Active Faults and Seismic Hazard in the Kabul Basin, Afghanistan

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The Kabul basin is the economic and political centers of Afghanistan. The basin is bounded by large active faults related to the convergence of the Indian and Eurasian plates and has a high risk of destructive earthquakes. However, little is known for the location, length, and slip rate of these active faults that are essential for seismic hazard analyses. We mapped the active faults in and around the Kabul basin based on the interpretation of stereo-paired satellite images and field observations. The left-lateral Paghman fault and northern Chaman fault on the western margin of the basin and the right-lateral Sarobi fault on the northeastern margin of the basin show geomorphic evidence for late Quaternary activity. Based on their lengths, these faults may be capable of producing earthquakes as large as M_w 7.8. Historical earthquake catalogs suggest that the Paghman fault last ruptured during the 1505 M 7.3 earthquake. The fault with a slip rate of ~4.6 mm/yr has accumulated enough elastic strain to produce a large inland earthquake close to the densely populated capital city of the country.

Key words: Afghanistan, Kabul basin, active fault map, historical earthquakes, seismic hazard

1. Introduction

Afghanistan is located in a geologically active region due to the convergence between the Indian and Eurasian plates. The Indian and Arabian plates move northward with respect to the Eurasian plate at rates ≥39 mm/yr and 23 mm/yr, respectively [1] (Fig. 1a). GPS observation shows approximately north-south shortening, with rates increasing eastward within the Himalayan orogenic belt [2]. The deformation is not only localized around the plate boundary in southeastern Afghanistan, but also it is spread up to hundreds of kilometers from the plate boundaries and caused lateral and depth variations of crustal thickness, composition, and density. The deformation caused the rock sequences to be faulted, folded and uplifted, and formed the high mountain ranges in the northeastern part of Afghanistan.

The Kabul basin is located in east-central Afghanistan, within the terrane called the Kabul block (Fig. 1b). The region is tectonically active because large active tectonic structures bound it. The Sarobi fault is located in the eastern margin of the basin, while the Hindu Kush suture is located in the north. The Paghman fault bounds the western margin of the Kabul basin. The Paghman fault is the northern extension of the Chaman fault and exhibits an intricate pattern of fault strands. The primarily left-lateral strike-slip motion on the Chaman fault changes into left-lateral oblique-thrust motion on the Paghman fault.

Kabul metropolitan area is located in the northern part of the tectonically active Kabul block and has a high risk of damaging earthquakes and related hazards. Kabul, with a population of more than 4 million, is the capital city of the country. It is one of the most rapidly growing cities on earth due to the influx of refugees and people from the countryside. However, many people live in houses and buildings that have been heavily damaged

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by war or constructed without adequate seismic enforcements. The slip rate of the active faults around the Kabul basin, particularly the Chaman and Paghman faults, is high [3] and these faults pose a high seismic risk to the area. A massive earthquake in the Kabul Province would cause hundreds to thousands of casualties and substantial damages. Although various strategies and actions can substantially reduce the seismic hazards, little work has been done for Kabul and surrounding regions. To better mitigate seismic hazards in the Kabul metropolitan area, we needed a detailed map of active faults, source of the destructive inland earthquakes.

The purpose of this study is to investigate the active tectonics and seismic hazard of the Kabul basin based on the interpretation of topographic anaglyph images produced from satellite images and digital elevation models. We mapped active and presumed active faults by interpreting these 3D anaglyph images and field observations. We show the detailed location and length of the faults that are essential to seismic hazard analyses and estimate the magnitude of maximum credible earthquakes from the active faults around the Kabul basin.

