

The Chaman and Paghman active faults, west of Kabul, Afghanistan: Active tectonics, geomorphology, and evidence for rupture in the destructive 1505 earthquake

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ABSTRACT

The city of Kabul, Afghanistan, lies within the Kabul Block, which is bounded by the Sarobi, Gardez and Paghman fault, the northern extension of the Chaman fault, accommodating oblique convergence between the Indian and Eurasian plates. In this paper, we describe the geologic structure and tectonic geomorphology of the northeast-striking Paghman fault and a ~10-km-long portion of the Chaman fault using a combination of field observations and remote sensing data, and assess evidence for rupturing in the 1505 historical earthquake. The Paghman fault is predominantly a left-lateral strike-slip fault with a minor dip-slip component along the eastern margin of the Paghman Mountains. The Chaman and Paghman faults displace Paleogene to Quaternary units with clear displacement of recent deposits. Continuous left-lateral movement of the both faults have caused stream deflection, capturing, abandonment, and finally, incision of alluvial deposits inside the Kabul Basin. We identify several stages in the alluvial fan development and displacement that were once a continuous unit displaced left-laterally as a single fan but are now incised by beheaded and offset stream channels. An approximately 30-km-long active fault trace is identified with geomorphic evidence of recent faulting and vertical offset ~0.5–3 m, which we interpret is related to the historical 1505 earthquake in the area along the Chaman and Paghman faults. Our observations indicate significant along-strike variations in faults trace geometry. The seismic event comprises several fault segments separated by discontinuities such as stepovers. The two faults have accumulated enough elastic strain to cause a larger earthquake since the 1505 quake.

1. Introduction

The Paghman fault is the northern extension of the greater than 850 km long Chaman fault (Fig. 1a), which extends from the Makran coast of Pakistan to the Hindu Kush in northeastern Afghanistan and accommodates left-lateral motion between the Indian and Eurasian plates. The Chaman fault is one of the most active faults in the region, with a GPS-derived slip rate of 18 mm/year (Mohadjer et al., 2010), which is about half of the ≥ 39 mm/yr rate of motion of the Indian plate with respect to the Eurasian plate (e.g., Wheeler et al., 2005) (Fig. 1a). Based on ¹⁰Be cosmogenic dating of two alluvial fans offset for 165 ± 15 m and 235 ± 24 m by the northern Chaman fault near Kabul with ages average 46.9 ± 3.5 kyr and 66.6 ± 4.9 kyr, respectively, Shnizai et al. (2020) found that the Chaman fault accommodates approximately 3.5–4.5 mm/yr of

left-lateral strike-slip (Fig. 1b). This slip rate is much less than the ≥ 39 mm/yr of overall relative motion between the Indian and Eurasian plates (Fig. 1a). The Chaman fault slip rate decreases with increasing distance from the southwest to the northeast. The slip rate on the main fault is locally partitioned, where there are segment splays such as Gardez and Makur faults, a large number of small faults and convergence of thrust faults (e.g., Crupa et al., 2017; Ruleman et al., 2007; Shnizai, 2020a; Shnizai et al., 2020; Szeliga et al., 2009).

The Paghman fault, at the northeastern end of the main Chaman fault, comprises many fault strands along the northern end of the Kabul Block. The Paghman fault is about 80 km long and strikes from N18°E to N38°E (Fig. 1b). The dominant left-lateral strike-slip motion on the Chaman fault switches to left-lateral oblique-thrust motion on the Paghman fault along the Kabul Basin (Ruleman et al., 2007; Shnizai and

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Tsutsumi, 2020). The motion switch of the faults could be due to various factors, including changes in the regional stress regime, fault bends, stepovers, interaction of other faults and local geology.

The geomorphic expression of the fault has been reported by previous works (e.g., Dronov et al., 1973a, 1973b; Ruleman et al., 2007; Shareq, 1981; Shnizai, 2020a, 2020b; Shnizai et al., 2020; Shnizai and

Tsutsumi, 2020; Wheeler et al., 2005). Most recently the Paghman fault was characterized and mapped by Ruleman et al. (2007) and by Shnizai (2020a) and Shnizai and Tsutsumi (2020), who mapped the entire fault trace and provided some geomorphic observation and clarification based on interpreting different satellite imagery and digital elevation data. However, no detailed mapping, explanation and discussion of the

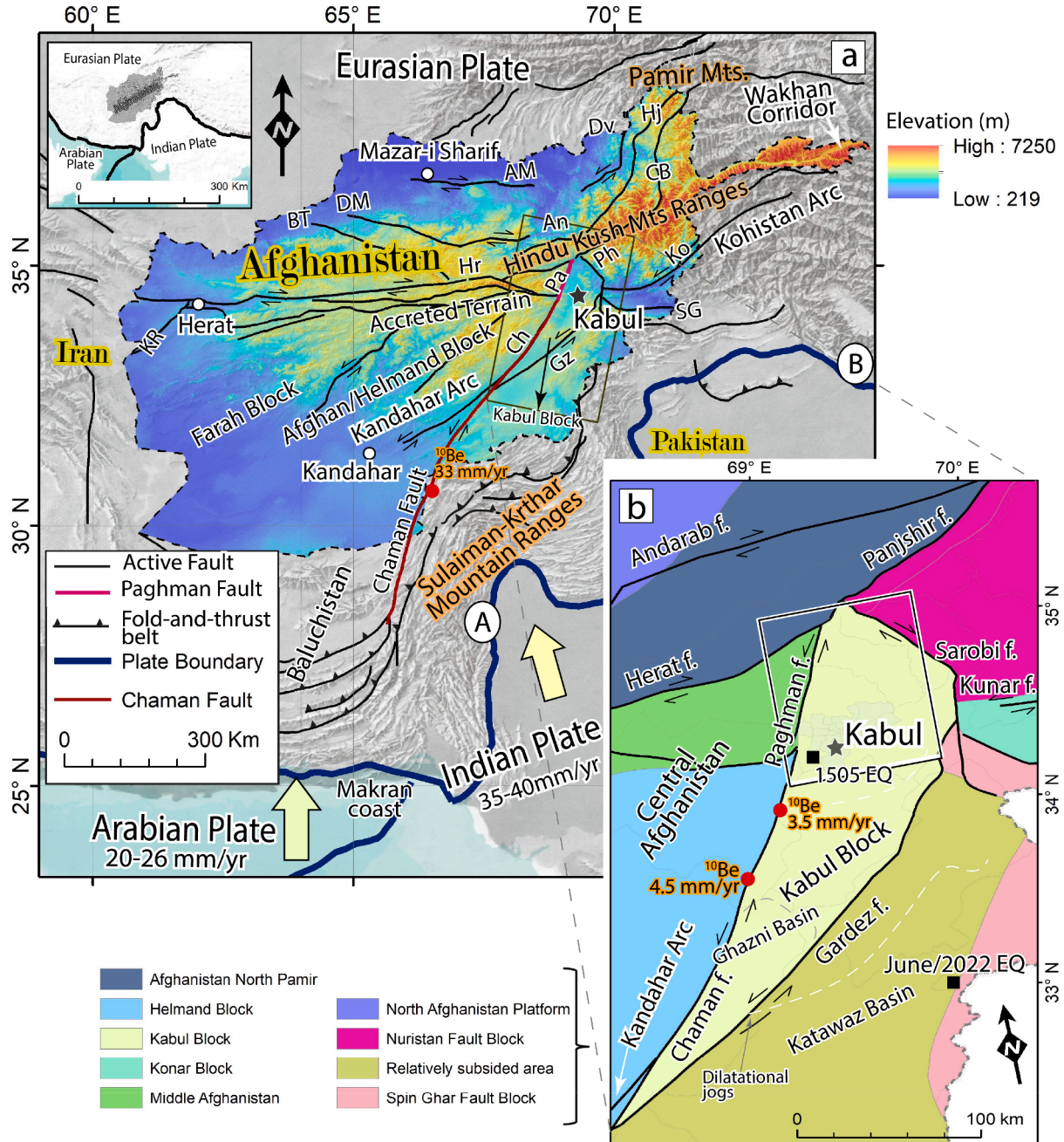


Fig. 1. A) tectonic map of Afghanistan and the surrounding region. a and b show regions of oblique convergence; a is the Sulaiman thrust-fold belt and the Chaman fault system, and b is the Himalaya collision zone and the salt range that contain the outermost hills at the northern fringe of the collision zone. abbreviations of faults: am, alburz mormul; an, andarab; bt, bande turkestan; ch, chaman; cb, central badakhshan; dv, darvaz; dm, dosi mirza-valang; gz, gardez; hj, henjvan; hr, herat; kr, kaj rod; ko, konar; pa, paghman; ph, panjshir; sg, spin ghar. the Indian and Arabian plates velocity is from DeMets et al. (2010) and Sella et al. (2002), respectively. b) Location of the study area at the northern end of the Kabul Block. The Kabul and other Afghan blocks are located along the Hindu Kush Mountains Ranges. The Kandahar Arc and Kohistan Arc (Nuristan fault block and Konar block) resulted from mostly Mesozoic subduction along the southern margin of the pre-collision of the Eurasian and Indian plates. Micro continental blocks such as the Afghan Block (Central Afghanistan), Afghanistan North Pamir, and North Afghanistan Platform developed during earlier collision episodes (Nakata et al., 1991). The tectonic zone map is modified from Dronov (1977). The red circles are the sites where the ^{10}Be terrestrial cosmogenic nuclides (TCN) exposure dating method was used for slip rate estimation (Shnizai et al., 2020). The white dashed line represents the Katawaz Basin boundary. The rectangle shows the location of Fig. 4. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

active fault traces and geomorphic evidence related to the 1505 seismic event has been provided. Kabul and its surrounding areas are vulnerable to earthquakes, with no detailed active fault maps due to the lack of studies. This study uses remote sensing and detailed fieldwork to present geomorphic evidence of recent fault activities along the Paghman fault. Thus, we have made a large-scale active faults map that is one of the most fundamental data sets for active tectonics studies and evaluating the potential seismic hazard in the region.

Damage from a destructive earthquake in 1505 with an estimated magnitude of Mw 7.3 centered on the District of Paghman (e.g., Ambraseys and Bilham, 2014), and it is likely the Paghman fault was likely responsible. The earthquake, which caused destruction and loss of life in Paghman and the surrounding region, including Kabul, is thought to have produced surface rupture along the Paghman and Chaman faults (e.g., Heuckroth and Karim, 1970, as cited in Quittmeyer and Jacob, 1979; Oldham, 1882). There are reports of surface rupture along the base of the Paghman Mountains, coincident with the fault (e.g., Heuckroth and Karim, 1970, as cited in Quittmeyer and Jacob, 1979; Oldham, 1882; Ambraseys and Bilham, 2014). However, there is no new identification or mapping of these ruptures, limiting our understanding of this important historical event (Fig. 2a, b).

The Paghman fault extends from west of Kabul city northeastward along the base of the Paghman Mountains to Jabal Saraj (Fig. 2b). The precise surface trace locations, offset geomorphic features (such as fault scarps, displaced and beheaded stream channels, alluvial fan, ridges and sag ponds), and rupture extent of historical earthquakes are essential to better understand the active tectonics of the Paghman fault and the northern end of the Chaman fault and to assess the seismic hazard of Kabul, with a population of more than 4 million (e.g., JICA, 2011). This metropolitan city (e.g., Fabrizio, 2019) has recorded the largest absolute increase in population in the last two decades. Shnizai and Tsutsumi (2020) reported that the elapsed time since the most recent earthquake on the Paghman fault and the northern end of the Chaman fault is close to the calculated average recurrence interval. Hence, the possibility of a future damaging earthquake is high.

This study aims to better understand the seismic hazard posed by the Paghman fault. We, therefore, studied the fault in detail based on stereo pairs of CORONA satellite images available from the United States Geological Survey (USGS) Earth Explorer (<https://earthexplorer.usgs.gov/>) and ALOS (Advanced Land Observing Satellite) PRISM (Panchromatic Remote-sensing Instrument for Stereo Mapping) images from the Earth Observation Data Utilization Promotion Platform (<https://satpf.jp/spf/?lang=en>). From March to the middle of April 2022, we also conducted field observations along the 60-km-long southwestern portion of the Paghman fault from Arghandi of Kabul to the south of Charikar city, Parwan Province. We found recent tectonic geomorphic features and potential evidence of surface rupture that may be associated with the 1505 earthquake (Fig. 2b).

2. Tectonic setting and seismicity

The active tectonics of Afghanistan and surrounding regions are predominantly controlled by the northward movement of the Indian plate relative to the Eurasian plate (Fig. 1a). After the initial collision at 55–60 Ma, the Indian subcontinent has under-thrusted beneath the Eurasian continent along a series of large thrust faults, whose movement causes destructive earthquakes (Shnizai et al., 2022; Tapponnier and Molnar, 1979; Wheeler et al., 2005). The motion rate of Indian Plate with respect to Eurasian plate is higher than 35–40 mm/yr (DeMets et al., 2010). Along the Sulaiman-Krthar Mountain Ranges, oblique India-Eurasia convergence is partitioned onto predominantly left-lateral structures such as the Chaman fault and adjacent fold and thrust belts (e.g., Quittmeyer and Jacob, 1979; Shnizai, 2020a) (Fig. 1a).

