Arabian Journal of Geosciences (2021) 14: 819
https://doi.org/10.1007/s12517-021-07159-3

ORIGINAL PAPER

Recent alluvial fan developments in Muğla (SW Turkey)

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Received: 22 May 2020 / Accepted: 23 April 2021 / Published online: 4 May 2021

Abstract

The Muğla Polje (SW Turkey), which formed as a result of the Pleistocene activity of the Muğla Fault, is an example of a rift basin with two alluvial fans (the Muğla Fan, 3.33 km^2 and the Düğerek Fan, 1.26 km^2). This study focuses on the development of these fans through the evaluation of aerial photos, Google-Earth images, the measurements of sedimentary sections, lithological examinations, mineralogical discriminations, and in situ observations. Fractured Jurassic-Cretaceous limestone and upper Miocene-Pliocene clastics have been observed in drainage areas of both fans. In the drainage area of the Muğla Fan, where low strength upper Miocene-Pliocene clastics are abundant, the river incision is higher. As a result, higher amount of sediment supply led to formation of the larger Muğla Fan. Small scale tectonic activities and rainy periods led to the formation of poorly sorted, angular-subangular, and coarser-grained pebblestone-cobblestone deposits, whereas, tectonically quiescent and dry periods were represented by the finer-grained sediments at the apex and upper fan of both fans. They pass into the finer-grained deposits in the downdip direction. Recently, the Muğla and Düğerek fans surface has been covered by urbanization. Man-made channel was built to protect humans from floods, which starts from the apex and extends beyond the distal fan in Polje center. Thus, sediment and water required for fan development have been all cut. Both fan development were initially controlled by nature, such as tectonic activities and climate, and now by humans. Therefore, this study recommends the constant monitoring of the impact of human interference on fan development while regulating the feeding mechanism of fan basin interiors, natural balance of local environment, and urban lives.

Keywords Graben · Polje fillings · Human interference · Recent sedimentation

Introduction

Alluvial fans are in conical-semi conical aggradational sedimentary bodies and arcuate in plain view between the upland catchments-sediment source and depositional basin (Hooke 1967; Bull 1972a, b; Blair 1999, 2003; Coulthard et al. 2002; Blair and McPherson 2009). They can be found at the edges of the river or fault controlled valleys (Wasklewicz and Scheinert 2016). Lithologically, fan deposits contain mainly coarse-grained and poorly sorted sediments (Blair and McPherson 1994, 2009).

Five major factors influence fan processes: (i) the lithology of bedrock in a catchment area, (ii) the shape of catchment area, (iii) the neighboring environment, (iv) the climate and (v) the tectonism and active faults (Schumm 1977; Coulthard et al. 2002; Crosta and Frattini 2004; Nichols 2005; Pope and Wilkinson 2005; Blair and McPherson 2009; Wasklewicz and Scheinert 2016; Ventra and Clarke 2018). Tectonic is considered as the main controlling factor on location, morphology of fans through creating a setting, relief, and accommodation for the alluvial fans (like in the Muğla, SW Turkey) (Ventra and Clarke 2018). Structural-morphological obstacle and to a lesser extent other factors such as river and human impact may prevent building of the regular fan geometry (Crosta and Frattini 2004). The climate is considered as a controlling factor in erosion, water discharge, vegetation covers, depositional processes (including sheet and channelized fluvial flow), and debris flows (Hooke 1968; Denny 1967; Starkel 1983; Crosta and Frattini 2004; Harvey et al. 2005; Ventra and Clarke 2018). The alluvial fans are widely developed in arid climatic conditions; however, change in climate may trigger fan

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Responsible Editor: Stefan Grab

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formations in various sizes (Harvey et al. 2005; Ventra and Clarke 2018). Some urbanization is located on alluvial fans. Thus human activities such as channels-embankment should affect the fan development, which may be added as the sixth controlling factor on alluvial fan environments (Constante et al. 2010; Walstra et al. 2010; Ortega et al. 2014; Wasklewicz and Scheinert 2016; Roberts et al. 2019).

The alluvial fans are one of the important landforms in Turkey (Kuzucuoğlu et al. 2019a). Recently, they develop under the dry climatic condition in eastern Turkey and mild climatic condition in western Turkey (Kazancı and Roberts 2019; Kuzucuoğlu et al. 2019a; Özsayın et al. 2019; Şaroğlu and Güngör 2019). They can be found in different ages and in diverse tectonic regimes such as normal fault and strike slip fault in Turkey (Brückner 2019; Kayan 2019; Kuzucuoğlu 2019; Kuzucuoğlu et al. 2019a, 2019b; Ocakoğlu 2020; Öner 2019; Özsayın et al. 2019; Sarıkaya et al. 2015; Şaroğlu and Güngör 2019). SW Turkey hosts four different types of basins during the Neogene-Quaternary; piggyback basin, pull-apart basin along oblique strike-slip faults, intermontane basin, and graben (Görür et al. 1995; Bozkurt and Mittwede 2005; Sözbilir 2005; Alçiçek 2007; Gürer et al. 2013; Seyitoğlu and Işık 2015; Elmas et al. 2019). The alluvial fan, colluvial, and fluvial deposits are found in the Çameli Basin in the SW of Muğla (Alçiçek et al. 2005; Alçiçek 2007); in the Gediz and Küçük Menderes Grabens (Süzen et al. 2006; Rojay et al. 2005); in the Manisa Basin of western end of the Gediz Graben (Özkaymak et al. 2013); and in the Söke-Milet Basin in western end of the Büyük Menderes Graben in the N of Muğla (Sümer et al. 2012).

The Muğla Polje is a 12-km-long, 6-km-wide NW-SE trending, normal fault-controlled basin and filled with the post Miocene deposits (Gürer et al. 2011, 2013). Only the basic characteristics of the Muğla and the Düğerek fans in the Muğla Polje were mentioned in previous studies (Figs. 1 and 2; Gürer et al. 2011, 2013; Gül 2015; Küçükuysal et al. 2018). No study has addressed the detailed sedimentological properties of these alluvial fans. How the human interference affect the fan development is less clear. The main purposes of this study are to describe the geometry of the alluvial fans based on aerial photos and Google-Earth images, to define the lithological-facies properties according to field study and borehole data, and to discuss the artificial impact on the fan developments.

Geological setting

The lithology of the region is of Permo-Carboniferous to Recent (Fig. 1). Permo-Carboniferous schist, Triassic-Eocene dolomite-limestone, Lower-Middle Triassic metasandstone-metaconglomerate, and Oligocene conglomerate-sandstone are exposed in the south of the study area. The investigated fans are located in the north part of the Muğla Polje that includes closed karstic depression and polje plain (Kayan 1979; Pehlivan 1993; Güner 2001). The north of the Muğla Polje is bounded by the active fault zone (Gürer et al. 2011, 2013) namely the Muğla-Yatağan Fault Zone (Şaroğlu et al. 1987) or Muğla Fault (Karabacak 2016).

The Gereme Formation, the Yatağan Formation, the Quaternary alluvium, and colluvium are exposed in the northern part of the Muğla Polje (Atalay 1980; Konak et al. 1987; Göktaş 1998; Gürer et al. 2011, 2013; Gül 2015). The northern rocky mountains are formed by the Jurassic-Cretaceous (Jcr), grey-colored, fractured limestones, and dolomites of the Gereme Formation (Figs. 1 and 2; Göktaş 1998; Gürer et al. 2011, 2013). The Yatağan Formation (upper Miocene-Pliocene) composed mainly of red-brown colored muddy conglomerate and mudstone alternations, and composed to a lesser extent light grey limestone-marl, tuff and travertine intercalations, which were created by horizontal-flat topography on the Jurassic-Cretaceous limestone (Atalay 1980; Konak et al. 1987; Aktimur et al. 1996; Göktaş 1998; Gürer et al. 2011, 2013). Narrow colluvial wedges, which composed of very poorly to poorly-sorted, angular to subangular, and clay to boulder sediments, have linear extensions in front of the northern faulted margin of the Muğla Polje (Gül 2015). The alluvial fans include angular to subrounded, poorly-sorted, clay to cobble-sized sediments (Gürer et al. (2011, 2013). To the Polje center, both colluviums and alluvial fan deposits laterally pass into the subrounded to rounded, poorly to moderately sorted, dominantly red-colored, clay and gravel-sized sediments bearing alluviums (Kayan 1979; Aktimur et al. 1996; Göktaş 1998; Gürer et al. 2011, 2013; Gül 2015; Küçükuysal et al. 2018).

Material and methods

The studied fans are located ~ 2 km east of the Muğla district (Figs. 1 and 2). Throughout the province of Muğla, a Mediterranean climate prevails (Köppen-Geiger classification), with warm-dry summers and cold-rainy winters (annual average precipitation of 1101 mm and annual average temperature of 15.3°; https://tr.climate-data.org/asya/tuerkiye/mugla/mentese-923599/ Access date: 25.01.2019).

The aerial photos and Google-Earth images were used to determine the alluvial fan boundary and settlement changes covering the last 45 years. Digital Elevation Model (DEM) and Google-Earth images were used to describe the geometry, transverse, and longitudinal profiles of fans. The lithological properties of the fan deposits were examined by field studies and the borehole data from the report of the Menteşe District of Muğla Metropolitan Municipality Microzonation (MMMM 2017). Results of sieve analysis and Unified Soil Classification System (USCS 1985) were used for sediment classification based on Folk (1954) system.

A sedimentary section was measured to determine the lithological variations in the main channel feeding the Düğerek Fan. Samples from selected beds of the Düğerek Fan (D-1) and the Yatağan Formation (D-2) were used to compare the mineralogical properties of the fan deposit and its possible source lithology. Cation exchange capacity (CEC) and Fourier transform infrared spectroscopy (FTIR) analyses, due to their fast-analytical capability and applicability in the present laboratory conditions, were selected to compare the fine fraction mineralogy of both samples (D-1 and D-2).

Cation exchange capacities of the samples were determined based on the Methylene Blue Test. The methods of Jones (1964) and Çokca and Birand (1993) were followed for the preparation of Methylene Blue (MB) solution and the determination of the CEC of the fine fractions of the samples. MB adsorption of the clay-water mixture was monitored until the complete exchange reactions happen between clay surface and the MB solution. The CEC values were calculated based on Çokca and Birand (1993) with the provided formula (1):

$$(\mathrm{C.E.C.}) = 100/f{*}\mathrm{Vcc}{*}\mathrm{NMB} = (\mathrm{meq}/100\mathrm{gr}) \qquad (1)$$

where f stands for a dry weight of clay sample (7.5 gr), Vcc is the amount of methylene blue diluted added to the clay sample, NMB is the normality of the MB solution (standard = 0.028).

Infrared (IR) spectra of the two samples were recorded in transmittance mode as a function of wavenumber using a Thermo Scientific Nicolet iS10 Smart iTR from 4000 to 400 cm^{-1} with a number of scan 32 and resolution 16 cm^{-1}. Attenuated total reflection FTIR (ATR-FTIR) technique was selected for FTIR analysis. FTIR-spectroscopy enables to determine the minerals, non-crystalline phases as well as organic matter present in the samples. As stated in Vaculíková and Plevová, (2005), absorption of infrared radiation is also affected by the crystallinity of the minerals and their grain sizes.

Characteristics of the fans

Muğla Fan

Morphology The Muğla Fan covers approximately 3.33 km^2, and its perimeter is roughly 7 km. It has almost radial distribution in plain view (Figs. 1, 2, and 3). It extends longitudinally 2.2 km (maximum) towards SW direction. An altitude of the fan is 700 m in apex part and 625 m in the distal part. The fan, located in front of the normal faulted hills, formed in the upper Miocene-Pliocene clastics (Fig. 3). The river, bounded with 70–80° inclined valley walls, incises into this older clastics and feeds the Muğla Fan (Fig. 2). A 850-m high hill is located at the apex part of the fan, skirts of the hill has a 45–

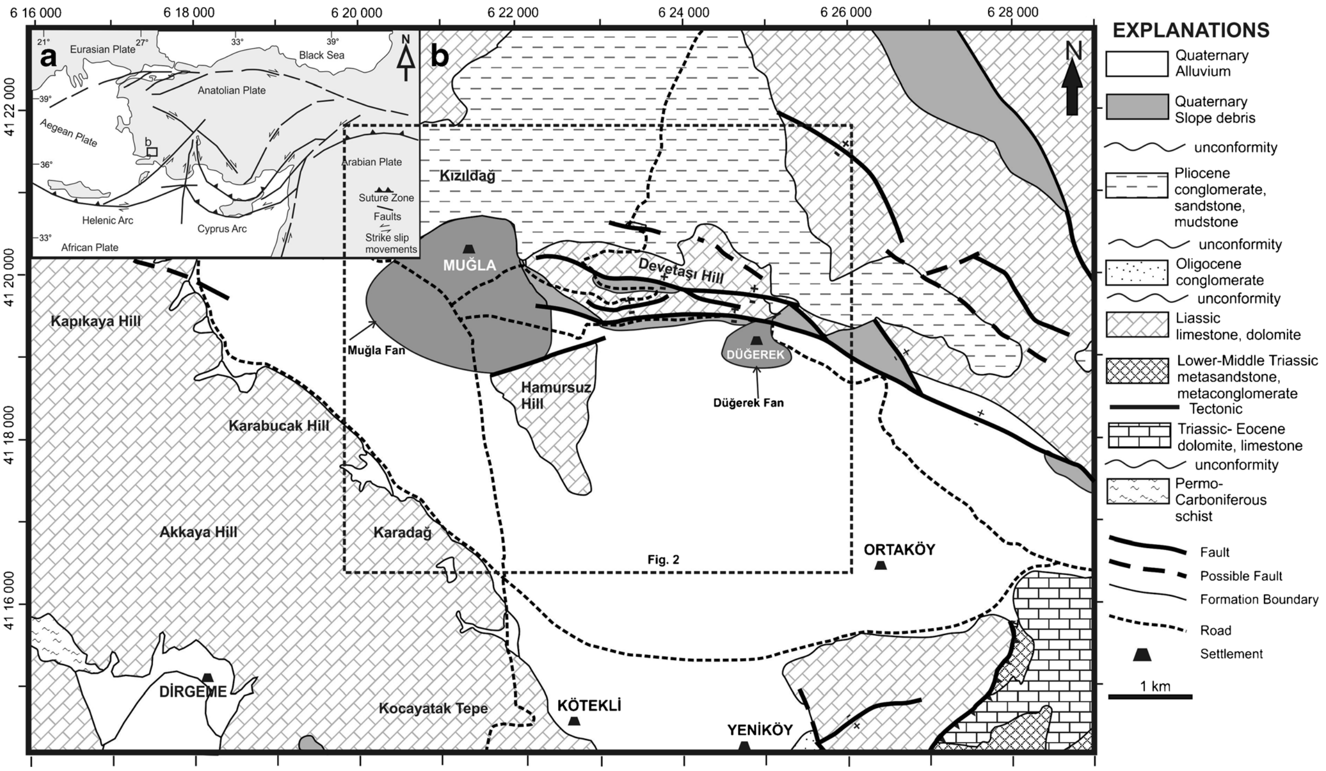


Fig. 1 (A) Main tectonic features of Turkey (modified from Savaşçın and Oyman 1998). (B) General geological map of the study area (modified from Aktimur et al. 1996; Gül et al. 2013; Akbaş et al. 2011; and http://yerbilimleri.mta.gov.tr/anasayfa.aspx: access date 10.04.2019). (C) The columnar section of the study area (modified from Aktimur et al. 1996; Göktaş 1998; Gül 2015)

