SOCIETÀ TOSCANA
DI
SCIENZE NATURALI
RESIDENTE IN PISA

ATTI
DELLA
SOCIETÀ TOSCANA
DI
SCIENZE NATURALI

MEMORIE • SERIE A • VOLUME CXXXII • ANNO 2025

Edizioni ETS

ATTI DELLA SOCIETÀ TOSCANA DI SCIENZE NATURALI
MEMORIE
Via Santa Maria, 53 - 56126 Pisa

Rivista di proprietà della Società Toscana di Scienze Naturali. Fondata nel 1875, la rivista pubblica Memorie e Note originali, recensioni, corrispondenze e notiziari nel campo delle Scienze Naturali. È inviata ai soci e depositata in biblioteche corrispondenti. Tutti i contenuti dei volumi a stampa (articoli originali, comunicazioni brevi, notizie e recensioni) sono liberamente disponibili in rete, in conformità all'Open Access, sulle pagine http://www.stsn.it/en/memorie-serie-a.html (Serie A) e http://www.stsn.it/en/memorie-serie-b.html (Serie B).
Journal owned by Società Toscana di Scienze Naturali. Founded in 1875, the journal publishes original papers, short communications, news and book reviews on Natural Sciences. The Journal is sent to Società Toscana di Scienze Naturali members and deposited in selected libraries. All content of the printed version (original papers, short communications, news and book reviews) is freely available online in accordance with the Open Access at http://www.stsn.it/en/memorie-serie-a.html (Serie A) and http://www.stsn.it/en/memorie-serie-b.html (Serie B).

Gli Atti sono pubblicati in due volumi (Serie A - Abiologica, ISSN 0365-7655; Serie B - Biologica, ISSN 0365-7450) all'anno nel mese di dicembre. Possono essere pubblicati ulteriori volumi, definiti Supplementi, su temi specifici.
Atti are published yearly in two Issues (Serie A - Abiological, ISSN 0365-7655; Serie B - Biological, ISSN 0365-7450) in December. Some monographic volumes may be published as Supplementi.

Le lingue usate dalla rivista sono l'inglese o l'italiano // *The languages of the journal are English or Italian.*

La corrispondenza deve essere inviata ai Segretari agli Atti (per la Serie A: A. Chelli, Dipartimento di Chimica, Scienze della Vita e della Sostenibilità Ambientale, Parco Area delle Scienze, 157/A - 43124 Parma, email: attia@stsn.it; per la Serie B: D. Ciccarelli, Dipartimento di Biologia, via Derna, 1 - 56126 Pisa, e-mail: attib@stsn.it).
The correspondence must be sent to Editors (for Serie A: A. Chelli, Dipartimento di Chimica, Scienze della Vita e della Sostenibilità Ambientale, Parco Area delle Scienze, 157/A - 43124 Parma, email: attia@stsn.it; for Serie B: D. Ciccarelli, Dipartimento di Biologia, via Derna, 1 - 56126 Pisa, e-mail: attib@stsn.it).

Per ulteriori informazioni / *For further information*: http://www.stsn.it/
Per informazioni editoriali / *For editorial information*: Edizioni ETS - https://www.edizioniets.com/

Autorizzazione n. 17/56 del 26 luglio 1956, Trib. di Pisa
Direttore responsabile (Editor in Chief): Paolo Roberto Federici

Atti Soc. Tosc. Sci. Nat., Mem., Serie A, 132 (2025)
pagg. 5-22; figg. 12; tabb. 2; doi: 10.2425/ASTSN.M.A.2025.01

Paolo Billi [1,2]

ALLUVIAL FANS AND DISTRIBUTARY SYSTEMS IN THE SEMI-ARID RAYA GRABEN, ETHIOPIA

Abstract - P. Billi, *Alluvial fans and distributary systems in the semi-arid Raya Graben, Ethiopia.*

In the Raya Graben, north-eastern Ethiopia, alluvial fans and distributary systems are present. These fluvial landforms have similar channel networks but different geomorphic and depositional characteristics. Alluvial fans are present along the eastern, lower elevated margin, whereas distributary systems are the terminuses in the graben floor centre of the larger rivers draining the more elevated western margin. Given the relatively small size of the graben, the climate is similar on both margins and bedrock lithology is similar as well. This setting is ideal for investigating the factors controlling the formation of alluvial fans and distributary systems and, through the analysis of their main geomorphic characteristics, demonstrating the distinctiveness of these fluvial landforms. The study was based on field and Google Earth® measurements of a few basic geomorphic parameters and confirmed the control of catchment size on alluvial fan and distributary system area. The catchment relief ratio also proved to discriminate between alluvial fans and distributary systems. Field measurements of channel width and gradient of both the parent channel and the downstream channel at bifurcations on three representative distributary systems were also carried out. The data showed that the total width of the downstream channels is equivalent to that of the parent channel and that, probably each of the downstream channels conveys 50% of the incoming discharge. Avulsion channels were found to be commonly slightly steeper than the parent channel. The study demonstrates that distributary systems are not relic lacustrine deltas that survived the lake's definitive evaporation as proposed by a few authors. Both alluvial fans and distributary systems seem to be examples of the natural tendency of closed systems to increase their entropy.

Key words - alluvial fan, distributary system, bifurcation, entropy, Raya Graben, Ethiopia

Riassunto - P. Billi, *Conoidi alluvionali e sistemi distributivi nel graben semi-arido di Raya, Etiopia.*

Nel Raya Graben, nel nord-est dell'Etiopia, sono presenti sia conoidi alluvionali che sistemi distributivi. Queste morfologie fluviali hanno un reticolo dei canali simile ma differenti caratteristiche geomorfiche e deposizionali. Le conoidi alluvionali sono presenti lungo il meno elevato margine orientale, mentre i sistemi distributivi sono le parti terminali al centro del graben dei fiumi più grandi che drenano il ben più elevato margine occidentale. Date la relativa modesta estensione del graben, il clima può essere considerato lo stesso sui due margini ed anche le rocce del substrato sono simili. Questa assetto fisiografico è quindi ideale per studiare i fattori che controllano la formazione delle conoidi e dei sistemi distributivi e, attraverso l'analisi delle loro principali caratteristiche geomorfiche, dimostrare l'unicità di queste due morfologie fluvio-deposizionali. Lo studio ha utilizzato misure di campagna e misure effettuate con la piattaforma Google Earth® di alcuni parametri geomorfici di base ed ha confermato la stretta relazione tra area del bacino ed area e delle conoidi e dei sistemi distributivi. Il rapporto di rilievo del bacino ha inoltre dimostrato di essere un parametro importante nel discriminare le condizioni di formazione delle conoidi rispetto ai sistemi distributivi. Sono state condotte anche misure di campagna in tre sistemi distributivi rappresentativi della larghezza e della pendenza dei canali a monte e a valle di una biforcazione. Questi dati mostrano che la larghezza totale dei canali a valle della biforcazione è uguale alla larghezza del canale principale a monte della biforcazione e che probabilmente i canali si dividono la portata in ingresso in modo equivalente. I canali di avulsione sono risultati avere una pendenza costantemente leggermente superiore a quella del canale principale. Lo studio, inoltre, dimostra che i sistemi distributivi non sono delta lacustri relitti che sono sopravvissuti all'estinzione del lago per evaporazione, come proposto da alcuni autori. Infine sia le conoidi che i sistemi distributivi sembrano rappresentare degli esempi della naturale tendenza dei sistemi chiusi all'aumento dell'entropia.

Parole chiave - conoidi alluvionali, sistemi distributivi, biforcazione, entropia, Raya Graben, Etiopia

Introduction

Since the dawn of the earth sciences, geomorphologists have been attracted by alluvial fans (e.g., Drew, 1873; Eckis, 1928). Alluvial fans are present in probably every climate (Blair & McPherson, 2009), provided there is an abrupt relief change as an uplifted block adjacent to an alluvial plain. Alluvial fans are important archives of past climate conditions, tectonic activities and paleoenvironmental changes and deserve to be studied for their contemporary morpho-dynamics, and the associated hazards.

Previous studies (see Nilsen & Moore 1984, Capitani *et al.*, 2007, Harvey, 2011, and Zhang *et al.*, 2020, for a comprehensive list of references) have highlighted the geomorphic characteristics of alluvial fans and investigated the factors controlling their formation, shape and size. Tectonics, bedrock lithology, climate and, recently, human activities were found to be the most relevant, though the level of their interplay is not still entirely clear.

[1] International Platform for Dryland Research and Education, Tottori University, Japan
[2] Department of Physics and Earth Sciences, University of Ferrara, Italy
Corresponding author: Paolo Billi (bli@unife.it)

Distributive systems (Nichols & Fisher, 2007) received much less attention from scientists for two main reasons: 1) they are not so ubiquitous as alluvial fans; 2) in the past, they were not clearly distinguished from alluvial fans and were commonly considered as end members of the same typology of depositional systems. Field and remotely sensed images show that distributary systems are substantially different from alluvial fans as regards the channel network, the size and shape of the depositional body, the frequency and loci of channel avulsion, the sedimentary architecture and the response to external forcings such as headwaters uplift, subsidence and climate variations.

For the reason exposed above, to the author's knowledge, no study aiming at comparing the main geomorphic characteristics of alluvial fans and distributary systems has ever been published. After a previous study (Billi 2021), aiming at characterising alluvial fans, distributary systems, fan deltas, lacustrine deltas and sea deltas from different arid environment in the world, here I present a preliminary attempt to discriminate alluvial fans from distributary systems based on a few geomorphic parameters.

Friend (1978) was probably the first to describe distributary systems, inferring their main channel characteristics from ancient deposits. Several following papers provided information about distributary systems based on their deposits sedimentological features (e.g., Nichols, 1987; Sadler & Kelly, 1993; Williams, 2000; Nichols & Fisher, 2007), whereas very few studies investigated modern examples of such distinctive fluvial systems (Lang *et al.*, 2004; Billi, 2007; Hartley *et al.*, 2010; Davidson *et al.*, 2013; Weissmann *et al.*, 2013; Davidson & Hartley, 2014). Except for the paper by Davidson & Hartley (2014), poor information is reported in the literature about modern distributary system geomorphic characteristics. The main aim of this study is to contribute to filling this gap of knowledge and to confirm that alluvial fans and distributary systems are distinct fluvial landscapes, though share some geomorphic processes.

In the Raya Graben (north-eastern Ethiopia), alluvial fans and distributary systems are present, on the eastern and western graben margin, respectively, about 15 km apart. Given the short distance, alluvial fans and distributary systems are subject to the same climate, though the western mountains are higher and receive a larger amount of precipitation. The bedrock lithology is also almost the same (trap basalts) on both graben sides, though in the eastern horst, small outcrops of metamorphic and sedimentary rocks are present, as well. This setting makes the Raya Graben the ideal place to analyse the differences and similarities between alluvial fans and distributary systems and to investigate the conditions leading to the formation of these fluvial networks and depositional bodies.

