The canal system of Ju-i Dokhtar: new insight into water management in the eastern part of the Pasargadae plain (Fars, Iran)

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The canal system of Ju-i Dokhtar: new insight into water management in the eastern part of the Pasargadae plain (Fars, Iran)

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Abstract
Within the territory of the ancient province of Persia, which corresponds approximately to the present-day region of Fars in southern Iran, numerous remains of hydraulic structures are known and reported. These have rarely benefitted from detailed studies, however, which results in functional uncertainties and unconfirmed chronological suggestions, including in particular hasty attributions to the Achaemenid period. The territory of the plain of Pasargadae, situated at the center of this province, was well suited to irrigated agriculture, exemplified by the famous gardens created in the capital of Cyrus in the first period of the Achaemenid Empire. As the region is situated in a mountainous and semi-arid environment, irrigation is necessary for regular agricultural production throughout the year. The region of Pasargadae contains many hydraulic features that are relatively well preserved. However, their dating and their functions still remain unclear, which has stimulated new research and examination of all the evidence concerning the hydraulics, using a combination of methods and approaches, including systematic regional mapping, photo-interpretation, precise topographic readings, and dating experimentation through OSL analyses. This article presents a synthesising study of the remains of the Ju-i Dokhtar canal and the dam of Sa'adatshahr, which is located at the outlet of the canal. These structures probably formed the backbone of a system of water exploitation, that included all of the south-east part of the plain of Pasargadae and the plain of Sa'adatshahr further downstream.

Keywords Pasargadae · 1st Millennium BCE · Achaemenid · Water management · Open-air canal · Dam

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Introduction

The site of Pasargadae is located in the present-day province of Fars in Iran, in the heart of ancient Persia (Fig. 1). It was founded in 550 BCE during the reign of Cyrus II, the first Great King of the Achaemenid Persian Empire, which dominated the ancient Near East for more than two centuries. Pasargadae served as the capital of the empire, until Persepolis—some 50 km to the south—was founded by Darius I in about 520 BCE. During the times of flourishing of the Achaemenid Empire, however, Pasargadae remained a place of great dynastic importance where imperial ceremonies took place and a place serving as a local center in charge of managing its surrounding territory (Henkelman 2008, pp. 427–438). In Persia, the Achaemenid administration certainly invested massively in the large-scale

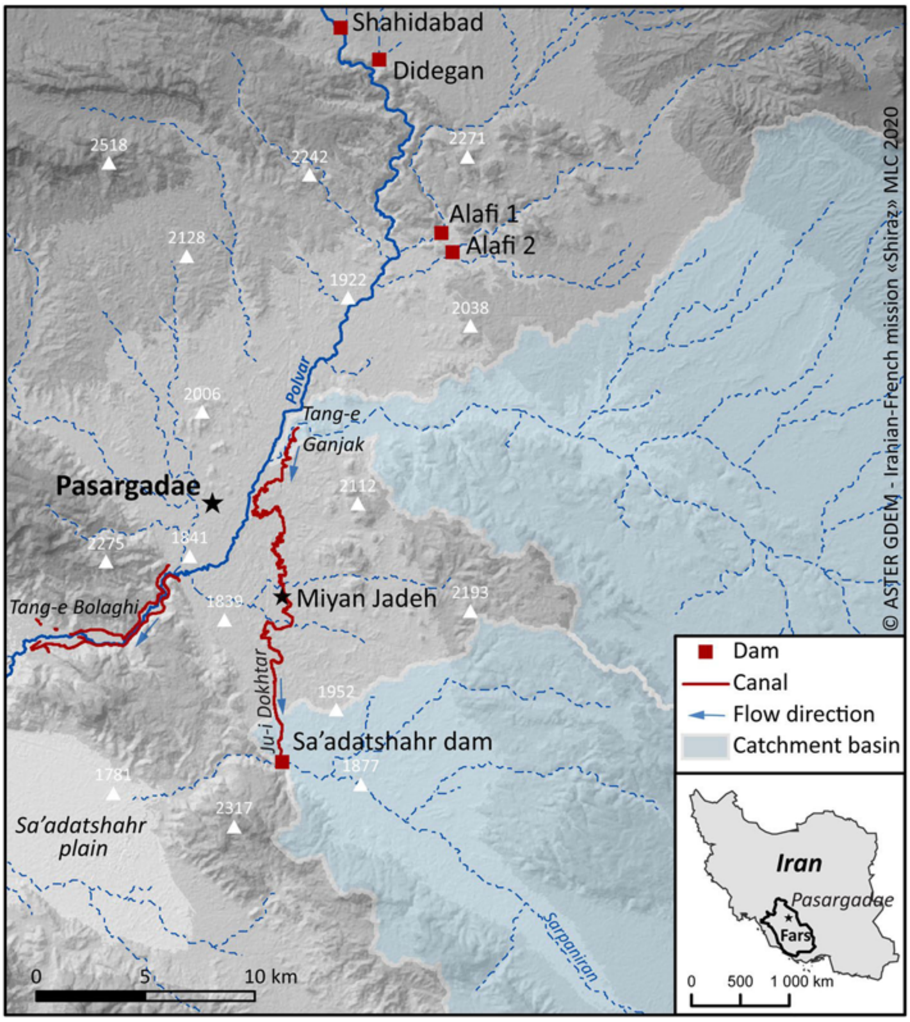

Fig. 1 Map of the principal hydraulic structures in the plain of Pasargadae and the sites discussed in the text

development of hydraulic works in order to support agricultural exploitation (Henkelman 2012, pp. 959–960, 2017, pp. 83–84; Vidale 2018, pp. 32–33).

The regions of Persepolis and Pasargadae are rich in hydraulic constructions of various nature (canal, dams, dikes). Given that the Achaemenid era is considered the main phase of development in the region, the hydraulic constructions are usually attributed to that period. However, we lack accurate descriptive and chronological data for asserting this theory. The particular value of the region of Pasargadae is that hydraulic remains have been better preserved from modern destruction than those of the Persepolis plain. As a result, the region of Pasargadae gives us an opportunity to better understand the management of water resources, and, as demonstrated in the present article, provides data of unprecedented detail on water works from the Achaemenid and post-Achaemenid period.

The subject of water has naturally been an important one since the beginning of research by the Irano-French archaeological mission "Shiraz" on the site of Pasargadae and its region in 1999 (Boucharlat and Benech 2002, p. 10; Atai and Boucharlat 2009, p. 2, pp. 23–31; Boucharlat 2014, pp. 50–53; De Schacht 2018). After an interruption of six years, the program in the field was resumed in 2015. Beginning in 2017, a line of research was devoted specifically to the subject of water management. Our aim is to complement the existing data concerning the hydraulic remains in the region, and to carry out a homogenization and a synthesis of both the original and new data.

This article will focus on a group of structures situated in the foothills of the south-east part of the plain of Pasargadae: the canal of Ju-i Dokhtar, the vast site of Miyan Jadeh, and the remains of the dam of Band-e Sa'adatshahr (Fig. 1). The previous work carried out on this sector of the plain suggests that these different structures were related and formed a single, possibly unfinished, hydraulic system (Karami and Talebian 2013; De Schacht 2018, pp. 148–150). To confirm this, however, further data were needed in order to enable systematic mapping of the features. This would involve combining surveys in the field, including high-resolution readings of the topography, and analyses of the aerial and satellite images. From a methodological point of view, it was also necessary to confront the difficult question of the absolute dating of the hydraulic structures, which for the most part contained very little datable material. Because of their large size and their relatively good state of preservation, the study of these structures in the south-east part of the plain of Pasargadae enables research into the management of water resources in Persia during the Achaemenid period and in the second half of the first millennium.

Development of irrigation networks in Persia beginning in the first millennium BCE and data for the plain of Pasargadae

Although the practice of irrigated agriculture may certainly be assumed for earlier periods, the Achaemenid period is the earliest period for which we have strong archaeological evidence for the development of large irrigation networks in what was the territory of Persia. It was a period of agricultural prosperity and the development of irrigated arboriculture is well documented, thanks to palynological data (Djamali et al. 2010, 2016; Brisset et al. 2019, pp. 124–125). Surveying and excavating in the region of Persepolis, situated 50 km south of Pasargadae, revealed several examples of hydraulic structures (dams and canals), dated more or less certainly from the Achaemenid period (Nicol 1970, pp. 249–265, 269–281; Sumner 1986, pp. 13–17; Moradi-Jalal et al. 2010, Boucharlat et al. 2012, pp. 272–275; Kleiss 2015, pp. 98–100). These remains indicate the existence of at least three large irrigation networks that spread from the upper plain to Persepolis. These structures prove that in Persia large areas of arable land were widely irrigated and exploited. They also indicate that during the Achaemenid period, the populations of Persia mastered several techniques for harnessing, controlling and transporting water through networks of open canals, and that various types of water resources – fluvial water and spring water – were used depending upon need.