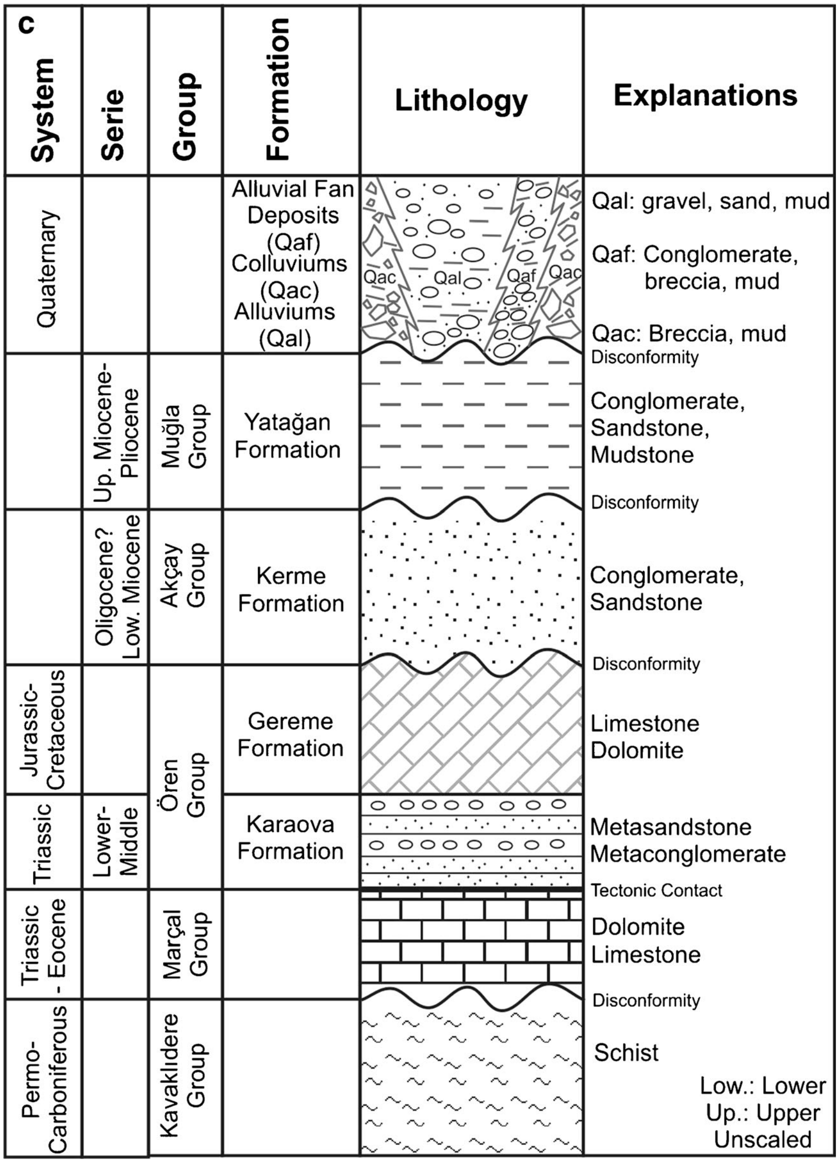


Fig. 1 (continued)

80° slope. The transverse sections of the Muğla Fan are plano-concave upwards geometry in the middle part, and wedge shaped at the edges. The apex part of the fan overlies the Yatağan Formation with angular unconformity. However, this relation was not clearly observed during the field studies due to soil cover and artificial fillings. The longitudinal section shows wedge shape of the fan deposits that laterally-gradually pass into the alluvial-colluvial deposits (Fig. 3). The upper part of Muğla Fan deposits is topographically higher than the alluvial deposits (Figs. 2 and 3). The older settlements of the Muğla City are located on top of the Yatağan Formation, and Quaternary alluvial fan deposits-colluviums (Fig. 3(A)). Recent settlements occupy the all fan deposits (Figs. 2 and 3(B)). After heavy rains (during winter), flash flooding waters directly flow to the western part of the Muğla Fan, cause local shallow ponding in a days. The pond area is larger than in the Düğerek area. Depending on the continuity of precipitation and temperature, ponding can survive a few weeks to one or two months.

Sedimentological properties The borehole data reveals that the proximal part of the fan contains the GM-GP (moderately to poorly graded gravels according to USCS (1985) – poorly sorted gravels) and the msG (muddy sandy Gravels and Gravel according to Folk (1954) classification). The GP-GM (poorly to moderately graded gravels according to USCS (1985) – moderately to well sorted gravels), the msG and mG (muddy sandy Gravels and muddy Gravel according to Folk (1954) classification) increase towards the mid fan and distal fan (Fig. 4). Locally, as in M-8 borehole (MMMM

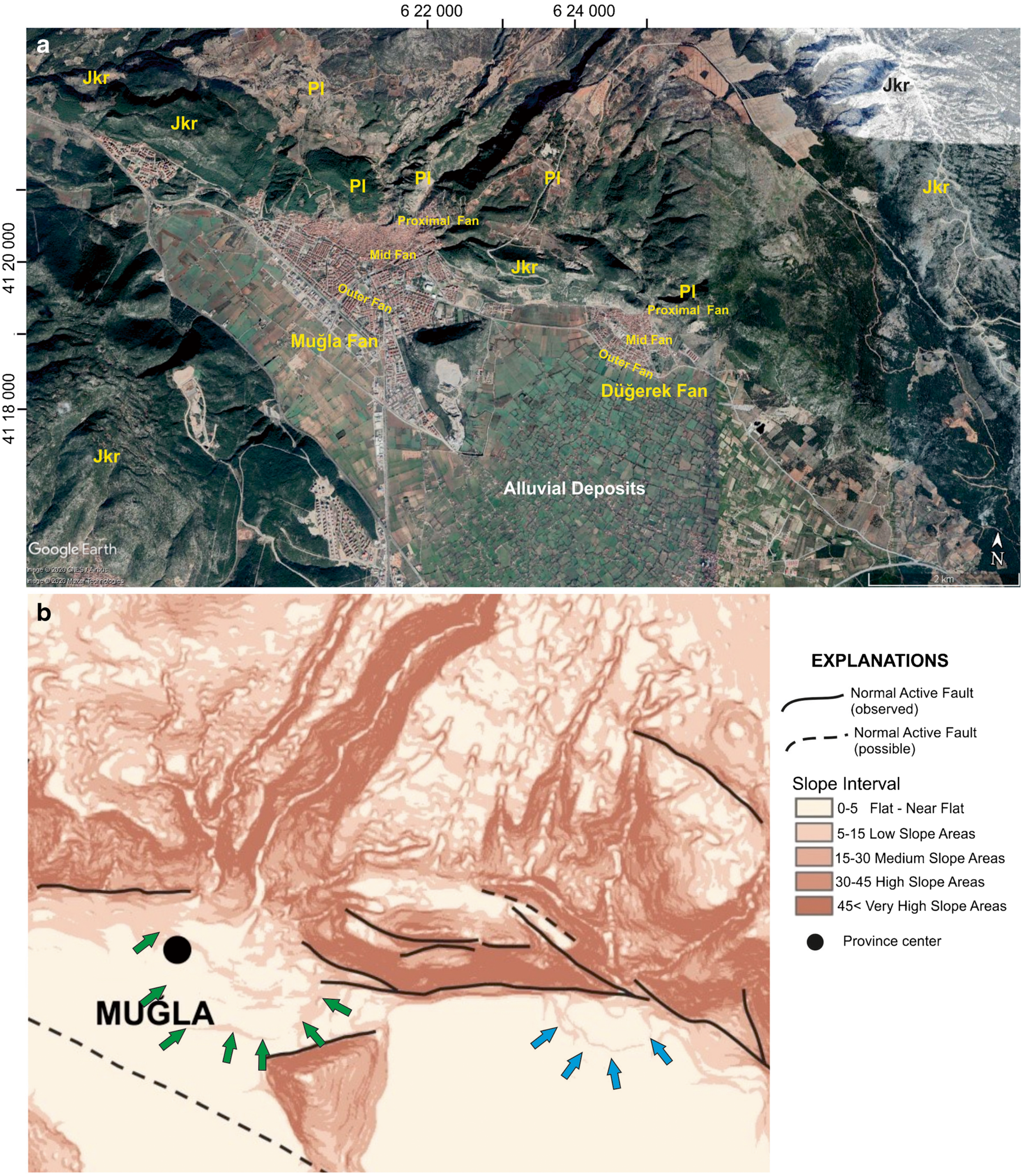
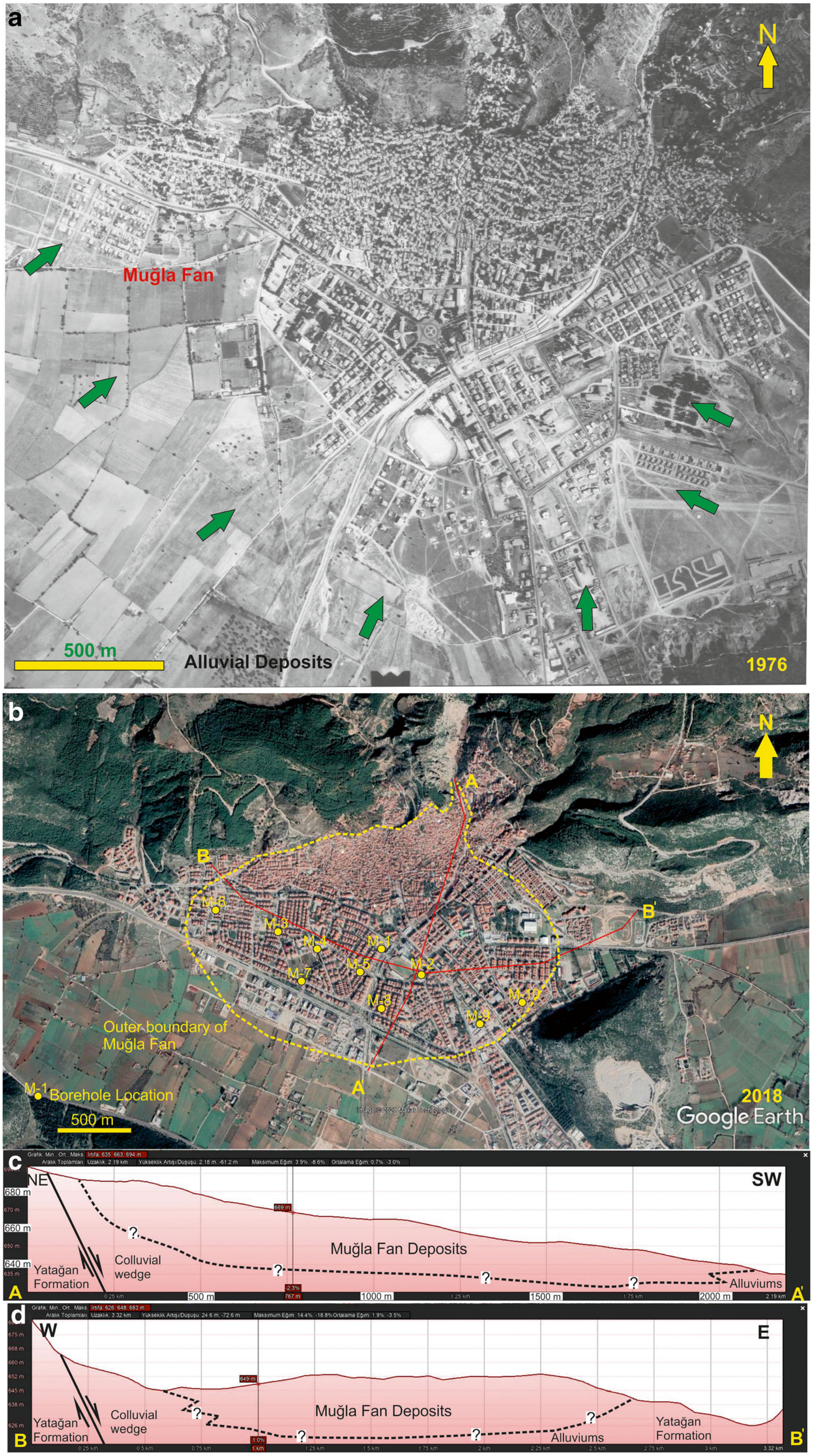


Fig. 2 (A) The Google-Earth view of the Düğerek and Muğla Fans in the Muğla Polje (Google-Earth 2020). (B) The DEM view of the Düğerek (blue arrow) and Muğla Fans (green arrow; modified from Gül et al. 2013)

2017), the GW (well graded-poorly sorted gravels) and the G (gravels) type sediments were detected. The mud size sediment bearing the CL (low plasticity Clay) – the gM or (g)sM (gravely mud or slightly gravely sandy mud) type sediment, the SM (silty sand), and the gM (gravely Mud) type sediments were also recorded (Figs. 4 and 5).