Study area

The Raya Graben is a structural, north-south oriented depression about 100 km long and 20 km wide (Fig. 1) stretching across the Tigray-Wollo border in north-eastern Ethiopia. The Raya Graben is part of the marginal tectonic structures parallel to the main escarpment of the Red Sea branch of the Ethiopian rift. Detailed information about the geology of the Raya Graben is missing. Several unpublished studies by Ethiopian scientists are difficult to find and the more accessible studies (Merla *et al.*, 1979; Ayenew *et al.*, 2013, Fenta *et al.*, 2015; Shishaye *et al.*, 2020) show evident discrepancies, especially about the lithology of the eastern margin. Combining the data of the available publications, the geology of the Raya Graben can be summarised as follows. The rock formation that more extensively outcrops in both the graben shoulders are the Tertiary Ashangi basalts, which are part of the vast Ethiopian trap series. Smaller outcrops of older rocks, outcropping in the eastern and north-eastern margin of the graben, include Precambrian metabasalts (Ayenew *et al.*, 2013; Shishaye *et al.*, 2020) and the Mesozoic sedimentary sequence consisting of upper Jurassic Antalo limestones and the lower Cretaceous Amba Aradom sandstones (Merla *et al.*, 1979), that outcrop at the foothill of the eastern and south-eastern margin. The Quaternary rocks include rhyolitic dikes and isolated small granite intrusions, the graben filling of predominantly fluvial gravel and sand and probably fluvial-lacustrine deposits at the bottom of the sequence. The physiography of the graben is markedly asymmetric. The western horst is substantially higher with a few peaks reaching 4000 m asl, whereas the eastern margin's higher elevations are around 2300 m asl. The graben floor is gently inclined to the east (0.015) (Fig. 1) suggesting a recent activity of the eastern margin faults. The eastern margin is also split into tilted blocks dipping to the east (Abbate & Sagri, 1969; Zanettin, 1993) (Fig. 1).

In the graben bottom, there are two meteo-stations, Alamata and Kobo (Fig. 1), but they are located only 30 km apart. Only one meteo-station is present on the western margin (Mai Ceu), whreas no one is active on the eastern horsts. Mai Ceu (Fig. 1) is located on the western margin top in the northern portion of the graben at an elevation of 2431 m asl. Alamata and Mai Ceu average climatic data, based on three decades of observations, were, therefore, used to describe the climate of the study area. The annual precipitation recorded at Alamata and Mai Ceu are 748 and 1131 mm, respectively. The monthly distribution of rain follows a monsoon-type pattern since the summer (June to September) rainfalls account

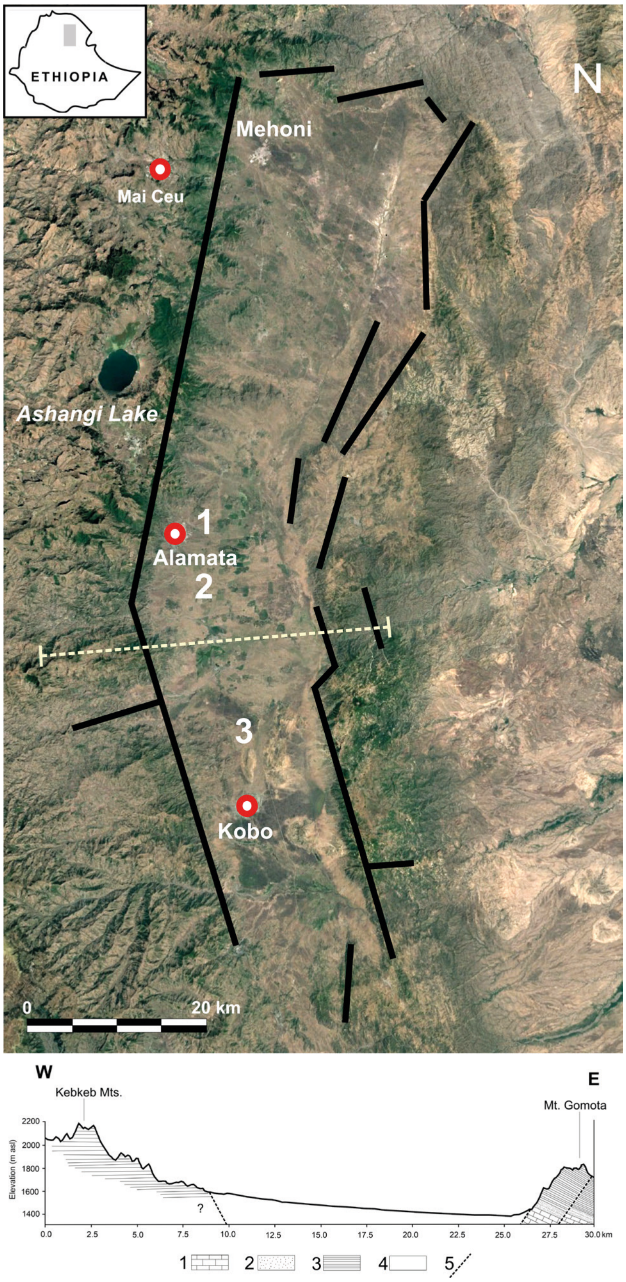

Figure 1. The study area of the Raya graben. The solid lines are main faults; the dashed, transverse line indicates the cross-section underneath.Hara, Harosha and Negharo distributary systems, selected for the field measurement of bifurcation channel data, are indicated by the numbers 1, 2 and 3, respectively. Legenda of the schematic west-east cross-section (dashed line): 1) Jurassic Antalo Limestone; 2) Cretaceous Amba Aradom Sandstone; 3) Tertiary trap basalts; 4) quaternary deposits; 5) normal faults.

for 52% and 78% of Alamata and Mai Ceu annual precipitation, respectively (Fig. 2). At Alamata the mean annual maximum and minimum temperatures are 30 and 15.5 °C, respectively, and the highest temperatures are recorded in June (34 and 18.5 °C). The climate in Mai Ceu is slightly cooler with mean maximum and minimum temperatures of 23.8 and 13.7 °C, whereas the highest temperatures are recorded in June, 27 °C. The lowest temperatures are recorded in January at Alamata and in December/January at Mai Ceu: 12.4 and 11 °C, respectively (Fig. 2).

The largest rivers originate in the western margin and their catchments are markedly larger than those of the rivers draining the eastern horst. All the rivers are ephemeral, that is their bed is dry during most of the time and flow is resumed only in response to downpours that typically occur in the summer rainy season. The only exception is the Golina River that crosses the graben floor close to the southern margin and proceeds towards the Danakil depression. This river has the largest catchment (298 km^2 – Billi, 2015) and a permanent flow, though it reduces significantly during the winter (December to February) dry season. Most of the western river reaches on the graben floor have a predominantly sand or gravelly sand bed, except the Golina River whose streambed consists of a large proportion of boulders and, subordinately, of medium to fine gravel with patches and thin interbedded lenses of sand (Billi, 2015).

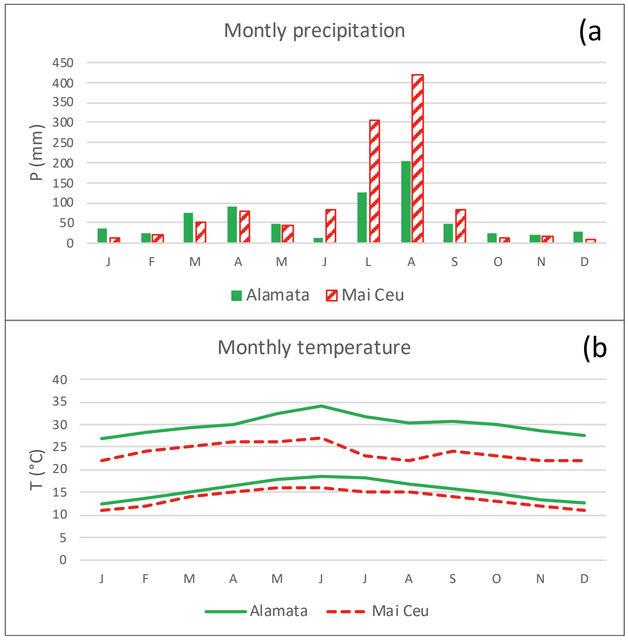

Figure 2. Distribution of a) mean monthly precipitation recorded by the rain gauges located in Alamata and Mai Ceu; b) mean maximum and mean minimum monthly temperatures recorded at Alamata and Mai Ceu. Notice the decrease in temperature during the rainy season due to cloud cover.

Definitions and terminology

According to the Encyclopedia Britannica, an alluvial fan is an unconsolidated sedimentary deposit that accumulates at the mouth of a mountain canyon because of a diminution or cessation of sediment transport by the issuing stream. Alluvial fans border the mountain fronts with their apex just within a canyon mouth that serves as the outlet for a mountain drainage system. Sediment transfer is thus frequently associated with sporadic flash floods that may also include debris flows and mudflows. Since the rivers that deposit alluvial fans tend to be fast-flowing, the first material to be laid down is usually coarse. Alluvial fans are built up in response to tectonic uplift, climatic change, and variations in the internal (autocyclic) balance between stream discharge, debris load, and surface gradient.
This description of an alluvial fan, which is similar to those reported in many geomorphology textbooks, also matches the geomorphological characteristics of the Raya Graben alluvial fans. The eastern rivers, in fact, exit the mountains, enter the graben floor, form depositional bodies and their channels end up shortly beyond them. These short rivers form distinctive alluvial fans spreading radially from the apex located within the canyon mouth at the mountain front (Fig. 3a). Though the main channels splitting mode follows the nodal, full avulsion model defined by Slingerland & Smith (2004), channel swinging, minor diversions and occasional rejoining with the parent channel may be present as well in the downstream reaches. The channels decrease in width downstream (as observed by North & Warwick, 2007; Stock *et al.*, 2007; Chakraborty & Ghosh, 2010; Ventra & Clarke, 2018) and vanish as floodouts (Tooth, 1999) in the graben floor, shortly beyond the fan body. Unlike reported in a few previous studies (e.g., Bull, 1964; Lecce, 1990; Blair & McPherson, 1994; Stock *et al.*, 2007), profile segmentation is not evident in the Rya graben alluvial fans. Yet, this alluvial fan definition also matches that proposed by Ventra & Clarke (2018). The study area alluvial fans, in fact, originate from relatively small, relief catchments, aggrade downstream of the river exit into the adjacent plain and attain steep slopes up to several degrees over a relatively short distance (Fig. 3a). The Raya Graben alluvial fans have a transverse convex shape and a concave longitudinal profile. The alluvial fans are both gravity (debris flow) and fluvial-dominated. Grain size tends to quickly decrease down fan from very coarse boulders in the apex to sand in the distal runout channels. Down fan grain size decrease is also reported by a few authors, e.g. Blair & McPherson, 1994; North & Warwick, 2007; Stock *et al.*, 2007; Zhang *et al.*, 2020).

