Finally, it is to note that the hydrographic network cannot be used to date channels, but other tools have to be used for this purpose, such as core drillings or archaeological evidences close to a river branch.

On balance, this work presented a methodological proposal for a preliminary survey of this specific area of the Murghab fan, in order to define a first work plan with the minor waste of money and human energy that it was possible. It was indeed useful to highlight areas of interests in which further surveys have to be done. For instance, it could be useful the acquisition of higher resolution images, such as LiDAR data—a very expensive datum, but very suitable for studying such a flat environment—or to plan next field missions. For further studies, we suggest however to take into consideration the *takyr* areas, also those ones in the northeastern part of the fan, beyond the previously investigated area, since they are often suitable contexts in such a kind of studies, to find out palaeoforms and archaeological evidences.

Choices of data, as well as the location of additional field surveys, will be however determined by specific

further aims of research in these areas of the Murghab alluvial fan.

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