Northeastern Afghanistan contains several north-northeast-trending shear zones and faults, particularly along the boundary between the Cimmerian and Variscan domains (e.g., Ruleman et al., 2007; Shnizai,

2020a; Shnizai et al., 2022; Siehl, 2017) (Fig. 2a). The Kabul Block is approximately 300 km long and up to 70 km wide, with a relatively aseismic interior without apparent signs of late Quaternary faulting (Fig. 1b, 2a). The western margin of the block is bounded by the Paghman and Chaman left-lateral fault system, separated from Central Afghanistan to the west, and the eastern and southern margins are bound by the Sarobi right-lateral and Gardez left-lateral faults, respectively (Fig. 1a, b). The right-lateral Herat fault binds the northern margin of the block. The Herat fault system is primarily located in bedrock and causes a noticeable shift in stream channels throughout the terrain. To the west, the Herat area is filled with tectonic features that are so prominent, which can be seen on satellite images (Fig. 1a). The active tectonics in the northern part of the Kabul Block changes to a system of E-W right-lateral faulting, which accommodates regional N-S left-lateral shear by anticlockwise rotation, in a mirror image of the east of Iran in which E-W left-lateral faults accommodate N-S right-lateral shear through clockwise block rotation (e.g., Walker and Jackson, 2002). The elongated Kabul Block itself is composed of a series of large basins, such as the Kabul and Ghazni Basins. The Katawaz basin lies towards the east of the Kabul Block. It is a transtensional basin that is mainly attributed to dilatational jogs related to left-stepping transfer zones within the left-lateral strike-slip motion at the block boundaries (Fig. 1a, 2a).

The Kabul Block and other associated Afghan Central Blocks (Helmand and Farah) are remnants of small tectonic domains that collided with Eurasia during the late Cretaceous-early Paleogene, which are preserved along the Alpidic belt extending from the Mediterranean to Southeast Asia (Collett et al., 2015; Tapponnier et al., 1981; Treloar and Izatt, 1993). These three studies also stated that the Kabul Block is a detached crustal remnant of the Indian continent, which accreted with the Afghan Central Blocks in the Paleocene. The Chaman and Paghman strike-slip faults separate the Kabul and Helmand blocks. The northernmost part of the Kabul Block reaches the Central Hindu Kush and the Herat-Panjshir suture zone (e.g., Collett et al., 2015) (Fig. 2a). According to Andritzky (1967), the present position of the Kabul Block is the result of northward wedge tectonics between the Nuristan Fault Block and Helmand Block (Fig. 1b). Nakata et al. (1991) stated that the Kandahar and Kohistan (Nuristan fault block) arcs resulted from mostly Mesozoic subduction along the southern margin of pre-collision Asia (Fig. 1a, 2a). North of these arcs lies a group of micro-continental blocks developed during earlier collision episodes, and eventually, the Paleozoic Eurasian continental mass has reached this region (Fig. 1a, 3). The Katawaz basin, southeast of the Kabul Block (Fig. 1b), is interpreted as a large flexural basin (Treloar and Izatt, 1993), which may be associated with pull-apart structures to the northern region (Fig. 1a).

Afghanistan experiences both shallow and deep earthquakes. Based on crustal activity and active fault mapping, some parts of the country are considered to be less susceptible to earthquakes (e.g., Boyd et al., 2007; Dewey, 2006; Shnizai, 2020a). Regions with significant active fault zones and recent earthquakes are more likely to experience higher rates of seismicity (Shnizai, 2020a). However, there have been significant seismic events in areas near or north and east of Kabul. The most recent powerful earthquake (Mw 6.1) struck southeastern Afghanistan on 22 June 2022 (Fig. 1b, 2a). It severely damaged the Paktika and Khost Provinces, killing over 1050 people and injuring almost 3000 more (Shnizai et al., 2022). Shnizai et al. (2022) determined that slip occurred on a north-south oriented left-lateral strike-slip fault parallel to the North-Waziristan-Bannu thrust fault system. According to Qiu et al. (2022), the June 2002 earthquake caused a slip to a depth of 8 km and over a length of 10 km. They also stated that the maximum slip of 2 m was at a depth of 2 km beneath the site 69°26'24.00"E and 32°57'36.00"N (Fig. 2a).

The Kabul Basin and the surrounding region has suffered moderate to large earthquakes throughout its history. The seismic hazard in this region has been analyzed through the historical earthquake records and the current tectonic environment (e.g., Boyd et al., 2007; Shnizai and

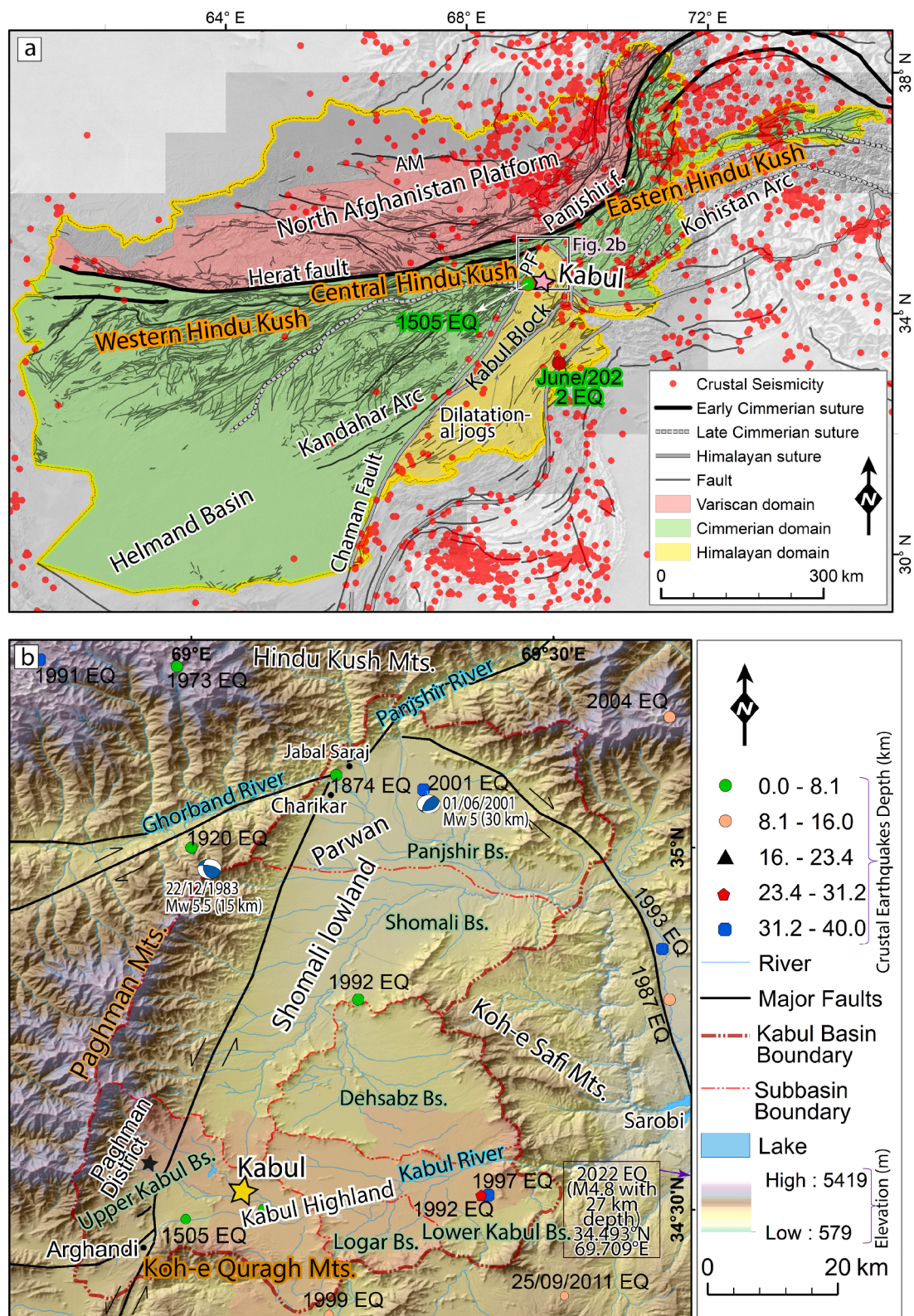


Fig. 2. a) Tectonic sketch map of Afghanistan's orogenic segments simplified from Abdullah et al. (2008), Shnizai (2020b), Siehl (2017), and Wheeler et al. (2005). b) Map of the Kabul Basin and all crustal earthquakes with magnitude ≥ 4 and depth less than 40 km from 1964 to 2004. The Kabul Basin can be divided tectonically into two zones: Shomali Lowland and Kabul Highland. Geomorphologically, the basin consists of six subbasins: upper Kabul, lower Kabul, Logar, Dehsabz, Panjshir, and Shomali. Each subbasin is separated topographically from the adjacent basin by prominent bedrock outcrops shown in Fig. 3. The yellow star indicates the location of the Kabul. This base map combines various datasets, including DEM, shaded relief, river network, and provincial shapefiles. It provides accurate elevation information and realistic landscape visualization and displays the water network pathways in each area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Tsutsumi, 2020). The western half of the basin is intersected by several prominent faults, such as the Paghman fault, which may have hosted significant earthquakes (e.g., Ambraseys and Bilham, 2014, 2003; Boyd et al., 2007; Shnizai, 2020a). Shallow earthquakes severely hit the study area in 1505, 1874, 1992, and 2022 (Ambraseys and Bilham, 2014) (Fig. 2b).

3. Geology of the study area

Geologically, the study area is located south of the Hindu Kush Mountain Ranges, which both are a part of the young Eurasian mountain range complex that has risen since the late Paleogene period (Fig. 1a, 2a). The region is characterized by complex geology, with numerous distinct rock types of Paleoproterozoic age and later sediments of Late Permian through Late Triassic age (e.g., Abdullah and Chmyriov, 1977; Broshears et al., 2005). The Paghman Mountains are deeply dissected. The composition of the rocks beneath the valley-fill sediments of the Kabul Basin has yet to be well known. Generally, the Kabul Basin is filled by the stratigraphic sequence of Miocene conglomerates and sandstone, Pliocene clay, lacustrine silt and very fine sand, and the Quaternary deposits (Abdullah et al., 2008; Doebrich et al., 2006). The Paghman fault separates thick unconsolidated Paleogene to Quaternary sediments in the Kabul Basin to the east from thrust metamorphic and intrusive rocks to the west (e.g., Bohannon, 2010; Shnizai and Tsutsumi, 2020) (Fig. 3). The sediments were deposited in various environments, including shallow marine, deltaic and alluvial plains. Elevation of the low ridges varies from 200 to 500 m higher than the adjacent valley floor (e.g., Shnizai and Tsutsumi, 2020). The central basin gently slopes toward the surrounding Koh-e Safi, Koh-e Quragh, and Paghman

Mountains.

The Kabul Basin sediments can be divided into younger and older units (e.g., Böckh, 1971; Bohannon, 2010). The study area contains a number of relict geomorphic surfaces displaying various morphologies and composed of differing sedimentary deposits based on their age and the processes that shaped them. These surfaces also exhibit features of prolonged exposure to weathering, erosion, and tectonic activity, such as deeply incised valleys and dissected alluvial fans, with a complex topography and developed drainage systems. The surfaces are displaced by active faulting, forming discrete scarps, and warped by folding. Lithologically, the sediments comprise conglomerates, sandstone, sands, gravels, and loess. The sediments are coarsest near the Paghman Mountains, the main source area for the Kabul Basin, and become progressively finer toward the basin's center. Most loess sediments are distributed along the Paghman and Koh-e Quragh Mountain fronts. However, they are mainly absent near perennial and ephemeral streams and are primarily removed by erosion over the northern end of the Paghman Mountains. The sediments south of Kabul city comprise Holocene-Pleistocene alluvial fans crossed by the Paghman fault. The sediments along the mountains are dissected and characterized by a drainage network (Fig. 3). The Pleistocene and Holocene deposits are the most widespread among all the types of geologic formations in the basin (Fig. 3). The deposits are of various ages of alluvium, colluvium and loess that geomorphically can be classified by the levels of dissections, stratification, and morphology. The top alluvial clay, silt, sand, gravels, pebbles, and boulders are poorly consolidated and easily separable into fractions in the eastern front of the mountains along the Paghman fault. The lower section of these deposits is relatively well lithified. The Pleistocene and Holocene deposits also include fine-