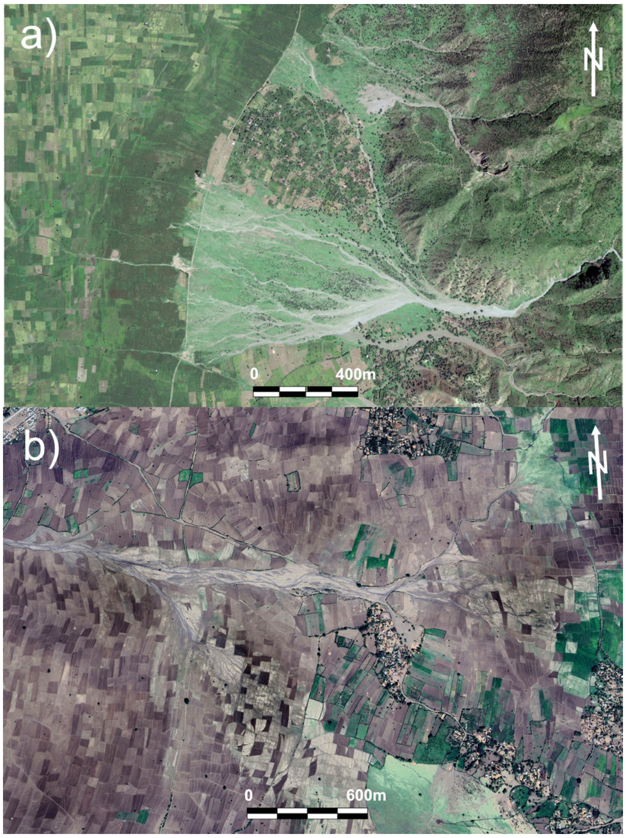

Figure 3. Typical examples of alluvial fan (a) and distributary system (b) of the Raya graben.

Unlike alluvial fans, inland distributary systems have not been studied so extensively and there is also some disagreement about their terminology. Some authors prefer to call them distributive systems (e.g., Hartley *et al.*, 2010; Davidson *et al.*, 2013; Weissman *et al.*, 2013; Davidson & Hartley, 2014; Billi, 2021). Other authors used the original, general term distributary (Billi, 2007; Nichols & Fisher, 2007; Billi, 2015). Hartley *et al.*, 2010, used the term distributive system indiscriminately for both alluvial fans and tree branches-like channel systems, whose channel network is more similar to that of the deltas (Syvitski, *et al.*, 2005). Kelly & Olsen (1993), instead, used the term terminal fan for fluvial distributary systems not ending in a lake or the sea. In this paper, the term distributary system is used to identify the river terminal distributary network, far from the mountain range and comparable to type IV of Davidson *et al.* (2013, their figure 19), and it is maintained in continuity with previous work on ephemeral streams of the Raya Graben.
In the Raya Graben, distributary systems are formed by the larger and longer rivers, coming from the high mountains of the western horst. These rivers proceed onto the graben floor and form distributary systems whose channels decrease progressively in width (Par-

kash *et al.*, 1983) and end up as floodouts (Tooth, 1999) in the centre of the graben. The distributary systems were recognised based on the definition by Allaby & Allaby (1999), as reported in North & Warwick (2007), Slingerland & Smith (2004) and the characteristics described by Billi (2007) and Hartley *et al.* (2010) (their figure 4 E and F). Distributary systems develop on the graben floor at some distance from the catchment exit into the adjacent plain and consist of two or three primary distributary channels departing from the trunk channel and arranged in a tree branch pattern (Fig. 3b). These primary distributary channels may further split into secondary channels that, on their turn, may further split into small branches matching the hierarchical avulsion mode defined by Slingerland & Smith (2004). Occasionally, secondary channels may rejoin downstream the parent channel. In the distributary systems, channel avulsion and downstream rejoining with the parent channel are more common than in alluvial fans channels. The distributary channels decrease in width downstream and terminate as floodouts (Tooth, 1999) or may occasionally form micro distributary systems with micro channels vanishing shortly downstream (Fig. 3b). The distributary systems have a radial structure over a range of 20 to 90° and form flat (less than two degrees) depositional bodies (Fig. 3b). The distributary system depositional body has a transverse, slightly convex shape and a straight longitudinal profile. The distributary systems are fluvially dominated and typical river-flood plain interaction processes are observed. Unlike alluvial fans, the configuration of the distributary channels network is rather stable but, sometimes, a channel may be cut off from the water flow supply even for decades and then be reactivated, though it is not clear if this follows a larger than usual or bankfull flood. The bed material of the distributary channels is predominantly sand or gravelly sand (Billi, 2007; Demissie *et al.*, 2017).
In the study area, channel splitting is a common process, especially in distributary systems and, to a lesser extent in alluvial fans. In the literature, there is no unanimity in naming this process whereby a channel divides into two downstream branches. The most used terms are avulsion, bifurcation and anabranching. Slingerland & Smith (2004) used the term avulsion when the flow is diverted out of a channel and forms a new channel in the adjacent floodplain. According to these authors, a full avulsion is when most of the discharge flows in the new channel, whereas we have a partial avulsion if the parent and the new channel host variable proportions of flow. Avulsions typically occur in aggrading rivers and floodplains. When a channel divides into two downstream branches, Kleinhans *et al.* (2013) use the term bifurcation for alluvial fans and a variety of river patterns, but throughout the paper, the term avulsion is used as well. According to these authors, avulsion is used by geomorphologists and sedimentologists to describe a channel switching to a new channel belt (in this latter case, however, the more appropriate term could be anabranching – Nanson & Knighton, 1996), whereas the term bifurcation is mainly used in modelling and experimental studies. Since in the literature there is no definitive agreement about the channel division terminology, in this paper the terms bifurcation and avulsion are used as synonyms.

Data and Methods

The main geomorphological parameters of both alluvial fans and distributary systems considered in this study (Fig. 4) were: fan/distributary area, depositional body slope, upstream catchment area and relief ratio (Schumm, 1956). The relief ratio is defined as the difference in elevation between the highest and the lowest points of a catchment divided by the longest dimension of the basin parallel to the main channel squared (Schumm, 1956). In this study, the relief ratio is a useful parameter to compare the relative relief of basins with different scales and topography as are those upstream of alluvial fans and distributary systems in the Raya Graben. The horizontal angles of the alluvial fan apex and that of channel bifurcation were measured as well. These basic data were measured from Google Earth Pro® using the ruler function. Though this methodology is very simple and intuitive, more details about the procedure used can be found in Billi (2021). The apex and bifurcation angles were measured by a goniometer after the alluvial fan margins and the bifurcation channel were marked by the line tool of Google Earth Pro®. Unfortunately, no flow discharge data is available since none of the rivers in the study area, also including the permanent Golina River, is equipped with any, even simple, water level recording system.
For investigating the channel avulsion morphology, the distributary systems of three rivers, namely Hara, Harosha and Negeharo (Fig. 4), were considered. Channel width and streambed gradient were measured in the field by the Leica DISTO™ D8 laser range finder and inclinometer, whose accuracy is 0.1 mm for horizontal distance and 0.1 degree for deviation from horizontal. The instrument is placed on a solid and stable tripod and includes a zooming video camera to aim at the target. To reduce the vertical angle error, the instrument is set on the tripod in a horizontal position and the difference in height with a target stake located 100 m downstream is marked by the laser light on the stake and recorded by the video camera. The position of each measuring point is obtained by a Garmin® handheld GPS.

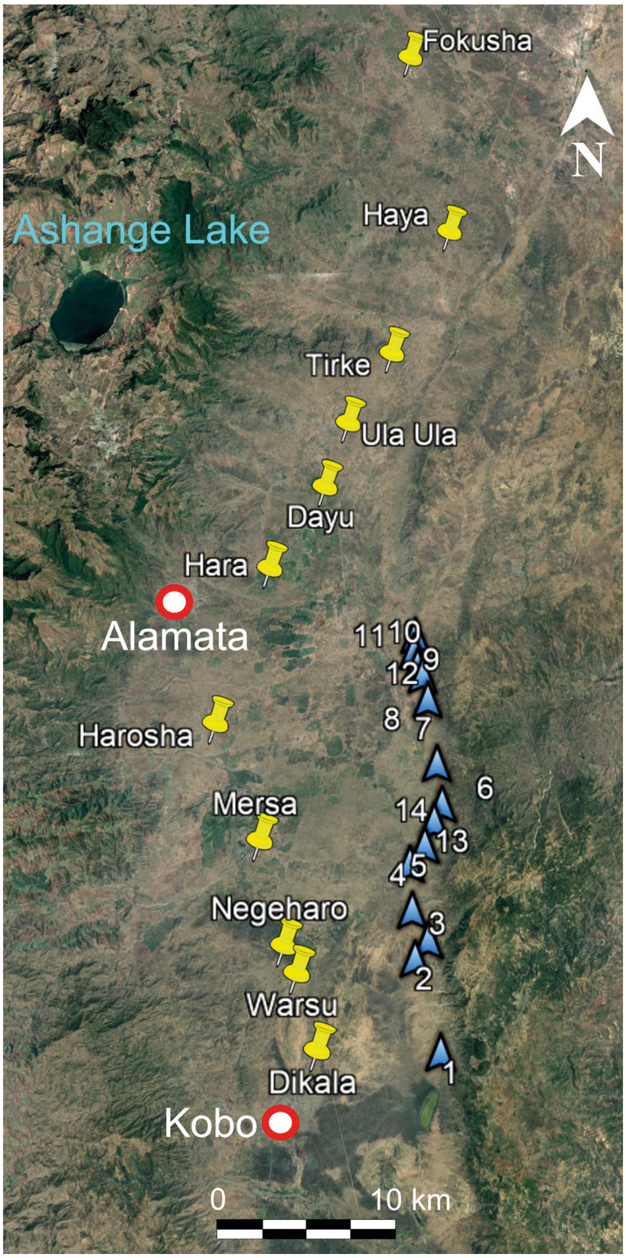

Figure 4. Location of the alluvial fans (triangles) and distributary systems (pinpoints) considered in this study.

Results

The datasets measured for both the alluvial fans and the distributary systems considered in this study (Fig. 4) are reported in Tab. 1. Alluvial fans are smaller and are fed by smaller catchments with a higher relief ratio than distributary systems. Alluvial fans are also one order of magnitude steeper than distributary systems. The average apex horizontal angle of the alluvial fans (63°) is wider than the average bifurcation angle of distributary systems (41°).