Due to the settlements, roads, parks, artificial fillings, and soil covers, there are not almost any field exposures of the

Fig. 3 (A) The aerial photo (1976) of the Muğla Fan, green arrows indicate approximate outer boundary of the Muğla Fan (modified from courtesy of the General Directorate of Mapping; 127, 1976, 153 21 3 78). (B) The Google-Earth view of the Muğla Fan (Google-Earth 2020). (C-D) Longitudinal (A-A’) and transverse (B-B’) cross-sections of the Muğla Fan



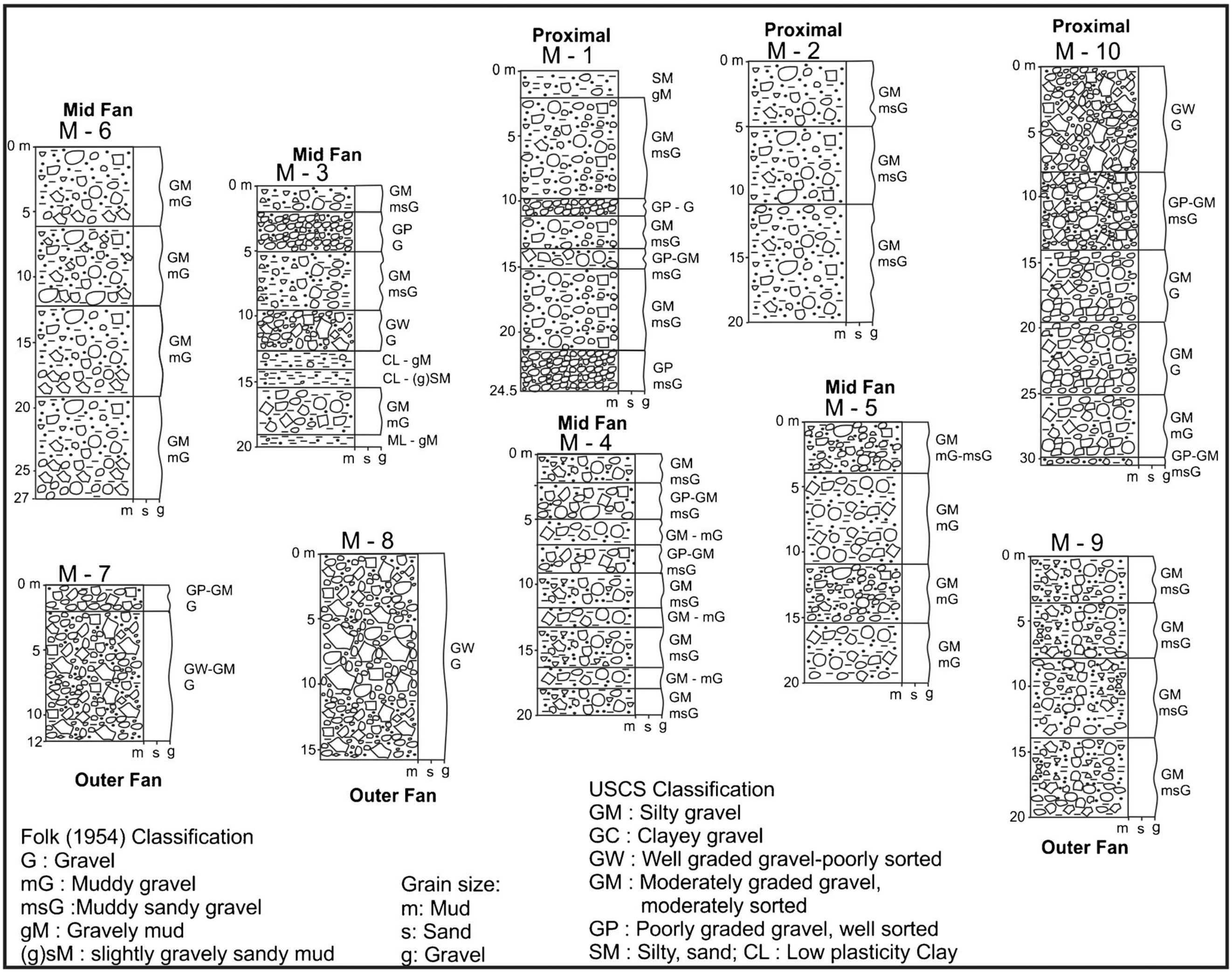


Fig. 4 Some borehole information's belongs to the different part of the Muğla Fan compiled from microzonation report of Menteşe District of Muğla Metropolitan Municipality (MMMM 2017)

Muğla Fan except some basement excavations of the constructions (Fig. 5(A)). Figures 5 (B) and (C) indicate the presence of > 5 m thick in the GP-GM (poorly to moderately graded gravels– moderately to well sorted gravels), the msG and the mG (muddy sandy gravels and muddy gravel). These are overlain by the 50-cm-thick muddy soil and later by the artificial filling. Figures 5 (D) and (E) point out roughly 9 m thick in the GP-GM (poorly to moderately graded gravels–moderately to well sorted gravels), the msG and the mG (muddy sandy gravels and muddy gravel). These are overlain by the alternation of GM – mG type gravel and paleosoil. All gravels are overlain by the recent soil with an erosive contact. Man-made channel including some stairs for decreasing the flow velocity is located at the apex of the fan (Fig. 5(A)). NE to SW directed channel carries the excess water and sediments directly to the center of the Polje.

Mineralogical properties The thin sections of the Yatağan Formation include only micrite and calcite mineral of limestone fragments (Zeybek 2017). Soil samples from distal part of the Muğla Fan contain kaolinite mineral based on CEC and XRD analysis (Küçükuysal et al. 2018).

Structural properties The Muğla Fault was not clearly detected in this region (Figs. 1(B) and 2). Gül et al. (2016) reported that Yatağan Formation inclined to NW with an angle of 20°–30°. They also defined various joint sets (73°/179° Dip/Dip direction; 71°/334°, 67°/174°, 74°/149°; 60°/160°, 72°/197°, 72°/8°, 74°/331°). Those joint sets led to densely fractured rocks at the apex of the Muğla Fan (Fig. 5(A)).

Düğerek Fan

Morphology The Düğerek Fan covers 1.26 km^2 area, and its perimeter is 4.53 km long, which longitudinally extends to a maximum of 1.2 km towards the SW direction. It has a radial distribution in down dip direction (Figs. 1, 2, and 6). The transverse sections of the Düğerek Fan illustrate the plano-

Fig. 5 Field photos of the Muğla Fan. (A) The apex part of the Muğla Fan is following the valley incised into the upper Miocene-Pliocene clastics of the Yatağan Formation. Man-made channel directly transfers the water from upper fan to the distal fan. Green arrows show a previous sediment route that recently occupied by buildings. (B, C) The basement photo from 200 m south of the M5 borehole. (D, E) The basement photo from 500 m northwest of the M9 borehole

concave upward geometry in the mid-part and wedge shape at the edges. An altitude of the fan is 750 m in apex part and extend to 620 m in the distal part. The fan is located in front of the normal faulted hills formed by the Jurassic-Cretaceous limestone and upper Miocene-Pliocene clastics. The rivers, bordered by 50–60° inclined valley walls, incised into older rocks and fed the Düğerek Fan (Fig. 2). A high of 950 m hills are located at the apex part of the fan; skirts of the hills have a 40–70° slope. Nearly horizontal and horizontal bedded, poorly sorted breccia of the fan deposits overlie the Yatağan Formation with angular unconformity (Figs. 6, 7, 8, and 9). The wedge shaped fan deposits laterally and gradually passes into the alluvial-colluvial deposits (Fig. 6). The Düğerek Fan deposits are topographically higher than the surrounding alluvial deposits (Figs. 2 and 6). The older settlements of the Düğerek district were located on top of the upper fan (Fig. 6(A)). Recent settlements occupy the all fan deposits (Figs. 2 and 6(B)). After heavy rains (during winter), flash flooding waters directly flow to the Polje center to the west of the Düğerek Fan and cause local ponding in a few hours. Ponding time, depending on the continuity of precipitation and temperature, can reach a few weeks to one or two months.

Sedimentological properties The Yatağan Formation (15°/310°, Dip/Dip direction) crops out below of the proximal part of the Düğerek Fan (Fig. 8). An alternation of 1–3 m thick, very poorly poorly sorted, clast supported breccia (pebblestone-cobblestone) levels and 5–20 cm thick marl-mudstone-calcilutite- rarely tuff levels were found in the Yatağan Formation. The gravels of the breccia levels are limestone fragments of the Gereme Formation and their sizes vary between 5 mm and 40 cm. The interstitial matrix of the gravels is the fine-grained sand and mud-sized sediments (Figs. 8 and 9).

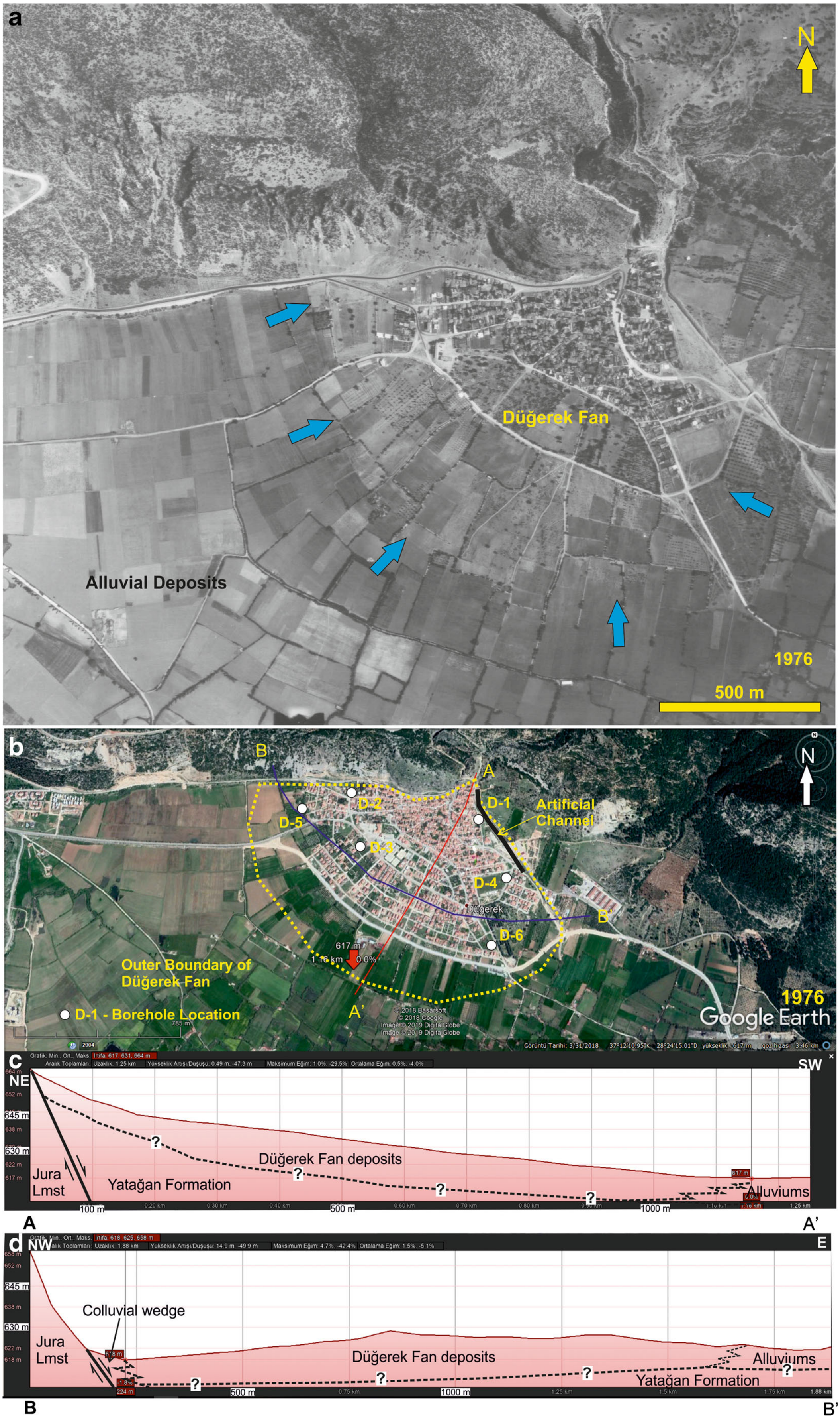
The Düğerek Fan starts with deformed, very poorly sorted, clast-supported breccia formed by subangular-angular limestone fragments of the Gereme Formation and lesser extent rounded limestone fragments of the Yatağan Formation (maximum clast size (MCS): ~ 35–40 cm, average clast size (ACS): ~ 8–10 cm) and crudely bedded units on footwall of the Muğla Fault (Figs. 7, 8, 9, and 10). A 5-m section was measured from the southern side of the fault scarp in the continuation of the fan (Figs. 9 and 10(A–C)). This part of the fan contains horizontally bedded breccia levels, whose thickness varies between 10 and 25 cm. The bottom part of the section is composed of relatively durable breccia level, including very poorly sorted, clast-supported, or matrix-supported cobblestone levels (Fig. 9(D)). The middle and upper parts of the section include poorly durable, matrix-supported, muddy breccia is covered with limestone fragments (Fig. 9(B)). The red colored muddy matrix quantity increases towards the upper levels (Fig. 9(C)).