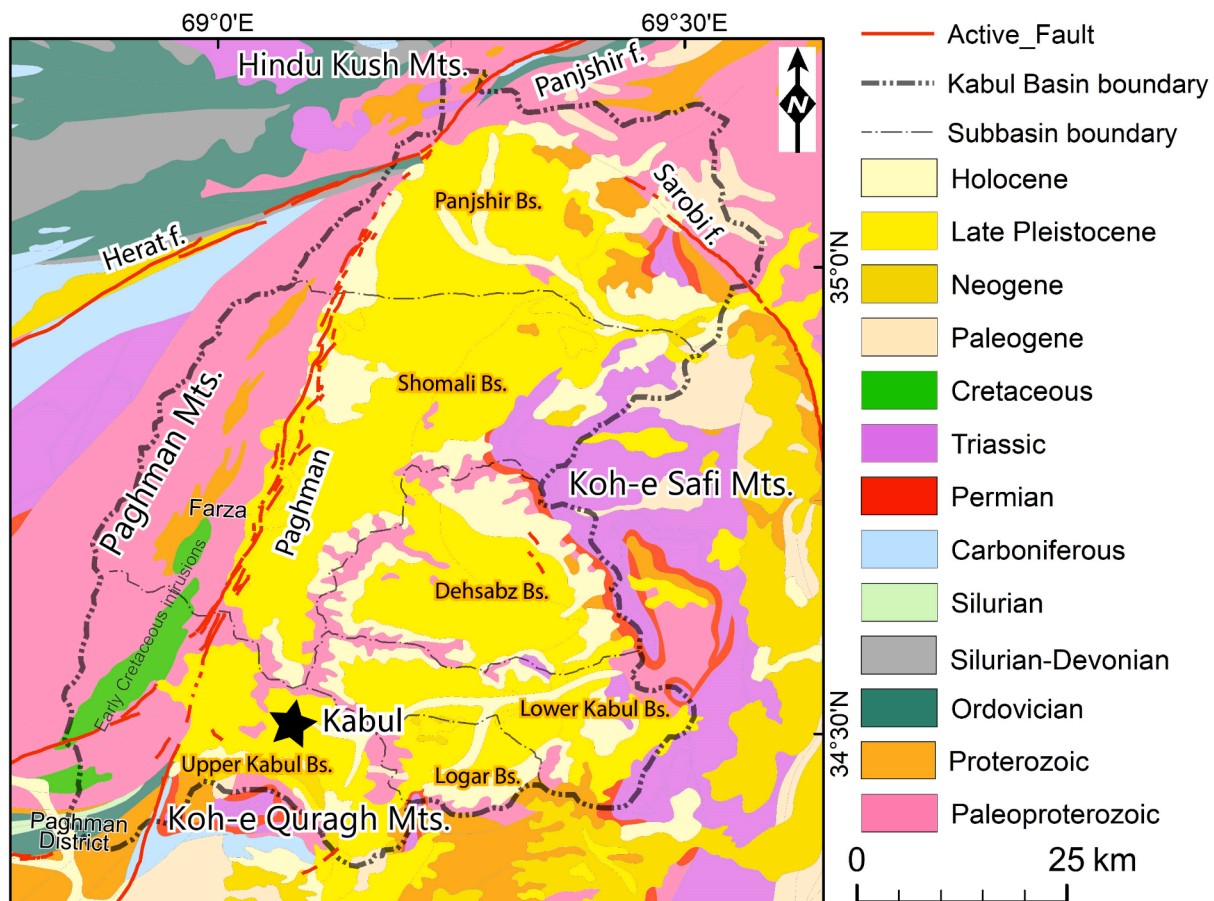


Fig. 3. Geological map of the study area modified from Doebrich et al. (2006). The map shows faults with known and suspected displacement in Quaternary deposits along the Paghman Mountainous terrain. The area west of the Paghman fault is topographically elevated terrain underlain by Early Cretaceous gabbro and monzonite intrusions, which are exposed in the Paghman Mountains.

grained deposits of windborne materials, local debris, rockfall and landslide masses, and agriculturally altered ground in the study area (e.g., [Abdullah et al., 2008](#); [Bohannon, 2010](#); [Mack et al., 2010](#)).

The Kabul Basin is fed by big rivers sourced in the Hindu Kush and Paghman Mountains flowing from north and west to east and southeast into the basin ([Fig. 2b](#)). Along the main stream channels that originate from Paghman Mountains, Pleistocene and Holocene alluvial fan and terrace-like cliffs rising to several meters above the stream beds. The sediment clasts vary between angular, sub-angular, rounded and sub-rounded with varying degrees of angularity or roundness indicating various stages of conditions of deposition and transportation over time ([Abdullah et al., 2008](#); [Bohannon, 2010](#)). Surface deformation has propagated along the Paghman fault western margin of the Kabul Basin. These alluvial fans merge gradually with the wide ranges of the Paghman Mountains, whose elevations range 2000–3000 m in the north and 3500–4670 m in the south. The section of the terraces consists of grey river pebbles, sands, and silt. A succession of terraces can be observed cutting into the Shomali Depression and Kabul Highland (e.g., [Bohannon, 2010](#)). The unconsolidated sediments consist of gravel, sand, talus, and loess, where the gravel and sand were deposited along the river channels. In the lower reach of the Panjshir and Kabul Rivers, Pleistocene and Holocene alluvial terraces fringe the flood plains, composed of pebbles, sands, and clays overlain by loess in some parts.

In Kabul City, the thickness of these Pleistocene and Holocene deposits is less than 80 m, which overlay nearly 800 m thick Tertiary sediments ([Böckh, 1971](#); [Shnizai and Tsutsumi, 2020](#)). The Paghman fault cut and displaced a sequence of terraces that overlie the steeply tilted and folded rocks with angular unconformity, but they disappeared by erosion or deposition on active fan surface ([Shnizai and Tsutsumi, 2020](#)). The Pleistocene deposits, which are the oldest surficial cover present, have undergone deep dissection and are now isolated several meters above the young Holocene deposits. These deposits are found at the tops of low hills along the Paghman fault. On the other hand, the Holocene deposits have been actively deposited as alluvial fans and terraces adjacent to stream channels.

4. Data and methods

All remote mapping was undertaken using stereo CORONA imagery (ground resolution around 12.9 m, acquired from 1960 to 1970), 2.5-m resolution ALOS (Advanced Land Observing Satellite) PRISM (Panchromatic Remote-sensing Instrument for Stereo Mapping) images (taken during 2008) for two small parts of the region, and the 1-arcsecond SRTM (Shuttle Radar Topography Mission) digital elevation model (DEM), together with the Environmental Systems Research Institute (ESRI) base map. The ALOS PRISM satellite images were used along the fault in Shomali Lowland due to cloud coverage in some areas of the CORONA images. Also, the ALOS PRISM offers RGB images, which are superior to those provided by CORONA. By combining multiple image sources with varying resolutions for our study area, we were able to enhance the data quality and coverage, resulting in more accurate mapping of different tectonic features on the surface. We prepared 3D anaglyph images from the SRTM DEM using SimpleDEMViewer Software ([Katayanagi, 2019](#)) and Adobe Photoshop. We used red-cyan glasses to enable 3D visualization of the anaglyph images, which aided in the detailed identification of fault-related landforms. Furthermore, we conducted geomorphic analyses through the use of shaded-relief, slope, and topographic maps to evaluate the presence of active faults. Hill-shade images created using ArcGIS and Global Mapper software were used as a base map for comprehensive fault mapping.

We identified and mapped tectonic geomorphic features based on their continuity and expression on the surface. Our focus was on young offset landforms and sediments, but in areas where they were scarce, we relied on the presence of prominent and continuous escarpments for interpretation, especially in steep mountain areas. Two categories of active faults were employed; active faults and presumed active faults,

indicated with red and black lines on the map, respectively. Active faults with strong evidence of displacement in the late Quaternary are represented by red lines, while presumed active faults with no strong evidence of late Quaternary (i.e., Late Pleistocene and Holocene) deformation are shown by black lines ([Fig. 4](#)). Faults whose sites are indistinct are mapped by a dashed line, and concealed faults by a dotted line (e.g., [Shnizai, 2020a](#); [Shnizai and Tsutsumi, 2020](#); [Tsutsumi and Perez, 2013](#)). In this study, we define concealed faults as those where the fault is obscured because of erosion or man-made features, and where the extension of the fault can be mapped clearly at both sides.

Our remote-sensing analysis was supplemented by two weeks of detailed field survey along the Paghman and Chaman faults from the northern end of the Chaman fault to Charikar City, in March and April 2022. During the fieldwork, we validated observations made from satellite imagery and DEMs. We built detailed observations and interpretations of the local fault structure and its influence on the landscape. By using a combination of field work and remote sensing analysis, we were able to identify precise locations, lengths, presence of fault scarps. We also observed zones of fresh outcrops in bedrock eroded terraces, offset and beheaded stream channels, pressure ridges, and amount of horizontal and vertical displacement for different fault strands within the fault zone and/or their topographic expression along the main Paghman and Chaman faults.

5. Results

5.1. 1. Tectonic geomorphology of the Paghman fault

The Paghman fault transects the western portion of Kabul City and extends northeastward along the base of the Paghman Mountains, terminating near the intersection of the Herat and Panjshir faults ([Fig. 1b](#)). To the south, the fault extends across the hilly terrain of the Arghandi ([Figs. 1, 4](#)). Based on satellite image interpretation and fieldwork, we identified recent geological formations offset by the fault, including Holocene deposits. The Holocene deposits are exposed in stream channels. They are unconsolidated and devoid of soil development. The part of the fault we examined during our field visit traverses the Kabul Highland and Shomali Lowland in a region covered by alluvial fans and debris materials originating from the Koh-e Quragh Mountains to the northern end of the Paghman Mountains ([Fig. 2b, 4](#)). This part of the fault is characterized by a left-lateral oblique slip (e.g., [Ruleman et al., 2007](#); [Shnizai, 2020b](#)). The fault strand cuts young gullies, displaying left-lateral-slip motion with some vertical component. Generally, the lateral versus vertical slip components are approximately 8:1.

The Paghman fault zone is characterized by distributed, parallel to sub-parallel, left-lateral strands in a zone as wide as 2 km ([Fig. 4](#)). Much of the fault zone is linear, and most of the traces are within young Quaternary deposits (Holocene and Late-Pleistocene), though sometimes also bound older bedrock hills such as in Paghman and Shakardara Districts of Kabul ([Fig. 3](#)).

To facilitate our geomorphic description along the Paghman fault, we divide the mapping area into four sections: 1, 2, 3, and 4. [Section 1](#) is from Maidan Shar (capital of Wardak Province) to Arghandi Substation, and we describe a section of the Chaman fault together with the Paghman fault located inside Kabul. This segment of the Chaman fault runs from Sayed Abad District of Wardak Province through the Koh-e Quragh Mountains to the Arghandi Substation and primarily consists of a single fault line. The fault passes about 10 km to the west of Kabul ([Fig. 4](#)). The [section 2](#) of the Paghman fault extends ~ 17 km from Kabul-Kandahar Highway to Samuchak Village. The [section 3](#) extends about 27 km from Shakardara to Farza. Lastly, the [section 4](#) extends approximately 30 km from the Istalif District of Kabul Province to Jabal Saraj near the Herat right-lateral strike-slip fault ([Fig. 4](#)).

In the following sections, we describe the geomorphology of the fault zone and surface deformation generally associated with the 1505 earthquake. The analysis depends on the expression and preservation of

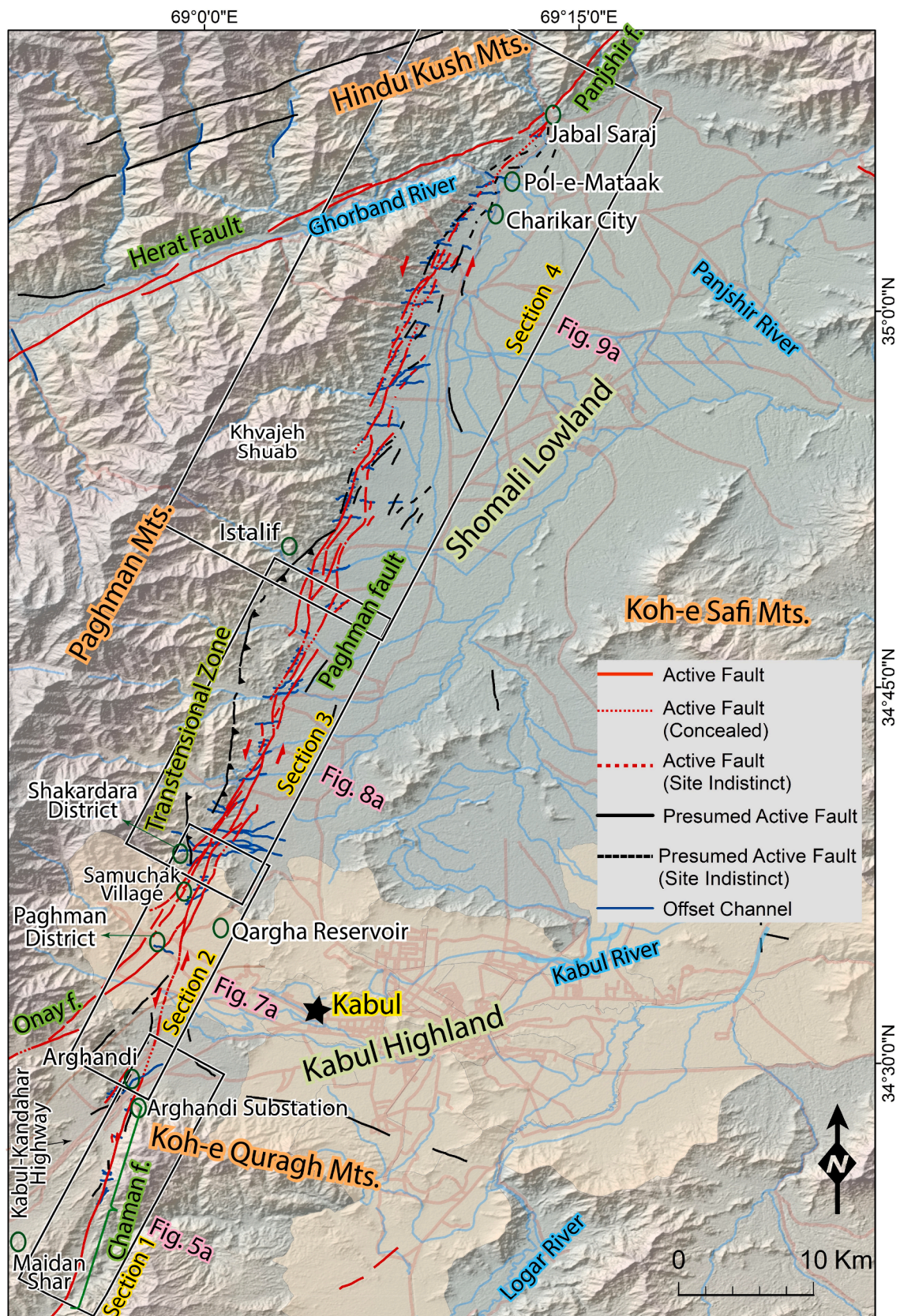


Fig. 4. Detailed map of the Paghman fault. Active faults are divided into active faults (red lines) and presumed active faults (black lines). Dotted and dashed lines indicate concealed fault and fault with site indistinct, respectively. The base map is created using DEM and shaded relief overlain with Kabul city, and provincial shapefiles, and road and river network data that offers a comprehensive and visually appealing representation of the geographical features and their interrelationships within the depicted area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the geomorphic features along the Paghman fault, which leads to variable preservation along the fault length. We then described some of the critical observations associated with the surface deformation related to the 1505 earthquake with other published structure maps and seismological analysis (e.g., Ambraseys and Bilham, 2003; Ambraseys and Jackson, 2003; Quittmeyer and Jacob, 1979; Rajendran and Rajendran,