Table 1. Basic data of the alluvial fans and distributary systems.

		Alluvia fans			
	A_b	A_f	S	R_r	a
Fan	**km²**	**km²**	**m/m**	**m/m**	**deg**
1	0.69	0.26	0.1071	0.34	67
2	1.01	1.39	0.0806	0.32	44
3	0.46	0.27	0.1493	0.40	32
4	3.59	2.68	0.0790	0.20	63
5	3.56	2.21	0.0849	0.27	68
6	2.07	0.58	0.1422	0.23	70
7	1.18	0.54	0.0679	0.13	107
8	1.27	0.42	0.0896	0.26	83
9	0.88	0.17	0.0913	0.25	64
10	1.1	0.37	0.0822	0.19	49
11	1.53	0.6	0.0786	0.23	65
12	1.49	0.38	0.0620	0.20	85
13	0.72	0.41	0.1550	0.36	45
14	1.21	0.33	0.1392	0.30	38
Mean	1.48	0.76	0.1006	0.26	63
CV	0.66	1.03	0.32	0.28	0.32
		Distributary systems			
	A_b	A_{ds}	S	R_r	a
River	**km²**	**km²**	**m/m**	**m/m**	**deg**
Dayu	26.47	3.25	0.0113	0.12	39
Dikala	37.69	4.63	0.0140	0.06	43
Fokusha	38.41	6	0.0177	0.11	65
Hara	28.79	2.73	0.0139	0.18	33
Harosha	67.62	17.67	0.0152	0.06	22
Haya	39.28	2.06	0.0101	0.13	49
Mersa	117.95	49.98	0.0095	0.10	32
Negeharo	8.5	1.23	0.0287	0.09	34
Tirke	17.4	0.74	0.0219	0.08	44
Ula Ula	35.77	1.03	0.0198	0.12	51
Warsu	15.88	1.89	0.0238	0.07	36
Mean	39.43	8.29	0.0169	0.10	41
CV	0.77	1.76	0.36	0.35	0.28

A_b = basin area; A_f = alluvial fan area; A_{ds} = distributary system area; S = fan-distributary system slope; R_r = basin relief ratio; a = fan apex horizontal angle/bifurcation angle; deg = degrees ; CV = coefficient of variation.

Geomorphology

Several studies have investigated the relationship between catchment area and fan/distributary system area and slope and have expressed their variability with power functions of the type:

$$A_f = c\, A_b^{\,n} \qquad [1]$$

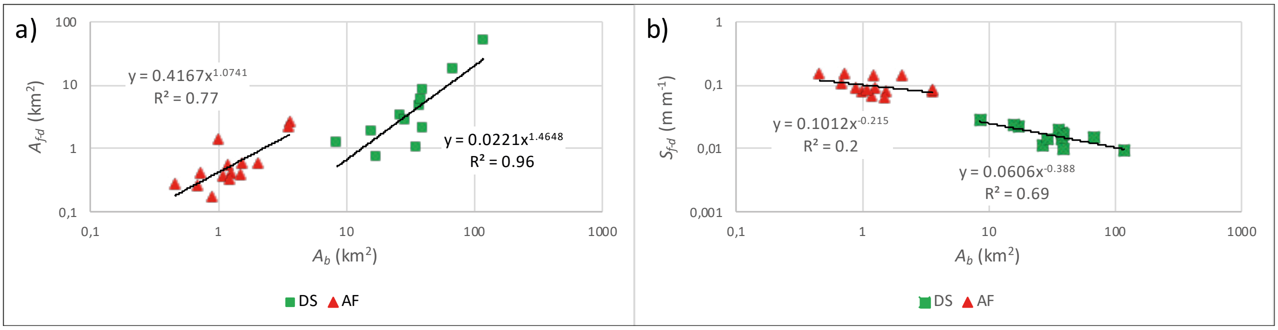

Figure 5. Correlation diagrams of catchment area (A_b) vs the area ($A_{f\text{-}d}$) (a) and slope ($S_{f\text{-}d}$) (b) of both alluvial fans and distributary systems. DS = distributary systems; AF = alluvial fans.

$$S_f = c\,A_b^{\,n} \quad [2]$$

in which A_f is the area of the fan/distributary system; A_b is the basin area; S_f is the slope of the fan/distributary system; c is a constant and n is the exponent.
For the alluvial fans and distributary systems of the Raya Graben, the correlation analysis returned the following equations (Fig. 5a):

$$A_f = 0.4167A_b^{1.0741}\ R^2 = 0.77 \quad [3]$$

$$A_{ds} = 0.0221A_b^{1.4648}\ R^2 = 0.96 \quad [4]$$

in which A_{ds} is the area of the distributary system. The correlation coefficient of eq. (3) indicates that the basin area explains 77% of the variability of the alluvial fan area. The variability of the distributary systems area is even more effectively (96%) controlled by the catchment area. Both correlations are highly significant since $p < 0.01$, which implies that there is only a probability of less than 1% that the two variables are casually correlated. These results are interesting for paleogeographic reconstructions because by reversing eqs. (3) and (4), it is possible to derive the catchment area from the alluvial fans and distributary systems area in regional-scale sedimentological investigations:

$$A_b = 1.784A_f^{0.557} \quad [5]$$

$$A_b = 17.62A_{ds}^{0.468} \quad [6]$$

Regression analyses were also conducted to obtain the constant and exponent of eq. (2) for the data set used in this study:

$$S_f = 0.1012A_b^{-0.215}\ R^2 = 0.20 \quad [7]$$

$$S_{ds} = 0.0606A_b^{-03885}\ R^2 = 0.69 \quad [8]$$

in which S_f is the slope of the alluvial fan and S_{ds} is the slope of the distributary system (Fig. 5b).

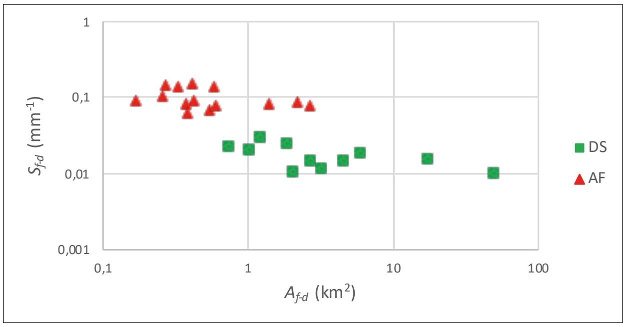

Figure 6. Plot diagram of alluvial fan and distributary system area ($A_{f\text{-}d}$) vs alluvial fan and distributary system slope ($S_{f\text{-}d}$). DS = distributary systems; AF = alluvial fans.

The determination coefficient of eq. (8) is not high but the correlation is statistically significant ($p < 0.05$). No correlation seems to exist for alluvial fans.
The data show that the alluvial fan and distributary system area do not exert any control on slope, but the two depositional body types plots are clearly separated in a slope/area diagram (Fig. 6). A similarly clear separation is obtained if the relief ratio (R_r) is plotted against the alluvial fan and distributary system area and slope (Fig. 7). Fig. 7a indicates that, in the Raya Graben, alluvial fans form only if relief ratio is higher than 0.13 and distributary systems do not form if relief ratio is lower than 0.18. In Fig. 7a, the data of alluvial fans and distributary systems plot in two distinct areas. The line separating these areas (traced by eye) can approximately be expressed by the following equation:

$$A_{f\text{-}d} = 0.0361e^{22.648Rr} \quad [9]$$

in which $A_{f\text{-}d}$ is the area of both alluvial fans and distributary systems and R_r is the relief ratio.
In the study area, an important factor for the formation of alluvial fans, other than a sudden decrease in the river profile gradient, seems to be the occurrence of a relatively small and steep upstream catchment.

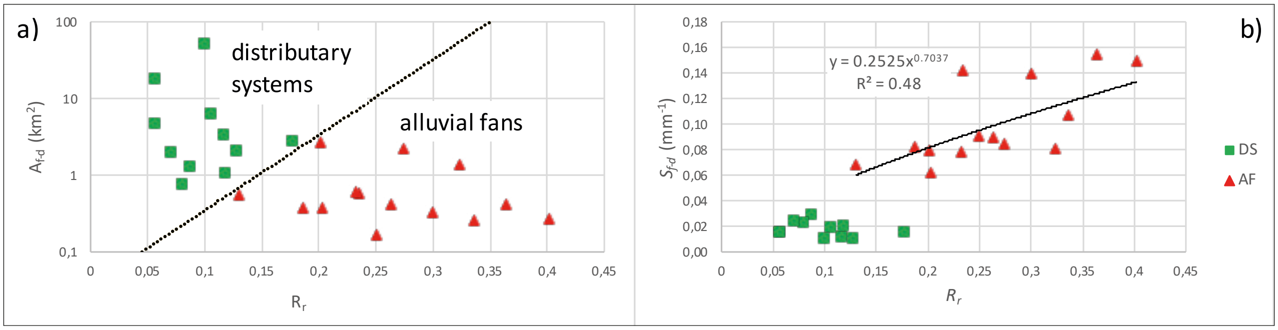

Figure 7. Plot diagram of relief ratio (R_r) vs the area ($A_{f\text{-}d}$) (a) and slope ($S_{f\text{-}d}$) (b) of both alluvial fans and distributary systems. DS = distributary systems; AF = alluvial fans.

Such a physiographic setting guarantees a high supply rate of coarse particles that can be easily and quickly transferred to the valley mouth beyond which they tend to deposit, giving way to an alluvial fan.

Distributary systems, by contrast, are fed by large catchments with a relatively low relief ratio. The sediment supply, which in the headwaters may be similar to that of the alluvial fan, has to travel a much longer way to reach the graben floor, where no topographic threshold is present, and abrasion and sorting processes reduce the calibre of the sediment delivered to the distributary systems. Studies on larger datasets are however desirable to verify if this threshold also occurs in other semi-arid structural basins underlain by basaltic rocks, like the Raya Graben.

The diagram of Fig. 7b shows a clear distinction between distributary systems and alluvial fans, with 48% of the latter slope variability explained by the catchment relief ratio ($p < 0.05$), whereas no correlation is found for distributary systems. The apex angle of alluvial fans and the bifurcation angle of distributary systems have no or little control on the slope of both depositional bodies, though there is a general tendency for alluvial fans to be steeper when their apex angle is narrower (Fig. 8).

Distributary system channel pattern and bifurcation

In the Hara, Harosha and Negeharo river distributary systems (Fig. 4), the channel width and gradient of the parent channel and the two downstream channels were measured in the field. The data indicate that the bifurcation width ratio (R_{bw}) of the parent channel (W_p) is equivalent to the sum of the downstream left (W_l) and right (W_r) channels widths: $R_{bw} = W_p/(W_l+W_r) = 1$.