Recent reviews of the available data for the plain of Pasargadae suggest the existence of water resource management for cultivatable alluvial sedimentary plains (Karami and Talebian 2013; Kleiss 2015, pp. 95–99; De Schacht 2018). The most well-known vestiges of irrigation in the region were brought to light at Pasargadae during the excavations carried out between the end of the 1920s and the middle of the 1960s. The famous garden of Pasargadae, which constituted the center of the royal sector of the capital of Cyrus, was revealed thanks to the discovery of a network of canals constructed in stone (Stronach 1978, pp. 107–112, 1994; Grob 2017, pp. 53–84). Beyond this site, some observations and brief descriptions of the remains of several dams and canals present in the plain of Pasargadae were also published (Kleiss 1988, 1991; Yamauchi and Nishiyama 2008). These structures were studied in a more thorough manner during the first phase (1999–2009) of the Irano-French archaeological mission in the region of Pasargadae as part of archaeological rescue operations. Trenches were excavated along the path of two canals running beside the Polvar river in the valley of Tang-e Bolaghi, which provided several elements for relative dating that placed these constructions in the first millennium BCE (Atai and Boucharlat 2009, pp. 23–31). To the north, uphill from the plain, two seasons of excavation (2008–2009) of two dams uncovered complex systems of flow regulation (Wilkinson et al. 2012, pp. 165–167; De Schacht et al. 2012; Boucharlat 2014, pp. 51–53; De Schacht 2018, pp. 145–148). These excavations also provided absolute dates for these constructions to the beginning of the Achaemenid period (De Schacht 2018, pp. 145). However, this work was interrupted after 2009 while the data concerning the hydraulic landscape of the plain of Pasargadae was still incomplete. Data from these earlier excavations must now be integrated into a systematic study of the assemblage of hydraulic systems in the plain. Certain sectors of the region remained insufficiently explored, such as the south-east part of the plain of Pasargadae and the canal of Ju-i Dokhtar, a major element in the hydraulic landscape, the study of which has been the focus of our efforts since 2017.

The data concerning the canal of Ju-i Dokhtar are fairly minimal, as it has never been systematically surveyed, recorded and described. The canal was first reported as belonging to the Islamic period on a map of the surroundings of Pasargadae (Stronach 1978, Fig. 3). Its path was discerned based on recent satellite images (Yamauchi and Nishiyama 2008, pp. 223–225; Karami and Talebian 2014, pp. 232–234) and on CORONA images from the early 1970s (De Schacht 2018: 146-Fig. 1, 148–150). These authors suggest that the two dams or dikes surveyed by Kleiss (1988, pp. 65–66, 1991, pp. 25–26), whose remains are situated downstream and upstream, constitute the origin and the outlet of this canal. Finally, important data for the relative chronology and the function of this canal were obtained during the rescue excavations carried out on the site of Miyan Jadeh, overlaying one of the branches of the canal (Zareh-Kordshouli and Mohammadi 2013, 2017). This site, whose existence was revealed thanks to CORONA image analysis, is clearly connected to the canal and has provided an assemblage of storage pottery which is probably Achaemenid in date. Although these various pieces of evidence pointed to the existence of an extensive system of water management in the south-east of the Pasargadae plain, possibly belonging to the Achaemenid period, the different structural elements remained to be comprehensively examined and recorded in a more accurate manner, in the field and through remote sensing, in order to better define their function and date.

Climatic and hydrological context of the plain of Pasargadae

The plain of Pasargadae, or plain of Morghab, is one of the vast alluvial sedimentary inter-mountain basins that are characteristic of the central and eastern part of the Zagros mountain range (Rigot 2010, pp. 59–60). Smaller in size than some of these basins, which can measure up to several hundred square kilometers, such as that of Persepolis/Marvdasht, the plain of Pasargadae offers an arable surface of about 50 km^2. Pleistocene pediments and Jurassic and Cretaceous limestone mountain ranges, some of which rise above for more than 800 m, surround the plain. It is crossed from north-east to south-west by the Polvar/Sivand river (Duva 2018), the principal watercourse of the region of Pasargadae, which joins the plain of Persepolis downstream where it flows into the Kur. The Polvar's catchment area, estimated at 9000 km^2, extends mainly upstream from the plain of Pasargadae (De Schacht et al. 2012, pp. 93–95). In that plain, the Polvar receives the waters of several tributaries whose catchment areas are of various sizes. The hydraulic works discussed here controlled the inputs of two catchment areas of the left bank, with a surface area of 1208 km^2 for the most northern and 423 km^2 for the southern basin (Fig. 1).

The climate of the Pasargadae region is semi-arid, of Mediterranean type, with a cold, humid winter season and a hot, dry summer season (Rigot 2010, pp. 62). At the meteorological station of the modern village of Pasargadae/Madar-e Soleiman (Fig. 2), average annual precipitation is 337 mm. Precipitation is characterised by strong seasonality, with 96% per cent concentrated between December and April, and high inter-annual variability, with minimal and maximal values of 98 mm for the year 2008–2009 and 519 mm for the year 2002–2003. The average annual temperature is about 12.4 °C, calculated between 1996 and 2009, with substantial differences between winter and summer months (Fig. 2). As the average altitude in the plain of Pasargadae is 1850m, its climate is under a strong mountain influence and thus has colder winters than the sedimentary basins more to the

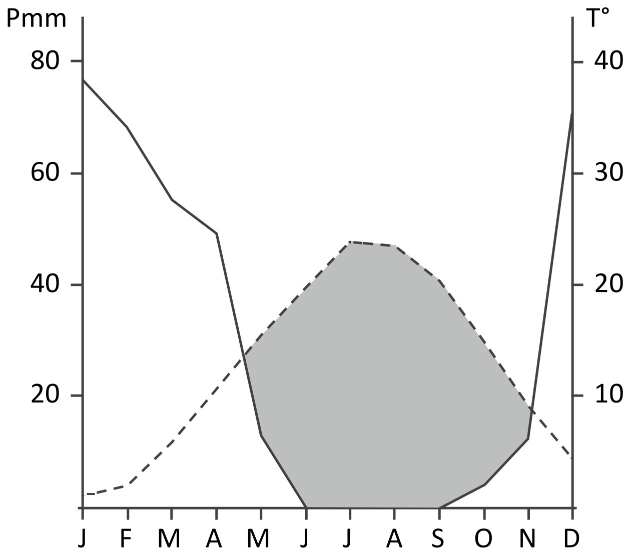

Fig. 2 Ombrothermic diagram of the Madar-e Soleiman station (Pasargadae) according to the averages of 25 years of precipitation readings (1983–2009) and 13 years of temperature readings (1996–2009) (Data provided by the Pasargadae World Heritage Center)

south, with minimum daily temperatures frequently dropping below 0 °C during winter. These regional and local climatic characteristics affect local agricultural strategies. For example, recent palynological studies reveal the strong impact of altitude on the development of agricultural techniques. In the Achaemenid period, arboriculture was widely developed for different altitudes in Persia. For example, in the central part of the province of Fars, near Persepolis and Pasargadae, the development of the Persian walnut tree and oriental plane trees is recorded (Djamali et al. 2010), while only a hundred kilometers to the south-west, in the region of Lake Parishan, 1000 m lower than the plain of Pasargadae, the cultivation of olive trees was identified (Djamali et al. 2016).

According to recent palaeo-environmental studies (Brisset et al. 2019), Fars would have benefitted from climatic conditions that were somewhat more favorable and more stable between the 2nd and the 1st millennia BCE than they are now. The climate was fairly constant over the long term, with a precipitation regime marked by strong seasonality. However, variations observed in lacustrine sedimentary archives indicate more stable water levels in the lakes of the region, indicating the region was less subject to seasonal dryness during the 1st and 2nd millennia compared to today. They reflect a higher volume as well as a greater inter-annual regularity of precipitation during the winter and spring seasons. These data correspond to those obtained locally in the region of Pasargadae which present a dynamic of sedimentation of the Polvar river beginning in the Early Holocene (Rigot 2010), followed by a phase of incision that might have started during the 1st millennium BCE (Rigot pers. comm.). Geomorphological and palynological analyses are being carried out in the region in order to better define these local palaeo-environmental dynamics (Gondet et al. 2018, pp. 17–19).

Like all the watercourses in the province of Fars, the Polvar is today affected by episodes of drought that have continued to increase in frequency since the middle of the 1990s (Samani and Jamshidi 2017) as well as by considerable exploitation for the purposes of irrigation (Brisset et al. 2019, p. 112). Before these recent developments, the Polvar was a permanent watercourse, as were probably its main tributaries. However, measurements taken between 1986 and 2010 in the valley of Tang-e Bolaghi (Fig. 1), downstream from the plain of Pasargadae, show that the flow of the Polvar was highly variable over the course of the year. It was on average six times higher at the end of winter than at the beginning of the autumn. These variations reflect the climatic seasonality, with a maximal flow at the beginning of spring related to snow melt, indicative of a pluvio-nival regime. Moreover, during intense episodes of rain, the basin of the Polvar can be subject to very abrupt flash floods, reinforced by its entrenchment and by the degradation of the plant cover on the slopes (De Schacht et al. 2012, p. 95).

Method

We recorded the hydraulic constructions in the south-eastern part of the plain of Pasargadae – the Ju-i Dokhtar canal and the dam of Sa'adatshahr – at high resolution in order to understand the details of how they would have functioned. This work allowed us to deal with issues that had remained after the preceding preliminary work:

- Identify the water intake point of the canal;
- Define the outlet of the canal and its possible relation to the dam of Sa'adatshahr;
- Date the construction and the abandonment of the structures;

– Recognize possible transformations or repairs;
– Understand the relation of the canal to the site of Miyan Jadeh.

The methodology applied was conceived for these goals and adapted to the specifics of the terrain, and in particular to the state of preservation of the remains, which led to the combination of several survey techniques. This methodology comprises three stages and is inspired by procedures that are widely used in Near Eastern archaeology (Wilkinson 2003; Lasaponara et al. 2018; Hammer 2019) and in Iranian archaeology in particular (Alizadeh and Ur 2008; Wilkinson et al. 2012; Lawrence and Wilkinson 2017).The stages are as follows:

– Photo-interpretation/remote sensing for general mapping;
– In the field, survey work, precise topographic survey and data on the morphology of the hydraulic structures in certain key sectors;
– Sampling of sediments for absolute dating by stimulated luminescence techniques (OSL/IRSL).

These new data provide a complement to the pioneering work carried out in the region during the first phase of the "Shiraz" mission and are indispensable for the completion of the study of the hydraulic system of the left bank of the Polvar.