2005; Ruleman et al., 2007; Shnizai and Tsutsumi, 2020) to place our analysis into a regional kinematic context.

5.1.1. Section 1 (Maidan Shar to Arghandi Substation)

This section includes the northernmost part of the Chaman fault and the intersection with the north–south Paghman fault (Figs. 4, 5a). There

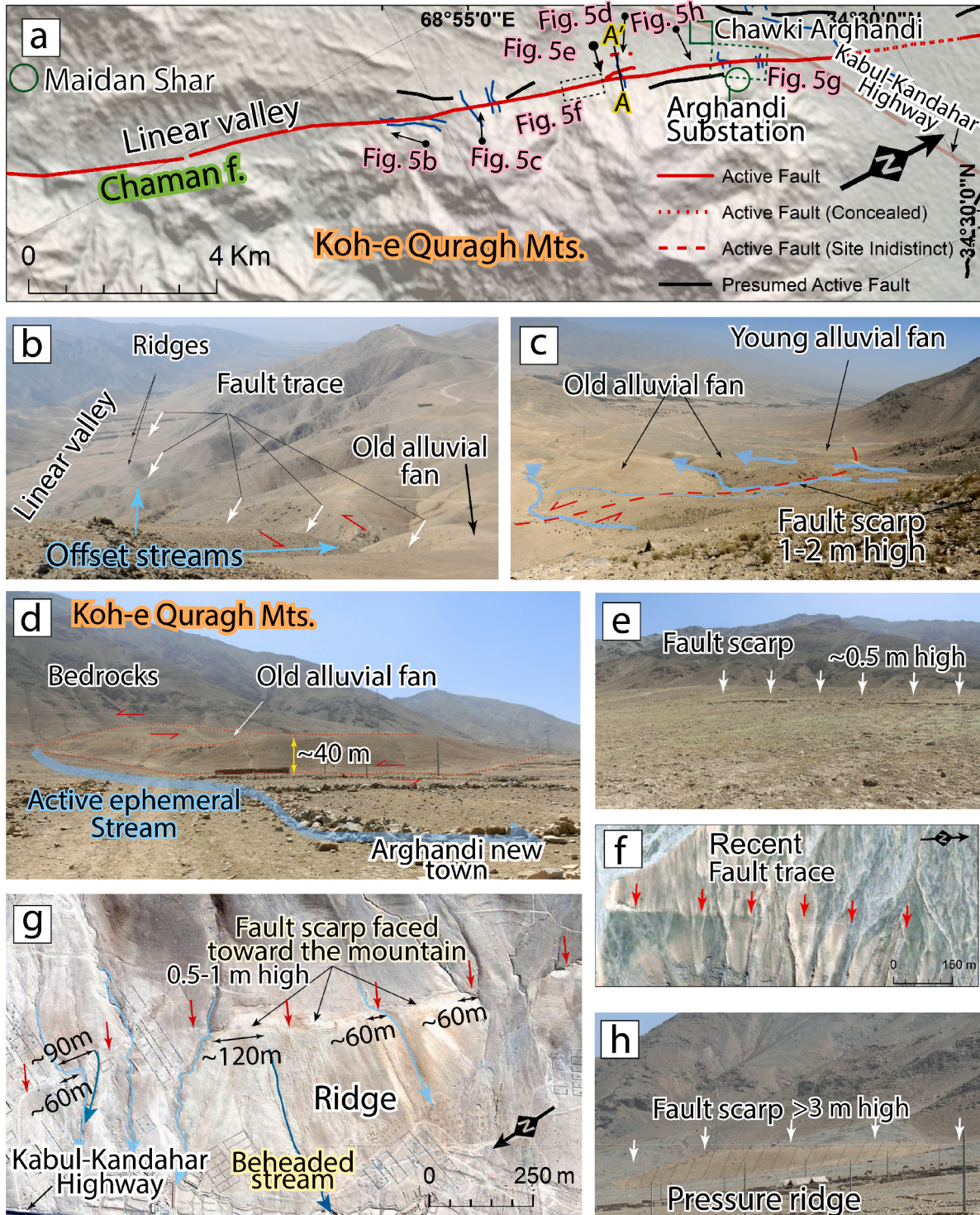


Fig. 5. A) detailed fault map from maidan shar to arghandi substation on top of dem and shaded relief. b) oblique view of a linear valley southwest of kabul city. c) view of the ephemeral streams and fans that have been displaced left-laterally. d) view of the arghandi alluvial fans that have been cut by a strand of the chaman fault, which has moved northward from the main fan body located in the south. e) Less than 0.5-m-high fault scarp on an alluvial fan, which might be related to the 1505 earthquake. f) Bird's eye view image of the Chaman fault where the fault trace is clearly visible. g) ESRI base map images that were captured in 2017. The fault forms a southeast-facing fault scarp with a maximum height of 1 m. h) A pressure ridge along the Chaman fault near Chawki Arghandi.

are numerous indicators of surface deformation in the study area (Fig. 5b-h). The striking fault scarp lies along the northwestern foot of the Koh-e Quragh Mountain, where alluvial deposits up to 40 m thick are displaced (Fig. 5d). Through measuring the fault scarp height, we observed the most recent vertical offset along the mountain front in Holocene deposits. We noticed during fieldwork that displaced geomorphic feature such as the scarps along the left-lateral fault are up to 3 m high, although the fault plane is significantly eroded due to weathering (Fig. 5h). The vertical fault offsets range from ~ 0.5 to 3 m along the mountain front (Fig. 5e-f).

The Chaman fault is expressed as linear and continuous northwest-facing fault scarps (Fig. 5a). Along most of the southern part, the fault is approximately 1 km wide. As a result of the fault left-lateral movement, the stream channels and the alluvial deposits have been displaced from their original sources by a significant distance. This displacement is only for a short distance on younger geomorphic surfaces and stream channels. The fault bounds bedrock hills and cuts geological units vertically, but most of the traces are within Quaternary deposits (Figs. 3, 5a), where the most recently active trace is identified along the front of the mountains (Fig. 5e, f). The fault movement has formed a linear valley from Maidan Shar to the start of the Arghandi Region (Fig. 5a, b). There is surface deformation along the fault, from which water and sand have been extruded in parts of the valley. Narrow ephemeral streams with well-defined banks have incised the alluvial fan surfaces (Fig. 5c). The fault scarp in the most recent deposits has a vertical offset less than 1 m, which may have arisen due to the 1505 earthquake (Fig. 5e). For a 6.5 km long stretch between the linear valley and Arghandi Substation, the cumulative fault scarp is between 0.5 to approximately 5 m on an older alluvial fan on the southeastern side of the Kabul-Kandahar Highway (Fig. 5e, 6a). The scarp is remarkably straight with a strike of N15°E along the Koh-e Quragh Mountains (Fig. 5f). In a small area, the fault has two strands that have displaced an older alluvial fan left-laterally (Fig. 5a). Towards the north (near the Kabul-Kandahar Highway), the scarp disappears due to landscape alteration by farming and building constructions.

The alluvial sediments originally formed a continuous unit but are now incised by northwest-flowing ephemeral drainage systems, which, due to left-lateral displacement, have been offset and beheaded (Fig. 5d, g). The maximum stream offset is 120 m (Fig. 5g). This offset was measured from ESRI base map images captured in 2016. However, the site has been destroyed due to the construction of an Electricity Substation, which was built along the fault trace in 2016. Where the Chaman fault enters the Arghandi area, it is marked by a series of aligned pressure ridges, which are about 450 m long, 150 m wide, and 30 m high. These pressure ridges gradually disappear when the fault extends into the Arghandi Valley at the northeastern termination of the Koh-e Quragh Mountain. The pressure ridges are near the Kabul Gate (Chawki Arghandi) (Fig. 5h).

Southeast of the Kabul-Kandahar Highway, at the Arghandi Substation, the Paghman fault scarp shows recent changes in its morphology. The left-lateral offsets between various terraces and modern stream channels, which the minimum offset is 60 m (Fig. 5e-g). The vertical displacement is less than one meter, and the fault on this alluvial fan makes a southeast-facing fault scarp toward the Koh-e Quragh Mountain. The small scarp, combined with the large lateral displacements, indicates that the fault is predominantly strike-slip (Fig. 5g). Up north, near the Kabul-Kandahar Highway, the evidence of recent deformation and geomorphic offsets was largely destroyed by constructing the electricity substation (Fig. 5a). The image in Fig. 5g was captured in 2017 and displays the fault trace prior to destruction. We used ArcGIS to convert an ESRI image with a clipped DEM to a 3D model and applied elevation profile tool for measuring the vertical offset. To make things easier, we cross-check our data with Google Earth. Northward from Arghandi, the fault trace is marked by transtensional deformation, with linear depressions developed along the fault zone.

5.1.2. Section 2 (Arghandi to Samuchak)

The Paghman fault starts in the south at the Koh-e Quragh Mountains and extends across the hilly terrain of the Paghman District (Fig. 4). For a 17 km long stretch between the Kabul-Kandahar Highway to Samuchak Village (northern boundary of the Paghman District), the fault is identified as a series of mostly east-facing fault scarps (Fig. 7a). From Arghandi Substation to Paghman River, the fault trace is expressed in some places as a series of scarps and pressure and pressure ridges (Fig. 7b-c). In other places (from 34°28'56.71"N, 68°57'25.49"E to 34°35'48.38"N, 68°58'43.97"E), the geomorphic expression is subtle because the fault trace is eroded or covered by farmland and young sediments (boulders, conglomerates, sands, and clay) (Fig. 7a).

The fault crosses the Kabul-Kandahar Highway, but there is no sign of a fault scarp because the fault scarp is destroyed by lateral erosion of the Paghman River and its tributaries, notably the Arghandi River (Fig. 7a). The tributary has destroyed most of the southern portion of the fault, while west of Kabul City the central portion of the fault is occupied by villages and farmlands. At the location near the highway (34°29'22.82"N, 68°57'14.11"E), the left-lateral offset of a modern stream channel is approximately 140 m, but it is difficult to assess whether this offset is caused by fault movement. The offset of the river may be attributed to either the movement of the Paghman fault or the effects of erosion and human activity. However, since the offset of the river is located along the fault trace, it is probably the fault movement caused it. Nevertheless, human activity is also prevalent in the area, and therefore, it cannot be ruled out as a possible cause of the river offset. On the other hand, the river channel seems to have a gradual offset, which could be due to erosion. Most of this area's sediments seem to be Holocene, and the Arghandi valley bottom is formed by recent fluvial accumulation (Fig. 7a).

North of Arghandi, there are anticlinal uplifts west of the fault trace toward the Paghman Mountains (Fig. 7b-d). The largest anticline is about 2 km long, ~70 to 550 m wide, and a few to ~ 60 m high (Fig. 6b, 7c). The eastern edge of the anticline is bounded by the Paghman fault (Fig. 7b-d). The southwest displaced part of the anticline has acted as a pressure ridge in shaping the stream network in the area. South of this pressure ridge (anticline), there is a restraining bend of the fault trace across which the direction of vertical displacement changes (Fig. 7a, c). Transverse streams in this area progressively cut across the anticline (pressure ridge) that has developed at the downstream side of the Paghman fault (an example is seen at 34°31'23.66"N, 68°57'59.85"E) (Fig. 7c). The east-facing scarp bounded ridge is comprised of large remnants of alluvial deposits, which were possibly a continuous apron of deposition that has now been incised by stream channels (Fig. 7b-c). In the study area, we also observed that pressure ridges have developed along the western side of the fault until Paghman Hill, showing left lateral strike-slip movement of more than 180 m (Fig. 7c). Beheaded and offset stream channels were used to calculate the greater than 180 m left-lateral displacement along the Paghman fault. The stream cut the pressure ridge. Movement of the pressure ridge first captured the stream and then offset. Finally, the continued activities along the fault caused the beheaded stream to cut across the pressure ridge (Fig. 7c). The offset distance was measured on the westward of the ridge.