Through the mid-fan and distal-fan, the coarser proximal fan deposits pass into the poorly-sorted, matrix-supported muddy breccia including limestone fragments in 5 mm to 10 cm size (Fig. 7). The amount of mud in these levels is considerably higher than the proximal part (Fig. 7). The borehole data points out that the proximal part of the fan contains the GM-GW (moderately to well-graded gravels according to USCS (1985) – poorly sorted gravels) and, the msG and G (muddy sandy gravels and gravel according to Folk (1954)). The GP-GM (poorly to moderately graded gravels are according to USCS (1985) – moderately to well sorted gravels) the msG and mG (muddy sandy gravels and muddy gravel according to Folk (1954)) increased towards the mid fan and outer fan (Fig. 7).

NE-SW directed man-made channel is extending from the apex part to the distal fan and ends within the alluvial deposits. This channel carries both the sediment and water, especially during the flash flood time. Excess sediment in channels cleaned periodically by the excavator and accumulated on the channel bank (Fig. 10(C)). The Düğerek Fan deposits pass into the alternations of mudstone and sub-rounded gravel-bearing conglomerate (Fig. 10(D)) (Küçükuysal et al. 2018) in 1 km south of the apex-proximal part.

Mineralogical properties The mineralogical composition of red colored mudstone part of the Yatağan Formation was determined by CEC and FTIR analysis (Fig. 9(E)). CEC value for D-2 was determined as a 5.22 meq/100g. Based on Grim (1968), the CEC value falls in a CEC range of kaolinites. Figure 9 (E) shows the FTIR spectra of D-2 with well-resolved bands of kaolinites in OH stretching vibrations of surface hydroxyl groups (3742, 3675, 3650 cm^{-1}) and one stretching vibration of inner hydroxyl groups (3618 cm^{-1}) (Saikia and Parthasarathy 2010; Djomgoue and Njopwouo 2013). Additionally, 875 cm^{-1} band corresponds to Al-OH bending vibration of kaolinite (Saikia and Parthasarathy 2010). Vibrations at 1744, 1457, and 875 cm $^{-1}$ are assigned to calcite (Vaculíková and Plevová 2005; Saikia and Parthasarathy 2010). Quartz was defined with Si-O bands at 1048 cm $^{-1}$ together with the doublet at 778–798 cm $^{-1}$ (Vaculíková and Plevová 2005). The existence of low intensity bands in 600–400 cm^{-1} range (Saikia and Parthasarathy 2010) and 1649 cm $^{-1}$ vibration figure out the presence of hematite. The results of D-2 sample revealed that the existence of kaolinite as dominant clay mineral associated with quartz, calcite, and to a lesser extent hematite (Fig. 9(E)). Calculated CEC value for D-1 (mud part of the Düğerek Fan) (6.72 meq/100 g) and almost the same FTIR-ATR spectrum as D-2 (Fig. 9(E)).

Structural properties The active Muğla Fault has created several fault scarps (Fig. 10(C)) that cut Jurassic-Cretaceous limestone, upper Miocene-Pliocene clastics (Fig. 10(A)), and


a
N
Düğerek Fan
Alluvial Deposits
1976
500 m
b
B
A
D-1
D-2
D-3
D-4
D-5
D-6
Artificial Channel
Düğerek
617 m
1.16 km
0.0%
B'
Outer Boundary of Düğerek Fan
D-1 - Borehole Location
A'
1976
Google Earth
c
NE
SW
645 m
630 m
Jura Lmst
Yatağan Formation
Düğerek Fan deposits
Alluviums
?
100 m
500 m
1000 m
A
A'
d
NW
E
645 m
630 m
Colluvial wedge
Jura Lmst
Düğerek Fan deposits
Alluviums
Yatağan Formation
?
500 m
1000 m
B
B'

◀ **Fig. 6** (A) The aerial photo (1976) of the Düğerek Fan, blue arrows indicate the approximate outer boundary of the Düğerek Fan (modified from courtesy of the General Directorate of Mapping; 137, 1976, 153.21 3.78). (B) The Google-Earth view of the Düğerek Fan (Google-Earth 2018). (C, D) Longitudinal (A-A') and transverse (B-B') cross sections of the Düğerek Fan

Quaternary alluvial fans (Fig. 10(C)) in the apex part. Figures 11 (A) and (B) show the topography and recent view of the Düğerek Fan. Two rivers cut the Gereme and Yatağan formations in the drainage feeding region of the Düğerek Fan, which merge in the proximal-apex part of the fan. Then, a single river valley cut and erodes the fault plane, the Yatağan Formation and the older Düğerek Fan deposits (Figs. 2, 6, and 11(A)). Pre-Pliocene topography of the northern Muğla region includes rugged topped Jurassic-Cretaceous limestone and nearly flat topped upper Miocene-Pliocene clastics (Fig. 11(C)). Subsequent normal faulting cuts both formation and led to the formation of the Muğla Polje (Fig. 11(D)) and numerous fault scarps as shown in Figs. 8, 10 (A), and 10 (C). Then, rivers eroded the older formations and carry the sediments to both formations and created colluviums and alluvial fan deposits, Fig. 10(B) (Fig. 11(E)). The latest activities' boundary fault cut all three units and present recent form of the Polje (Fig. 11(F)).

Discussion

The Muğla and Düğerek Fans have similar properties such as radial shape in plain view (Figs. 1 and 2), poorly sorted gravel bearing deposits (Figs. 4 and 7), occupied by settlements (Figs. 5(A) and 11(B)), and limitation in development due to man-made activities (Figs. 5(A) and 10(C)). However, they are also some significant size difference, even in close distance, ranging from feeding from identical provenance, development under the same climatic condition to tectonic activities. The Muğla Fan has been fed by the relatively big stream. This big stream has a large drainage area and is deeply incised into upper Miocene-Pliocene clastics and to a lesser extent Jurassic-Cretaceous limestone (Figs. 1 and 2). The Düğerek Fan has been fed by two small rivers which has two small branches. These branches have small drainage area and are relatively surficial/incised into Jurassic-Cretaceous limestone and to a lesser extent the upper Miocene-Pliocene clastics (Figs. 1 and 2). Strength of the upper Miocene-Pliocene clastics is lower than the Jurassic-Cretaceous limestone. The Muğla Fan is three times bigger than the Düğerek Fan (Figs. 1 and 2). Thus, more sediments have been obtained from the Muğla Fan drainage area. Other differences are related with tectonic activity in the apex of fans; for example, the two relatively small segments of the Muğla Fault, which are

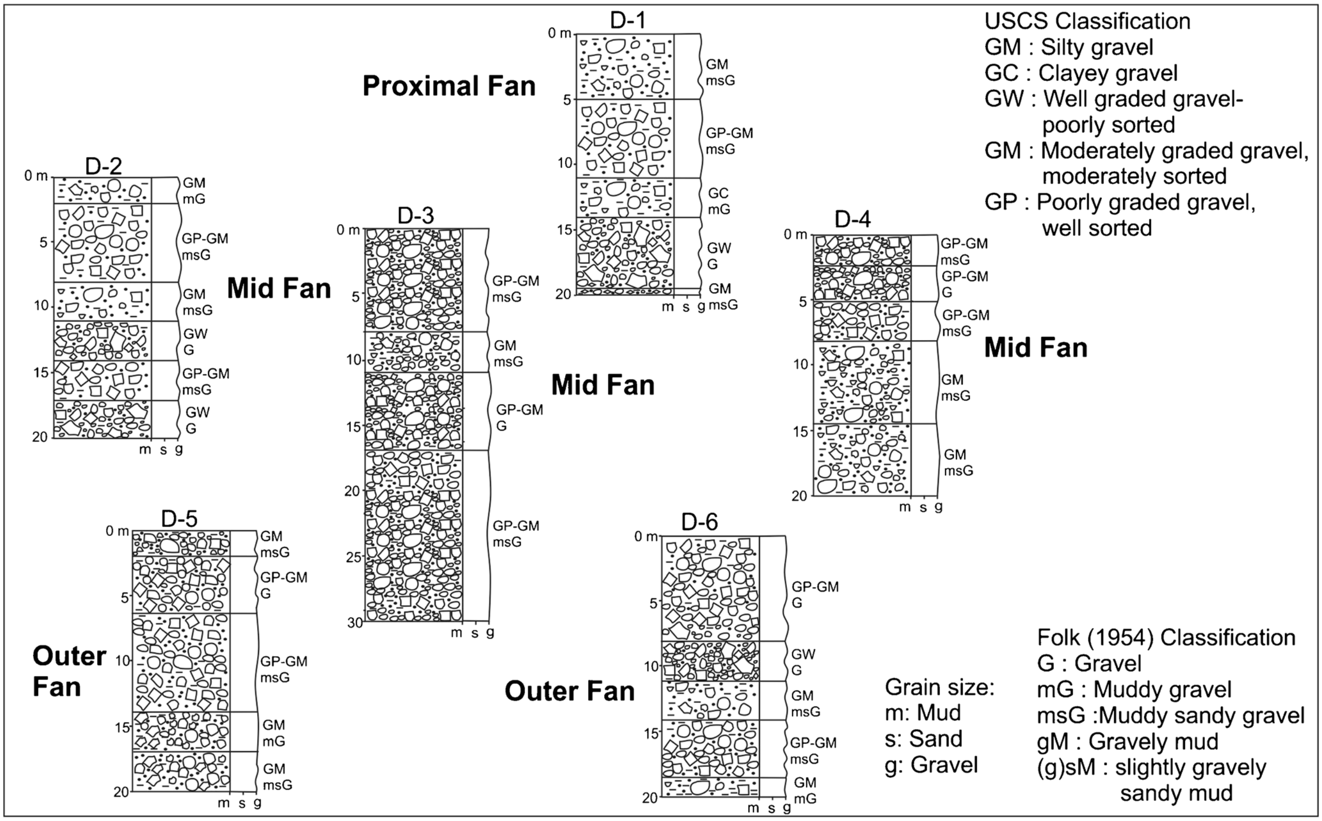


Fig. 7 Some borehole information's belonging to the different parts of the Düğerek Fan compiled from the microzonation report of Menteşe District of Muğla Metropolitan Municipality (MMMM 2017)

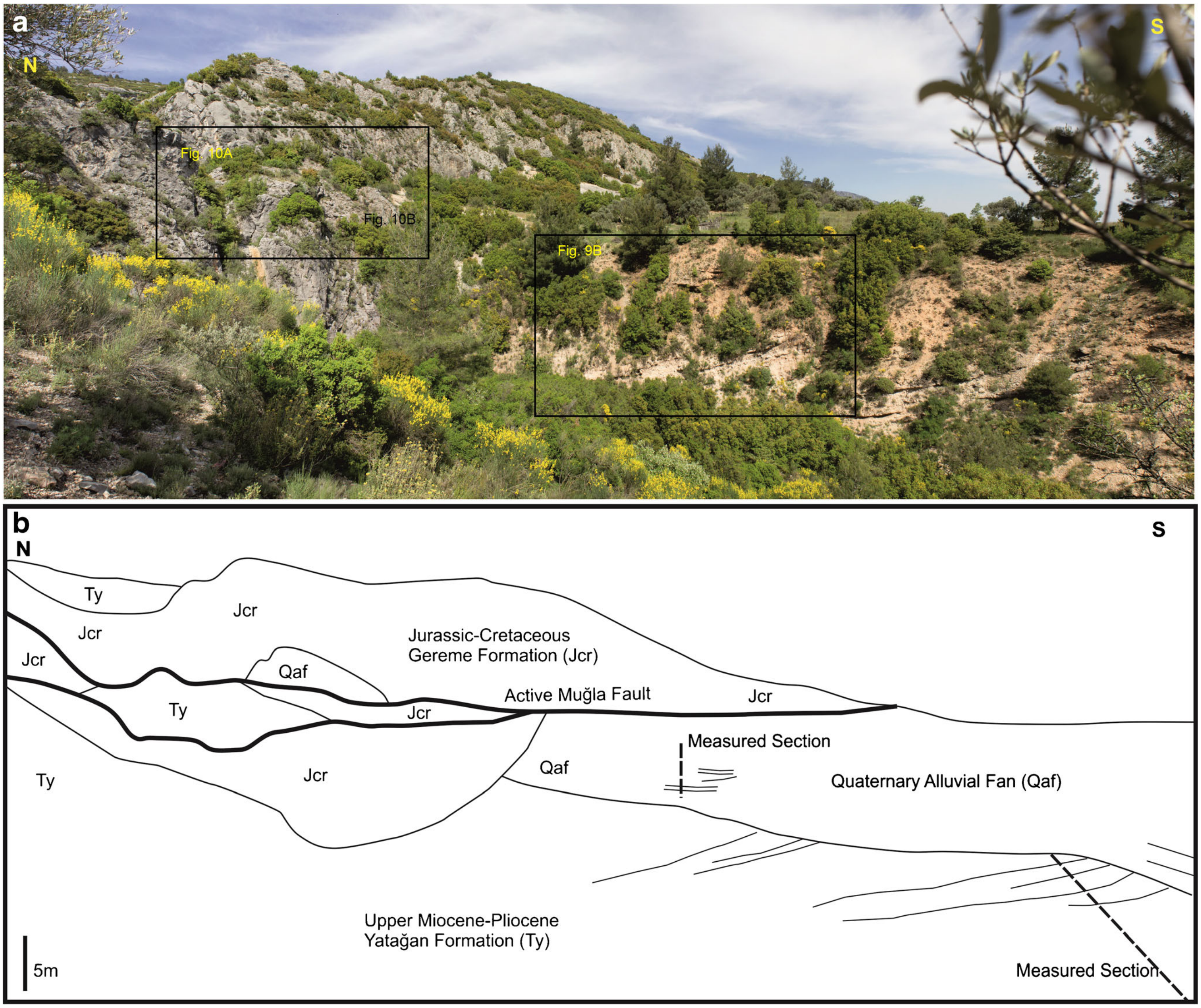


Fig. 8 (A) The cross-section of apex of the Düğerek Fan, whose deposits overlie the Yatağan Formation with angular unconformity. (B) Sketch diagram of the cross-section given in A

located at the apex of the Düğerek Fan (Fig. 11(E)). Deformation of fan sediments was determined in the Düğerek Fan, while it is not observed in the Muğla Fan.