Reconstruction of the path of the canal using photo-interpretation

We used aerial and satellite images to reconstruct this hydraulic feature. The interpretation of these images aided planning for the survey work, complemented the topographical data about the preserved parts of the canal (Fig. 3) and increased our understanding of the functions of the structures as well as their position in the regional context. We made use of recent satellite images, because of their high resolution and their correlation to current conditions. We acquired very high-resolution images taken in 2013 (resolution 50 cm per pixel) by the Pleiades satellites and in 2014 (resolution 2.5 m per pixel) by SPOT 6–7, which complement the Google Earth and Microsoft Bing images, which are free of access and usable in the field.

In addition to erosion by lateral flows and infilling by colluvial deposits, various structures have been regularly damaged in the past thirty years by the implementation of modern infrastructure projects (enlargement of the Isfahan/Shiraz motorway and construction of a railway line) as well as by agricultural exploitation and quarrying. We therefore also analyzed an assemblage of earlier aerial photographs that enabled detection and tracing of the path of the canal and its associated structures as they were preserved before modern damage. Among these, we used photographs taken in 1970 by the American reconnaissance satellite CORONA J-3 KH-4B (provided by the U.S. Geological Survey) and two series of aerial photographs taken at low altitude, in 1998 and particularly in 1966–1967, acquired from the Iranian National Cartographic Center (INCC) of Tehran. For this study, the aerial photographs proved to be much more precise and detailed than the CORONA images.

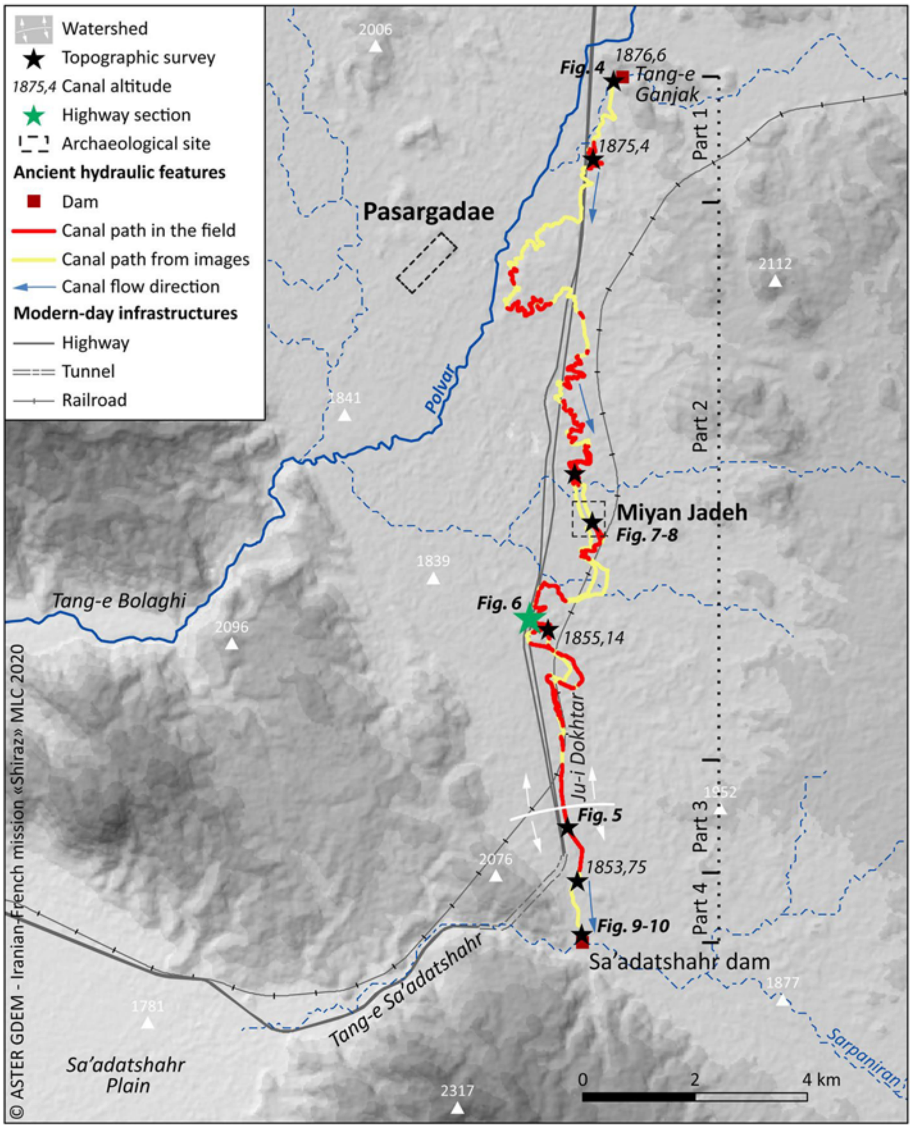

Fig. 3 Map of hydraulic constructions located in the eastern part of the plain of Pasargadae

Ground survey

In the field, we first conducted a field-walking survey of all the preserved hydraulic structures. We followed the Ju-i Dokhtar canal using freely accessible satellite images recorded on a touch-screen tablet, the Huawei Mediapad M3, equipped with the free application Oruxmaps. During this stage of the survey, we recorded the canal's path using a GPS single-antenna Trimble Juno SB equipped with the program Arcpad. Given the various states of destruction of the canal, access in the field to the satellite images on the tablet proved to be essential to our recording process. We complemented this general mapping with more refined surveys in three sectors: the upstream part of the canal to characterize its intake system, the site of Miyan Jadeh to define its relation to the canal, the outlet of the canal and the dam of Sa'adatshahr (Fig. 3). These sectors were recorded through topographic surveys with precision to the centimeter made on the Leica differential GPS with real-time correction. A complete set of data with high cartographic precision of the hydraulic structures was thus produced, including transverse sections and longitudinal profiles of the canal as well as plans, sections and profiles of the dam. These readings enabled the reconstruction of the general morphology of the structures, the study of the construction techniques used and the calculations of slope of the entire canal as well as the water level above the dam.

Dating of the hydraulic structures by the OSL technique

The recent damage to the remains of the hydraulic construction does still provide opportunities for more detailed study of the internal structure, the fill and the morphology, as well as for dating the structures without recourse to excavation. The survey as a whole also had as an objective to determine places along the canal and on the dam to make these observations and take samples for dating.

The north-western part of the dam of Sa'adatshahr is damaged by clean bulldozer cuts and the canal is gashed across its width in several places because of the construction of the Isfahan/Shiraz highway. The transverse profile of the canal is therefore clearly visible in the banks of the highway, cut into the Pleistocene pediments, and needed only cleaning of the sections to be read and analyzed. In the absence of any visible datable element – archaeological material or organic macro-remains – we took samples of sediments in the fill of the canal and in the spoil bank, as well as in the earth body of the dam to carry out dating by the OSL/IRSL technique, which enables estimation of the age of the last burying of sediments. This dating technique has been applied with success in different spatio-temporal contexts, to canals (Berger et al. 2009; Huckleberry et al. 2012) and in sediment accumulations upstream from a dam (Aiuvalasit et al. 2010). In Iran, it has been used to date the spoil heaps of *qanats* shafts (Fattahi 2015; Bailiff et al. 2018) and the fills of canals (Gillmore et al. 2011). However, to our knowledge this technique has not yet been tested on the core of the earth mass of a dam.

Prior to the campaigns of sampling, we first evaluated the possibility of OSL dating in the context of sediments in the region. A sediment analysis carried out in 2016 by J.-B. Rigot, geomorphologist of the mission, on alluvial deposits sampled on the site of Pasargadae confirmed the presence of quartz grains and thus the possibility of applying OSL dating. However, the tests carried out by the Department of Geochemistry and Laboratories of Mining and Geological Survey of Hungary at Budapest, under the supervision of Dr. E. Thamó-Bozsó, on the quartzes of two samples indicated that the latter presented a poor recycling ratio and/or poor recuperation. IRSL analyses were then made of the feldspars; we will return to this in the discussion on the consequences for interpreting the results of the analyses.

During the 2017 campaign, we took three samples of sediment in the sections of the canal (PAS17-G-DK-01-01 and -02, and PAS17-G-DK-02-01) and one in the dam (PAS17-G-SAD-01) for dating. By sampling from the core of the earth mass of the dam, our objective was to date its construction. In the case of the canal, we took advantage of two possibilities: that of obtaining a *terminus ante quem* by dating the process of infilling after abandonment and that of dating the construction of the canal, or its maintenance during use, by taking a sample from the spoil bank.

Results

The Ju-i Dokhtar canal runs in a north–south orientation in the eastern foothills of the plain of Pasargadae. The canal follows a distance of 17 km as the crow flies and 28.6 km in total along the contour lines, between the valleys of the Tang-e Ganjak in the north and that of the Sarpaniran in the south, where the dam of Sa'adatshahr (Fig. 3) is situated. Almost at mid-distance lies the site of Miyan Jadeh. The results of our cartographical studies, operations on the ground and analyses will now be presented in detail, starting at the most northern point – the intake site of the canal –, up to its most southern point – the dam.

Upstream sector and intake site of the Dokhtar canal

The first portion of the canal that is clearly identifiable, in the field as well as in the images, is located 600 m south of the gorges of the Tang-e Ganjak (alt. 1875.4 m in Fig. 3). At this location, the canal is dug in the Pleistocene pediments, at an elevation of 6 m higher than that of the water flowing from the Tang-e Ganjak river. As De Schacht (2018) pointed out, the intake point is to be found further upstream, in the gorges, but is difficult to trace due to agriculture activity and the exploitation of quarries.