The variation coefficient of the bifurcation width ratio is 0.38 and indicates that the dispersion of the data around the mean (1) is modest (Tab. 1). This implies that when an avulsion channel is formed, the discharge of the parent channel tends to be equally distributed in the two downstream channels. Unfortunately, in the Raya Graben, there is no field observation of the fraction of flow in the distributary channels. Though at a given time some distributary channels may convey a flow larger or smaller than 50% of the parent channels discharge ($0.5Q_p$), the data suggest that, at least in the long term, an equilibrium between the discharge in the upstream channel and half of the parent channel discharge in both the downstream distributaries is attained. According to Slingerland & Smith (2004), if the gradient of an avulsion channel is four to five times that of the parent channel, the former is able to take all the incoming flow. This is not the case with the Raya Graben distributary channels. The field data, in fact, confirm that when an avulsion channel forms it takes the most favourable direction, which coincides with a streambed gradient steeper than in the parent channel. In Fig. 9, almost all the data plot over the equality line between parent and avulsion channels bed gradient. The average difference between the gradient of the parent channels (0.007) and the avulsion channels (0.009) is small, 0.002, but enough to let the new channel flow to make its way on the graben floor, even if it is only 50% of the parent channel discharge. For these reasons, the term bifurcation is preferable to avulsion (Slingerland & Smith, 2004; Kleinhans *et al.*, 2013) for the Raya Graben distributary channels.

The longitudinal profile of the main channel from a couple of kilometres upstream of the first bifurcation to the most downstream runout of the Hara, Harosha and Negeharo representative distributary systems (Fig. 4) was also measured in the field. The longitudinal profile data of the main channels is best interpolated by a straight line (Fig. 10). This result is surprising, as the typical concave upward profile would be expected. In the Raya Graben, this marks a clear difference with alluvial fan channels whose longitudinal profile shows a moderate concavity as commonly observed by other authors (e.g., Blair & McPherson, 1994; Stock *et al.*, 2007; Harvey, 2011; Ozpolat *et al.*, 2022).

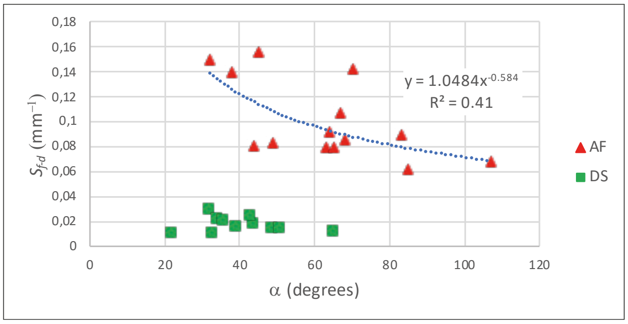

Figure 8. Plot diagram of fan apex and bifurcation horizontal angles (α) vs the slope (Sf-d) of both alluvial fans (AF) and distributary systems (DS).

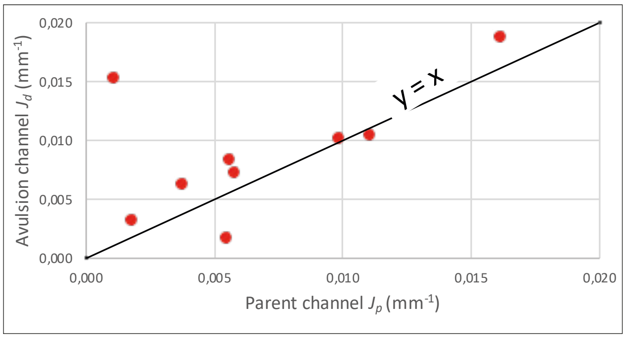

Figure 9. Comparison between the streambed gradient of the parent channel (J_p) and the downstream avulsion channels (J_d). Most of the data plot over the equality line.

Another interesting, complementary result of the longitudinal profile measurements is the distinctive patterns between the field data measured by the laser level and the GPS data (Fig. 10). Even neglecting the marked difference in elevation, it remains impressive the difference between the data measured with the two methods, which tends to substantially increase toward the centre of the graben. Of major concern is the fact that the discrepancies of the GPS with the field data are not erratic, as one would expect, but systematic. Though this result is beyond the aims of this study it is worth underlining it, especially for future field surveys in the Raya Graben.

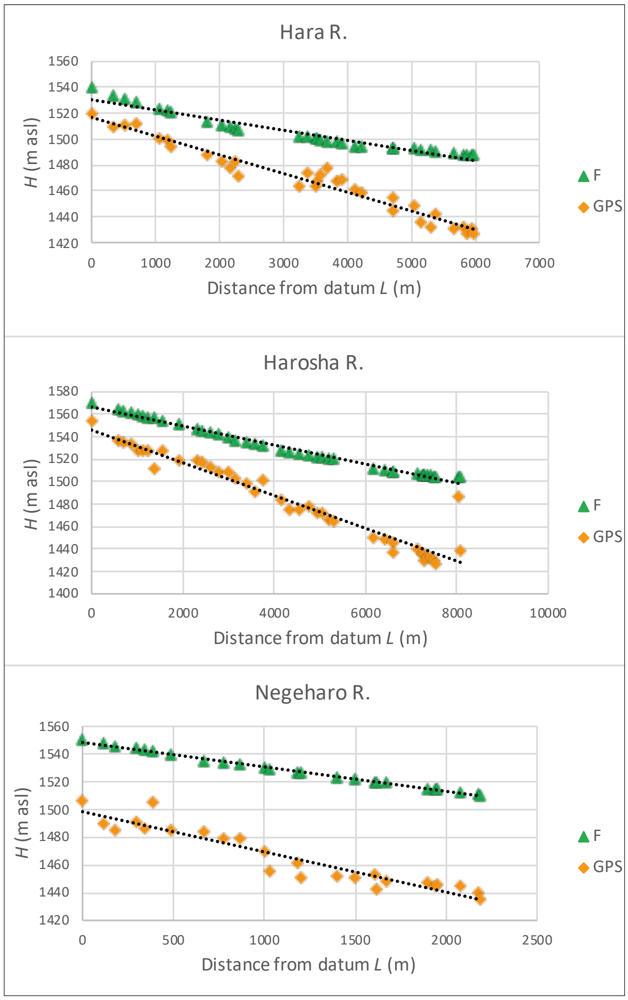

Figure 10. Longitudinal profile of the three representative distributary systems. H = elevation (m asl); F = field measurement with the laser distantiometer; GPS = Global Positioning System measurement.

Discussion

Structural evolution of the study area

In the Raya Graben, the western and eastern margin have different structural and physiographic characteristics resulting in a prominent asymmetry. The high subsidence rate of the depression's eastern side, associated with graben bottom tilting, generated a substantial accommodation space accompanied by a modest horst uplifting, especially if compared with the older, highly uplifted western horst involved in the primary opening of the Red Sea. This setting favoured the formation of small and steep alluvial fans. The western margin, by contrast, has seen a longer tectonic history, though only the recent depositional components are preserved. The river valleys deeply incised in the western horst are now filled with alluvium and the transition from the source area to the depositional zone is no longer abrupt, like in the past, as documented by uplifted old alluvial fan deposits (see further on). The larger rivers of the western margin generated from high mountains, have larger catchments and higher sediment supplies. In their gradual transition from the source area to the graben bottom, these rivers lose gradient, energy and water (for infiltration), thus forming the modern distributive systems.

An unknown reviewer has proposed an interesting alternative hypothesis that is worth considering. The reviewer suggests that the eastward inclination of the graben floor could be related to more extensive areal and longitudinal depositional processes driven by the sedimentary systems fed by larger rivers draining the western margin of the depression. The sediment transported by the western river is enormously larger than that of the eastern alluvial fans but none of the western rivers reaches the eastern margin. A narrow no man's land stretches between the distributary systems and the alluvial fans and only very occasionally it is reached by their deposits. No detailed, recent study of the eastern margin geology is available. Early studies (e.g., Abbate & Sagri, 1969) suggest that the eastern margin consists a flexure with antithetic faults that has been translated eastward by a major fault associated with the rifting of the Red Sea. This implies an eastward movement of the eastern margin and may have contributed to generate the accommodation space of the alluvial fans. Unfortunately, this structural hypothesis has not yet been confirmed, but it does not exclude the more traditional one.

Are alluvial fans and distributary systems part of the same morpho-depositional continuum?

Since the early studies on alluvial fans, a few authors (e.g., Eckis, 1928; Bull, 1964; Denny, 1965) recognised that the catchment area exerts some control on alluvial fan size. The following research has confirmed this relationship, though other factors such as climate and rock resistance to erosion were found to play an important role as well.

In Raya Graben, the size of both alluvial fans and the distributary systems were also found to be controlled by the upstream catchment area. Two functions expressing the control of catchment area on alluvial fan and distributary system area (eq. 3 and eq. 4) were obtained and their correlation statistical significance is high. The constant c and exponent n of eq. (1) obtained for alluvial fans by previous investigations are reported in Table 2 for a comparison with the result of this study. Unfortunately, the same comparison for distributary systems is not possible because very few papers have been published on the geomorphic characteristics of these distinctive river systems. In Tab. 2, also the constants and exponent of eq. (2) expressing the relationship between alluvial fan slope and catchment area, presented in previous studies, are reported for a comparison with this study results. Tab. 2 also includes the constant and exponent of the power function expressing the correlation between the alluvial fan slope and area, though no correlation was found for the Raya Graben alluvial fans. The n exponent of eq. (1) is the least variable since the coefficient of variation (CV) is relatively low (0.38) and indicates that the catchment area has an effective, probably predominant role in controlling the alluvial fan area. The exponent n for the Raya Graben alluvial fan, 1.074, is very close to the average value, 0.918, obtained from the literature data. The data of Tab. 2, except for the Svalbard example, are all from areas with arid and semiarid climates, to which the Raya Graben is subjected as well. The study alluvial fans are almost entirely underlain by the Oligo-Miocene basaltic rocks of the trap series. Other studies reporting similar values, close to one, of the n exponent were obtained in areas underlain by volcanic, basement granitic and metamorphic rocks or a mixture of them. Alluvial fan fed by catchments underlain by sedimentary, both clastic and limestone, and recent volcanic rocks show lower values of the n exponent. Such a dichotomy is well represented by the work of Lecce (1991) in which erodible and resistant rocks have contrasting values of the n exponent, 0.65 and 1.22, respectively. These results indirectly confirm the conclusion of Whipple & Trayler (1996) that lithology can significantly influence the fan area catchment area relationship where conditions are appropriate (e.g., uplift increase).