Tectonic activity and climate were suggested as the two main controlling factors on alluvial fan development (Pope and Wilkinson 2005; Chen and Guo 2017; Bouzari 2020). Tectonic processes control the boundary, irregularity of the bottom topography, and the size of the sedimentary basin (Harvey et al. 2005; Gül et al. 2013; Gül 2015; Bouzari 2020). Both tectonic process and climate govern the amount-input-transportation of sediment and water (Harvey et al. 2005; Gül et al. 2013; Gül 2015; Houa et al. 2020; Blackburn et al. 2021). In addition to these factors, gravity, host rock type, drainage pattern, and human impact were all proposed as the other controlling factors for the development of alluvial fans (Coulthard et al. 2002; Crosta and Frattini 2004; Nemec and Kazancı 1999; Harvey et al. 2005; Shukla 2009; Sanders 2010; Walstra et al. 2010; Villacorta et al. 2019).

Tectonic

Normal fault (numerous example from Turkey have been listed in the introduction section), thrust fault (Shukla 2009; Bouzari 2020), and strike slip fault (Şaroğlu and Güngör 2019) activities can lead to form of alluvial fans. Ocakoğlu (2020) emphasized that the tectonic activity initiated a rapid geomorphologic change in the high angle normal faulted Büyük Menderes Graben. Polje evolution in the Isparta Angle with marsh and alluvial fillings in the east of the Muğla Fan was developed due to tectonic subsidence, karstification, and climatic changes (Deynoux et al. 2005; Kuzucuoğlu et al. 2019a). Development of the tectono-karstic plain in Central Anatolia with a river deposits, alluvial

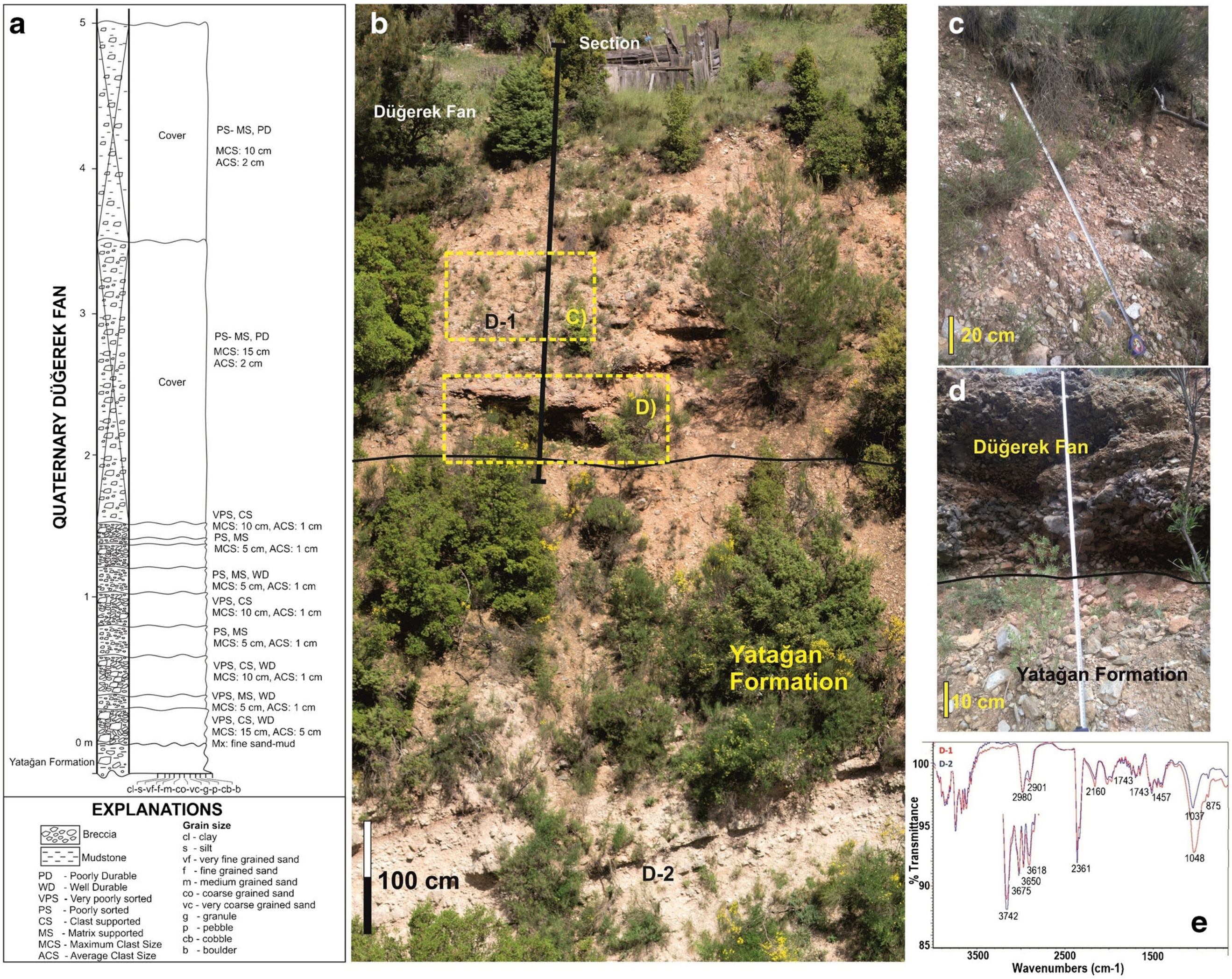


Fig. 9 (A) Measured section of the proximal part of the Düğerek Fan. (B) General field view of the location of the cross-section. (C) Close-up view of the fan deposits. (D) Close view of the contact between the Düğerek Fan and the Yatağan Formation clastics. (E) FTIR spectra of the muddy matrix of breccia in proximal part of the Düğerek Fan (Quaternary, D-1) and mudstone Yatağan Formation (upper Miocene-Pliocene; D-2)

fan, and lacustrine deposits was related with tectonic activity, karstification, and river erosion (Kuzucuoğlu et al. 2019a).

Indo-Gangetic Plain in N of India consists of numerous laterally coalescing mega alluvial fans (e.g., Gaula Fan, 30 km long) that developed under the thrust tectonic activity of the basin margin (Shukla 2009). Thrust tectonic along the Central and Eastern Alborz Mountains in the Eyvanekey, Garmsar, Semnan areas, northern Iran led to formation of the 131 alluvial fans (Bouzari 2020). Larger primary fans initiated with under the effect of the high tectonic subsidence and uplifting, secondary fans developed on first fans under the effect of the minor faults (Bouzari 2020). Normal tectonic activity initially controlled the compartment of the rifting, then basement topography, stratigraphic architecture and spatial distribution of the depositional basin in Guaizihu sag, Yingen-Ejinaqi Basin in China (Houa et al. 2020). Guaizihu sag contains graben-half grabens separated by local highs and alluvial fan and fan deltas (Houa et al. 2020). Fault segments created topographical highs acts as sediment source for alluvial fans (Houa et al. 2020).

Moreover, highly jointed rocks allow more physical weathering as well as higher amounts of sediments (Pope and Wilkinson 2005). Sequences with upward fining characterize the tectonically quiescent periods, while the coarsening upward sediments typify the intense tectonic activity period (Fidolini et al. 2013). Similarly, breccia level in colluvial wedge can be formed as a result of the tectonically active periods, while subsequent muddy parts represent the quiet period (Gül 2015). Thus, the alluvial sediment ages can be used for the interpretation of the activation age of the faults (Sarıkaya et al. 2015). The asymmetric profile of the Pliocene Eşen Graben in SW Anatolia was the result of intense tectonic activity and sediment input (Öner 2019).

Tectonic activities are the primary controlling factor for both the Muğla and Düğerek fan developments. Muğla and surrounding region have been developed as a depressional

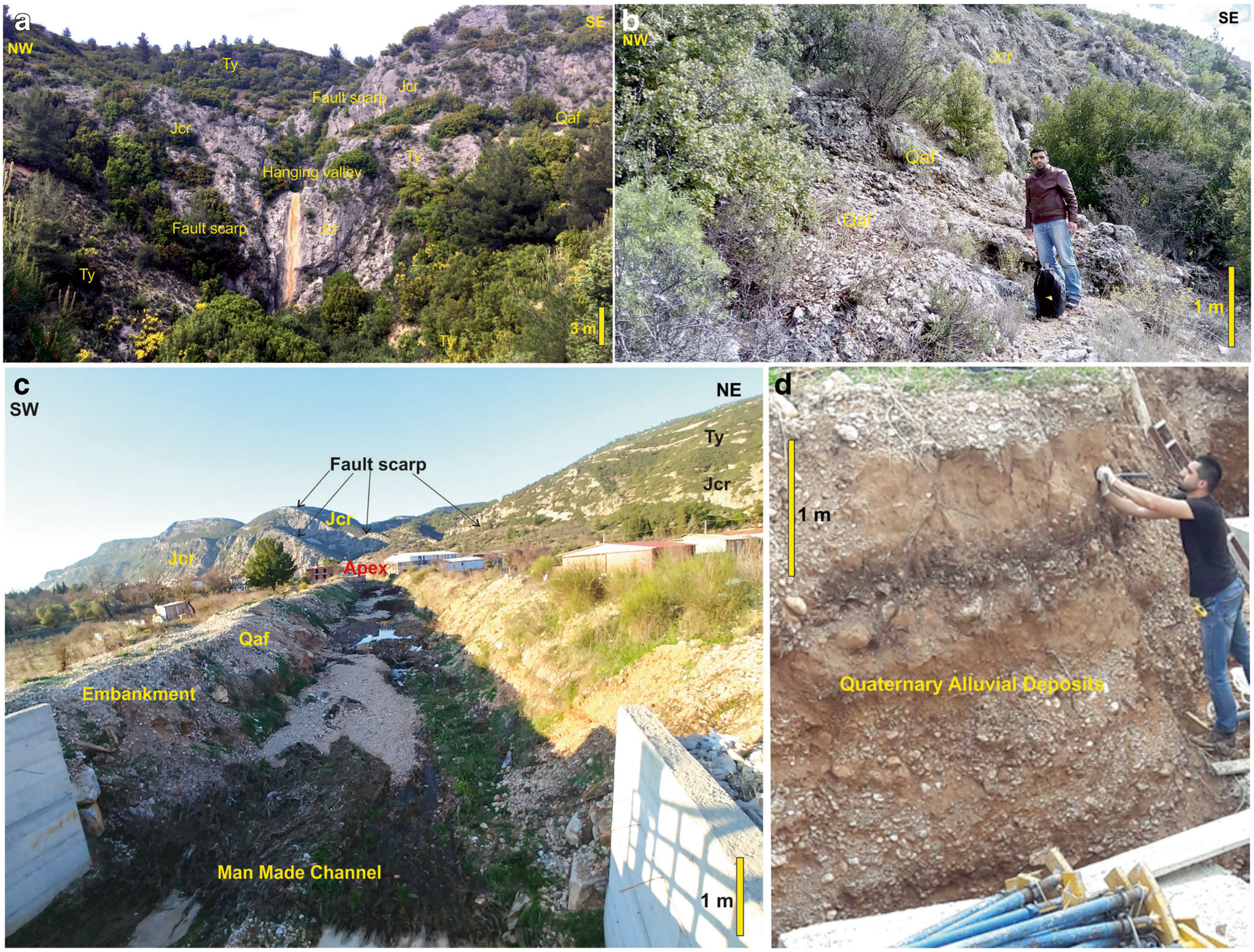


Fig. 10 (A) Two faults cut the Yatağan Formation and Düğerek Fan at the proximal part of the fan (faulting at the lower level and erosion cause the hanging valley). (B) General field view of the deformed Düğerek Fan deposits that attached to the footwall of the Muğla Fault Plane (Jcr: Jurassic-Cretaceous Limestone; Ty: Yatağan Formation; Qaf: Düğerek Fan deposits). (C) Man-made irrigation channel extends from the apex to the distal fan. Heavy rainfall at the mid December 2020 carries sediments to downdip direction from apex. Those sediments have been cleaned by the excavator and pour on to embankment. (D) The fan deposits pass into the subrounded-rounded limestone gravel bearing the muddy Gravel, and soils of the alluvial deposits at 1 km southwest of apex

basin and filled with clastics during the post-Pliocene (Kayan 1979), or late Miocene (Gürer et al. 2011, 2013). Intense tectonic activities during the Pleistocene created half graben-Muğla Polje (Kayan 1979). Those tectonic activities also led to some local highs that separated the Muğla and Düğerek Fans (e.g., by Houa et al. 2020). They also shaped a small, suitable, flat, and unhampered environment for fans. Complex tectonic history of the region also produced closely jointed rocks. Sezer (2003), Karabacak (2016) and Türe (2017) have emphasized the seismic activity of the Muğla Fault since ancient times. Perpendicular to the basin margin faults, structural alignments created weakness zone along small and large valleys, which transport the sediment down to dipper areas. Fault segments act as a sediment source that similar to Houa et al. (2020) observation. Big-scale tectonic activities caused sediment tilting and throwing like in the Düğerek Fan (Fig. 11(C–F)). Small scale tectonic activities with ground shaking have triggered the evolution, removing, and initiation of the downdip transportation of unstable–loose sediments on hinterland-source rocks. The tectonically active periods resulted in the deposition of coarse-grained sediments, while quiescent periods bring along the development of relatively finer-grained, muddy, and matrix-supported sediments. Due to the conical shape of the fans, both fans were evaluated as an unconfined fan and aggrading fan (Crosta and Frattini 2004; Scheinert et al. 2012).