A fresh east-facing scarp exists between the Paghman River and Samuchak Village (the northern end of the Paghman District) (Fig. 7e, g). East of the fault trace, the Qargha Reservoir is located (Fig. 4), which has gradually been filled with sediments and become shallower with time. North of the Paghman Hill (Park Tap-e Paghman) in Noorkhail village, the fault cuts an old alluvial fan and displaces it left laterally (Figs., 7a-b, and 7f). Field studies in this area reveal valley deflections and aligned, elongated hills of Late Pleistocene sediments (Fig. 3). Some of the sediments appear younger and are related to faulted Holocene deposits (Fig. 7e-f, h). These geomorphic relationships and landforms strongly indicate recent seismic activity and surface rupture on this fault. The long-term activity of the fault has caused the formation of a north-south valley (Fig. 7e, f). The Quaternary deposits of the area

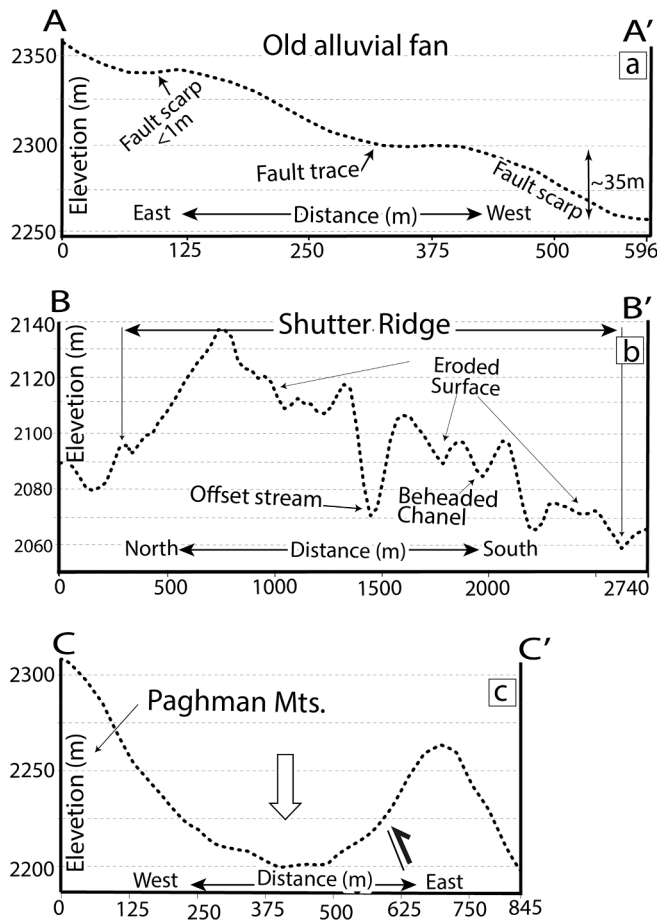


Fig. 6. A) profile along offset alluvial fan in front of the koh-e quragh mountains (see Fig. 5a for the cross-section location). b) Longitudinal profile across pressure ridge near Arghandi River cut by some ephemeral streams. The elevation decreases from north to south (see Fig. 7a for the cross-section location). c) A topographic profile across the upslope-facing scarp west of the strike-slip fault section in Shakardara District (see Fig. 8a for the cross-section location).

consist of fine-grained sediments such as silt, clay, and sand deposited by flowing water across floodplains and riverbeds that are displaced left-laterally (Fig. 7f-g).

The main trace of the Paghman fault is clear west of the Qargha Reservoir, along the eastern margin of north-trending low hills on which the Noorkhail Village is located (Fig. 7g). At this site, an east-trending terrace riser is offset left laterally. North of Noorkhail Village, the fault trace is recognized as a greater than 3 km long zone of left-stepping fault strands with east-facing scarps. Maximum offset of the alluvial fan reaches to ~ 120 m. We mapped four separate parallel fault strands along this section of the fault, which were also identified by Ruleman et al. (2007) and Shnizai and Tsutsumi (2020) (Fig. 7a, e).

This portion of the Paghman fault also intersects the east-trending Onay fault system (Fig. 4). The Onay fault has continuous and discontinuous linear and arcuate range-front and piedmont scarps primarily within the interior of the Paghman Mountains (Fig. 1a-b). In Samuchak Village, deflected streams and displaced fan surfaces show left-lateral strike-slip faulting (Fig. 7h). Based on geological mapping, middle to late Pleistocene and Holocene deposits are offset (Figs. 3, 7e). The fault zone in this area consists of a few short parallel surface traces, which may merge within the bedrock. The scarps are up to 20 m high but only about 0.5 m high or less on younger alluvial fans (Fig. 7h). These small east-facing fault scarps in recent deposits appear to be very young, and we suspect they represent rupture from the 1505 earthquake (Fig. 2a).

The Paghman active fault strands dissect the landforms and exposed bedrock between Samuchak Village and Shakardara District (Figs. 4, 7e, g-i). The bedrock in the area is composed of both metamorphic and igneous rocks. The hills to east of the Samuchak Village are comprised of late Paleozoic and Mesozoic sedimentary rocks (Abdullah and Chmyriov, 1977; Bohannon and Turner, 2007; Broshears et al., 2005). In addition, there are gabbro and monzonite intrusions occurred during the Early Cretaceous period and are now exposed in the Paghman Mountains. The overlying Quaternary deposits primarily consist of loess with minor amounts of sand and clay. According to Ambraseys and Bilham (2014), a landslide occurred between Paghman and Begtut due to the 1505 earthquake, in the valley just north of Paghman District, which we assumed is somewhere in this area. The landslide could occur in the upper layer of loess due to its high porosity, which make it easily saturated and unstable. Additionally, the unconsolidated loess layer is prone to collapsing and earthquake failure. During the fieldwork, we observed the presence of seeps and deformation features such as linear troughs and springs throughout the area.

5.1.3. Section 3 (Shakardara to Istalif)

From Shakardara District to Istalif, the Paghman fault consists of a series of strike-slip faults, with several of the faults also having measurable dip-slip motion. Northwest-trending discontinuous scarps form a prominent lineament across bedrock terrain (Fig. 8a). Generally, the fault zone is 0.5 to 4 km wide along most of this section. This zone is less well-structured along the eastern portion in the vicinity of Ghaza Village (34°38'31.88"N, 69°0'4.49"E), where evidence for recent activity has been largely destroyed due to recent erosion like flooding and human activities. South of Ghaza Village, two linear valleys have been made as a result of the fault activities (Fig. 8a-b). We confirmed some of the original observations and measurements of Shnizai and Tsutsumi (2020) and Ruleman et al. (2007), and quantified additional measurements ranging from 70 to 300 m in lateral displacement across the fault. The fault offsets alluvial fans and stream channels, and beheaded stream channels can be clearly seen toward the south and central valley both in field and satellite imagery (Fig. 7h and 8b-d).

North of Ghaza Village, we mapped an alluvial fan that has been displaced left-laterally along the fault zone, as well as left-lateral displacements of active streams and river channels on some fault strands (Fig. 8b-c). The alluvial fans here are highly dissected and appear older than other alluvial fans in the Shakardara District (Fig. 8c, e-f). The old alluvial fan has been moved northward along the fault strands relative to its source drainage, which is situated to the west of Ghaza Village in Paghman Mountains (Fig. 8b). Near the source drainage, the height of the fault scarp in the oldest fan is about 1–10 m (Fig. 8e-f) and the total lateral offset is about 200 m (Fig. 8b, d). These fans are now adjacent to small mountain drainages, which appear insufficient to be the sources of such large alluvial fans (Fig. 8f).

The surface trace of the fault between the offset alluvial fan and the Shah wa Arus Dam is unclear due to various factors such as human activity, erosion, and/or sedimentation caused by the Shakardara River and its tributaries (Fig. 8a). We also observed an increase in the relative influence of human activity in this area. While in the hilly terrain, a clear east-facing fault scarp extends north of the offset mapped fans. On the western side of this alluvial fan, the fault has made a west-facing scarp toward the Paghman Mountains with a height of more than 50 m (Fig. 6c). In this portion, various fault strands run approximately parallel to one another (Fig. 8a).

The ~ 70 m high Shah wa Arus Dam is located between strands of the Paghman fault. It is a concrete gravity dam built on the Shakardara River near a village with the same name located about 24 km northwest of the Kabul City. As the dam is located within the Paghman fault zone, this site has been strongly affected by tectonic activity and seismic shaking, and the rocks are fractured, showing brittle deformation. Near the Shah wa Arus Dam, the Shakardara stream channel is offset by the fault for about 300 m (Fig. 8b, d). To the west of this region lies another stream

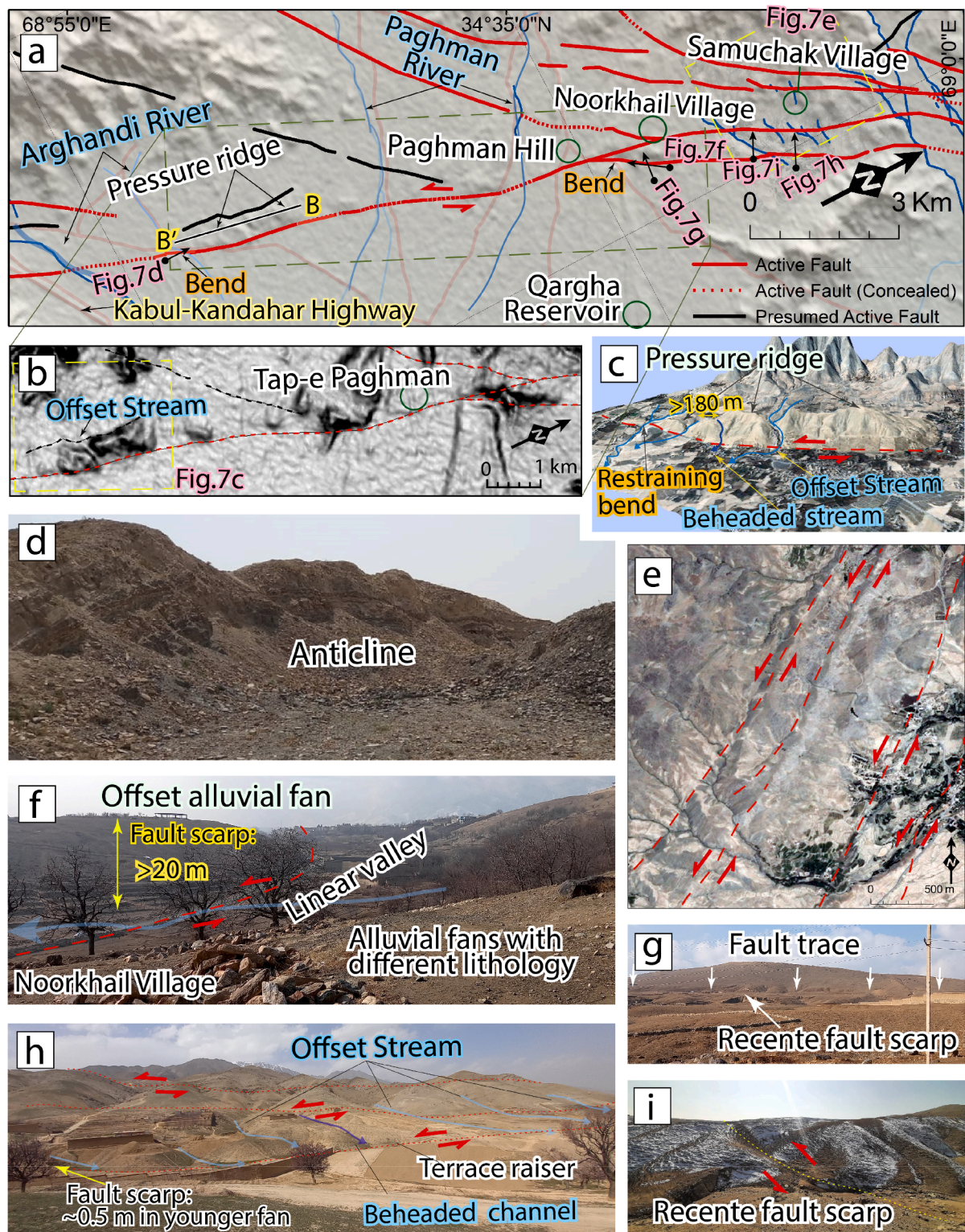


Fig. 7. A) detailed fault map of the paghman fault from arghandi to the end of Samuchak Village. We mapped four parallel fault strands between Samuchak Village and Shakardara Districts. b) The SRTM 1-arcsecond DEM generated slope map of the fault showing pressure ridges and displaced alluvial fans. c) 3D view of the pressure ridges south of the Park Tap-e Paghman on ESRI image. Movement of the pressure ridge firstly captured the stream and then offset left-laterally along the Paghman fault. d) Photo of the anticline (pressure ridge) that is located on the western side of the main fault, indicated by red dashed lines. e) ESRI image of offset alluvial fans and fault strands of the Paghman fault. The red dashed line marks the main faults, and reddish arrows mark the direction of the lateral displacement. f) Oblique view looking south along the Paghman fault showing typical left-lateral incision of the old alluvial fan. The fault movement made a linear side-hill valley north of the Paghman Hill (Tape-e Paghman). g) Photograph of a fault scarp in Noorkhail Village. h) Displaced fan, beheaded, and offset channels along the fault zone that contains multiple strands. i) Recent fault scarp along the Paghman fault strand in Samuchak Village. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