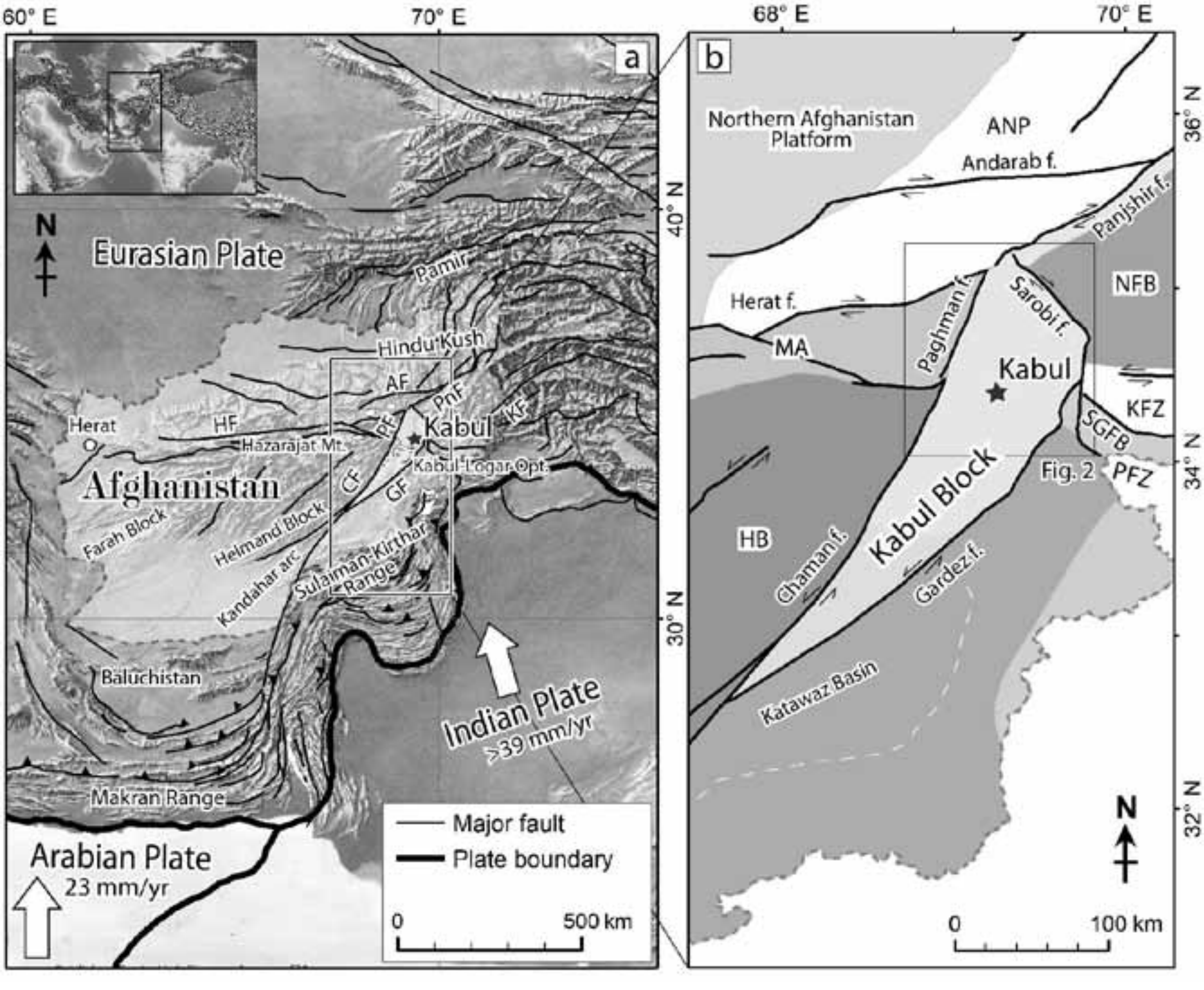

Fig. 1. a) Tectonic setting of Afghanistan. Abbreviations of faults: An, Andarab fault; CF, Chaman fault; GF, Gardez fault; HF, Herat fault; KF, Konar fault; PF, Paghman fault, PnF, Panjshir fault. b) Location of the study area in the northern part of the Kabul block. ANP, Afghanistan North Pamir; HB, Helmand block; KFZ, Konar fault zone; MA, Middle Afghanistan; NFB, Nuristan fault block, PFZ, Parachinar fault zone, SGFB, Spin Ghar fault block. The rectangle shows the location of Fig. 2a.

2. Data and Methods

We analyzed tectonic geomorphology of the Kabul basin using several satellite images covering the area 34.03°-35.25°N and 68.71°-69.82°E. We firstly prepared 3D anaglyph images from the 2.5-m-resolution ALOS (Advanced Land Observing Satellite) PRISM (Panchromatic Remote-sensing Instrument for Stereo Mapping) satellite images using Adobe Photoshop. Anaglyph images have a stereoscopic 3D effect by encoding each eye's image using filters of different colors. For regions that are not covered by the ALOS images, we prepared shaded relief maps constructed from the DEM (digital elevation model) of 1-arcsecond SRTM (Shuttle Radar Topography Mission) together with the ESRI (Environmental Systems Research Institute) base map. We also imported the SRTM DEM to Simple DEM Viewer software [4], to produce anaglyph images. Large scale images were constructed from 2.0-m-resolution SPOT earth observation satellite, which is freely available from ESRI as a base map. All these images were imported to ArcMap for geo-referencing into a global framework and manipulated to highlight the scenes to map the critical geomorphic elements of the Kabul basin. We also conducted fieldwork in the broader area, particularly along the Paghman and Chaman faults, to examine the details of the tectonic geomorphic features.

We mapped active and presumed active faults based on geomorphic criteria commonly used for active fault mapping in Japan [5, 6]. The first criterion for the identification of an active fault is the evidence of movement in recent geologic time, i.e., late Pleistocene and Holocene [7]. We paid close attention to the presence of young offset landforms and deposits along the foot of the mountain ranges. In places where young (Quaternary) strata and landforms are scarce or absent, we identified active and presumed active faults based on systematic offsets of stream channels. Geomorphic surfaces within the basin were classified based on morphology and degree of dissection.

3. Geomorphology of the Kabul Basin

The Kabul basin is located in the northern part of the Kabul block that is approximately 300 km long and up to 70 km wide (Fig. 1). The Kabul block is bounded on the east and west by major active strike-slip faults. The Chaman and Paghman faults bound the western margin and separate the Kabul block from the Helmand block and middle Afghanistan (Fig. 1b). The northeastern margin is bounded by the Sarobi fault that separates the Kabul block from the Nuristan fault block. The left-lateral Gardez fault defines the southeastern margin of the Kabul block against the Katawaz basin. The northern end of the Kabul block extends to the central Hindu Kush Mountains and is bounded by the Herat-Panjshir Suture Zone [8].

The Kabul basin is bordered on its four sides by mountain ranges (Fig. 2). The Paghman Mountains on the west reach the maximum elevation of 4400 m and are the primary source of sediments deposited within the basin. In the east, the basin is bordered by the Koh-e Safi Mountains ~2900 m high. The northern margin of the basin is bounded by the Hindu Kush Mountains, while the Koh-e Quragh Mountains bound the southern margin of the basin (Fig. 2a).

The Kabul basin can be divided into six geomorphological subbasins separated by prominent bedrock outcrops [9]: the Panjshir, Shomali, Dehsabz, Upper Kabul, Logar and Lower Kabul subbasins (Figs. 2a, b). These subbasins are the depositional centers of sediments shed from the surrounding surficial deposits and bedrock outcrops. The Kabul basin is fed primarily by the Panjshir, Ghurband, Paghman and Logar Rivers, which flow eastward from the Hindu Kush and Paghman Mountains (Fig. 2a).