Climate

Climate controls both physical and chemical weathering of rocks and transportation of sediments (Clemmensen et al. 2001; Mackel et al. 2003; Hartley et al. 2005; Löwner et al.

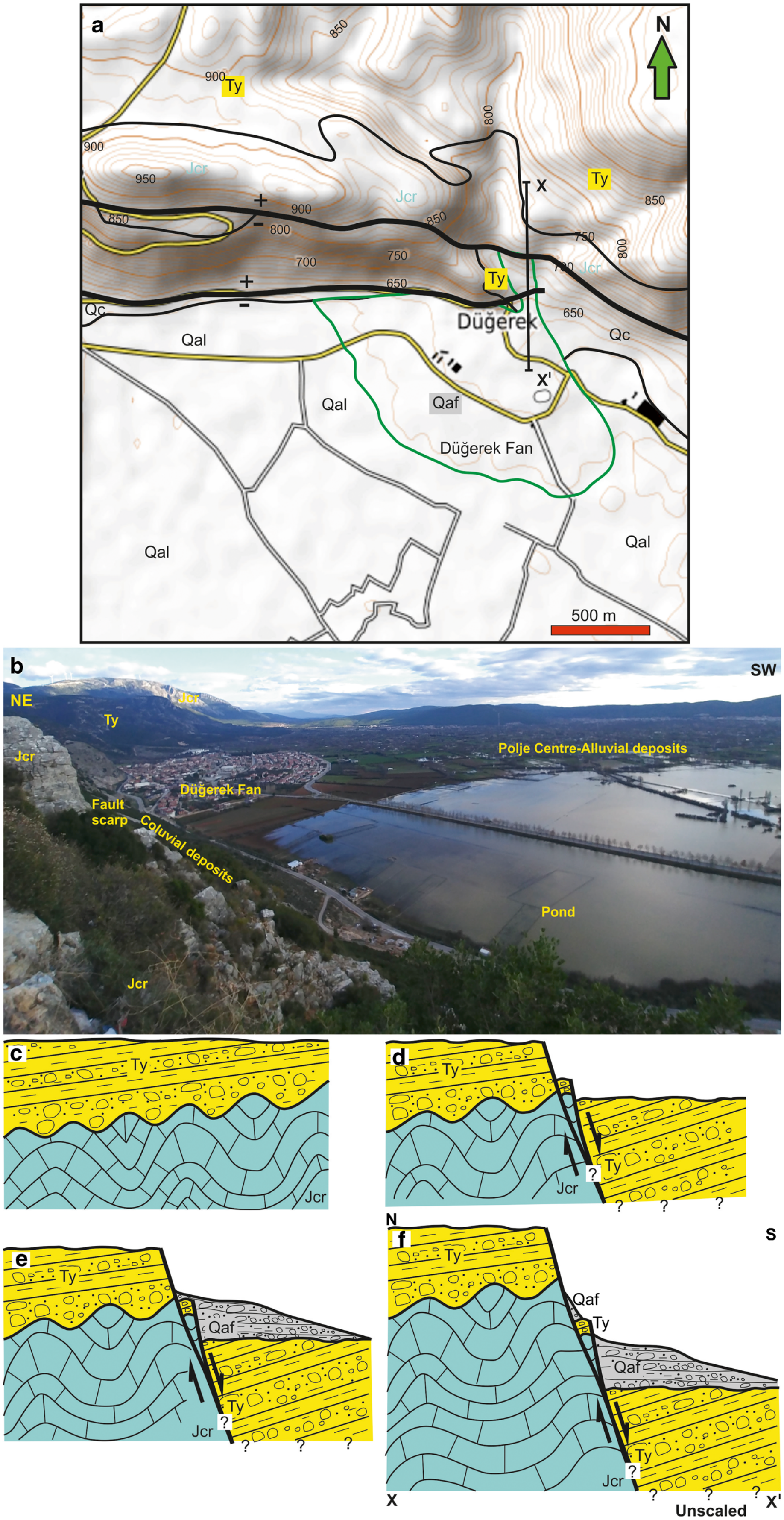


Fig. 11 Geological evolution of the Düğerek Fan. (A) The Yatağan Formation (upper Miocene-Pliocene; Ty) overlies the Gereme Formation limestone (Jurassic-Cretaceous; Jcr) with angular unconformity during late Miocene-Pliocene (Kayan 1979). (B) Field view of the Düğerek Fan. After the heavy rainfall at the mid December 2020, surface waters and percolated waters were accumulating at the Polje center. (C) After deposition of the Yatağan Formation, the Muğla Fault was active, and led to formation of the Muğla Polje (Pleistocene, Kayan 1979; end of Pliocene Gürer et al. 2011, 2013). (D) The Düğerek Fan deposits (Plio-Quaternary; Qaf) overlie the Yatağan Formation with angular unconformity. (E) Quaternary activity of the Muğla Fault (Türe 2017) was also cut the Düğerek Fan deposits. (F) Continuous erosion and deformation have been supplying the recent topographical view of the Düğerek Fan and surroundings

2005; Boggs Jr 2006; Blackburn et al. 2021). Climatic conditions were suggested as a main control on sediment supply, lithofacies, and sedimentary features in Guaizihu sag, Yingen-Ejinaqi Basin in China (Houa et al. 2020). Similarly, changing climate controlled the sediment supply, fluctuating water budget, lateral migration of channel of the Gaula Fan in N India (Shukla 2009). Humid climate promoted the gravel size sediments carried by the powerful rivers with a steeper gradient (fan expansion cycle A of Gaula Fan), while dry phase represented by debris flow sedimentation deposited due to catastrophic rains (cycle B) (Shukla 2009). Alluvial fan sediment characteristics including permeability organized the surface water flow, infiltration to the ground, and so hydrogeological condition (Blackburn et al. 2021). Those water also is feeding the ephemeral stream and lake at the end of the alluvial fan (Blackburn et al. 2021). Moreover, the freeze-thaw weathering and wetting-drying cycles under the climatic effects are the main physical weathering processes (Boggs Jr 2006).

Gül (2015) proposed that recent climatic conditions of the Muğla (including rainy winter and spring season; daily and seasonal temperatures differences) and closely jointed rock, promote the disintegration of source rock (physical weathering), and therefore controls the sediment quantity. The coarser-grained fan sediments signify intense rainy seasons. On the contrary, dry-arid climatic conditions resulted in less amount of water and sediment inputs, and compose the fine-grained sand-silt-clay dominated sediments. CEC values (Fig. 9(E)) confirmed the mineralogical compositions and the dominant clay mineral phase of the Düğerek Fan (D-1) to be identical to that Yatağan Formation (D-2). Presence of kaolinite as predominant clay mineral (low CEC values and intense spectral vibrations) in the bulk compositions of samples reveals the intense weathering and subsequent leaching. Zhang et al. (2016) proposed that kaolinite product of highly hydrolytic weathering under the effect of warm-humid climate with a minimum perennial temperature ~ 15 °C like in the Muğla. The hematite reddening represents mild to intense hydrolysis conditions due to the high internal drainage in such karstic nature of the carbonate host rocks (Boero and Schwertmann 1989). Fan properties affect the hydrogeological condition, such as surface flow and ground water circulation. They cause short-term ponding after heavy rainfall-flashflood.

Gravity

Slope with gravity effect diverts the sediment and regulates the sediment transportation type (debris flow, grain flow, rock fall) in recent sedimentation (Miall 1977; Sanders 2010; Gül 2015). Facies A (matrix supported cobble conglomerate), facies B (pebble conglomerate), facies C (pebbly sandstone), facies D (fine-grained sandstone), and facies E (mudstone) were separated in the Fangyan Formation in Danxia landform in Jianglangshan geopark in SE China based on lithology, sedimentary structures, bed thickness, and geometry (Chen and Guo 2017). Stream-flow dominated sediments were responsible from formation of the Fangyan Formation along the mountain fronts (Chen and Guo 2017). The poorly sorted, matrix-clast supported, disorganized granule-cobble conglomerates were alternated mudstone and sandy mudstone (in lesser amount) in alluvial fan environment of the Guaizihu sag, Yingen-Ejinaqi Basin, China (Houa et al. 2020). Disorganized matrix-clast supported conglomerates were interpreted as a product of the pseudoplastic (or viscous) debris flow or hyperconcentrated flood flow on the proximal fan, while sandy conglomerates and pebbly sandstones interpreted as a density flows or cohesionless debris flow (Houa et al. 2020). Four facies (disorganized gravel, horizontal bedded gravel, cross bedded gravel, sandy gravel and mottled sandy silt in proximal fan; horizontal bedded gravel, cross bedded gravel, laminated silty mud, mottled sandy silt in midfan; cross bedded sand, laminated silty mud, mottled sandy silt in distal fan; marix supported gravel, mottled sandy silt) were defined in 30-km-long Gaula Fan sequence in N India (Shukla 2009).

Similarly, high slope of both fan drainage areas and highly inclined fault scarp at the Polje margin led to form a debris flow dominated products such as poorly sorted, angular-subangular gravel (pebble-cobble breccia, GW-GM-GP types, G-msG types) at the apex and upper fan area. Several studies confirmed that sediment grain size is decreasing to downdip direction in alluvial fan (Alçiçek et al. 2005; Arzani 2005; Rojay et al. 2005; Shukla 2009; Sümer et al. 2012; Özkaymak et al. 2013; Houa et al. 2020). Similarly, the coarser deposits of Muğla and Düğerek fans pass into the pebble-fine cobble bearing muddy breccia (GP-GM types, msG-mG types) (waning flood deposits), which are mostly soft, reddish brown mudstones with desiccation cracks and plant debris, and product of waning flow at middle and distal part of the fan. Both fan deposits pass into fluvial clastics including pebble-cobble conglomerate and thick red colored mudstone. These sediments are probably the product of hyperconcentrated debris flow and debris flow (Hartley et al. 2005; Harvey et al. 2005; Houa et al. 2020).

Anthropogenic causes

Alluvial and colluvial sediments offered preferable settlement areas due to agriculturally fertile soil and soft-easily workable ground for the construction (Bauziene 2002; Mackel et al. 2003; Constante et al. 2010; Villacorta et al. 2019). Ventra and Clarke (2018) emphasized that the topographic changes, inundation, and run out in the length of sediment transport are complicated in urbanized areas on fan surfaces. Humans settled on the fan surfaces are under the risk of flood and debris flow hazards (Ortega et al. 2014; Ventra and Clarke 2018). An intensive agriculture, reforestation, and urbanization change the water velocity, upstream channelizing-scouring, bank undercutting, which decrease the sediment load that triggers the channel incision, and induces entrenchment and narrowing the fan (Ortega et al. 2014). Man-made levee, ancient irrigation channels, and dam construction played an important role in the rapid fan development and maintaining low gradient of the fan in the Lower Khuzestan (SW Iran) (Walstra et al. 2010). Wasklewicz and Scheinert (2016) showed the channelization effect on the embryonic-telescopic fan development in a few years. The capital city of Peru, Lima, is also located on top of the alluvial fan, 31% of the Peruvian live on it (Villacorta et al. 2019). Earthquakes, floods, debris flows, and landslides caused a significant death toll in this region (Villacorta et al. 2019). Rimac river channel migration and sediment transportation has been affected by the intense human intervention (Villacorta et al. 2019). Sediments in man-made channels decrease the river drainage efficiency, thus settlements near the present river channels under the risk of fast moving floods (Villacorta et al. 2019). Roberts et al. (2019) found catchment erosion during the intense human land use that decrease forest area, more sediment supply to the Nar Lake in the Central Anatolia. SW Turkey includes several grabens filled by the Neogene to Quaternary deposits (Alçiçek et al. 2005; Bozkurt and Mittwede 2005; Sözbilir 2005; Rojay et al. 2005; Süzen et al. 2006; Alçiçek 2007; Sümer et al. 2012; Özkaymak et al. 2013; Seyitoğlu and Işık 2015; Sümer et al. 2018; Elmas et al. 2019). Similar to the Muğla Polje, several settlements were marked on top of the alluvial fan, fluvial deposits such as the Söke town (Sümer et al. 2012), Ödemiş, Tire, Kiraz, Bayındır towns (Rojay et al. 2005) in north of the Muğla.

Early settlements in the Muğla region were in the northern rocky area, especially in ancient times (Fig. 3(A), 5(A), and 6(A); Güner 2001). The aerial photos in 1976 reveal that the distribution of the settlements concentrated on the apex part of the fan deposits (Figs. 3(A) and 6(A)). However, after the establishment of a university, the population drastically increase to over a hundred thousand (https://www.nufusu.com/ilce/mentese_mugla-nufusu, Access date 11.05.2020). These settlements cover the whole alluvial fan deposits and extend to the alluviums (Figs. 3, 5, 6, and 11). Man-made channel construction (Figs. 5(A) and 10(C)), extension of the previous channels and asphalt-impermeable roads directed the surface water flow into the Polje center (Pehlivan 1993). Thus, excess water has accumulated in Polje center especially during the winter-autumn season, then this water discharged into underground karstic system via dolines (Üstün et al. 2017). After heavy rainfall in mid-December 2020, coarse sediment accumulated in man-made channel in the eastern part of the Düğerek Fan (Fig. 10(C)). However, surface water inside Polje are immediately ponded in the west of the fan (Fig. 11(B)). Man-made channels now carry the sediment and water further away from the fan to the Polje center. The water initially accumulating in the channel and lowland agriculture area is then leaked to the underground, while the sediments are captured in the channel, and were later cleaned by the excavator in the embankment (Fig. 10(C)). Hydrogeological properties of both fans, ponding evolution time after rainfall, duration of ponding, and settlements effect on them are required continuous monitoring and researching for sustainable agriculture and irrigation, and for avoiding the negative effects of flashfloods.