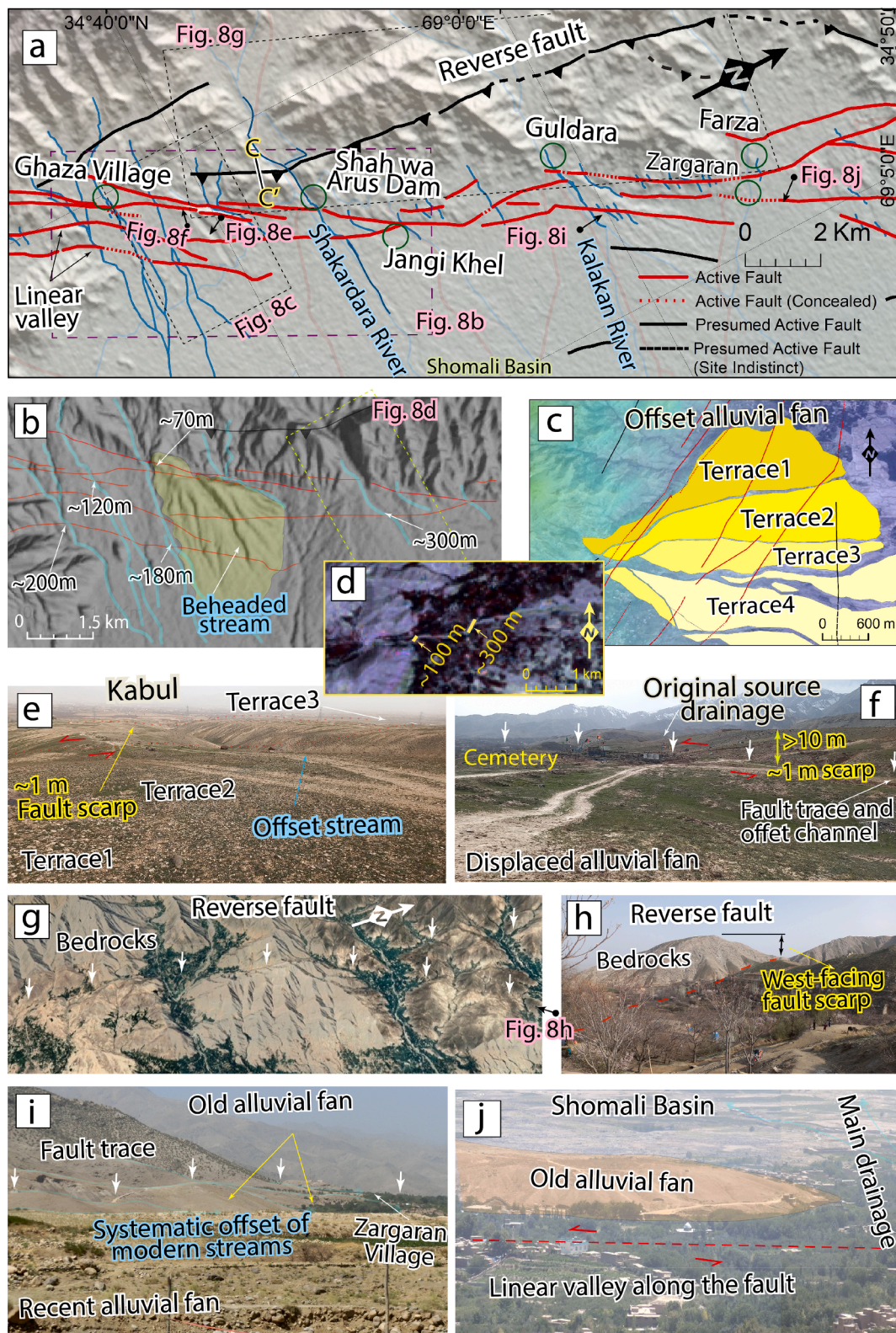


Fig. 8. A) map of the paghman fault strands from shakardara to farza district of kabul. b) aster 1-arcsecond hillshade of the fault strands and left-laterally displaced channels. the fault movements cause the displacement of alluvial fans and streams by varying distances. c) map of alluvial terraces showing apparent left-lateral displacement along the paghman fault north of the ghaza village. this map was modified from [Shnizai and Tsutsumi \(2020\)](#). d) Landsat 8 image (bands combination of 1, 4, and 7) shows stream displacements for ~ 100 and ~ 300 m east of Shah wa Arus Dam. e) Photo of the offset alluvial fan along the fault zone on the west side of the Shomali Basin. Map of this offset alluvial fan is shown in [Fig. 5c](#). f) Incised alluvial fan near the source drainage network in Shakarda District. The white arrows show the fault trace. g) View of the Paghman Mountains' front, where the Paghman fault offsets metamorphic rocks between Farza and Istalif Districts of Kabul. h) An oblique view looking south across the Paghman fault to showing west-facing fault scarp. i) Systematic stream offsets along the fault east of the Paghman Mountains near the Gul dara District. j) Oblique view of the old alluvial fan on the northern side of the Farza District that has been displaced left-laterally along the fault and made west-facing scarp.

offset of 100 m, which caused by another fault strand of the Paghman fault. This offset was measured in the field, which is located 500 m from the water reservoir (Fig. 8a). East of the Shah wa Arus Dam in Jangi Khel Village, the trace is in vegetated farmlands, and cannot be recognized in the field (Fig. 8a).

We also mapped a reverse fault west of the Shah wa Arus Dam almost parallel to the left-lateral Paghman fault strands (Fig. 8a, 6c). A west-facing fault scarp extends northward to the Farza District of Kabul (Fig. 8g-h). The total length of the reverse fault is about 22 km. The fault trace with a reverse component is also evident in satellite imageries and the field (Fig. 8g). Possibly, a section of reverse fault strand locally displaced Quaternary deposits over metamorphic rocks in Farza. However, we mostly observed the reverse fault, which is entirely in bedrock terrain (Fig. 8a, h). In this area, a series of ridges are uplifted from adjacent topography, suggesting recent reverse faulting. The ridges are mostly continuous but alternate between east and west-facing scarps. The west-dipping reverse faults on the western side of the Paghman fault are subsidiary structures to the main fault, which have been formed due to left-lateral slip and compression on the main fault. Comparing the displacement amounts of alluvial deposits (70–180 m) along the strike-slip faults shows a much more significant displacement component.

Further north in the Guldara District, we mapped systematic offsets of modern streams across a topographic lineament. These left-lateral systematic offsets range from 40 m to 220 m (Fig. 8a, i). In the western segment of the Paghman fault system, left-lateral displacement of the old and young alluvial surfaces and rivers across the Paghman Mountain front has been observed (Fig. 8i). In the Farza District of Kabul, strands of the Paghman fault cut old alluvial fans and offset its incised drainage directly along the fault trace to the south (Fig. 8j). The fans are deeply dissected remnants of the late Pleistocene deposits that have been displaced northwards relative to its source drainage, which is located in south of Zargaran Village (Fig. 8a).

5.1.4. Section 4 (Istalif to Ghorband River Valley)

This last section of the Paghman fault is interpreted as the north-western border fault of the Kabul Block (Fig. 1b, 9a). Generally, the fault becomes less and less clear as it approaches its northern termination at the Herat right-lateral strike-slip fault (e.g., Shnizai et al., 2020). This could lead to the slip rate of the fault reaching a value closer to Zero. Additionally, the fault trace has become covered due to various human activities and recent deposits caused by the steep slope and flooding. At its northern end near Jabal Saraj, the Paghman fault trends ~ N39°E, more northeasterly than the Chaman fault (Fig. 4).

The Paghman fault strand network has a typical northeast trend, but some features have variable orientations (Fig. 9a-d, 10a). The Shomali Lowland is located at the northern end of the Kabul Block, which is a gently sloping surface west of the Paghman fault occupying the lowest part of the Kabul Basin (Fig. 4). There are also major east-flowing streams between Baghe Mola and Qadzyan Village that some of them have been offset left-laterally (Fig. 9a-b, g). Southwest of the Takhte Istalif, an elongated linear and deep depression extends along the fault (Fig. 9c). The depression is explained as tectonic in origin. The lowland is a plateau with a gently sloping surface, surrounded by mountain ranges that were formed by tectonic activity (e.g., Shnizai, 2020b). The northern edge of the lowland is defined by the Herat fault. To the east and west, the Shomali Lowland is bordered by the Sarobi and Paghman faults respectively. This area belongs to the Kabul Block, which is a tectonic fragment located at the meeting point of the Indian and Eurasian tectonic plates. The area is part of the northern end of the Kabul Block, which is a tectonic fragment formed at the junction of the Indian and Eurasian plates (Faryad et al., 2016). Several isolated alluvial fans stand out as low hills east and west of the main fault. The strata exposed at a hill southwest of Takhte Istalif (34°50'3.14"N, 69° 4'53.21"E) are mainly composed of reddish yellow unconsolidated conglomerates, coarse to fine-grained sand, clay, and loess with round igneous and metamorphic gravels that range from tens of centimeters to a meter or

more in diameter. Tectonic features, such as lineaments, are expressed in the bedrock on top of the Istalif District and displaced alluvial fans in the eastern part (see the location in Fig. 9a).

West-facing scarps suggest left-lateral oblique faulting along the continuation of the reverse fault that began in the Shakardara District (Figs. 4, 8a). In the area, the reverse fault scarp is visible as a cliff and an uplifted slope along the Paghman Mountains. The fault scarp has a steep orientation, and one side of it can be seen as an elevated block. This feature is clearly visible in anaglyph images as well as in elevation models. The height of the west-facing scarp in this area ranges from 1 m to tens of meters. These clear west-facing scarps continue north of the Istalif River to Baghe Mola Village (Fig. 9a). The reverse fault is typically located approximately 1 km to the west of the Paghman fault strand, where an offset active stream channel is present (34°51'50.33"N, 69° 5'52.02"E) (Fig. 9b). Based on our observation, the reverse fault appeared as a single, distinct fault plane with a clear separation between blocks of rocks. In contrast, the Paghman fault zone shows a complex network of fault strands oriented in different directions and with varying displacement amounts. Also, the reverse fault may be associated with a localized zone of deformation, while the Paghman fault extends over a larger area along the mountain front. This east-flowing channel is deflected to the left for approximately 120 m (Fig. 9b). At this location, the offset stream may be associated with the fault strands that made a linear valley southwest of the Takhte Istalif. Many mounds are lined up along the Paghman fault from south to north, making a west-facing scarp (Fig. 9d-f).

The deformation features observed in the fracture zone indicate a strike-slip with a minor northeast-striking southwest-verging thrust fault (Fig. 9f, 10a). This movement is due to compression tectonic forces that cause crustal shortening in the area. Bedrock exposures of the Paghman fault along the fault zone show clear strike-slip components throughout, with dip-slip motion mostly apparent in the bedrock (Fig. 9f). The middle Pleistocene sand and gravel with conglomerates and shingly detrital sediments possibly thrust to the northwest above the metamorphic rocks. It can also be traced into the late Pleistocene and/or Holocene deposits, but the fault line is obscured or hidden beneath vegetation and agricultural fields (Fig. 9g). We observed systematic stream and surface offsets along this portion of the Paghman fault (Fig. 9a, 9d). We measured an offset of an active stream channel displaced about 130 m in Qadzyan Village Bagram District of Parwan Province (34°53'50.41"N, 69° 6'10.47" E). However, in most places, the fault scarp is destroyed by land cultivation and lateral erosion by perennial and ephemeral streams.

Further north, the fault bounds the northern end of the Paghman Mountains (Figs. 3, 9a). South and northeast of the Ghorband River Valley, the fault trace was initially mapped as discontinuous and highly eroded. We found the fault zone primarily obscured by erosion and sedimentation of the ephemeral streams from steep mountains. In contrast, in some places, the fault is occupied by houses and farmlands. The unconsolidated sediments are younger and consist of gravel, sand, talus, and loess, where the gravel and sand were deposited along the river channels. The fault trace is continuous except for places where sedimentation or erosion of modern stream channels obscures tectonic landforms, such as close to the Ghorband River Valley. Southwest of Charikar City, tectonic geomorphic features of the Paghman fault are well preserved (Fig. 4).