The ridges within the basin are 200-500 m higher than the adjacent valley floors. The central parts of the subbasins are generally flat and rise gradually towards the surrounding mountains. Elevation of the central plains varies from 1800 m to 2200 m. Perennial and ephemeral stream channels have dissected the central plains, but they rarely exceed 20 m in width and 8 m in depth. Some isolated topographic depressions in the Logar and Lower Kabul subbasins act as catchments for surface water runoff and are the sites of playa lakes or ephemeral marshes [10] (Fig. 2a).

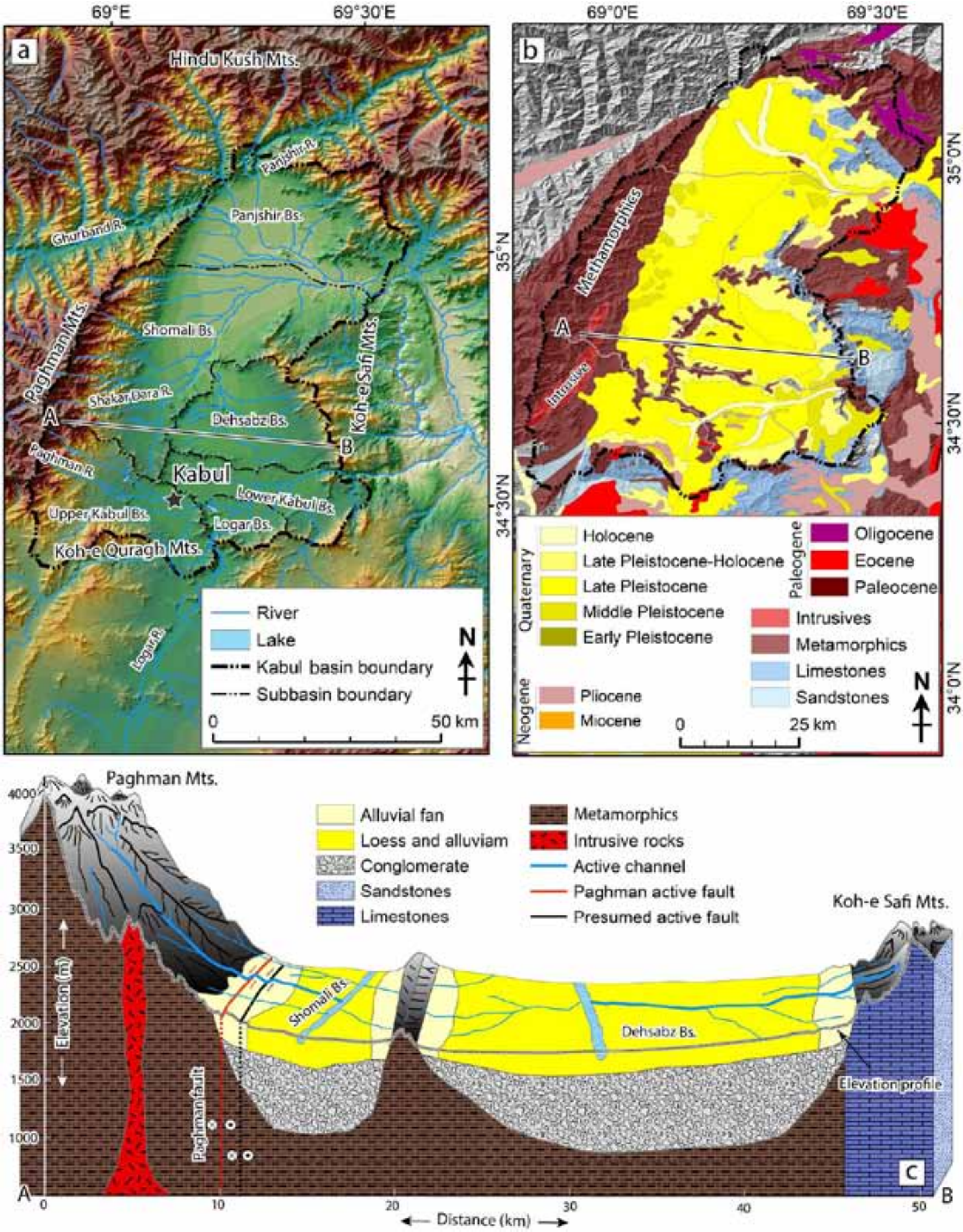

Fig. 2. a) Topography of the Kabul basin. The black line (A-B) indicates the location of the geologic cross-section shown in Fig. 2c. b) Geologic map of the Kabul basin simplified from Doebrich et al. (2006) [11]. c) Schematic geologic cross-section across the Kabul basin.

The surrounding mountain ranges consist of Paleoproterozoic gneiss and Late Permian through Late Triassic strata. The Koh-e Safi interbasin ridges (between Dehsabz and Shomali or Dehsabz and Lower Kabul subbasins) are composed of Paleoproterozoic migmatite and gneiss. The basement rocks in the Koh-e Safi Mountains, to the east of the Kabul basin, are overlain by Permian to Jurassic shelf or platform carbonate rocks [12] Early Cretaceous gabbro and monzonite intrusions are exposed in the Paghman Mountains.

The basin is filled by less than 80 m thick Quaternary deposits [13], that overly approximately 800-m-thick Tertiary strata in Kabul City [14, 15]. Surficial deposits are alluvial fan deposits of various ages and are differentiated by the degree of dissection and morphology. River deposits are present in the active floodplains of the Panjshir and Logar Rivers (Fig. 2a). Eolian Loess deposits accumulated in the Paghman and Koh-e Safi Mountains. Terrace deposits are well exposed along the major rivers and mountain fronts (Fig. 3).