The inverse relationship between catchment area and alluvial fan slope (eq. 2) is more obscure and, commonly, statistically less significant. In fact, except for the data of Bull (1964), Mokarram *et al.* (2014) and Lecce (1991) (resistant rocks), whose correlation coefficient, R^2, ranges between 0.82 and 0.84, in the other studies reported in Tab. 2, R^2 varies from no correlation at all, 0.20, to a modest, insignificant correlation, 0.67. The n exponent obtained for the Raya Graben alluvial fan is the same as the average value of Tab. 2, i.e. -0.215. The negative exponent implies that larger catchments tend to produce alluvial fans with a gentler slope, though the low values of the correlation coefficient indicate that fan slope is mainly controlled by other factors. Steeper fans are expected to consist of coarse material, especially in the fan head and middle fan portion, but Stock *et al.* (2007) conclude that the down fan reduction in grain size is not the only factor responsible for the fan longitudinal profile. Bowman (2019) explains the inverse relationship between fan slope and catchment area with larger catchments having larger discharge, higher velocity and shear stress capable of transporting sediment over lower slopes. Though the first part of this conclusion is sharable, since shear stress is the product of the water mass times the energy slope, commonly assumed parallel to the streambed gradient, for the same unit discharge, a lower slope implies a lower shear stress. As shear stress decreases down the fan the coarser particles are deposited and the finer sediment can be transported for longer distances, provided no water infiltration in the fan body occurs and a substantial water flow is sustained.

Table 2. Morphometric relationships and their determination coefficient (R^2) reported by several authors for alluvial fans in different regions of the world.

$A_f = cA_b^n$	*c*	*n*	R^2	**comment**
Bull, 1964	2.093	0.857	0.94	Central Valley, California
Denny, 1965	0.104	1.129	0.563	Death Valley, California
Beaumont, 1972	1.180	0.946	0.90	Elburtz Mts., Iran
Lecce, 1991				Sierra Nevada, California
	0.650	0.650	0.75	Erodible rocks
	0.700	1.220	0.80	Resistant rocks
Whipple & Trayler, 1996				Owens Valley, California
	1.259	0.864	0.62	Low subsidence rate
	0.662	0.582	0.55	High subsidence rate
Milana & Ruzycki, 1999	0.100	0.526	0.41	NW Precordillera, Argentina
Mather *et al.*, 2000	0.822	0.676	0.83	South-West Spain
Viseras *et al.*, 2003	0.607	1.187	0.77	South East Spain
Harvey, 2011	0.807	0.675	0.82	Dryland fans
Stokes & Gomes, 2020	0.859	0.289	0.75	Cape Verde Islands
Tomczyk, 2021	0.130	0.580	0.22	Svalbard
Woor *et al.*, 2023	0.460	1.020	0.77	Hajar Mts., S-E Arabia
This study	0.417	1.074	0.77	
Mean	0.723	0.918		
CV	0.71	0.34		
$S_f = cA_b^n$	*c*	*n*	R^2	
Bull, 1964	0.031	-0.281	0.82	Central Valley, California
Beaumont, 1972	0.423	-0.128	0.67	Elburtz Mts., Iran
Mather *et al.*, 2000	0.068	-0.253	0.50	South-West Spain
Mokarram *et al.*, 2014	1.014	-0.377	0.84	Lorestan, Iran
Lecce, 1991				Sierra Nevada, California
	0.590	-0.120	0.61	Erodible rocks
	0.570	0.060	0.84	Resistant rocks
Saito & Oguchi, 2005	0.039	-0.290	0.46	Japan, Taiwan, Philippines
Viseras *et al.*, 2003	0.080	-0.245	0.51	South East Spain
Stokes & Gomes, 2020	0.150	-0.240	0.23	Cape Verde Islands
Woor *et al.*, 2023	0.030	-0.280	0.51	Hajar Mts., S-E Arabia
This study	0.101	-0.215	0.20	
Mean	0.281	-0.215		
CV	1.16	0.54		
$S_f = cA_f^n$	*c*	*n*	R^2	
Mather *et al.*, 2000	0.068	-0.253	0.50	South West Spain
Viseras *et al.*, 2003	0.071	-0.220	0.62	South East Spain
Saito & Oguchi, 2005	0.030	-0.380	0.28	Japan, Taiwan, Philippines
Stokes & Mather, 2015	0.001	-0.466	0.53	Atlas Mts., Morocco
Stokes & Gomes, 2020	0.709	-0.188	0.34	Cape Verde Islands
Woor *et al.*, 2023	0.020	-0.280	0.68	Hajar Mts., S-E Arabia
This study			nc	
Mean	0.150	-0.298		

A_f = alluvial fan area; A_b = basin area; S_f = alluvial fan slope; *c* = constant; *n* = exponent; nc = no correlation; CV = coefficient of variation.

Williams *et al.* (2006) and Bowman (2019) found that fan gradient and area are inversely correlated and that fans dominated by debris flows are shorter and steeper than fluvially dominated fans (Harvey, 2011). The data in Tab. 2 show a poor correlation between fan slope and area and no correlation for the Raya Graben alluvial fans. The tectonic setting of the Raya Graben (see below) suggests that other factors such as basin subsidence (Whipple & Trayler, 1996; Weissmann *et al.*, 2005) and changes in accommodation space (Weissmann *et al.*, 2005; Harvey, 2011; Ventra & Clarke, 2018; Bowman, 2019; Ozpolat *et al.*, 2022) may substantially influence the fan slope/area ratio, at least as much as the quantity of sediment supply associated with upstream catchments of the variable size (Whipple & Trayler, 1996; Davidson *et al.*, 2013).

At first glance, the channel network of the study distributary systems looks like that of deltas. Despite that, the channel dynamics and hydrological functioning of semi-arid, inland distributary systems channels are different from deltas. Syvitski *et al.* (2005) have analysed a large number of global deltas and found that in natural deltas, during floods, the smaller distributary channels act as conduits of the main channel overflow and convey larger than average discharges. In the distributary systems, this process is reversed since the number of distributary channels is much smaller than in a delta and the incoming discharge is almost equally subdivided into the whole distributary network with the larger channels initially experiencing the larger proportions of the incoming flow.

From field data and theoretical considerations, Coffey & Shaw (2017) have obtained an average bifurcation angle of 72°. These authors also found that in their study deltas, the bifurcation angles are highly variable and their distribution is characterised by large standard deviations. The average bifurcation angle of the study distributary systems is 41°, that is 43% smaller than in deltas, and the data dispersion around the mean is also modest as the low variation coefficient of 0.28 indicates (Tab. 1). Notwithstanding that inland distributary systems and deltas apparently have distributary networks with similar shapes and considering that the former are steeper and not subjected to the effects of waterbody level changes and waves (Billi, 2021), it seems evident that inland distributary systems are distinct from lake and sea deltas. Nichols & Fisher (2007) consider inland distributary systems as relict deltas that formed during phases of ephemeral lake high stands and classify them as ephemeral-lacustrine floodplain deltas. The GIZ (1976) drillings, geoelectrical and seismic data obtained along a survey line parallel to the Kobo-Alamata road witness the presence of fine sediments, probably of lacustrine origin, of variable thickness, from 50 to 150 m. These deposits of probable lacustrine origin rest on volcanic (Miocene trap basalts?) and metamorphic rocks densely faulted into blocks whose vertical displacement ranges from 200 m below the ground surface to outcropping, as observed midway between the towns of Kobo and Waja. The lacustrine deposits are covered by a 20 to 100 m thick layer of sand and gravel, likely of fluvial origin. By contrast, field inspections of gullies and river cutbanks in the centre of the graben floor did not reveal recent (Late Pleistocene-Holocene?) lacustrine deposits. The above stratigraphic considerations and the absence of a lake in the recent (historical) past led to the conclusion that distributary systems are a standalone, terminal fluvial system, clearly distinct from deltas and fans (Billi, 2021) and the hypothesis that distributary systems are relict deltas formed during the high level of temporary lakes remains unproven.

The theoretical analysis of channels with equal energy slope carried out by Bolla Pittaluga *et al.* (2003) suggests that the parent and bifurcation channels are stable only if water discharges are unequal. In the Raya Graben, distributary system channels have similar gradients (Fig. 10), width at the bifurcation and discharge. In the study area, the analysis of distributary channel network changes through time using Google Earth® multi-temporal images, though carried across a short interval (the last 10-20 years), indicates substantial stability. The field data contrast with the results of Bolla Pittaluga *et al.* (2003) and confirm the statement of Slingerland & Smith (2004) that the conditions causing a river bifurcation are not yet well understood and that further field research is needed.

From sedimentological and stratigraphic investigations on Devonian and Tertiary fluvial deposits in Greenland and Spain, Friend (1978) recognised distributary systems with distinctive characteristics: a) downstream decrease in channel depth; b) shallow channel incision resulting from alternation of incision and aggradation; c) convex-upwards shape of depositional bodies. These features are also distinctive of the Ray Graben distributary systems. Nichols & Fisher (2007) describe the proximal facies of distributary systems as consisting mainly of planar cross-bedded gravels, with imbricated clasts, and trough cross-bedded pebbly sand associated with braided river deposits. The distal deposits include mainly horizontally laminated sand and channel fill facies, in places showing lateral accretion of the inner bank of a meander bend. The deposits of the Raya Graben rivers and distributary systems described by Billi (2008) have slightly different characteristics. Gravel and pebbly sand horizontal bedding prevail in the proximal areas, whereas in the distal deposits massive and horizontally laminated sand are the dominant facies. Cross-bedding and cross-lamination, sand dunes and ripples are very uncommon in both coarse- and fine-grained sediments and channel fills are barely discernible. Though these sediment characteristics are typically expressions of flash floods in arid and semiarid rivers (Hassan *et al.*, 2009), they support the conclusion that, at least in the Raya Graben, distributary systems are a fluvial landform different from lacustrine deltas (Smith, 1991; Olariu *et al.*, 2021) and alluvial fans (Blair & McPherson, 1994).

The GPS and the laser level measurements returned two different longitudinal profiles of the representative distributary systems surveyed in the field. Such a difference is rather wide and can be explained as a merely technical failure. The step-by-step laser lever profile measurement can be considered as reliable, since the data were measured on short distances, and virtually not affected by a systematic error. The quality of the handheld GPS used was not high, which is a crucial shortcoming given the difficulty for any GPS in get accurate elevation data without post processing. Moreover, the number of satellites operating during the field work was very small and the signal frequently changed.