6. Discussion

Our observations along the Paghman and the northernmost Chaman faults confirm some of the mapped faults of Ruleman et al. (2007) and Shnizai and Tsutsumi (2020). Further, we mapped and noted the abundant evidence for late Quaternary tectonic activity (Figs. 3, 4, 10b). This also indicates the importance of the fault in the transfer of N-S lateral shear across the Kabul Basin (Fig. 2b). The fault trace is generally composed of a series of left-stepping en echelon faults that correspond to

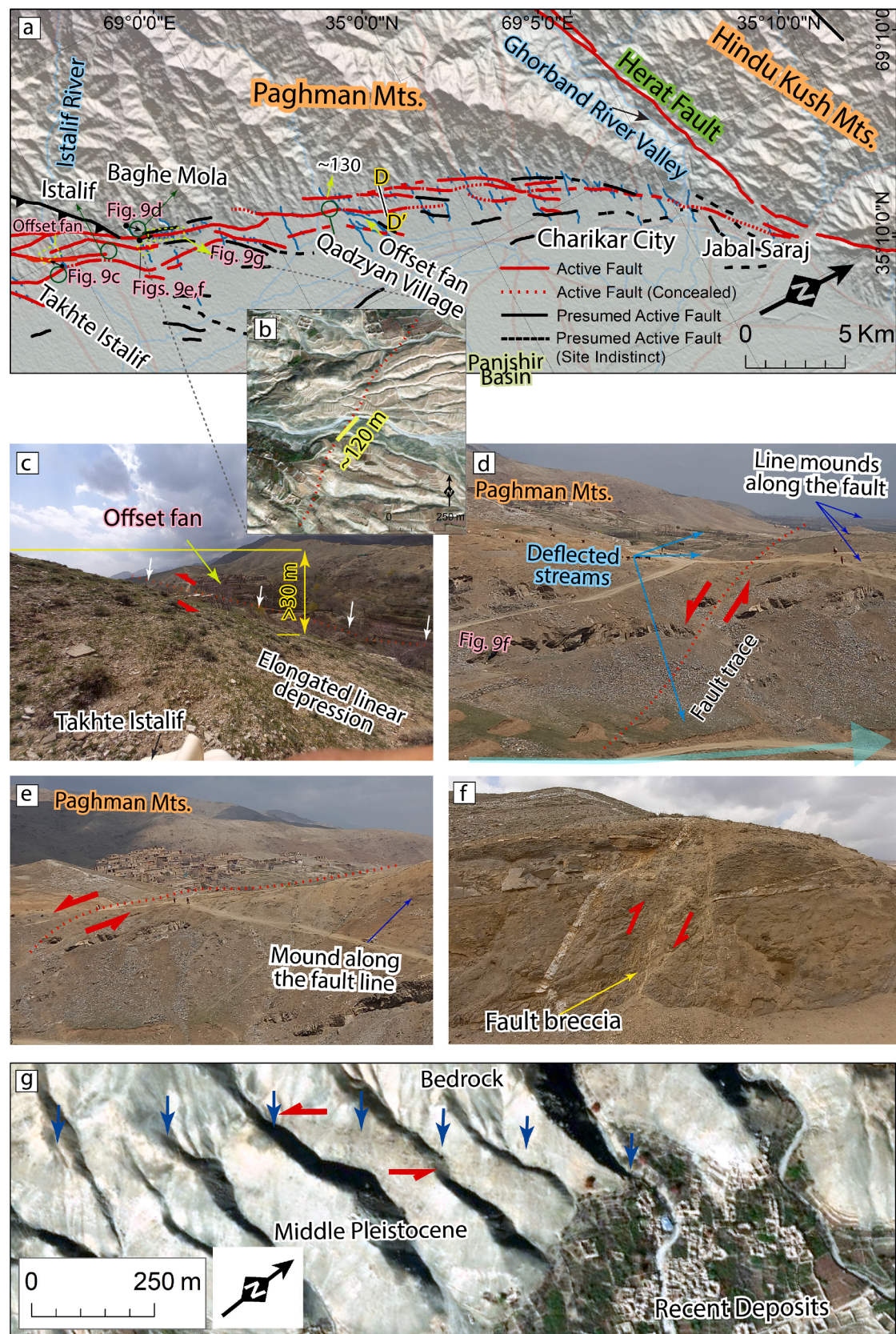


Fig. 9. A) a detailed map of the paghman fault strands from istalif to ghorband river valley. b) esri base map shows ~ 120 m left-lateral offset along the fault. c) Location of an elongated linear and deep depression along the fault south of the Takhte Istalif. d) Oblique view of mountains lined up along the fault strand from south to north. e) A closer view of a mound along the Paghman fault that made west-facing scarp. f) A photograph of the fault strand in the outcrop area (34°51'9.49"N, 69° 5'19.13"E) northeast of the Istalif District. g) Sediments from the Pleistocene have been thrust to the west above the metamorphic rock.

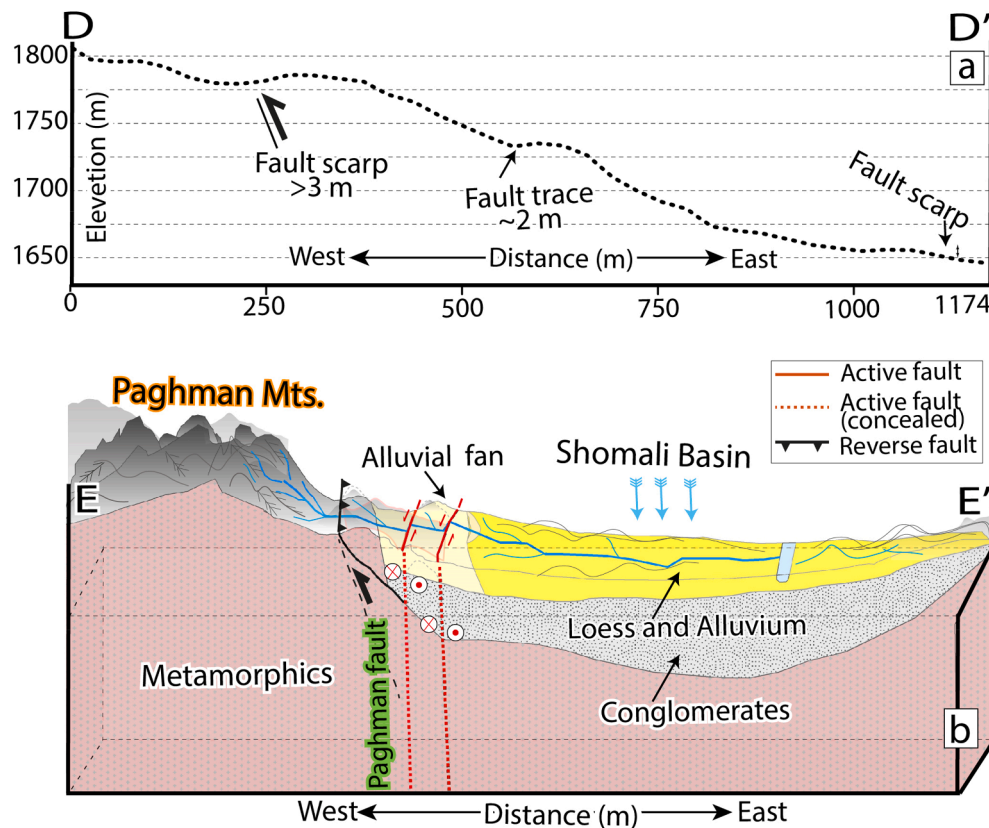


Fig. 10. A) a topographic profile across the upslope-facing carp north of qadzyan village near charikar city, parwan province (see Fig. 9a for the cross-section location). b) Schematic diagram across the Kabul Basin, Shomali Lowland (see Fig. 11a for the cross-section location).

Riedel shears (Figs. 4, 11a). The collection of minor faults in the study area may be related to internal deformation within the Kabul Block (Fig. 4). As the Paghman fault moves, it creates a shear stress field in the surrounding area and causes the rocks to deform and break. These en echelon faults appear as a series of slight left-steps indicating complex stress patterns and interaction within the geologic structure. Slip on the Paghman fault is therefore distributed onto several subsidiary fault segments that display a range of styles from transpressional to tensional faulting (e.g., Ruleman et al., 2007) (Fig. 4). The pronounced segmentation and discontinuous fault structure may play a controlling role in limiting the length of individual surface ruptures (e.g., Wesnousky, 2006). Deformation features such as linear troughs and spring lines are generally observed along the fault zone (Fig. 11c). The dip of the Paghman fault in the south is close to vertical based on the remarkably straight fault trace. The faulted geomorphic features gradually become less distinct, and the offset amount diminishes towards the fault's northern end. Therefore, there are different aspects to consider regarding both the Chaman and Paghman faults. Firstly, most of the slip rate occurs in the southern border region with Baluchistan (e.g., Beun et al., 1979; Lawrence et al., 1992; Shnizai et al., 2020; Ul-Hadi et al., 2013). Secondly, the Chaman fault plays into several synthetic faults in Afghanistan, where the slip rate on the main fault is locally portioned (Ruleman et al., 2007; Shnizai, 2020b) (Fig. 1a). Due to this, the geomorphic features become gradually less clear toward north and have been experiencing a decrease in slip rate. Thirdly, according to Shnizai et al. (2020) the slip rate along the northern termination of the Chaman and Paghman fault approaches zero, making the fault less clear. Lastly, numerous small faults that don't produce large earthquakes can absorb a significant amount of the shear to the south, and making the fault less clear towards the northeast (Ruleman et al., 2007; Shnizai, 2020b).

A significant historical earthquake with M 7.3 is known to have occurred in Kabul ($34^{\circ}40'48.00''\text{N}$, $69^{\circ}0'36.00''\text{E}$) in 1505 (Fig. 11a). The

1505 earthquake (e.g., Ambraseys and Bilham, 2014) is the largest reported along the Chaman fault system in Afghanistan. It was felt in Delhi and its neighboring area, but no significant damages can be attributed. As for other large earthquakes, the effects of the 1505 earthquake are well documented in historical records (Ambraseys and Jackson, 2003; Beveridge, 1979; Jackson, 2002; Quittmeyer and Jacob, 1979; Rajendran et al., 2013; Rajendran and Rajendran, 2005). The historical documents indicate that on July 6, 1505, an earthquake caused massive damage and loss of life in the Paghman District, with destruction reported from Isterghij, through Tibeh, where most houses were destroyed, to Paghman, where all houses were destroyed, and 70–80 people were killed. There were numerous casualties in other nearby towns and villages. It is not clear from the text where Isterghij and Tibeh are located. There is no village or place that goes by the name of Isterghij in the Kabul and Parwan Provinces. We, therefore, believe that the Isterghij may refer to Estarghech ($34^{\circ}53'49.8''\text{N}$, $69^{\circ}06'08.8''\text{E}$) located on the northern side of the Istalif (Fig. 11b). There is also no place by the name of Tibah in Kabul, but it may refer to Qola Village ($34^{\circ}40'31.1''\text{N}$, $69^{\circ}00'15.6''\text{E}$) located in Shakar Dara District, where the alluvial fan has been displaced by faulting for a long distance (Fig. 8b, 11b). According to Ambraseys and Bilham (2014), the geographic coordinate of Tibah or Tipa is $34^{\circ}40'48.00''\text{N}$ and $69^{\circ}0'36.00''\text{E}$, matching with the Qola Village. The Bala Hissar fortress of Kabul, approximately 20 km east of the Paghman fault (Fig. 11b), was damaged and required a month to repair. About 30 aftershocks were felt in one day, and the earth shook two or three times every 24 h for the following month (e.g., Ambraseys and Bilham, 2014). The distribution of damage, with the destruction of towns and Villages along the Paghman fault, suggests the Paghman fault as the source.