In the study area, terrace deposits are present on flat-lying areas around the drainage systems and their second-order branches (Fig. 3). They are up to 70 m higher than the current drainage system (Fig. 4a). The Paghman fault displaces a sequence of terraces along the Paghman and Koh-e Quragh Mountains (Figs. 3, 4b). The terraces overlie the steeply tilted and folded rocks with angular unconformity. The lower section of the terrace deposits is relatively well lithified, whereas the upper section is weakly lithified, altered, and loose. The fault strands cut them, but the tectonic geomorphic features are rapidly erased by erosion or deposition on active fan surfaces (Fig. 4b).

4. Active Deformation

Tectonically, the Kabul basin can be divided into two zones: 1) Kabul highland and 2) Shomali lowland (Fig. 3). The Kabul highland is bounded by large active faults. Several small faults, such as the Onay fault, separate the highland from the Helmand block located to the west (Figs. 1b, 3). Within the Kabul highland, the lower Kabul basin is ~250 m lower than the upper Kabul basin (Fig. 2a).

The Shomali lowland is a gently inclined surface that occupies the lowest part (~1500 m) of the Kabul basin. The Shakar Dara River incises the southern part of the lowland (Fig. 2a). The north, west, and east edges of the area are characterized by a series of alluvial fans from the surrounding mountains. The western margin of the lowland is bounded by the steep Paghman Mountains. In the north and northeast, the lowland is bounded by the Hindu Kush Mountains, which are cut by the east to northeast-trending right-lateral Herat, Andarab and Panjshir faults [4] (Fig. 1a) The Hindu Kush Mountains are seismically active and have been uplifting at a rate as much as 10 mm/yr based on recent GNSS measurements [16]. The eastern side of the Shomali lowland is marked by a faulted ridge composed of Neogene-Quaternary deposits, which has been incised by small stream channels (Fig. 2b).

4.1 *Active faults*

4.1.1 *Paghman fault*

The Paghman fault extends for a length of ~80 km. The strike of the fault ranges from N16°E to N35°E (Fig. 3). The Paghman fault is the northern extension of the Chaman fault. It extends from Paghman district west of Kabul City northeastward to the northern margin of the Kabul basin. The fault is marked by continuous, linear or arcuate fault scarps on piedmont alluvium at the mountain front. The termination of the recent geologic units (e.g., Quaternary) was also used to delineate the fault strands along the Paghman Mountains.