Earlier formation of alluvial fans of the Muğla Polje was controlled by tectonic and climate, and recently, the development or renewing of fans have been stopped due to human interference. While the disadvantages created by these new conditions have been proven in different places (e.g., Ortega et al. 2014; Ventra and Clarke 2018; Villacorta et al. 2019), this situation has not yet been revealed in the Muğla polje. It requires comprehensive studies in terms of the agriculture, hydrogeology, and socio-economic impact.

Conclusion

The Muğla Polje is one of the good examples of grabens in SW Anatolia, which were filled by the Miocene - Quaternary deposits. Recent sedimentation in the Polje gives an example of the tectonism and climate relation. The Muğla Polje contains two alluvial fans (the Muğla and Düğerek fans) developed in front of the normal faulted basin margin. Both fans unconformably overlie the upper Miocene-Pliocene clastics rocks and Jurassic-Cretaceous limestone. They also laterally gradually pass into the colluvial close to the basin margin and alluvial deposits to the basin center. Tectonism and climate were determined as the main nature controlling factor for these alluvial fans at the beginning. Tectonic activities promote the disintegration of the bedrocks (Jurassic-Cretaceous limestone and upper Miocene-Pliocene clastics) and irregular basement topography of the Polje. The basal topography of Polje and sediment input point lead to form a two separate alluvial fans. The seismically active periods triggered the downdip movement of sediments and created coarse-grained (pebblestone and cobblestone) sediments of the fan. The subsequent tectonic cessation period was represented by the finer-grained-mud dominated levels. Excess and powerful water input during rainy periods carry coarser-grain sediment. Thus, this promote the coarse-grained (pebblestone and cobblestone) sediments of the fan. Those sedimentological properties also affect the hydrogeological properties and surface-subsurface flow in downdip direction. These flows cause ponding at the end of the fans. Fan deposits serve topographically higher and suitable area for settlements, subsequently the urbanization, man-made channels, and road cover fan deposits. Thus, human interference has now cut the sediment and water input from the apex to the downdip fan parts. At least, human impact allowed that flashflood can reach to ponding area in short time. However, other effects such as on agriculture, irrigation are unclear. This study suggests constant monitoring of the alluvial sedimentations to generate and balance between the local environment and urban life.

Acknowledgements The authors of this manuscript would like to thank the anonymous reviewers and the editors for their invaluable comments which significantly improved the quality of the paper. The efficient use of FTIR facility in Chemistry Department at Mugla Sitki Kocman University is highly acknowledged. The authors would like to thank Mr. Iliya Bauchi Danladi for English editorial checking of the paper.

References

Akbaş B, Akdeniz N, Aksay A, Altun İE, Balcı V, Bilginer E, Bilgiç T, Duru M, Ercan T, Gedik İ, Günay Y, Güven İH, Hakyemez HY, Konak N, Papak İ, Pehlivan Ş, Sevin M, Şenel M, Tarhan N, Turhan N, Türkecan A, Ulu Ü, Uğuz MF, Yurtsever A, et al. (2011) 1: 1.250.000 scaled Turkey Geology Map. Publication of Mineral Research and Exploration Institute of Turkey (Maden Tetkik ve Arama Genel Müdürlüğü Yayını), Ankara-Turkey

Aktimur HT, Sarıaslan MM, Sönmez M, Keçer M, Uysal Ş, Özmutaf M (1996) Muğla İlinin (Merkez İlçe) Arazi Kullanım Potansiyeli (Field Usage Potential of Muğla Province (central town)), Mineral Research and Exploration Institute Report, Report No: 9853; 33 p. (unpublished in Turkish)

Alçiçek MC (2007) Tectonic development of an orogen-top rift recorded by its terrestrial sedimentation pattern: the Neogene Eşen Basin of southwestern Anatolia, Turkey. Sediment Geol 200:117–140

Alçiçek MC, Kazancı N, Özkul M (2005) Multiple rifting pulses and sedimentation pattern in the Çameli Basin, southwestern Anatolia, Turkey. Sedimentary Geology 173:409–431

Arzani N (2005) The Fluvial Megafan of Abarkah Basin (Central Iran): an example of flash-flood sedimentation in arid lands. In: Harvey AM, Mather AE, Stokes M (eds) Alluvial Fans: Geomorphology, Sedimentology, Dynamics. Geological Society, London, Special Publications, 251:41-59

Atalay Z (1980) Muğla - Yatağan ve Yakın Dolayı Karasal Neojen'inin Stratigrafi Araştırması. (Stratigraphical investigations of Continental Neogene deposits of Muğla – Yatağan and vicinity). Türkiye Jeoloji Kurumu Bülteni (Bulletin of Geological Society of Turkey) 23:93–99 (in Turkish with English abstract)

Bauziene I (2002) Colluvisols as a component of erosional and accumulative soil cover structures of East Lithuania, 147-151 p. In: Micheli E, Nachtergaele FO, Jones RJA, & Montanarella L (2002) EUR 20398 EN, Soil Classification. European Soil Bureau Research Report No:7. 248p. Office for Official Publications of the European Communities, Luxembourg

Blackburn J, Comte JC, Foster G, Gibbins C (2021) Hydrogeological controls on the flow regime of an ephemeral temperate stream flowing across an alluvial fan. Journal of Hydrology 595:125994

Blair TC (1999) Cause of dominance by sheet flood versus debris flow processes on two adjoining alluvial fans. Death Valley, California. Sedimentology 46:1015–1028

Blair TC (2003) Features and origin of the giant Cucomungo Canyon alluvial fan, Eureka Valley, California. In: Chan MA, Archer AW (eds.) Extreme depositional environments: mega end members in geologic time. Geological Society of America Special Paper 370: 105-126

Blair TC, McPherson JG (1994) Alluvial fans and their natural distinction from rivers based on morphology: hydraulic processes. sedimentary processes, and facies assemblage. Journal Sedimentary Research 64: 450–489

Blair TC, McPherson JG (2009) Processes and forms of alluvial fans. Geomorphology and Desert Environments (2nd ed.) 413 - 467

Boero V, Schwertmann U (1989) Iron oxide mineralogy of terra rossa and its genetic implications. Geoderma 44:319–327

Boggs S Jr (2006) Principles of sedimentology and stratigraphy. Pearson Prentice Hall, Fourth Edition, 662 p

Bouzari S (2020) Fan morphology evidence on Late Quaternary deformation in the southern front of the Central and Eastern Alborz Mountains in the Eyvanekey, Garmsar, Semnan areas, Northern Iran. Arabian Journal of Geosciences 13:1106

Bozkurt E, Mittwede SK (2005) Introduction: evolution of continental extensional tectonics of western Turkey. Geodinamica Acta 18(3–4):153–165

Brückner H (2019) Rapid delta growth in historical times at Ephesus and Miletus—the examples of the Küçük and the Büyük Menderes Rivers. In: Kuzucuoğlu C, Çiner A, Kazancı N, eds. Landscapes and Landforms of Turkey. World Geomorphological Landscapes (10.1007/978-3-030-03515-0_4), Springer, 635 p, 293-306

Bull WB (1972a) Recognition of alluvial fan deposits in the stratigraphic record, In Rigby JK, Hamblin WK (Eds) Recognition of ancient sedimentary environments. Society of Economic Paleontologists and Mineralogists Special Publication No -16: 63–83

Bull WB (1972b) The alluvial-fan environment. Progress in Physical Geography 1:222 p

Chen LQ, Guo FS (2017) Upper Cretaceous alluvial fan deposits in the Jianglangshan Geopark of Southeast China: implications for bedrock control on Danxia landform evolution. Journal of Mountain Science 14(5):926–935. https://doi.org/10.1007/s11629-016-4024-1

Clemmensen LB, Lisborg T, Fornos JJ, Bromley RG (2001) Cliff front aeolian and colluvial deposits, Mallorca, Western Mediterranean: a record of climatic and environmental change during the last glacial period. Bull Geol Soc Den 48:217–232

Çokca E, Birand AA (1993) Determination of cation exchange capacity of clayey soils by the methylene blue test. Geotechnical Testing Journal 16(4):518–524

Constante A, Peña JL, Muñoz A, Picazo J (2010) Climate and anthropogenic factors affecting alluvial fan development during the late Holocene in the central Ebro Valley, northeast Spain. Holocene 21(2):275–286

Coulthard TJ, Macklin MG, Kirkby MJ (2002) A cellular model of holocene upland river basin and alluvial fan evolution. Earth Surf. Process. Landforms 27:269–288

Crosta GB, Frattini P (2004) Controls on modern alluvial fan processes in the Central Alps, Northern Italy. Earth Surf. Process. Landforms 29: 267–293

Denny CS (1967) Fans and pediment. American Journal of Science 265: 81–105

Deynoux M, Çiner A, Monod O, Karabıyıkoğlu M, Manatschal G, Tuzcu S (2005) Facies architecture and depositional evolution of alluvial fan to fan-delta complexes in the tectonically active Miocene Köprüçay Basin, Isparta Angle, Turkey. Sediment Geol 173(1–4): 315–343

Djomgoue P, Njopwouo D (2013) FT-IR spectroscopy applied for surface clays characterization. Journal of Surface Engineered Materials and Advanced Technology 3:275–282

Elmas G, Seyitoğlu G, Kazancı N, Işık V (2019) Syn-sedimentary tectonic markings in the Oligocene Datça-Kale-Acı Göl basin, western Anatolia. Bulletin of the Mineral Research and Exploration 160:1–20

Fidolini F, Ghinassi M, Aldinucci M, Billi P, Boaga J, Deiana R, Brivio L (2013) Fault-sourced alluvial fans and their interaction with axial fluvial drainage: An example from the Plio-Pleistocene Upper Valdarno Basin (Tuscany, Italy). Sedimentary Geology 289:19–39

Folk RL (1954) The distinction between grain size and mineral composition in sedimentary rock nomenclature. Jour. Geology 62:344–359

Göktaş F (1998) Stratigraphy and sedimentology of Neogene sedimentation around Mugla (SW Anatolia) (Mugla çevresi (GB Anadolu) Neojen tortullaşmasının stratigrafisi ve sedimantolojisi). Mineral and Research Institute of Turkey (Maden Teknik ve Arama Genel Müdürlüğü) Report No: 10225, Ankara, Turkey (unpublished, in Turkish) 181 p

Google-Earth (2018) (March 3, 2018). Muğla. 37° 12' 10.95" N 28° 24' 15.01"E. Eye alt 3.46 km. Image Başarsoft 2018. (Access date: 06.04.2019).

Google-Earth (2020). Image Maxar Technologies (Access date: 08.05.2020).

Görür N, Şengör AMC, Sakınç M, Tüysüz O, Akkök R, Yiğitbaş E, Oktay FY, Barka A, Sarıca N, EcevitoğluB DE, Ersoy Ş, Algan O, Güneysu C, Aykol A (1995) Rift formation in the Gökova region, Southwest Anatolia: implications for the opening of the Aegean Sea. Geol Mag 132(6):637–650

Grim RE (1968) Clay Mineralogy. McGraw-Hill, New York, pp 185–223

Gül M (2015) Lithological properties and environmental importance of the Quaternary Colluviums (Mugla, SW Turkey). Environmental Earth Sciences 74:4089–4108. https://doi.org/10.1007/s12665-015-4506-4

Gül M, Karacan E, Aksoy M (2013) An investigation of general geologic and engineering geological properties of Mugla city centre and surrounding (Mugla kenti yerleşim alanı ve yakın çevresinin genel jeolojik ve mühendislik jeolojisi özelliklerinin araştırılması), Mugla Sıtkı Koçman University Research Fund: BAP Project No: 12/54. 25 p. (in Turkish)

Gül M, Özbek A, Karacan E (2016) Rock fall hazard assessment in Asar Hill, ancient Mabolla City, Mugla—SW Turkey. Environmental Earth Sciences 75:1310. https://doi.org/10.1007/s12665-016-6113-4

Güner İ (2001) Muğla ve çevresindeki yerleşmelerini gelişimlerini etkileyen coğrafik faktörler (Geographical factors affecting the development of settlements in Muğla and its surroundings). Muğla Üniversitesi SBE Dergisi (Muğla University SBE Journal). Bahar-Spring 4:1–31 (in Turkish with English abstract)

Gürer ÖF, Özburan M, Sanğu E, Gürbüz A (2011) Muğla-Yatağan Havzası ve Çevresinin Neotektonik İncelemesi (Neotectonic investigation of Muğla-Yatağan Basin and surroundings), Scientific and Technological Research Council of Turkey (TUBİTAK) Project No: 108Y277, 102 p (in Turkish)

Gürer ÖF, Sanğu E, Özburan M, Gürbüz A, Sarıca-Filoreau N (2013) Complex basin evolution in the Go¨kova Gulf region: implications on the Late Cenozoic tectonics of southwest Turkey. Int J Earth Sci (Geol Rundsch) 102:2199–2221