Alluvial fans and distributary systems formation conceptual model

In the Raya Graben, the conditions necessary for the formation of alluvial fans are present. According to Blair & McPherson (1994), these conditions include: the juxtaposition of an uplifted mountain block and a valley bottom; an upland catchment whose main channel enters the valley bottom at the mountain front; active weathering processes producing sediment; intense rainfalls generating flash floods capable of transferring the sediment to the canyon mouth; an abrupt change in slope at the mountain front-valley bottom transition and water flow infiltration in the coarse-grained fan apex, resulting in a decrease of the feeder channel sediment transport capacity (Stock *et al.*, 2007, their figure 19) and thus favouring sedimentation all along the fan body. In the study area, the incoming sediment is almost entirely deposited on the fan and the export of sediment beyond the fan toe is restricted to fine particle wash since no river channel proceeds onto the graben bottom.

The radial shape of the alluvial fans is due to channel swinging. The feeder channel is hinged in the canyon mouth where any lateral shifting is hindered by the resistant bedrock in which it is incised. Beyond the apex, however, there is no lateral constraint and the channel is free to move across the fan body. Channel migration results from avulsion and bifurcation processes. During high floods, in-channel deposition of a large quantity of coarse material takes place because water infiltrates and the flow loses part of its bedload transport capacity. The accumulated bed material may be enough to clog the channel and force the flow laterally favouring the formation of an avulsion channel. The reiteration of this process produces the radial movement of the distributive channels providing the fan with its typical radial shape. Reitz *et al.* (2010) proposed a four-stage cyclic model of channel avulsion on alluvial fans that is slightly different from the one proposed here, but the channel backfilling is the main cause of channel avulsion also in these authors' conceptual model.

If the mountain front is rectilinear, the apex angle of the fan can be as much as 180° (Fig. 11). Where the mountain frontline is irregular, as in the Raya Graben, the apex angle is typically less than 90° (Tab. 1) and the fans have an oblong shape (Fig. 3), which also results from the lateral constraint imposed by neighbouring alluvial fans. An alluvial fan tends to occupy all the accommodation space available and the radial shifting of the channels can be seen as the product of the uniform distribution of energy dissipation. This observation recalls and confirms the entropy concept expressed by Leopold (1994) for fluvial systems. According to this author, entropy is a measure of the energy distribution in a system. If the energy is more dispersed or more uniformly distributed in a system, the possibility that energy is used for mechanical work (sediment transport, bank erosion, etc.) decreases and, by definition, entropy increases. The alluvial fans of the study area can be considered as closed systems. Flow energy enters the fan but is confined within the fan perimeter and, due to water infiltration, no flow exits the fan and, even if the fan perimeter may change through time, no work is done beyond it. The law of physics tells us that entropy always tends to increase since energy naturally transforms from a concentrated state to a dispersed one. On the alluvial fan, the flow energy is dissipated for the friction with the rough streambed and for transporting the sediment, generating heat. This energy loss is not recoverable and conforms to the principle of entropy. According to Silvestrini (2011), every system naturally evolves towards a dispersed configuration, that is incommensurably and statistically more probable than an ordered one. Adapting the reasoning of Silvestrini to alluvial fans, if a fan has four channels, it is very improbable that they are all concentrated on one side. They may be in different positions such as one on the right and three on the left, or vice versa or two on the right and two on the left, etc. In the long term, while shifting radially on the fan surface, a channel takes many different positions (actually any position) that finally will result in the conical shape of the alluvial fan. The probability of scattered channel positions is much higher (Fig. 11) than a channel staying in only one position. Alluvial fans can be considered a natural example of increasing entropy.

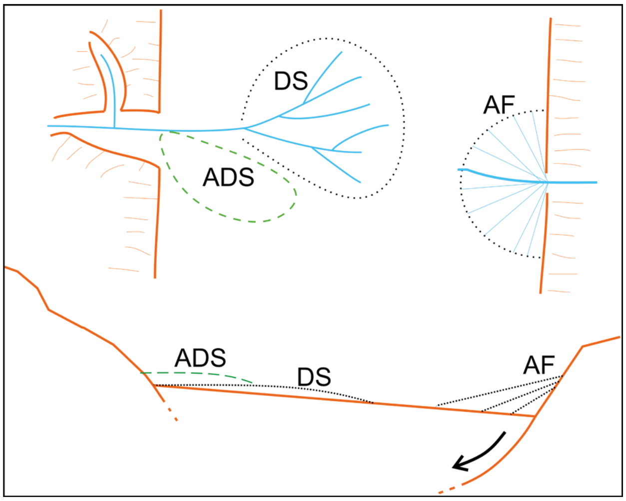

Figure 11. Sketch setting of alluvial fans and distributary systems in the Raya Graben. AF = alluvial fan; DS = distributary system; ADS = abandoned distributary system. Not in scale.

Reitz *et al.* (2010) approached the problem of channel avulsion on alluvial fans by a model in which channel paths are random walks in a system with memory. These authors also found that the system achieves a dynamic steady state in which flow oscillates among a set of 3 to 5 channels and the probability of reoccupying old channels is rather high. This approach recalls that used by Leopold (1994) for explaining the natural tendency of rivers to meander. Though Reitz *et al.* (2010) did not envisage the entropy theory, their analysis is very similar to that proposed in this study.

As mentioned above, the accommodation space is also an important issue associated with alluvial fan size and gradient. According to Bowman (2019), in grabens with high rates of tectonic subsidence, alluvial fans tend to be smaller and show a lower correlation with the catchment area. By contrast, in areas with lower subsidence rates, alluvial fans tend to prograde further onto the graben floor. This concept has been also expressed by other authors (e.g., Lecce, 1990; Whipple & Trayler, 1996; Weissmann *et al.*, 2005; Ozpolat *et al.*, 2022), though with some distinctions. The alluvial fans of the eastern margin of the Raya Graben are relatively small but their respective catchment size is only twice the fan area. By contrast, the data presented by Stokes & Mather (2015) for their fans in Morocco, i.e. in a region with negligible tectonic activity, indicate a catchment-to-fan area ratio of 820. This marked difference may be explained by the sedimentary rocks outcropping in the Moroccan catchments compared to the basaltic and metamorphic rocks of the Raya Graben eastern horst. The rocks outcropping in the Argentinian study area of Milana & Ruzycki (1999) are similar to those of the Raya Graben eastern margin, but the climate is drier and the catchment area to fan area ratio is 59. These contrasting results confirm the complex influence of lithology and climate on fan size. Whipple & Trayler (1996), instead, conclude that climate and lithology play only a secondary role, whereas tectonic uplift rate variations are considered the preeminent factor in controlling fan size.

The Raya Graben is a half-graben with the floor dipping to the east by about one degree (Figs 1 and 11). According to Ayenew *et al.* (2013), the Quaternary fluvial-lacustrine filling of the valley floor is associated with the eastern horst uplifting. Such recent tectonic activity is witnessed by very well preserved (with little signs of erosion) fault planes that, in places, are visible in the eastern margin. Alluvial deposits terracing in the opposite margin of the graben (see further in this section) is coherent with stepped subsidence that should have resulted in fan profile segmentation and apex incision (Lecce, 1990). Nevertheless, the feeder channels of the study alluvial fans are not incised in the apex and the fan longitudinal profiles do not show a clear segmentation. This suggests that high sediment supply and deposition rates probably obliterated the fan segmentation and feeder channel incision and resulted in relatively large fans compared to the source areas, notwithstanding the changes in accommodation space associated with the graben floor subsidence (Hunt & Mabey, 1966, cited in Blair & McPherson, 2009).

In the Raya Graben western shoulder, there is no evidence of modern alluvial fans. Though the western escarpment is imposing and almost twice as high as the eastern horst, in the lower part, the occurrence of low relief hills makes the transition to the graben floor not so abrupt as by the eastern block (Fig. 1). The lower portion of the rift main escarpment is crossed by parallel valley (Figs 1 and 4), filled with alluvial deposits and drained by river systems that reach the graben centre where they form distinctive distributary systems and vane out. Old (Quaternary?) alluvial fan deposits can be found in the upstream portion of the lower valleys. Commonly, these deposits rest on bedrock, and show the typical arrangement of alluvial fan deposits including debris flows (Fig. 12a) and sheet floods (Fig. 12b), basinward dipping layers and a marked reduction in grain size within a short distance. In the inner valley, old alluvial fan deposits are incised by the modern rivers resulting in, at least, three orders of terraces. The GIZ (1976) logs, though valuable for a general framing of the graben floor tectonic structure and the depositional sequence, do not allow to infer the river channel morphology, nor the presence of distributary systems. At the exit of a few valleys onto the graben floor, older (Holocene?) depositional bodies are incised or bypassed by the modern rivers (Fig. 11). These depositional bodies are rather flat and slightly convex, but it is not possible to recognise an alluvial fan shape. Their size and low slope (0.042) suggest that they are rather old distributary systems or terminal fans. At that time the landscape can be imagined as a piedmont plain formed by the coalescence of terminal fans, similar to those that can be seen today in the alluvial plain adjacent to the Red Sea rift escarpment of the Danakil (Billi, 2022a) or the northern Somali coast (Billi, 2022b). The progressing of the graben floor subsidence has forced the modern rivers to incise the older alluvium, while the uplift of the eastern margin has turned the Raya plain into a semi-endoreic basin, where all the western rivers, except the Golina which has cut through the eastern block, end up in the centre of the graben floor where they form distributary systems.

The distributary systems of the western rivers are about ten times larger than the alluvial fans of the eastern margin (Tab. 1), but the catchments of the former are 26 times larger than those of the latter. These results confirm that alluvial fans formed under conditions of higher tectonic activity associated with the subsidence of the eastern margin of the graben floor, while hinged in the western side.

Like alluvial fans, the study distributary systems are closed systems and respect the natural tendency of increasing entropy. The incoming water flows through the distributary network but, due to infiltration, does not exit the distributary system perimeter. The distributary system perimeter is defined by the runout mouths and may change through time, but no work is done beyond it. Leopold (1994) was the first scientist to apply the concept of entropy to explain the longitudinal profile of a river and the tendency to meandering. Further studies are however necessary to verify if the concept of entropy can be extended to other fluvial processes, including also the channel network morphology of alluvial fans and distributary systems.