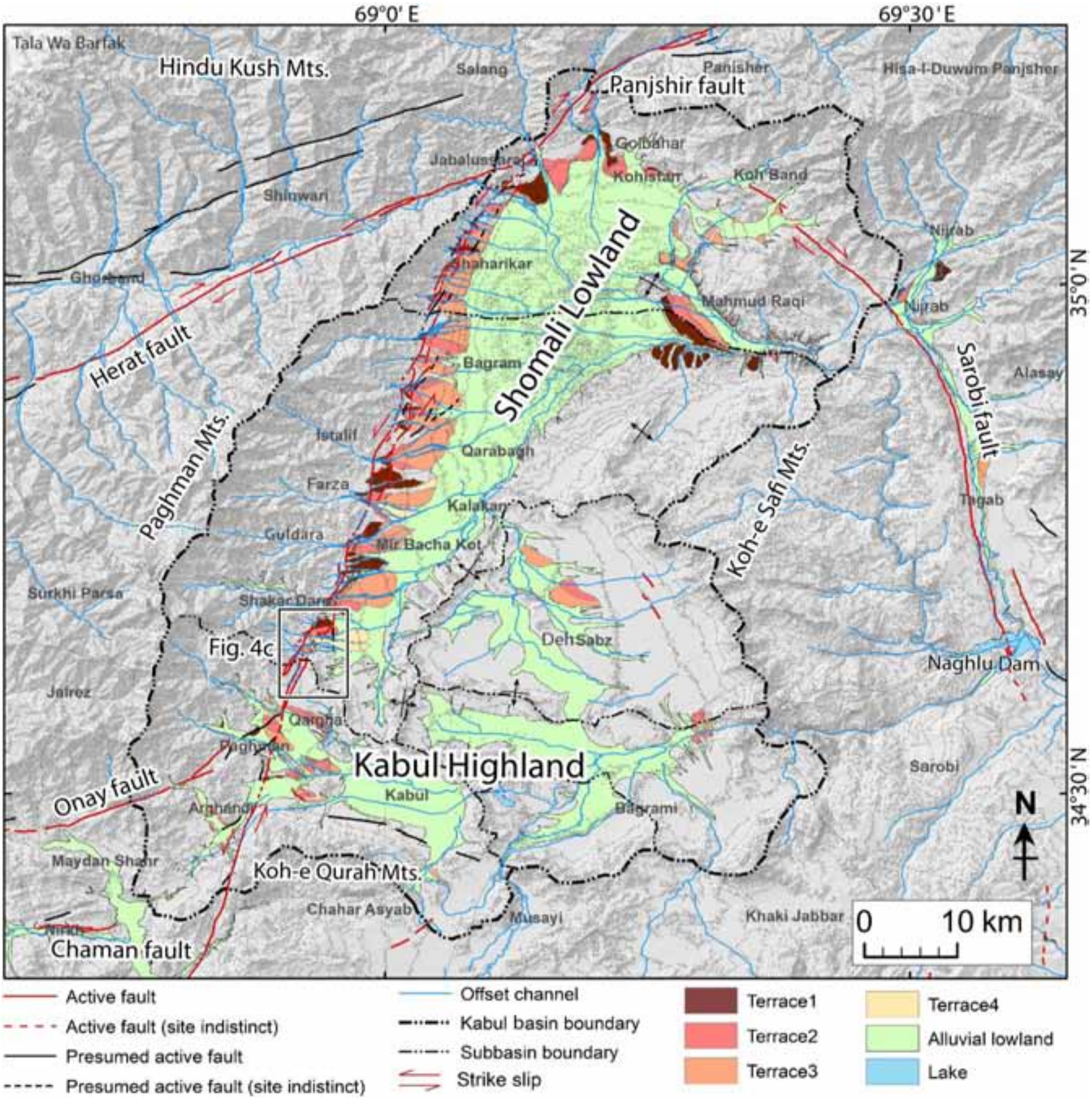

Fig. 3. Map of active faults and geomorphic features in the Kabul basin based on interpretation of ALOS PRISM and SRTM satellite anaglyph images as well as ESRI base map. Red lines denote active faults and black lines denote presumed active faults. The rectangle shows the location of Fig. 4c.

The fault typically offsets late Pleistocene and Holocene deposits and is marked by continuous fault scarps (Figs. 2b, 3, 4c). The old alluvial fans are preserved as deeply dissected remnants of thick fan deposits that are now isolated at the top of low hills in the southwest part of the basin as well as along the Paghman Mountains' front (Fig. 4d). Tectonic geomorphic features such as offset and beheaded stream channels, offset fans, shuttle ridges, fault scarps, and tilted alluvial surfaces are common (Figs. 4c, e). The fault also formed a linear valley between Qargha and Shakar Dara district (Fig. 3). It is hard to identify the fault trace along the range front from Arghandi to Qargha because of intensive human modification for farming.

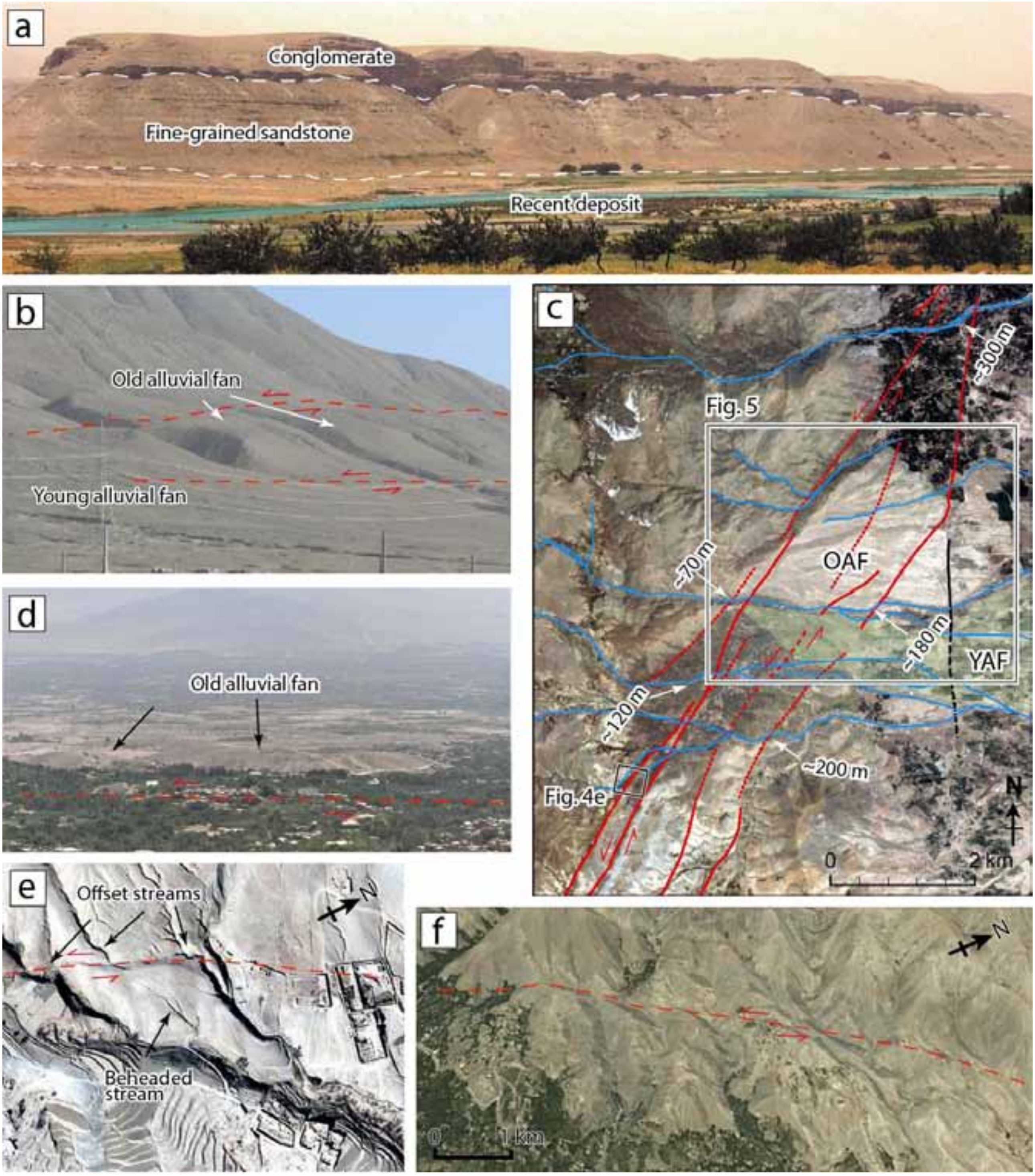

Fig. 4. a) View of the river terraces along the Panjshir River. The image is modified from Bohannon (2010) [12]. b) Photograph of small fault-bounded terraces near Arghandi, Paghman district (34°27'3.04"N, 68°56'34.66"E). c) Young and old alluvial fans (YAF and OAF) as well as fault strands of the Paghman fault on top of the ESRI base map. The old alluvial fan has moved northward relative to its source drainage. The location of Fig.5 is also shown by the box. d) Oblique view looking east across the Paghman fault (34°48'23.46"N, 69° 4'3.27"E). The hill is the old alluvial fan that has been transported left-laterally and made west-facing fault scarp. e) Satellite image showing beheaded and offset channels along the fault between Shakar Dara and Paghman districts. f) View of the Paghman Mountains' front, where the Paghman fault offsets metamorphic rocks between Farza and Istalif districts. The fault dips to the northwest and has large reverse and strike-slip components of displacement. The image is modified from Google Earth.