The ruins of a stone construction in the banks of the watercourse, some 250 m upstream from the outlet of the gorges, however, may offer a possible indication of an intake point (Fig. 4b). The preserved parts of the structure consist of non-squared blocks measured in decimeters. On the left bank, in the lower part, the blocks of the base of the construction partially merge with a natural level of blocks polished by fluvial flows. However, higher in the bank, they form a clearly identifiable assemblage of blocks with a width of between 1 and 2 m. They are arranged perpendicular to the watercourse and stand out above the surface. On the right bank, the blocks form a mass that is preserved over 3 m in width and 1 m in height, in the core of the bank, 50 cm above the present-day bed. On this bank, no outcropping alignment is visible above the bank, because of levelling and removal of stones from the alluvial terrace for agriculture.

The location of this structure corresponds to the position of a dike discovered by Kleiss (1991, pp. 26–27). He has described a 100 m long and 8–9 m large embankment, preserved on the two banks of the stream, crossing over the whole width of the valley. Indeed, it is possible to precisely identify the location of this embankment thanks to aerial photographs of the 1960s, in which 30 m of this construction is recognizable on the alluvial terrace (Fig. 4a). Today, on the right bank, the embankment has entirely disappeared from the terrace surface that has been levelled for agriculture. On the left bank of the stream, it rests upon a cone of fallen rocks situated at the foot of the cliff. The sections in the banks of the stream show that this construction is deeply embedded in alluvial sediment (Fig. 4b): Kleiss saw the upper part of a mostly buried construction. After its abandonment, alluvial sedimentation might have filled the valley, covering part of the embankment. This embankment could have been a dam that would have enabled raising the water level at the starting point of the canal. According to our hypothesis, and based upon Kleiss' description and our topographic survey (Fig. 4a), we estimate that the water level for the reservoir could reach an altitude of 1876.6 m (Fig. 4b). This

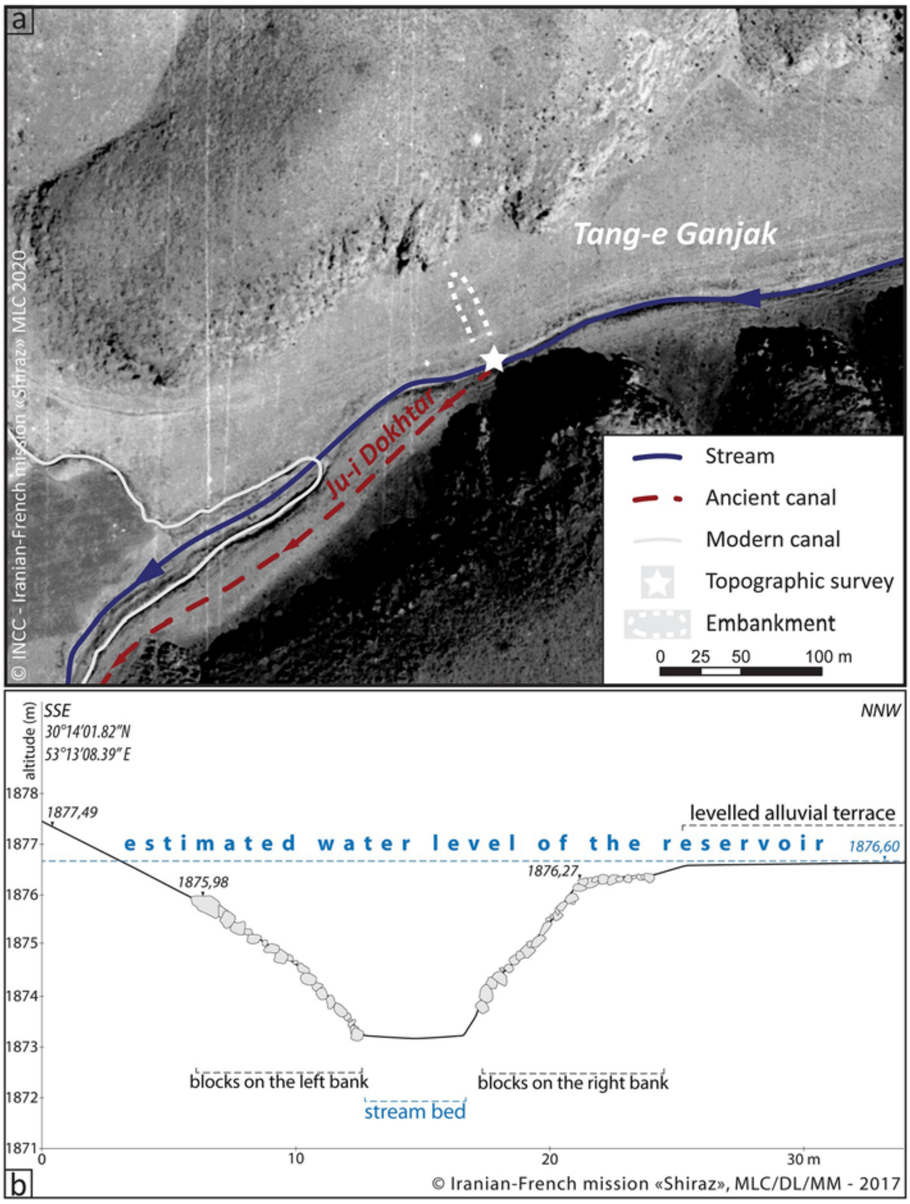

Fig. 4 Intake site of the Ju-i Dokhtar canal. **a** Plan of the site based on aerial photography (INCC 1966–67). **b** Transverse profile of the embankment's remains

hypothesized dam at the intake point of the Ju-i Dokhtar canal would have raised the water high enough to reach the level of the Pleistocene pediments from which the canal was cut. According to the regional topography, this solution was the only one that enabled linking the valley of the Tang-e Ganjak in the north to the valley of the Sarpaniran in the south by a canal (Fig. 3).

Modes of construction, path and profiles of the Dokhtar canal

We distinguished four parts of the canal (Fig. 3), defined according to their morphology and modes of construction. To summarize, upstream to downstream, they change from a channel that is narrow and probably constructed (in part 1) to that of a channel that is wide and deeply dug, bordered by two spoil banks in part 3.

In its first part, downstream from Tang-e Ganjak (part 1 in Fig. 3), the channel is reinforced by a stone line that can be seen at the surface in the lower part of the slope. The width of the canal is here 1.50 m, 2 m including the stone line. It then enlarges progressively. The sediment dug out of the ground forms a bank that enables clear identification of the path of the canal along the slopes (part 2, Fig. 3). Further downstream, at about 25 km from its intake and 3 km from its outlet, the canal must cross a watershed to attain the catchment basin of the river Sarpaniran. Over a distance of more than a kilometer, the canal was dug much more deeply to compensate for the higher altitude of the pediments separating the two basins (part 3 in Fig. 3). In this part, the depth of the canal can attain more than 4 m, the width at its base being almost 7 m, with the banks having a width of more than 20 m on each side of the channel. Thus, the canal attains in places a total width of almost 70 m (Fig. 5). In the context of the early 1st millennium BCE in the Near East, this configuration can also be observed in the Neo-Assyrian canals of the region of Nineveh (Morandi Bonacossi 2018). Finally, when approaching the canal's outlet, the general altitude of the land diminishes, as does the depth of the construction (part 4 in Fig. 3).

Today, the channel of the Ju-i Dokhtar canal is partially or totally filled with alluvial or colluvial deposits. The altitudes that have been measured at the bottom of the channel are those of this infilling, variable according to the contexts of sedimentation. Measured at regular intervals along the length of the preserved sections, these altitudes provide an estimation of the bed gradients along the canal. These slopes, calculated based on topographic data for five portions of the canal, are between 0.02 and 0.13%. The average general slope is 0.08%. This value is situated in the low range of average slopes measured for Neo-Assyrian canals (Ur 2005, 340, Table 1) and several ancient aqueducts (Hodge 2000a, pp. 50–51, Table 2).

The infilling of the canal hinders the reconstruction of the different transverse profiles of the canal and the interpretation of its modes of construction. However, two clean cuts (Highway section on Fig. 3) on both sides of the highway (west and east), enabled a precise reconstruction of the profile of the canal and its infilling, along the longest portion of its course (part 2, Fig. 3). The canal was dug into the Pleistocene glacis, composed of coarse (pebbles, boulders) to sometimes hardened sandy deposits (Fig. 6). Its profile corresponds well to canal types with spoil banks and those with deflated spoil banks as defined by Wilkinson (2003, pp. 46–47, Fig. 4.1-d-e), with a slight rupture visible at the bottom of the south-south-west slope, which should mark the location of the circulation channel. The spoil bank is only preserved in the eastern cut. The infilling of the canal is very homogenous in composition, consisting of colluvial silty-sandy sediments, rarely containing pebbles or rocks. The absence of a stratum of water-lain sedimentation may indicate regular maintenance of the channel during its use. Moreover, we have not found any trace of coating to ensure the water-tightness of the channel, the absence of which has also been noted for other ancient canals of the region (Atai and Boucharlat 2009, p. 26).