Hartley AJ, Mather AE, Jolley E, Turner P (2005) Climatic Controls on Alluvial Fans Activity, Coastal Cordillera, Northern Chile, In: Harvey AM, Mather AE, Stokes M, (Eds) Alluvial Fans: Geomorphology, Sedimentology, Dynamics, Geological Society, London, Special Publications 251: 95-115

Harvey AM, Mather AE, Stokes M (2005) Alluvial fans: geomorphology, sedimentology, dynamics-introduction. A Review of Alluvial-Fan Research, In: Harvey AM, Mather AE, Stokes M (Eds) Alluvial Fans: Geomorphology, Sedimentology, Dynamics. Geological Society, London, Special Publications 251: 1-7

Hooke RL (1967) Processes on arid-region alluvial fans. Journal of Geology 75:438–460

Hooke RL (1968) Steady-state relationships of arid-region alluvial fans in closed basins. American Journal of Science 266:609–629

Houa Y, Wanga H, Fan T, Zhang H, Yang R, Li Y, Long S (2020) Rift-related sedimentary evolution and its response to tectonics and climate changes: a case study of the Guaizihu sag, Yingen-Ejinaqi Basin, China. Journal of Asian Earth Sciences 195:104370

Jones FO (1964) New fast accurate test measures bentonite in drilling mud. Oil & Gas Journal:76–78

Karabacak V (2016) Seismic damage in the Lagina sacred area on the Mugla Fault: a key point for the understanding of the obliquely situated faults of western Anatolia. Journal of Seismology 20(1): 277–289

Kayan İ (1979) Muğla-Yatağan Neojen Havzalarının Jeomorfolojisi (Geomorphology of the Muğla and Yatağan Neogene Basins), Scientific and Technological Research Council of Turkey (TUBİTAK) Project No TBAG:-189, 272 p. (in Turkish)

Kayan İ (2019) Landscape development and changing environment of Troia (North-western Anatolia). In: Kuzucuoğlu C, Çiner A, Kazancı N (eds.) Landscapes and Landforms of Turkey. World Geomorphological Landscapes (10.1007/978-3-030-03515-0_4), Springer, 635 p, 277-292

Kazancı N, Roberts N (2019) The lake basins of South-west Anatolia. In: Kuzucuoğlu C, Çiner A, Kazancı N (eds.) Landscapes and Landforms of Turkey. World Geomorphological Landscapes (10.1007/978-3-030-03515-0_4), Springer, 635 p, 325-338

Konak N, Akdeniz N, Öztürk EM (1987) Geology of the South of Menderes Massif: IGCP Project No.5: correlation of Variscan and Pre-Variscan events of the Alpine-Mediterranean Mountain Belt. Field Meeting, Turkey, Sept. 13-19, 1987a, Guide Book For the Field Excursion Along Western Anatolia, Turkey, 42-53

Küçükuysal C, Gül M, Aghayev T (2018) Muğla Polyesi Kırmızı Akdeniz Toprakları (Terra Rossa): Mineralojik, Mikromorfolojik, Jeokimyasal Ve Pedolojk Özellikleri (Red Mediterranean Soils (Terra Rosa) of the Muğla Polje: Mineralogical, Micromorphological, Geochemical and Pedological Properties). Scientific and Technological Research Council of Turkey (TUBİTAK 1002), Project No:116Y027, 74 p. (in Turkish)

Kuzucuoğlu C (2019) Geomorphological landscapes in the Konya Plain and surroundings. In: Kuzucuoğlu C, Çiner A, Kazancı N (eds.) Landscapes and Landforms of Turkey. World Geomorphological Landscapes (10.1007/978-3-030-03515-0_4), Springer, 635 p, 353-368

Kuzucuoğlu C, Çiner A, Kazancı N (2019a) The geomorphological regions of Turkey. In: Kuzucuoğlu C, Çiner A, Kazancı N (eds.) Landscapes and Landforms of Turkey. World Geomorphological Landscapes (10.1007/978-3-030-03515-0_4), Springer, 635 p, 41–178

Kuzucuoğlu C, Şengör AMC, Çiner A (2019b) The tectonic control on the geomorphological landscapes of Turkey. In: Kuzucuoğlu C, Çiner A, Kazancı N (eds.) Landscapes and Landforms of Turkey. World Geomorphological Landscapes (10.1007/978-3-030-03515-0_4), Springer, 635 p, 17–40

Löwner MO, Preston NJ, Dikau R (2005) Reconstruction of a colluvial body using geoelectrical resistivity. Z Geomorph N F 49(2):225–238

Mackel R, Schneider R, Seidel J (2003) Anthropogenic impact on the landscape of southern Badenia (Germany) during the Holocene—documented by colluvial and alluvial sediments. Archaeometry 45(3):487–501

Miall AD (1977) A review of the braided river depositional environment. Earth-Sci. Rev. 13:1–62

MMMM (2017) Microzonation study report based on the zoning plan of a total of 2069,6 ha region located within the boundaries of the county of Menteşe in Muğla province (by Zemson company), 605 p (unpublished report in Turkish).

Nemec W, Kazancı N (1999) Quaternary colluvium in west-central Anatolia: sedimentary facies and palaeoclimatic significance. Sedimentology 46:139–170

Nichols G (2005) Tertiary alluvial fans at the Northern Margin of the Ebro Basin a review, In: Harvey AM, Mather AE, Stokes M (eds) Alluvial Fans: Geomorphology, Sedimentology, Dynamics. Geological Society, London Special Publications 671: 187-206

Ocakoğlu F (2020) Rapid Late Quaternary denudation of the Karacasu Graben in response to subsidence in the Büyük Menderes Corridor: insights from morphotectonics and archaeogeology. Geomorphology 357:107–117

Öner E (2019) Landscape development of the Eşen Valley and Delta Plain (Letoon and Patara Sites). In: Kuzucuoğlu C, Çiner A, Kazancı N (eds.) Landscapes and landforms of Turkey. World Geomorphological Landscapes (10.1007/978-3-030-03515-0_4), Springer, 635 p 307-324

Ortega JA, Razola L, Garzón G (2014) Recent human impacts and change in dynamics and morphology of ephemeral rivers. Nat. Hazards Earth Syst. Sci. 14:713–730

Özkaymak Ç, Sözbilir H, Uzel B (2013) Neogene–Quaternary evolution of the Manisa Basin: evidence for variation in the stress pattern of the İzmir-Balıkesir Transfer Zone, western Anatolia. Journal of Geodynamics 65:117–135

Özsayın E, Gürbüz A, Kuzucuoğlu C, Erdoğu B (2019) Salted landscapes in the Tuz Gölü (Central Anatolia): the end stage of a Tertiary Basin. In: Kuzucuoğlu C, Çiner A, Kazancı N (eds.) Landscapes and Landforms of Turkey. World Geomorphological Landscapes (10.1007/978-3-030-03515-0_4), Springer, 635 p 339-352

Pehlivan AR (1993) Muğla havzası ve dolayındaki polyelerin hidrojeolojik incelemesi (Hydrogeological investigation of Mugla basin and surrounding poles) İstanbul Üniversitesi Deniz Bilimleri Enstitüsü (Istanbul University, Institute of Marine Science), Yüksek Lisans Tezi (M.Sc. Thesis), 153 p. (unpublished, in Turkish)

Pope RJJ, Wilkinson KN (2005) Reconciling the Roles of climate and tectonics in Late Quaternary fan development on the Spartan Piedmont, Greece, In: Harvey AM, Mather AE, Stokes M (eds) Alluvial Fans: Geomorphology, Sedimentology, Dynamics. Geological Society, London, Special Publications 251: 133-152

Roberts N, Allcock SL, Barnett H, Mather A, Eastwood WJ, Jones M, Primmer N, Yiğitbaşıoğlu H, Vannière B (2019) Cause-and-effect in Mediterranean erosion: the role of humans and climate upon Holocene sediment flux into a central Anatolian lake catchment. Geomorphology 331:36–48

Rojay B, Toprak V, Demirci C, Süzen L (2005) Plio-Quaternary evolution of the Küçük Menderes Graben Southwestern Anatolia, Turkey. Geodinamica Acta 18(3-4):317–331

Saikia B, Parthasarathy G (2010) Fourier transform infrared spectroscopic characterization of kaolinite from Assam and Meghalaya, Northeastern India. J. Mod. Phys. 1:206–210

Sanders D (2010) Sedimentary facies and progradational style of a Pleistocene talus-slope succession, Northern Calcareous Alps, Austria. Sediment Geol 228:271–283

Sarıkaya MA, Yıldırım C, Çiner A (2015) No surface breaking on Ecemiş fault, central Turkey, since Late Pleistocene (64.5 ka); new geomorphic and geochronologic data from cosmogenic dating of offset alluvial fans. Tectonophysics 649:33–46

Şaroğlu F, Güngör Y (2019) Fairyland in the Erzurum High Plateau, 25 Eastern Anatolia. In: Kuzucuoğlu C, Çiner A, Kazancı N (eds.) Landscapes and Landforms of Turkey. World Geomorphological Landscapes (10.1007/978-3-030-03515-0_4), Springer, 635 p 461-470

Şaroğlu F, Emre Ö, Boray A (1987) Türkiye'nin Diri Fayları ve Depremsellikleri (Active faults and seismicity of Turkey). General Directorate of Mineral Research and Exploration, Ankara, 394 p. (in Turkish)

Savaşçın MY, Oyman T (1998) Tectono-magmatic evolution of alkaline volcanics at the Kırka-Afyon-Isparta structural trend, SW Turkey. Turk J Earth Sci 7:201–214

Scheinert C, Wasklewicz T, Staley D (2012) Alluvial fan dynamics – revisiting the field. Geography Compass 6(12):752–775

Schumm SA (1977) The fluvial system. Wiley, New York, 338 p

Seyitoğlu G, Işık V (2015) Late Cenozoic extensional tectonics in western Anatolia: exhumation of the Menderes core complex and formation of related basins. Bulletin of the Mineral Research and Exploration 151:49–109

Sezer İL (2003) Seismic risk and activity in Mugla region (Mugla yöresinde deprem aktivitesi ve riski). IV. Quaternary Colloqium-Kuvaterner Çalıştayı. Istanbul Technical University-Eurasian Earth Science Institute (İTÜ Avrasya Yerbilimleri Enstitüsü), 111-120 (in Turkish)

Shukla UK (2009) Sedimentation model of gravel-dominated alluvial piedmont fan, Ganga Plain, India. Int J Earth Sci (Geol Rundsch) 98:443–459

Sözbilir H (2005) Oligo-Miocene extension in the Lycian orogen: evidence from the Lycian molasse basin, SW Turkey. Geodinamica Acta 18(3–4):255–282

Starkel L (1983) Climatic change and fluvial response. In: Gardner R, Scoging H (eds) Mega-geomorphology. Clarendon Press, Oxford, pp 195–211

Sümer Ö, İnci U, Sözbilir H (2012) Tectono-sedimentary evolution of an Early Pleistocene shallow marine fan-deltaic succession at the western coast of Turkey. Geodinamica Acta 25(3-4):112–131

Sümer Ö, Uzel B, Özkaymak Ç, Sözbilir H (2018) Kinematics of the Havran-Balıkesir Fault Zone and its implication on geodynamic evolution of the Southern Marmara Region, NW Anatolia. Geodinamica Acta 30(1):306–323

Süzen ML, Toprak V, Rojay B (2006) High-altitude Plio–Quaternary fluvial deposits and their implication on the tilt of a horst, western Anatolia, Turkey. Geomorphology 74:80–99

Türe O (2017) Tectonic geomorphology of Muğla - Yatağan region. Master of Science Thesis, Muğla Sıtkı koçman University, Institute of Applied Sciences, 132 p

USCS (1985) Classification of soils for engineering purposes: annual book of ASTM Standards, D 2487-83, 04, American Society for Testing and Materials, 395–408

Üstün AB, Osmançelebioğlu R, Boyraz-Aslan S (2017) Muğla Polyesi ve tortulları (Muğla Polje and Its Sediments). Abstracts of the 70th Geological Congress of Turkey. 10-14 April 2017, Ankara, 400-401 (in Turkish with English abstract)

Vaculíková L, Plevová E (2005) Identification of clay minerals and micas in sedimentary rocks. Acta Geodyn. Geomater. 2(2-138):167–175

Ventra D, Clarke LE (2018) Geology and geomorphology of alluvial and fluvial fans: current progress and research perspectives In: Ventra D, Clarke LE (eds) 2018. Geology and Geomorphology of Alluvial and Fluvial Fans: Terrestrial and Planetary Perspectives. Geological Society, London, Special Publications 440: 1–21.

Villacorta SP, Evans KG, De Torres TJ, Llorente M, Prendes N (2019) Geomorphological evolution of the Rimac River's alluvial fan, Lima, Peru. Geosciences Journal 23-3:409–424

Walstra J, An Heyvaert VM, Verkinderen P (2010) Assessing human impact on alluvial fan development: a multidisciplinary case-study from Lower Khuzestan (SW Iran). Geodinamica Acta 23(5-6):267–285

Wasklewicz T, Scheinert C (2016) Development and maintenance of a telescoping debris flow fan in response to human-induced fan surface channelization, Chalk Creek Valley Natural Debris Flow Laboratory, Colorado, USA. Geomorphology 252:51–65

Zeybek M (2017) Geological factors controlling cave occurences within clastic sediments of Yatağan Formation (Upper Miocene-Pliocene, SW Turkey). Mugla Sıtkı Koçman University, Institute of Natural and Applied Sciences, Master of Science Thesis, Muğla-Turkey, 89 p. (unpublished)

Zhang C, Guo Z, Deng C, Ji X, Wu H, Paterson GA, Chang L, Li Q, Wu B, Zhu R (2016) Clay mineralogy indicates a mildly warm and humid living environment for the Miocene hominoid from the Zhaotong Basin, Yunnan, China. Scientific Reports 6:20012. https://doi.org/10.1038/srep20012