In some places, the mountain ranges are deforming primarily by strike-slip faulting, with minor northeast-striking thrust faults. For example, two strands of the Paghman fault offset gneiss between Farza and Istalif districts, which caused a scarp facing upslope toward the mountain (Fig. 4f). Middle-late Pleistocene conglomerate and sandstone rocks in the low hills possibly thrust to the west above the gneiss. Near Chaharikar, the age of the strata of these low hills was reported as Neogene [12] (Fig. 3).

The fault strands cut across alluvial fans along the piedmonts of the Paghman Mountains. We were able to measure the amount of left-lateral displacement of stream channels (Figs. 3, 4c, 5). The old alluvial fans have been displaced let-laterally >200 m from their sources. These fans are now located near small drainages, which cannot be the source of such massive fans [17] (Fig. 5b). In contrast, the young alluvial fan was offset for a smaller amount (~70 m) (Fig. 4c). Both glacial and fluvial processes are the primary agents of terrace formation. Sediments were deposited in the mountain ranges during the previous glacial periods, then transported by streams and formed fans. The alluvial fans were disrupted by the fault movement, and fluvial action has caused the formation of several terrace surfaces (Figs. 3, 4c, 5).

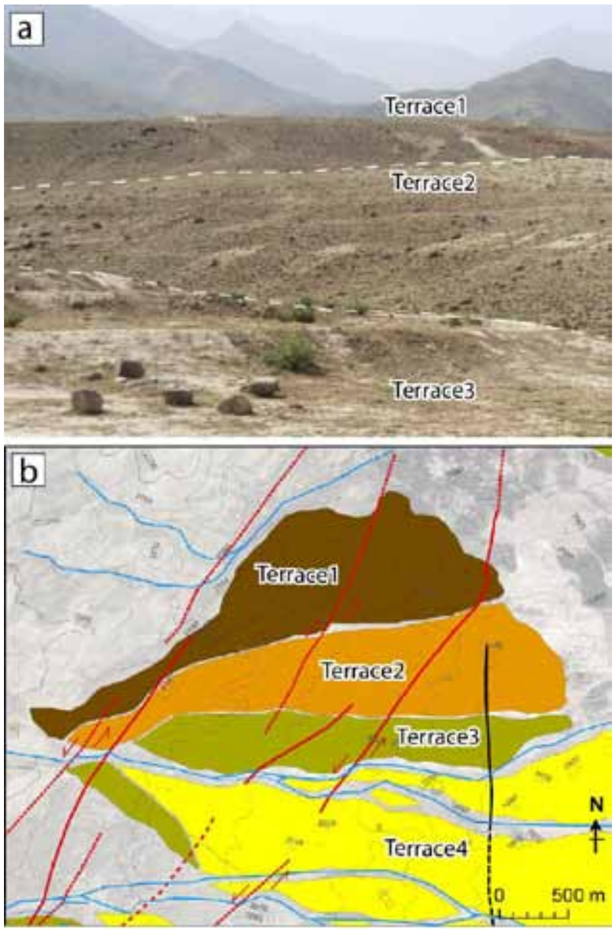

Fig. 5. a) Photo of the offset alluvial fans along the Paghman fault. b) Map of the alluvial fan surfaces showing apparent left-lateral offsets.

4.1.2 *Sarobi fault*

The 150-km-long Sarobi fault is one of the most noticeable structures northeast of the Kabul basin. The southwestern segment of the fault extends from the Parachinar fault zone, through the Kabul-Logar ophiolite belt to the Sarobi district (Figs. 1, 3). The northern segment of the fault extends northward from the Naghlu Dam (Fig. 3). The fault runs along the Tagab valley, crosses the Koh-e Safi Mountains, and reaches the north end of the Kabul block. We interpreted the Sarobi fault as a right-lateral strike-slip fault (Fig. 6). Based on the high-resolution 3D anaglyph images, we interpret that the fault plane dips steeply to almost vertical, particularly from Naghlu Dam to Tagab district (Figs. 3, 6a).

The Sarobi fault has a steep, linear, and arcuate range-front scarp south of the Nijrab district (Fig. 3). The fault scarp is not distinct on piedmont alluvium further north from Koh-e Malikar to Golbahar, Kapisa Province. Fault scarps are present for a distance of ~40 km north of the Naghlu Dam and faces to the east toward the valley. The Sarobi fault probably has been active in the Quaternary (Fig. 6). Late Pleistocene deposits along the piedmont suggest enough activity for the burial of middle Pleistocene and older deposits on the hanging-wall of the main fault trace. The Sarobi fault forms a prominent north-trending fold that deforms recent (Pleistocene) alluvial deposits near the Tagab district.