We took three samples of sediments for dating by stimulated luminescence techniques: two in the fill of the canal (western section; PAS17-G-DK-01–01 and PAS17-G-DK-01–02) to date the process of infilling of the canal posterior to its abandonment,

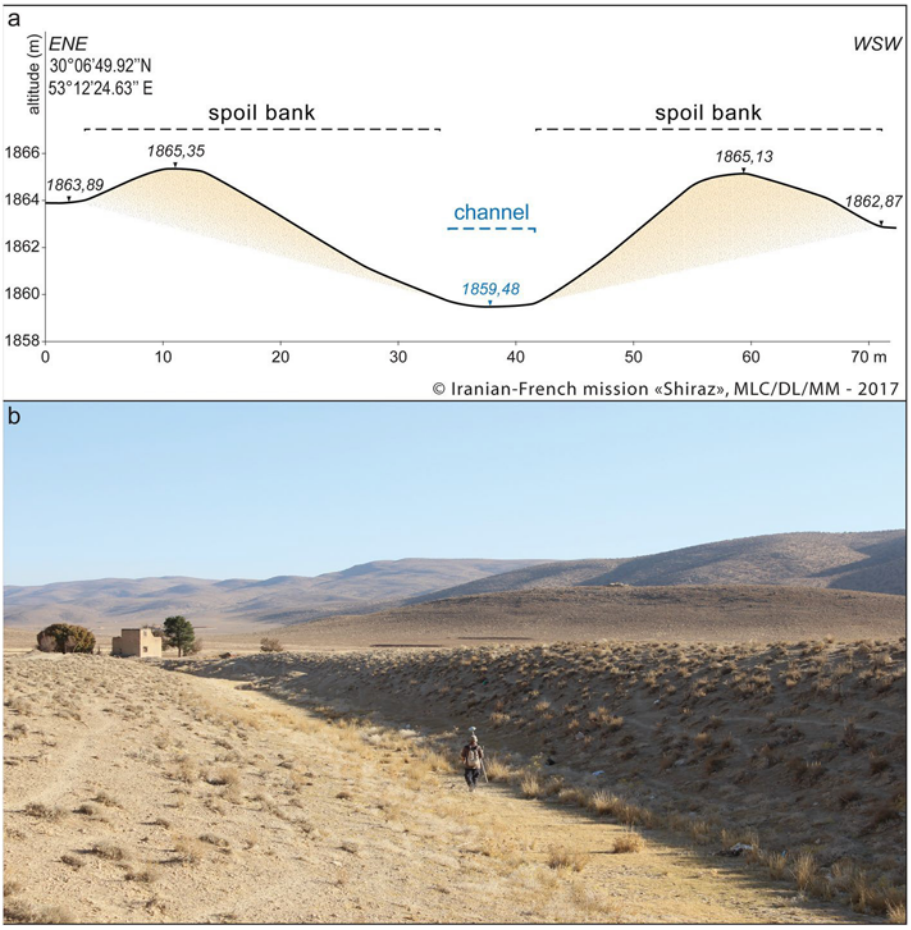

Fig. 5 Part 3 of the Ju-i Dokhtar canal at the crossing of the watershed **a** Transverse profile; **b** Photograph of the canal seen from the north

and one in the spoil bank (eastern section; PAS17-G-DK-02–01; Fig. 6), to date either the original digging of the canal or its maintenance during its period of use. The date obtained for the spoil bank, from sample PAS17-G-DK-02–01 (14.8 ky, ± 3.1; Table 1), would correspond to the latest phase of the creation of the Pleistocene glacis. The feldspars used to date the sediments were probably not bleached long enough during the digging of the canal to enable dating of the construction. The dates obtained from the samples taken from the fill of the canal are more pertinent (2.2 ± 0.1 ky and 2.1 ± 0.2 ky; Table 1). They confirm a gradual infilling of the channel after abandonment, implied by the homogeneity of the sediment fill. The speed of the infilling for 0.46 cm, which corresponds to the difference in height between the two samples, is about a century. These dates indicate that this infilling occurred progressively during the last quarter of the first millennium BCE. The Dokhtar canal would thus have functioned up to the second century BCE at the latest.

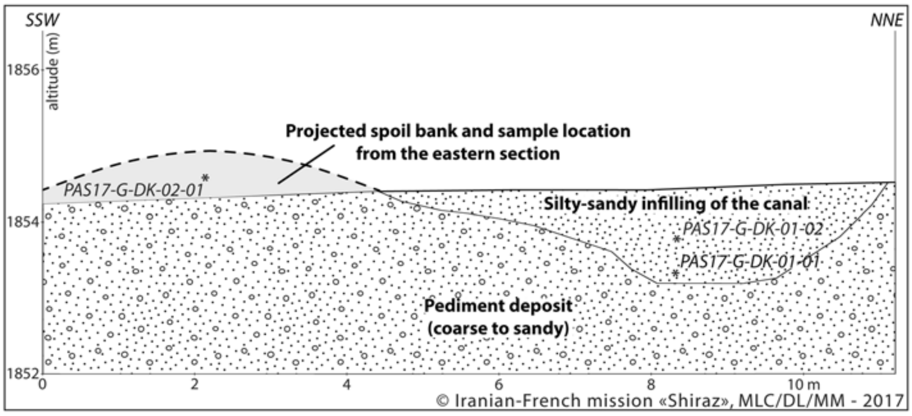

Fig. 6 Profile of the Ju-i Dokhtar canal dug into a Pleistocene pediment (western cut) (the spoil bank is reconstructed according to its reading in the opposite cut)

Table 1 IRSL ages calculated on feldspars with estimated water content of the sediments (after the analyses report transmitted by E. Thamó-Bozsó)

Sample	Depth (m)	Water content (%)	Post-IR $IRSL_{290}$ age (ky)	Residual subtracted post-IR $IRSL_{290}$ age (ky)
PAS17-G-DK-01-01	1.09	7± 1	3.0 ± 0.2	2.2 ± 0.1
PAS17-G-DK-01-02	0.62	10± 2	2.7 ± 0.2	2.1 ± 0.2
PAS17-G-DK-02-01	0.56	5± 1	21.8 ± 4.6	14.8 ± 3.1
PAS17-G-SAD-01	5.53	7± 1	8.7 ± 0.4	7.1 ± 0.3

Notable features of the path of the Ju-i Dokhtar canal

Here and there, the path of Ju-i Dokhtar presents certain notable features (crossing of a watercourse, extra channels, etc.). The absence of any visible offtake channel along the path of the canal, except at Miyan Jadeh, is also notable. We observed specific features at the crossings of intermittent streams coming from the slopes of the eastern foothills. The aerial photographs revealed a more or less prominent outwards curve in the canal path. This curve is particularly strong just upstream and downstream of Miyan Jadeh, where we find the most active channels, created by the watercourse at the outlet of which the site is located (Fig. 8). It is probably related to an intention to reinforce the resistance of the structure to the passage of these channels, acting as a breakwater to distribute the flow to either side of the curves. In addition, in the field, the dimensions of the spoil banks appear to be larger, which is probably a consequence of more frequent cleanings due to the large accumulation of colluvial deposits from the lateral streams.

The other notable element of the canal is that, in part 2 (Fig. 3), there are two sections that have two extra parallel segments or branches of the canal, over distances, respectively from north to south, of 3.8 and 3 km. At Miyan Jadeh, the canal presents a third additional segment measuring over 230 m (Figs. 7 and 8). In total, these sections with extra branches represent almost 25% of the total path of the canal. For the Assyrian region, Ur (2005, pp. 338–339) also described such parallel channels north of Nineveh and suggests several explanations for this morphology. The second canal would have been a replacement canal built after a problem of design or destruction of the first canal, or more probably a distributary canal. In the case of the Ju-i Dokhtar canal, the data collected demonstrate that we probably face a replacement canal. In order to explain the reasons for these extra branches, we compared the altitudes of the two branches of the canal at different points, then we compared these same altitudes with those of the last portion of the canal (part 4 in Fig. 3). According to the transverse topographic sections surveyed at Miyan Jadeh, the eastern branch of the canal (channel 1a in Fig. 7) is situated between 1 and 3 m higher in altitude than the western branch (channel 2, Fig. 7). The altitudes measured along part 4 of the canal (Fig. 3), at the outlet of the principal channel of the Ju-i Dokhtar (about 1853 m), are similar to those measured on the last western branch of the canal situated 6 km upstream (channel 2 in Fig. 7). The altitudes along this branch are thus too low to allow a flow of water up to the outlet, as opposed to those of the eastern branch (about 1856 m; channel 1a in Fig. 7). The altitude data and the observations made based on the aerial photographs and in the field, suggest that there were difficulties in linking up different segments of the canal constructed simultaneously. The construction of the canal was thus carried out using several teams working at the same time on several sections. This method probably resulted in errors in joining the different segments of the canal. The western portions of the canal were clearly abandoned, or perhaps never used, and a second parallel course was constructed at a higher altitude. A problem connecting two segments could also be the reason for the third eastern segment of canal near Miyan Jadeh (channel 1b in Fig. 7). Moreover, the transverse profiles surveyed at Miyan Jadeh show clear morphological differences of the spoil banks between the eastern branches and the western branch, the spoil bank of the

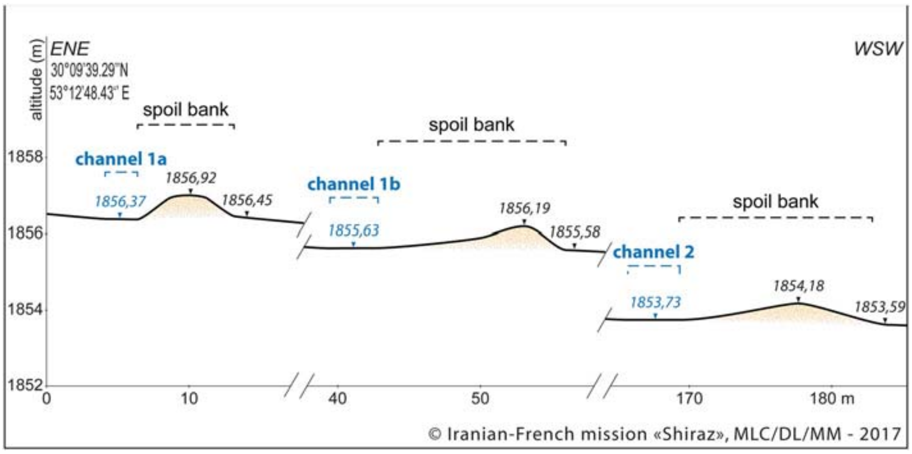

Fig. 7 Transverse profile of the three channels of the Ju-i Dokhtar canal at Miyan Jadeh (location of the profile indicated in Fig. 8)