The earthquake is reported to have produced primary surface rupture (e.g., Ambraseys and Bilham, 2014; Ambraseys and Jackson, 2003; Quittmeyer and Jacob, 1979; Rajendran and Rajendran, 2005),

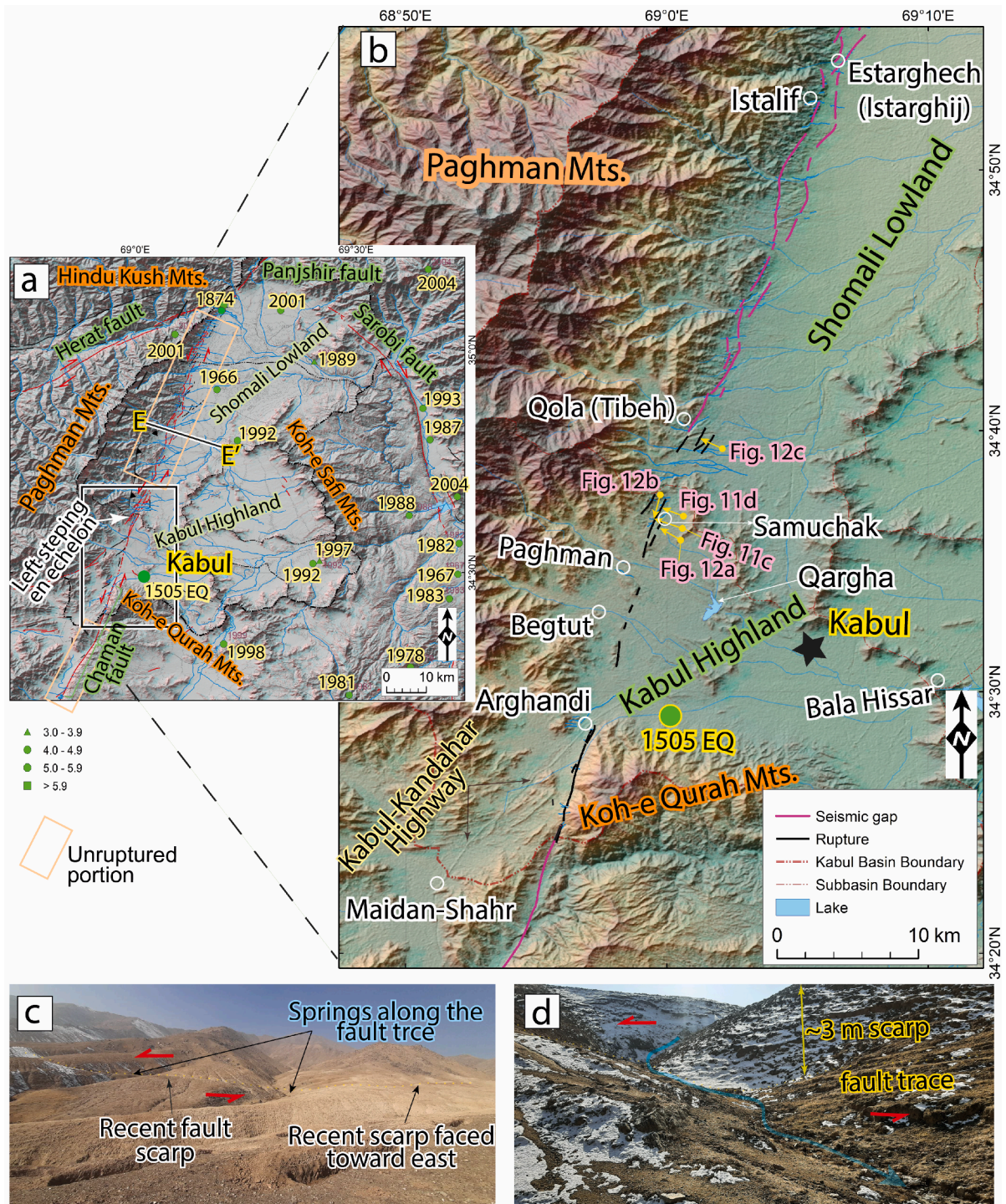


Fig. 11. A) paghman fault map, seismicity, and location of the surface rupture. b) map of surface rupture of 1505 historical earthquake along the paghman and chaman faults. the surface rupture associated with the 1505 earthquake is almost straight along the paghman mountains. c) a photograph of the paghman fault strand displays a recent fault scarp, offset streams, and springs along the fault line. yellow dotted lines indicate the fault trace. d) a field photo of the paghman fault scarp and the stream offset to the west of samuchak village. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

with a contemporary account stating that for a distance of 31–42 km (6–8 farsakhs) between Estarghech (Istarghij) and the plain the ground rose in places as high as an elephant, and in others, sank as deep (reported in [Ambraseys and Bilham \(2014\)](#), which also note an ambiguity in whether the term “plain” of Maidan, refers to the mountain pediment or the nearby town of Maidan-Shahr capital of Wardak Province at the southern end of the Paghman Mountains Range, west southwest of

Kabul). The ruptures were substantial, with a statement that in many places, the rupture was so wide that a person might have hidden oneself in the gap (e.g., [Jackson, 2002](#)). [Quittmeyer and Jacob \(1979\)](#) reported 60 km long surface faulting and [Beveridge \(1979\)](#) stated in Babur-nama six farsangs (24 miles). [Ambraseys and Jackson \(2003\)](#) interpreted the historical records to suggest at least 40 km of surface rupture along the Paghman fault. From the descriptions, the contemporary sources suggest

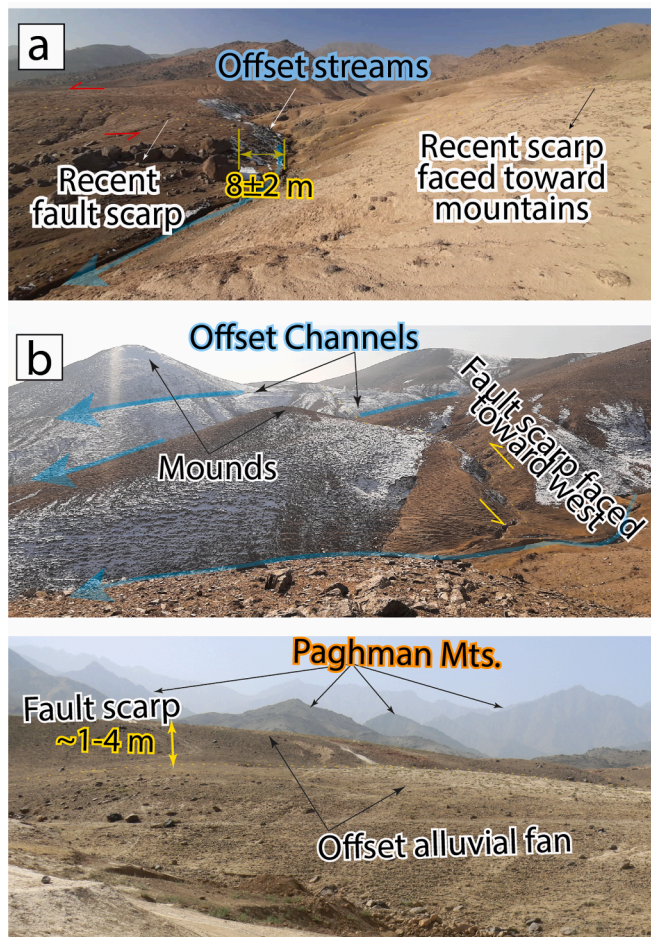


Fig. 12. A) field photograph of a stream offset looking west toward the paghman fault. b) mounds are lined up along the paghman fault strand on the western side of the samuchak village. c) field photograph of the paghman fault shows a recent fault scarp in offset alluvial fan, shown in Fig. 8b-c. The Fig. 12a, 12b, and 12c depict a recent scarp facing towards the mountains and fault scarp facing towards the west, respectively.

vertical offsets of up to 3 m within the general transpressional tectonic framework; however, descriptions of extensive fissuring (Ambraseys and Bilham, 2003; Boyd et al., 2007) throughout the fault zone suggest a significant amount of unknown strike-slip component of faulting during the 1505 event.

To better determine the source of the 1505 earthquake, we identified possible surface ruptures through observations and measurements made during fieldwork (Fig. 11b). Ruptures were identified from a qualitative assessment of the freshness of the scarp based on its height and no dissection, from the geomorphic evidence of recent faulting along some parts of the fault, and from the consistent vertical offset of alluvial fan surfaces (Fig. 5a, 7a, 11b). We restricted our observations to those places where we see the youngest alluvial and fluvial surfaces, where the small scarps can be traced along the fault trend from larger, compound fault scarps preserved on older alluvial surfaces (Fig. 11c-d). Within farmlands near the Arghandi River and Paghman River, we could not identify discrete primary surface ruptures and fault scarps. In this region, the fault is expressed as pressure ridges northeast of the Kabul-Kandahar Highway (Fig. 7a, 7b). The southern and northern extent of the rupture is poorly defined, mainly because of erosion of landforms and artificial disturbance. In the south, the surface ruptures trend into and terminate at an elongated valley parallel to the Koh-e Quragh Mountains in the Arghandi Region (Fig. 5a, 5f).

Based on our field observation, the approximate length of the surface

rupture due to the 1505 earthquake is about 30 km along the Chaman and Paghman faults (Fig. 11b). The rupture is generally continuous along its southern part, and in the northern part is typically composed of shorter fault segments separated by steps (Fig. 11b). We identified and mapped the dominant, primary rupture northeast of the Paghman District to ensure a consistent length of the rupture (Fig. 11b, 12a-b). The vertical displacement component is a commonly observed geomorphic feature, typically measuring less than 1 m (Fig. 5d-g, 11c-d). The vertical offset along the Paghman fault range from 1 to 30 m, and we assume that the smaller offset (1–3 m) may be associated with the last surface rupture earthquake in 1505 (Fig. 8c, 9f, 12a-c). The fault is an oblique slip with multiple strands, so we assumed it produced a surface offset of ≤ 3 m. This is because a lot of small faults could affect locally with slip rate partition. Additionally, the fault is mostly located along the Paghman Mountain front, where the surface offset is smaller than in areas with weaker rocks. Several mounds oriented along a straight line north of Paghman District form a west-facing fault scarp (Fig. 7b, 9c, 12b). Additionally, west of the Samuchak Village, many springs occur along the Paghman fault strands, possibly due to the vertical enhancement of groundwater flow (Fig. 11c, 12b). The fault traces are a typical tectonic landform, and the morphology suggests a strong strike-slip component of fault movement (Fig. 5a, 7a, 11b). From the relative amounts of strike-slip and vertical slip recorded on older compound fault scarps, we expect this component to be the dominant component; however, we could not find measurable markers to quantify the amount of lateral slip in the most recent earthquake. The vertical component appears related, at least in part, to local factors such as small-scale steps, bends, and jogs in the predominantly left-lateral fault system.

Based on our observation and previous reports (e.g., Beveridge, 1979; Quittmeyer and Jacob, 1979; Rajendran et al., 2013; Rajendran and Rajendran, 2005; Ruleman et al., 2007; Shnizai and Tsutsumi, 2020), the 1505 earthquake did not rupture the entire section of the Paghman fault (Fig. 11a-b). This means that the northern part of the Paghman fault and the Chaman fault south of the Kohe Quragh Mountain could potentially form a seismic gap, which could host a large earthquake on the Paghman fault (Fig. 11a). This area has not experienced a major earthquake in a long time, and it's believed to be one of the most likely spots for a major earthquake to occur along the eastern front of the Paghman Mountains. Relative to the fault segment where the 1505 large earthquake occurred, there is a seismic gap with high stress or strain levels (Fig. 11b). This increases the likelihood of another large earthquake happening in the future along the Paghman fault and the Chaman fault south of Kohe Quragh Mountains.

Detailed mapping of the surface rupture helps us improve the understanding of the tectonics and the fault-related hazards of the Kabul Basin (Fig. 11b). The numerous small fresh scarps and displacements identified here may represent a rupture in the 1505 earthquake, though confirmation requires detailed paleoseismic work. Based on the empirical relationship between the moment magnitude (M_w) and the surface rupture length, the northern part of the Chaman fault located in Kabul and Paghman faults could produce an M_w 7.3 to 7.8 earthquake in the study area (Shnizai, 2020b) (Fig. 11a-b). The elapsed time since the 1505 earthquake, is close to the calculated recurrence interval ~ 400 –650 years on the northern Chaman fault and the Paghman faults (Shnizai and Tsutsumi, 2020). The potential accumulated slip since the last faulting event is 1.8–2.6 m. If a large earthquake occurs with a magnitude of 7.3, like the one that hit Kabul in 1505, could cause significant damage to both humans and property. Today, Kabul has a population of over four million people (e.g., Fabrizio, 2019), and many buildings have been constructed illegally on steep slopes without following proper safety standards. Additionally, the houses are constructed using mud blocks that are mortared together with mud. The houses have flat roofs made of dried mud, supported by wooden beams. However, the mud-block walls are not braced against horizontal shaking (e.g., Shnizai et al., 2022).

7. Conclusions

The ~ 80 km-long Paghman fault is the northern extension of the Chaman fault and connects the western margin of the Kabul Block with the Afghanistan accreted terrain across an intricate pattern of fault strands. We mapped the Paghman fault from satellite imagery, digital topography, and field survey. We divide the Paghman fault into four sections to better facilitate geomorphic description: 1) Maidan Shar to Arghandi Substation, 2) Arghandi to end of Samuchak Village, 3) Shakardara to Farza, and 4) Istalif to Ghorband River Valley. The Paghman fault is identified through a series of primarily east-facing fault scarps. From Shakardara District to Istalif, the Paghman fault manifests at the surface as strike-slip fault strands, with several of the faults also having measurable dip-slip motion, where bends and jogs occur in the fault zone. Continued left-lateral movement of the fault has offset many incised range-front alluvial fans, with amounts ranging from tens to 300 m. The fault zone is 0.5 to 4 km wide and is most diffuse along the western portion of Shomali Lowland. We also identified possible surface ruptures of the historical 1505 earthquake and attempted to map the entire surface rupture associated with the historical event. We found the historic ruptures to extend for approximately 30 km along the range front in the Arghandi and Paghman region and connecting the main Chaman fault from the south to the Paghman fault in the north. We interpret vertical displacements along this rupture to be predominantly caused by local structural complexity and bending of the fault, such that the predominant slip is left-lateral. We also mapped systematic cumulative stream displacements ranging from 8 to 300 m. The vertical offset ranges from less than 1 to ~30 m in height along the fault strands but remains much smaller than the horizontal component. However, we should confirm this interpretation with paleoseismic trenching.

CRedit authorship contribution statement

Zakeria Shnizai: Conceptualization, Data curation, Investigation, Writing – original draft. **Richard Walker:** Conceptualization, Investigation, Supervision, Writing – review & editing. **Hiroiyuki Tsutsumi:** Conceptualization, Investigation, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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