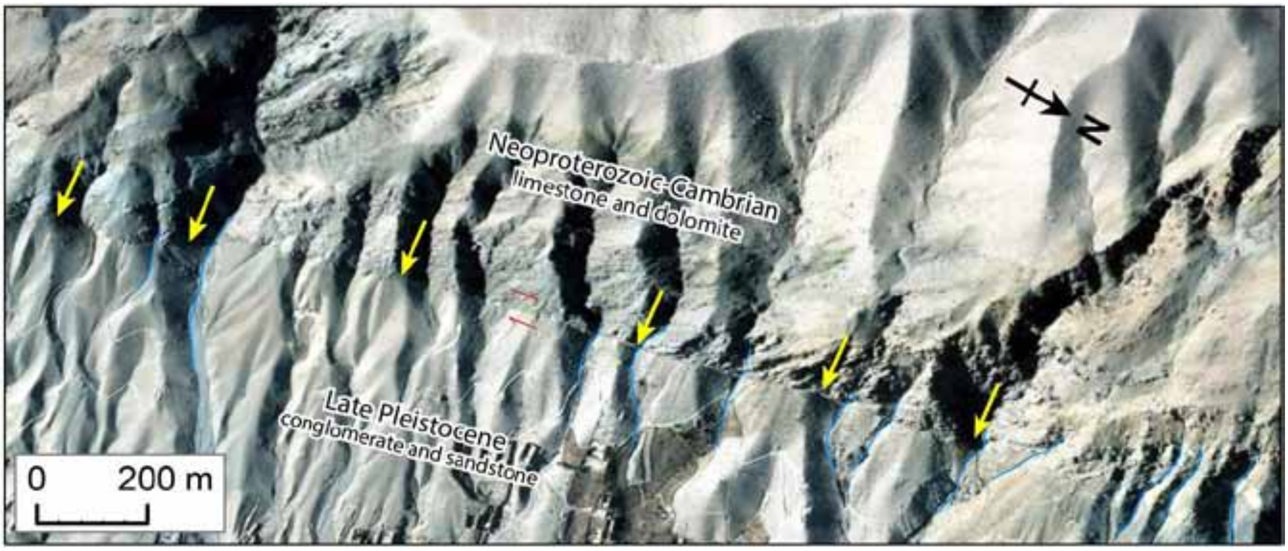

Fig. 6. Satellite image of the Sarobi fault near the Naghlu Dam. Yellow arrows indicate the fault trace.

5. Seismic Potential and Related Hazards in the Kabul Basin

Northeastern Afghanistan, including the Kabul basin, has a long history of damaging earthquakes (Fig. 7a). The occurrence of both shallow (<40 km) and deep (>70 km) earthquakes characterizes this region. The intermediate-depth (40-70 km) earthquakes are interpreted to be a result of lithospheric subduction due to the convergence of the Indian and Eurasian plates [18]. Much of the north-south compression is believed to be accommodated by major active faults such as the Chaman, Paghman, Gardez, Sarobi, Konar, Panjshir, Andarab and Herat faults (Figs. 1b, 7b). The Chaman and Sarobi faults have been active during the Quaternary. It is important to accurately estimate the seismic hazard of the Kabul area to reduce the damages from future earthquakes.

We can learn the seismic hazards of the Kabul area from the 1505 earthquake on the Paghman fault (Fig. 7b). The M 7.3 earthquake occurred on the northern end of the Chaman fault near Kabul City (34.53°N, 69.13°E). The earthquake produced approximately 60-km-long surface rupture [19, 20]. The earthquake destroyed all houses in Paghman district and killed about 80 people in Paghman and many more in the nearby villages and towns [19].

The moment magnitude (M_w) of crustal earthquakes has the following relationship to the surface rupture length (SRL).

$$M_w = 5.08 + 1.16 \times \log(\text{SRL}) \quad (1)$$

The total length of the Chaman fault is ~860 km. It is ~650 km long in Afghanistan and splays northward into several synthetic strands. South of the Kabul block, the Gardez fault branches northeast from the Chaman fault [17]. The length of the Chaman fault north of the branching point is 240 km, and this portion of the Chaman fault could produce an M_w 7.8 earthquake based on the empirical relation. The length of the Paghman fault (80 km) suggests an M_w 7.3 earthquake. Out of the 150 km length of the Sarobi fault, the northern 40-km-long section shows evidence of active faulting. Judging from the length of the fault (40 km), the size of the resultant earthquake would be M_w 6.9.

The slip rate of the northern Chaman fault near Kabul has been estimated at 4.6 mm/yr [3]. Since the 1505 earthquake, 1.8-2.6 m of potential slip should be stored on the northern Chaman fault. If we divide the horizontal displacement (2-3 m) during the 1505 earthquake [19] by the geomorphic slip rate, the average recurrence interval of a large earthquake would be ~400-650 yrs. The elapsed time since the last earthquake event on the northern Chaman fault and Paghman fault is close to the calculated recurrence interval, and the likelihood of future big earthquake is high. If a large earthquake similar to the M 7.3 1505 earthquake occurs near Kabul, the human and property losses could be devastating, and vastly more severe than in 1505, when Kabul was a relatively small garrison town. Kabul now has a population of over 4 million, including many refugees living in mud-block houses similar to those that collapsed in the 2002 Nahrin earthquake of magnitude 6.1 that killed more than 1,200 people [20].

There are little data on the late Quaternary activity of the right-lateral Herat and Panjshir faults. However, an earthquake of Mw 7.4 (1956) struck a region northeast of Bamyan (35.55°N and 67.81°E) between the Andarab and Herat faults (Fig. 7a). Another event occurred in 1874 north of Kabul near or on the eastern extension of the Herat fault [20] (Fig. 7b).