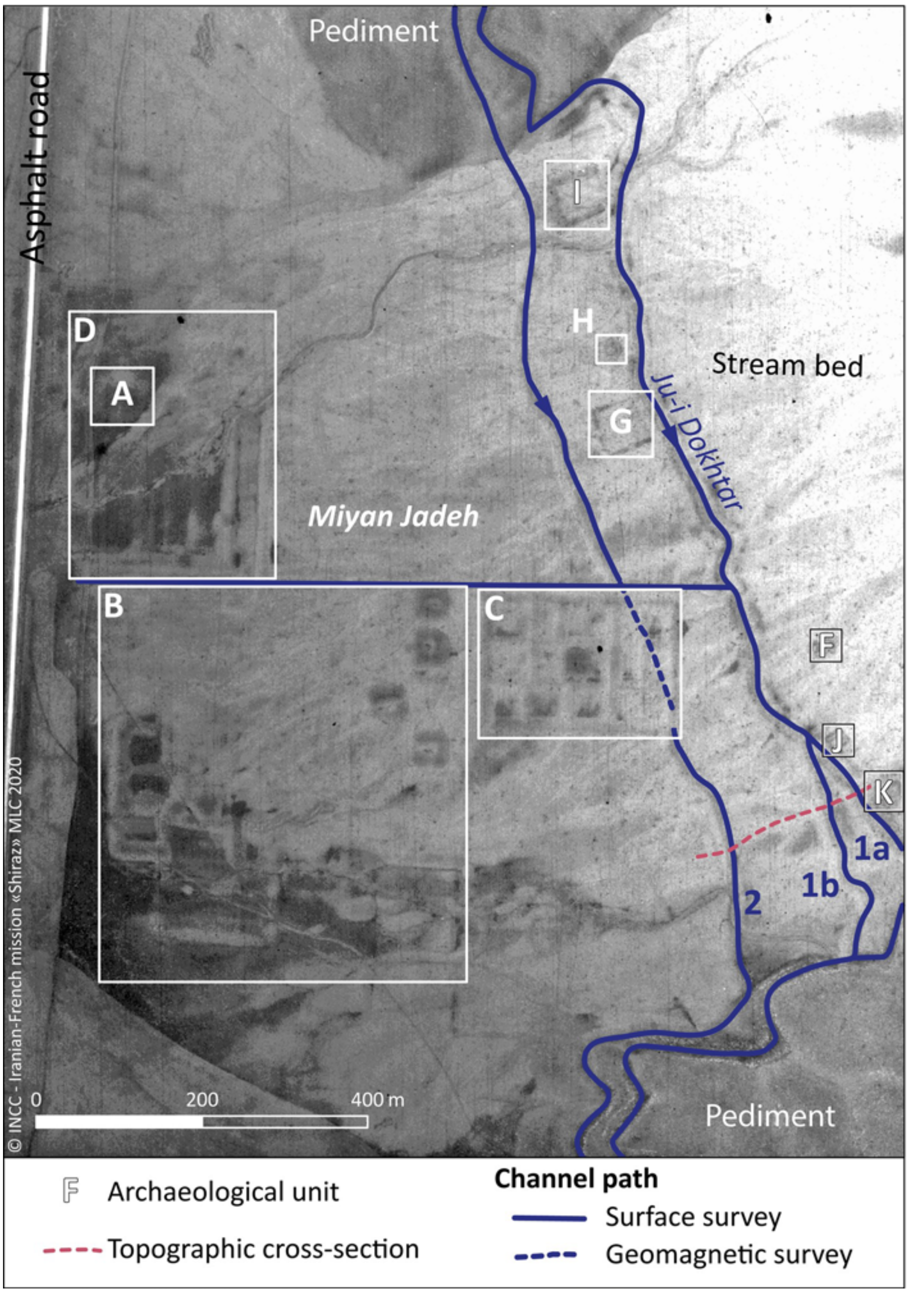

Fig. 8 Plan of the site of Miyan Jadeh based on aerial photography (INCC 1966–67) (Treatment of the image in ArcGIS—Standard deviation stretch, Grey scale inverted—and Adobe Photoshop—adjustment dark tones/light tones—)

latter being less developed (Fig. 7); these differences were probably due to a more or less brief use of these extra western branches.

Miyan Jadeh

Miyan Jadeh appears to be a very important site for understanding the historical occupation of the plain of Pasargadae. The site is located along part 2 of the canal (Fig. 3), at the halfway point of the Ju-i Dokhtar canal. It was established about 10 m above the plain, at the outlet of a lateral stream coming from the eastern slopes. The remains of structures that are visible in the old photographs and in the field form a complex that extends over more than 85 ha.

Zareh-Kordshouli and Mohammadi (2013, 2017) divide their analysis of this complex in nine distinct structural blocks, labeled A to I, to which we have added blocks J and K (Fig. 8; block E, a fortified Islamic site, lies outside the figure). Block A corresponds to a *tepe* that is about 50 m in diameter and 5 m in height, the dating of the occupation being uncertain because of the small amount of pottery present on the surface. Blocks B and D, with surface areas of 20 ha and 7.5 ha respectively, contain various groups of structures. In the north-east of block B, four square buildings are present in the photographs, each with a surface area of 1200 m^2, the remains of which included a very large number of sherds of storage jars, fragments of burnt mud bricks, and indications of combustion (ovens or burnt levels). Block C is one of the principal features of the site; its plan is the clearest in the aerial photographs. It consists of a rectangle 237 m long and 167 m wide, forming an area of about 4 ha whose internal space is divided into an irregular grid pattern. Blocks F to I are isolated structures in the rest of the complex, small in size (between 350 and 2500 m^2), in connection with the active branch of the Dokhtar canal. Between 2008 and 2009, archaeological rescue operations were conducted at Miyan Jadeh by Zareh-Kordshouli and Mohammadi (2013, 2017), before the construction of a petrol station in the north of the site. Twenty-two archaeological trenches of 2 m^2 were excavated over the whole of the site and geophysical surveys were conducted. Although the small size of these trenches does not allow definitive discussion of the nature and function of the structures of Miyan Jadeh, they produced an assemblage of pottery that dates to the second half of the 1st millennium BCE.

Several observations indicate a connection and a contemporaneity between the site of Miyan Jadeh and the Ju-i Dokhtar canal. Three branches of the canal are preserved at the level of Miyan Jadeh (Figs. 7 and 8, channels 1a, 1b and 2). Magnetometry geophysical surveys during the archaeological rescue operations revealed the presence of the western channel (channel 2) beneath block C (Fig. 8). This confirms the installation of block C on the most western branch of the canal, indicating that this section was not in use after the structure was built. A diversion channel that is connected perpendicularly to the eastern branch of Ju-i Dokhtar can be seen both in the field and in aerial photographs (Fig. 8). This channel runs westward towards the alluvial plain of Pasargadae, and is situated along blocks C, B and D. Structures G to K, all associated with the eastern canal, are rectangular, in the form of compartments (reservoirs?). They adjoin the western spoil bank (structures G to I) and towards the south, an eastern bank, which may have functioned to protect against flooding (structures J and K). The path of the eastern canal (channel 1a) appears to be protected from streams of water by a second bank parallel to the canal, not as clear as the spoil bank, but nevertheless visible in the old aerial photographs. This is the only portion of the Dokhtar canal that benefits from this type of layout, which could have provided protection for the canal, and the site, against flooding from the lateral stream. These different elements indicate that the installation of Miyan Jadeh was at least partly contemporary to the period of use of the canal.

Outlet of the Dokhtar canal and the dam of Sa'adatshahr

The recently acquired data from aerial photographs, combined with observations in the field, also provide details about the outlet of the canal. The clearly identifiable presence of spoil banks in the 1960s aerial photographs indicates that the path of the canal continues over a distance of about 400 m towards the south (Fig. 9). This confirms the observations made in the field of highly eroded remains of spoil banks. The altitude data in this area are also coherent with the topographic survey made further upstream along the canal. Given this extension, the path of the canal runs clearly towards the hypothesized reservoir of the dam of Sa'adatshahr. The canal then merges with a later canal that was (re)dug with an outlet in the bed of the Sarpaniran watercourse, just upstream of the ruins of the dam of Sa'adatshahr (Fig. 9).

The dam of Sa'adatshahr is located 350 m upstream from the entrance to the eponymous gorges. It is perpendicular to the course of the Sarpaniran river, which flows from the south-east and is today intermittent. This watercourse, whose catchment area extends over

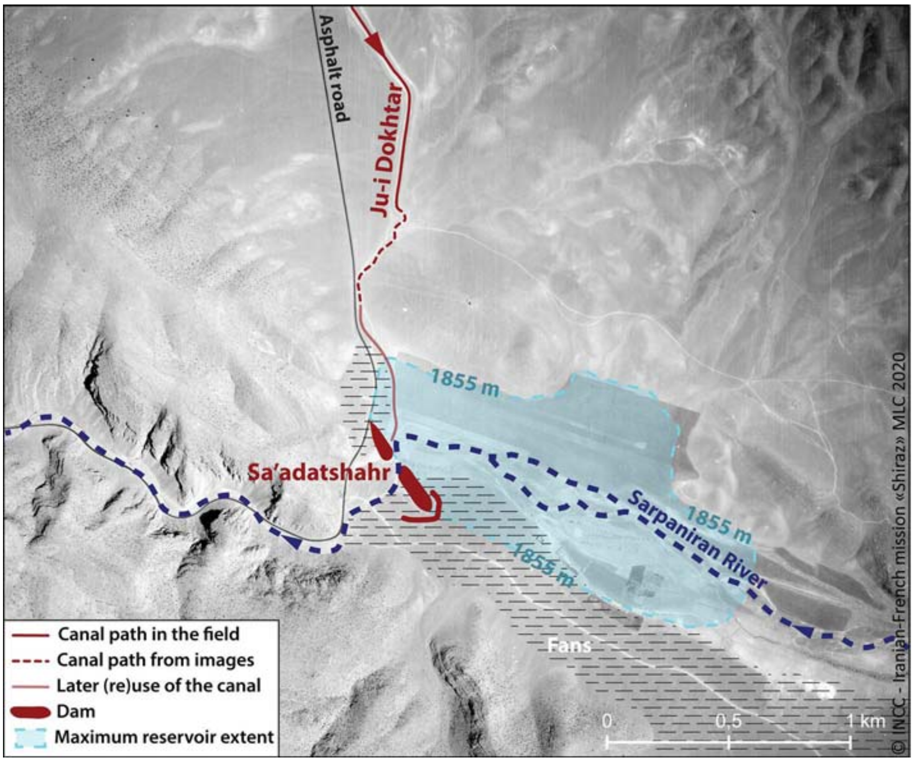

Fig. 9 Reconstruction of the outlet of the Ju-i Dokhtar canal and of the dam of Sa'adatshahr on an aerial photograph background (INCC 1966–1967)

423 km^2, takes its source about 30 km upstream from the dam, then circulates in the center of a valley, narrowing progressively up to the point where it reaches the gorges. From that point, its bed can be followed over 6 km to where its course divides and it becomes lost downstream in the plain of Sa'adatshahr, beneath the modern town of the same name.

The dam is rectilinear in form, oriented north-west/south-east, and rests on alluvial fans which are present where short torrents flow from the slopes that hem in the gorge of Sa'adatshahr (Fig. 9). Its length is 450 m (500 m with spillway canal included), its width about 40 m in the best preserved part, and its maximum height is 7–8 m (Fig. 10). It is an embankment dam that functions as a gravity dam.

The dam is highly damaged today. It was cut in two by the Sarpaniran river and half of the section situated on the right bank was longitudinally cut away by a bulldozer (cf. "destroyed part" in Fig. 10a). On the left bank, a looting hole was dug in the upstream earth part of the dam, and the local inhabitants have long had the habit of reusing the stones for their own constructions. In spite of this damage, we have been able to reconstruct the different constituent elements of the dam thanks to our field observations, complemented by the descriptions published by Kleiss (1988).

The internal structure of the dam is composed of compact clayey-silty earth, reinforced by longitudinal stone walls constructed in its upstream part. These walls were identified on the surface as well as in the cuts created by modern activity. Although only intermittently visible, the line of the walls can be followed along the entire length of the structure (Fig. 10a). They are composed of squared 10-cm blocks, forming walls of about 1 m wide. Intended to reinforce the earth core, these stone constructions on the interior of the dam structure could also have served as drains in the case of water infiltration from the reservoir. In addition, Kleiss (1988) describes a glacis of stones on the reservoir side which no longer exists today. This missing glacis accounts for the larger number of stone blocks present on the upstream face of the dam than on the downstream face, with a slight break observable at mid-slope.

At the south-east extremity of the dam, a canal was dug into the loose sediments of the alluvial fan upon which the dam rests (Fig. 10a). This canal, linking along a concave line the reservoir of the dam to a point upstream of the structure, would have served as a spillway to prevent overflow from the reservoir lake. Considering the very low altitude of the outlet of the reservoir (1852 m), the spillway was probably controlled by a gate. This could have been located at the point of an alignment of blocks dimensioned in decimeters, in the spoil bank of the spillway (Fig. 10a). Kleiss (1988, pp. 65, 65-Abb. 5, Taf. 37.3) also described this feature, which was then better preserved, and interpreted it in the same way.

In the better preserved south-east part of the dam, the topography of the structure presents a depression 67 m in depth over a length of about 15 m. This depression is characterized by a high concentration of blocks as well as by alignments of stones parallel to the line of the dam. These elements suggest the existence of a water gate to control the downstream flow from the reservoir (Fig. 10). The presence of this depression cannot be explained by recent damage, as no recent bulldozing activity is present in this area, although blocks of stone were removed in the past to construct a funerary cairn at the top of the dam. This depression is probably the result of the collapse of the hypothesized water gate that constituted a weak point in the dam.

Based on the preserved height of the dam, we estimate the maximum altitude of the reservoir to have been 1855 m (Fig. 10b), corresponding to a maximum water level of about 5 m. Considering the altitude of the lower part of the hypothetical water gate, the lowest level of usable water would have been situated at about 1852 m. At its maximum level of water, we estimate the surface of the reservoir to have been about 95 ha. This surface area

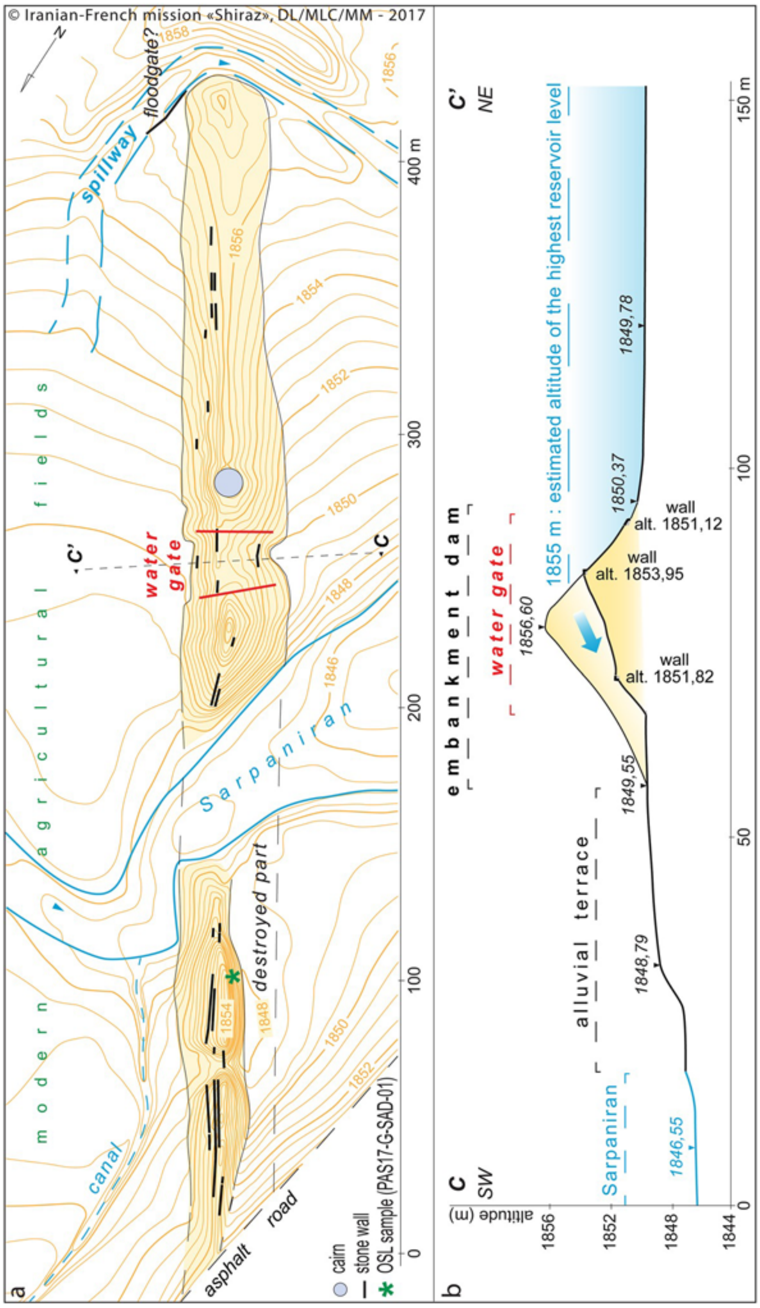

Fig. 10 Plan **a** and profile **b** of the dam of Sa'adatshahr

can only be estimated cartographically (Fig. 9) and cannot be verified in the field given the major disturbance of the general topography of the sector related to the construction of a modern concrete dam, 300 m upriver from the ancient dam (Fig. 11).

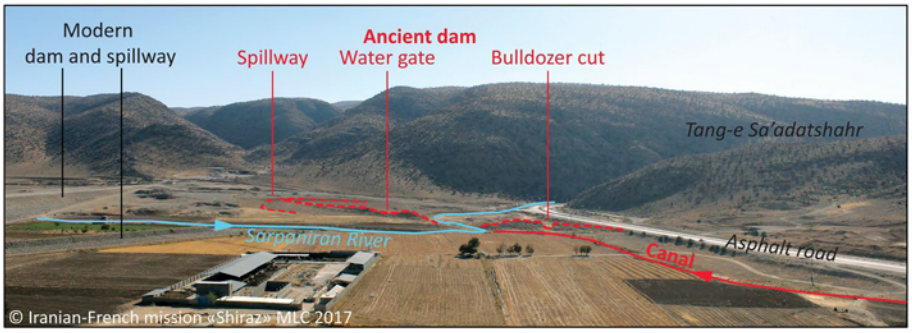

Fig. 11 Photograph of the sector of the dam of Sa'adatshahr seen from the north

According to Kleiss (1988, p. 66), the dam of Sa'adatshahr dates to the Achaemenid period. The bulldozer that cut in the core of the dam opened a window into the internal earth structure, from which we sampled sediments for OSL dating of the construction (PAS17-G-SAD-01; Table 1 and Fig. 10a). The date obtained from this sample is very early (7.1 ky ± 0.3) and corresponds to the end of the 5th millennium BCE. However, according to present knowledge, the earliest gravity dams, situated in the eastern Mediterranean region, date to the 3rd millennium (Hodge 2000b; Viollet 2007). It is possible that we obtained a date for the natural deposition of the sediments used for the construction of the dam and not the date at which they were used and removed for the construction of the dam. These sediments could have come from nearby Holocene deposits, perhaps the alluvial terraces of the Sarpaniran river.