Earthquakes cause liquefaction, ground displacement, landslide and fire. The Kabul metropolitan area is located on water-saturated granular materials, which can lose their frictional strength during severe ground shaking. Several landslide masses are present on the steep slopes in the study area. The 1505 earthquake triggered a landslide in the valley just north of Paghman [20]. In the region close to the Sarobi fault, rockslides occur nearly every year, particularly during the rainy season. In the mountainous terrains, such as in northeastern Afghanistan, the high topographic relief is one of the causes of landslides. The Kabul basin presents significant variations in relief from low-lying valleys (~1500 m) to high altitude mountains (>4000 m). Thus, the likelihood of coseismic landslides is very high.

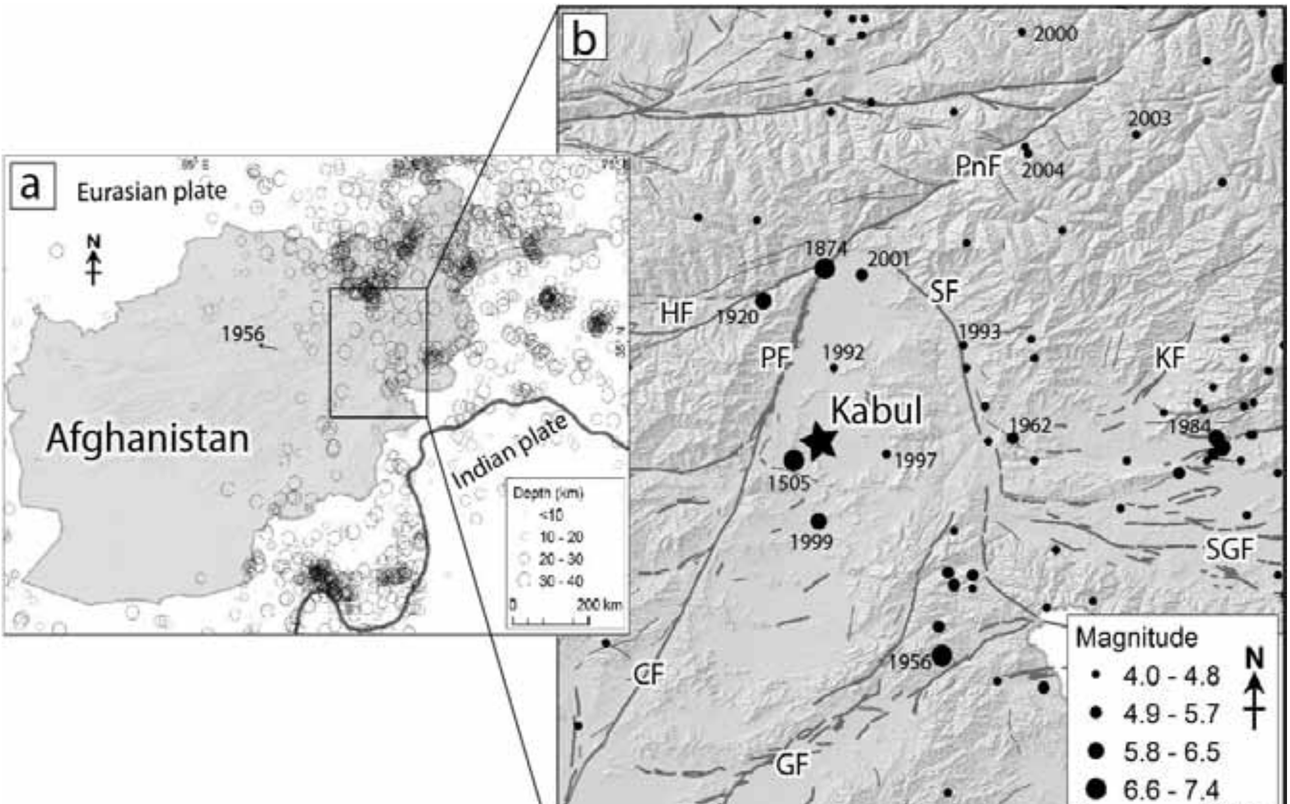

Fig. 7. a) Map representing the location of all crustal earthquakes occurring between 734 and 2004 with magnitudes 4.0-7.4. b) Location of all crustal earthquakes (<40 km deep) in the Kabul basin and surrounding regions. The seismicity data is modified from Dewey (2006) [21].

In this earthquake-prone area, many buildings are built illegally on steep slopes (Fig. 8). The houses are cut into the hill and constructed by mud-block mortared together with mud. Although most homes have flat roofs, consisting of 20-50 cm of dried mud supported by wooden beams, the mud-block walls are not braced against horizontal shaking. The 2005 Kashmir earthquake (M_w 7.6) struck the Himalayan region with >87,000 deaths, and most of the fatalities were due to widespread collapses of buildings and stone barns [22].

Fig. 8. Homes, seemingly built on top of the next, on the south slope of Koh-e Asmai Mountain, Kabul City (Photo by Mohamad Hamid Hamdard).

6. Conclusions

This study provides the first detailed description of active faults in the Kabul basin, Afghanistan. We mapped two large active strike-slip faults (the Paghman and Sarobi faults) as well as several small faults. The regional left-lateral shear is accommodated mainly by the Chaman and Paghman faults. The Sarobi fault is a right-lateral fault northeast of the basin. These faults are clearly expressed in landforms and offset Quaternary deposits. The lengths of these faults imply that they are capable of generating earthquakes larger than Mw 6.9. We hope this study serves as a foundation for a more detailed evaluation of seismic hazard in the Kabul basin. To better assess the seismic hazard of Kabul, trenching investigations along the Paghman fault and northern Chaman fault are needed. We now know the precise location of the faults, but do not know earthquake history along the faults. Through trenching studies, we need to collect data on the recurrence interval of large surface-rupturing earthquakes and the timing of the most recent earthquake events.

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