Discussion

Function of the structures related to the Ju-i Dokhtar canal and hypotheses of their use

De Schacht (2018) suggests that the remains of hydraulic structures in the plain are the result of unfinished construction or at best were used only briefly. We have demonstrated, however, that the Ju-i Dokhtar canal could have been fully functional. Until now, the historical dams in the region of Pasargadae were considered check dams for controlling the flow of watercourses in the region rather than reservoir dams holding water for irrigation (De Schacht et al. 2012; De Schacht 2018, pp. 144–145). Within the framework of our study, the location of the Sa'adatshahr dam, set back from the entrance of the gorges, would point to its having been a protection for this natural passage while preserving access to it. According to Kleiss (2000, p. 755), the dam would have secured a route that linked the plains of Morghab (Pasargadae) and Sa'adatshahr. However, if the hydraulic structures in the east of the plain of Pasargadae are considered as a whole and in their hydrographic context, the Ju-i Dokhtar canal and the dam of Sa'adatshahr could certainly be related, and may constitute the elements of the same system of water resources management. The dam would then have served a double function rather than being limited to protection against floods. The Ju-i Dokhtar canal could have served to transfer the water of the Tang-e Ganjak catchment area towards that of the Sarpaniran, in order to supply the reservoir of the Sa'adatshahr dam. The reserve of water thus provided during the winter and spring months could have served to ensure a regular supply of water throughout the year for the arable lands of the plain of Sa'adatshahr situated downstream. We note that in the field no remains of canals have been identified in the gorges of Sa'adatshahr, thus the water would have flowed in the bed of the Sarpaniran, although it is also possible that the construction of the asphalted road through the gorges destroyed any trace of ancient canals.

The eastern part of the plain of Sa'adatshahr has very few local sources of water for irrigation. The south-east extremity of the plain is supplied only by very short torrents from the surrounding mountains, which flow through the southern foothills into the Polvar

Fig. 12 Location map of the alluvial plains cited in the text and of the Ju-i Dokhtar hydraulic system on a SPOT satellite image background (© Airbus DS 2014)

river in the south-west (Fig. 12). Moreover, for topographic reasons this part of the plain is too high to be irrigated by the Polvar. In the absence of available local water, agricultural exploitation of these areas could only be ensured by water brought from the Sarpaniran river, which receives water from only a small catchment area. With these constraints, the solution found for agricultural exploitation of the plain of Sa'adatshahr was to bring water via the Ju-i Dokhtar canal. The water resources of the canal came from a much larger catchment area than that of the Sarpaniran and higher in altitude (up to 3000 m, as opposed to only 2300 m in the catchment area of the Sarpaniran), fed by snow melt from an area having a larger snow cover. The canal could have also received the lateral streams flowing down the slope and watercourses all along its path. The alluvial plain of Pasargadae is not large (50 km^2) and is cut across by hilly zones; the agricultural exploitation of the eastern part of the plain of Sa'adatshahr enabled the doubling of cultivated areas in the region (60 km^2 more) spread over a continuous area (Fig. 12). In this part of the plain, archaeological sites, some of them Achaemenid, and the remains of canals have been discovered by archaeologists of the Pasargadae World Heritage Center (Karimi and Talebian 2014, p. 234-Fig. 7).

Another function of the Ju-i Dokhtar canal appears to have been to supply water to the site of Miyan Jadeh, which is located at the mid-point of the canal. It has been proposed that this site had an economic and administrative function, in particular because of the presence of structures interpreted as storage areas, related to the royal site of Pasargadae (Zareh-Kordshouli and Mohammadi 2017, p. 54). We propose that Miyan Jadeh could also have hosted agricultural activities. The morphology of block C for example, visible on the surface and in aerial photographs, presents an internal organization of 15 vast compartments, some more than 3000 m^2, a total constructed surface area of 40,000 m^2. Given that the largest covered spaces known in Achaemenid buildings are the audience halls of the Apadanas of Susa and Persepolis which measure about 3600 m^2, we suggest that block C of the site of Miyan Jadeh could not be the remains of a single, or even several, buildings. It may instead represent irrigated plots (gardens or orchards), with water supplied by the east–west canal connected to the Ju-i Dokhtar canal. From a strictly functional point of view, the plan of the whole of block C goes back to a traditional mode of spatial organization and irrigation of date orchards, using low walls of earth, recorded by Iranian hydrologists for later periods in the south-east of Fars (Javaheri and Javaheri 2006, p. 163). Blocks A and B also integrate other large structures, less visible in the plan, but which also appear to be related to irrigated agriculture. These linear structures appear to continue towards the west in the direction of the alluvial plain. It is thus possible that from Miyan Jadeh, the irrigated zone extended further into the south-east part of the plain of Pasargadae.

Summary and reflections on the chronology of the structural elements in the hydraulic system

During the field operations carried out on the structures related to irrigation agriculture in the south-east part of the plain of Pasargadae, we took samples for dating by stimulated luminescence. The analyses were made on feldspars rather than on quartz, which, for the samples taken in a natural context and tested to date the alluvial terraces of the Polvar river, showed a poor recycling ratio of the radioactive irradiation dose. The IRSL dating based on the feldspars produced convincing results in contexts marked by regular processes of sedimentation, such as the infilling of the Ju-i Dokhtar canal (Table 1). The samples taken from the terraced structures – the spoil bank of the canal and the earth structure of the dam – provided IRSL dates that are less coherent in the archaeological context. It appears that in these two cases, the samples date the period of the deposition of the sediments and not that of their extraction. During the terracing operations, the exposure to light of the sediments would have been too short, as feldspar minerals need a longer time for bleaching than quartz (9 min as opposed to 10 s for a full resetting; Bailiff et al. 2018, p. 76). New dating by OSL will be attempted on quartz samples to date the construction of the dam and the canal.

We were able to determine that the Ju-i Dokhtar canal was in use up to the second century BCE, that is, before the Parthian period. Although we do not have absolute dating of its period of construction, the regional archaeological context allows us to suggest that it dates to the Achaemenid period. In the middle of the 1st millennium BCE, the founding of Pasargadae would have been accompanied by agricultural exploitation of the surrounding plain. We know of no site of such importance for earlier periods. The site of Miyan Jadeh, established on one of the branches of the canal, has provided a small amount of Achaemenid to post-Achaemenid material. In addition, the northern part of the site of Pasargadae contains a large occupation which probably dates to the post-Achaemenid period (Gondet et al. 2018, pp. 11–16). We cannot therefore exclude a period of construction between the 4th and the third centuries BCE, as Pasargadae and its surrounding territory might have still been densely settled in post-Achaemenid times.

The dating of the dam of Sa'adatshahr remains unclear at this time. It is notable that its structure, which includes walls of internal reinforcement, is clearly unique to this dam in comparison to other ancient dams in the region. It is, however, difficult to determine whether this structural feature might indicate a different function and/or a different period of construction. The five ancient dams known in the region of Pasargadae have all been attributed to the Achaemenid period through various means. For the two dams farthest to the north, De Schacht (2018, p. 145) pointed out the similarities between the modes of construction of the ashlar canal structures at Shahidabad and Didegan (Fig. 1) and the architectural practices in the early Achaemenid period. For these two dams, radiocarbon dates obtained at the time of rescue excavations carried out on their floodgate systems, confirms the Achaemenid date of the structures. For the dam of Sa'adatshahr, Kleiss (1988, p. 66) observed the cut blocks that bring it closer to the Achaemenid period in comparison to those of Didegan, blocks which are no longer present today in situ. On several of the dams of the region, including that of Sa'adatshahr, funerary cairns have been constructed on top by reusing the covering blocks from the slopes of the dams. Although their dating in the region remains difficult, these types of tombs are attributed to the Partho-Sassanid period and particularly to the first half of the 1st millennium CE (Stronach 1978, p. 167; Farjamirad 2015, Gondet et al. 2018, pp. 22–23). Thus, they provide a *terminus ante quem* for the use of the dams which tends towards an Achaemenid/post-Achaemenid date. We hope that future OSL analyses will enable determination of the chronological range as well as the contemporaneity and thus the relationship between the Ju-i Dokhtar canal and the dam of Sa'adatshahr. This relationship makes complete sense on a functional level and takes into account the hydrography and the topography of the region.

Conclusion

It has been proposed that the dams of the region of Pasargadae functioned above all as check dams, but the many canals discovered through survey, the agricultural settlements excavated in the valley of the Tang-e Bolaghi, and the royal residences and "paradises", imply the existence of large agricultural works. This must have been all the more the case around a major site such as Pasargadae and, more generally, to ensure the prosperity of the empire. Irrigation would have compensated for restricted water in the dry season, secured the water supply during the rainy season, and enhanced agricultural production all year long. We would then expect the existence of highly ambitious hydraulic installations, as illustrated by the system of the Ju-i Dokhtar canal/Sa'adatshahr dam, to ensure the exploitation of all the available arable zones. Examples of such installations have also been recovered in the plain of Persepolis (Boucharlat et al. 2012), and it is unlikely that these would have been isolated cases, especially at the heart of the empire.

The evidence points towards the exploitation of surface water resources during the Achaemenid period as well as towards the choice of open-air networks. The networks of *qanats* known in the region of Pasargadae date mostly to the late Islamic period at the earliest, some of these being still in use, exploiting the underflows of the dry beds of the tributaries of the Polvar (Gondet et al. 2018, pp. 20–21). In the present state of research, we propose that surface water resources, rather than subterranean or sub-surface waters, were the major water resource for the populations of the 1st millennium BCE in the north-west of Fars.

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