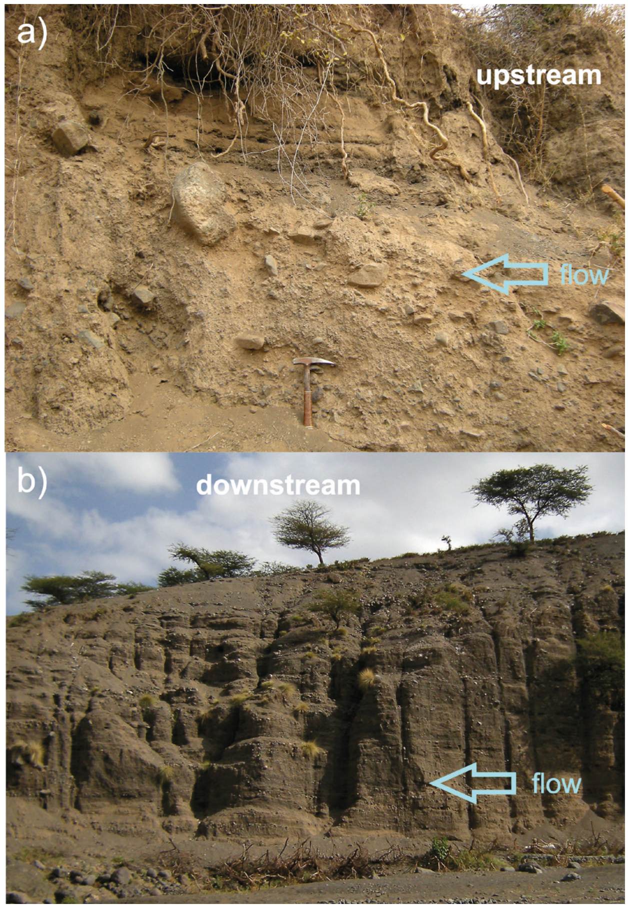

Figure 12. a) Debris flow deposits in the inner part of the western river valleys, in places resting on bedrock; b) thin sheet flood deposits gently dipping to the graben centre. Flow from right to left.

Conclusions

The Raya Graben, north-eastern Ethiopia, is a long, rectangular structural depression parallel to the main escarpment of the Red Sea branch of the Ethiopian Rift Valley. The rivers draining the lower elevated eastern block form alluvial fans, whereas those draining the higher mountain range of the western horst enter the graben floor and form distributary systems. The Raya Graben is therefore an appropriate physiographic setting to investigate the conditions controlling the formation of these two different fluvial systems. Field and Google Earth® measurements and literature data were used to define the main geomorphic characteristics of alluvial fans and distributary systems and to point out the main factors controlling their morphology. The results of the data analysis allowed to reach the following conclusions:

1) Alluvial fans and distributary systems are distinct fluvial landforms. Alluvial fans are steep depositional bodies, whereas distributary systems are rather flat. Alluvial fan deposition is triggered by a marked topographic discontinuity at the river entrance onto the graben floor. Distributary systems are not affected by any topographic discontinuity and form far from the graben margin in the middle of the valley floor. Distributary systems are predominantly fine-grained (sand and pebbly sand), whereas alluvial fans are very coarse (even big boulders) in the apex zone and become finer-grained in the distal zone.
2) This study confirms that catchment size controls the area and slope of alluvial fans and distributary systems, but the correlation with distributary systems is stronger and statistically significant.
3) In the Raya Graben, alluvial fans and distributary systems are associated with distinct fields of fan/distributary system area vs. catchment relief ratio. Alluvial fans are expected to form when their

catchment relief ratio is higher than 0.13. By contrast, distributary systems form only if their catchment relief ratio is lower than 0.18. Further studies are however necessary to verify if these threshold values are valid also in areas with different climates, bedrock lithology and tectonic settings.

4) A few authors (e.g., Nichols & Fisher, 2007) have proposed that distributary systems are relict lacustrine deltas that became terminal fans after the lake base level lowered and the lake ultimately dried up. In the Raya Graben, there is no evidence of lacustrine deposits in the upper part of the valley fill stratigraphic sequence nor in the distal area of the distributary systems. Moreover, the average bifurcation angle of the distributary systems channels is 41% smaller than that of lacustrine deltas. The deposits of the latter consist mainly of trough cross-bedded sands, whereas in the distributary systems deposits, horizontal bedding and lamination of sand and pebbly sand prevail. This study indicates that the distributary system and lacustrine deltas are distinct river systems and confirms a similar finding reported by Billi (2021) for dryland distributive systems.
5) Alluvial fans and distributary systems can be considered as closed systems and the radial shape of their channel networks can be seen as the result of the uniform distribution of flow energy. This suggests that both fluvial landscapes are examples of the natural tendency of closed systems to increase their entropy. Further studies are, however, necessary to confirm this approach.

ACKNOWLEDGMENTS

Prof. Ernesto Abbate is greatly acknowledged for the elucidative discussions on the geology and tectonic development of the study area that largely contributed to improving the manuscript.

CONFLICT OF INTEREST STATEMENT

The author declares that he has no conflict of interest neither known competing financial interests nor personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

ABBATE E., SAGRI M., 1969. *Dati e considerazioni sul margine orientale dell'altopiano Etiopico nelle Province del Tigrai e del Wollo.* Bollettino della Società Geologica Italiana 88: 489-497.

ALLABY A., ALLABY M., 1999. *Oxford dictionary of earth sciences.* Second Edition, Oxford University Press, Oxford.

AYENEW T., GEBREEGZIABHER M., KEBEDE S., MAMO S., 2013. *Integrated assessment of hydrogeology and water quality for groundwater-based irrigation development in the Raya Valley, northern Ethiopia.* Water International 38(4): 480-492. doi:10.1080/02508060.2013.821640

BEAUMONT P., 1972. *Alluvial fans along the foothills of the Elburz Mountains, Iran*. Palaeogeography Palaeoclimatology Palaeoecology 12: 251-273.

BILLI P., 2007. *Morphology and sediment dynamics of ephemeral stream terminal distributary systems in the Kobo basin (northern Welo, Ethiopia*). Geomorphology 85: 98-113. doi:10.1016/j.catena.2008.04.002

BILLI P., 2008. *Flash floods, sediment transport and bedforms in the ephemeral streams of Kobo basin, northern Ethiopia*. Catena 75 (1): 5-17. doi:10.1016/j.catena.2008.04.002

BILLI P., 2015. *Ephemeral streams in the Kobo basin*. In: Billi P. (ed.), Landscapes and landforms of Ethiopia. Springer, Heidelberg: 213-226. doi:10.1007/978-94-017-8026-1_12

BILLI P., 2021. *Geomorphic characteristics of dryland distributive systems*. Revista de Geomorfologie 23: 5-16. doi: 10.21094/rg.2021.101

BILLI P., 2022a. *Landscape and landforms of the Samoti Plain, Eritrean Danakil*. In: Billi P. (ed.), Landscape and landforms of the Horn of Africa: Eritrea, Djibouti, Somalia: 169-186. Springer, Cham, Switzerland.

BILLI, P., 2022b. *Fluvial landscape of the Daban Basin, Northern Somalia*. In: Billi P. (ed.) Landscape and landforms of the Horn of Africa: Eritrea, Djibouti, Somalia: 265-280. Springer, Cham, Switzerland.

BLAIR T.C., MCPHERSON J.G., 1994. *Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies*. Journal of Sedimentary Research A64: 451-490.

BLAIR T.C., MCPHERSON J.G., 2009. *Processes and forms of alluvial fans*. In: Parsons A.J., Abrahams A.D. (eds), Geomorphology of Desert Environments: 413-467. Springer, Dordrecht. doi 10.1007/978-1-4020-5719-9 14

BOLLA PITTALUGA M, REPETTO R, TUBINO M., 2003. *Channel bifurcations in braided rivers: equilibrium configurations and stability*. Water Resources Research 39 (3): 1046.

BOWMAN D., 2019. *Fan morphometry*. In: Bowman D. (ed.), Principles of Alluvial Fan Morphology: 37-42. Springer Nature, Cham, Switzerland.

BULL W.B., 1964. *Geomorphology of segmented alluvial fans in western Fresno County, California*. US Geol. Surv. Prof. Paper 352-E, Washington.

CAPITANI M., CASAROSA N., FEDERICI P.R., RIBOLINI A., 2007. *Paraglacial fans in the Stura di Demonte Valley (Maritime Alps)*. In: Federici P.R., Chelli A., Firpo M., Ciampalini A., Pappalardo M., Bini M., Biagioni F., Rapetti F., Capitani M., Casarosa A., Cyr A., Granger D.E., Spagnolo M., Stefanini M.C., Ribolini A. (eds), *Guide Book for the Excursions in Western Liguria and on the Maritime Alps*, 12° Belgium - France - Italy - Romania Geomorphological Meeting "Climate Change and Related Landscape, Savona 26-29 September 2007. Brigati, Genova, 116 pp.

CHAKRABORTY T., GHOSH P., 2010. *The geomorphology and sedimentology of the Tista megafan, Darjeeling Himalaya: Implications for megafan building processes*. Geomorphology 115(3): 252-266.

COFFEY T.S., SHAW J.B., (2017). *Congruent bifurcation angles in river delta and tributary channel networks*. Geophysical Research Letters 44: 11,427-11,436. doi.org/10.1002/2017GL074873

DAVIDSON S.K., HARTLEY A.J., WEISSMANN J.S., NICHOLS G.J., SCUDERI L.A., 2013. *Geomorphic elements on modern distributive fluvial systems.* Geomorphology 180-181: 82-95. doi.org/10.1016/j.geomorph.2012.09.008

Davidson S.K., Hartley A.J., 2014. *A quantitative approach to linking drainage area and distributive-fluvial-system area in modern and ancient endorheic basins*. Journal of Sedimentary Research 84: 1005-1020. doi.org/10.2110/jsr.2014.79

Demissie B., Billi P., Frankl A., Haile M., Nyssen J., 2017. *Excess river sedimentation at bridges in the Raya Graben (Northern Ethiopia)*. Land Degradation & Development 28: 946-958.

Denny C.S., 1965. *Alluvial Fans in the Death Valley region, California and Nevada*. US Geological Survey Professional Paper 466, Washington.

Drew F., 1873. *Alluvial and lacustrine deposits and glacial record of Upper Indus Basin*. Geological Society of London Quarterly Journal 29: 441-471.

Eckis R., 1928. *Alluvial fans of the Cucamonga District, Southern California*. Journal of Geology 36, 111-141.

Fenta A.A., Kifle A., Gebreyohannes T., Hailu G., 2015. *Spatial analysis of groundwater potential using remote sensing and GIS-based multi-criteria evaluation in Raya Valley, northern Ethiopia*. Hydrogeology Journal 23: 195-206. doi 10.1007/s10040-014-1198-x

Friend P.F., 1978. *Distinctive features of some ancient river systems*. In: Miall A.D. (ed.), Fluvial Sedimentology: 531-542. Canadian Society of Petroleum Geologists, Memoir 5.

Giz (German Agency for Technical Cooperation), 1976, *Geoelectrical and seismic cross sections, Map 7*. Kobo Alamata agricultural development project. Provisional Military Government of Socialist Ethiopia, Relief and Rehabilitation Commission, Addis Ababa.

Hartley A.J., Weissmann G.S., Nichols G.J., Warwick G.L. 2010. *Large distributive fluvial systems: Characteristics, distribution, and controls on development*. Journal of Sedimentary Research 80: 167-183.

Harvey A., 2011. *Dryland alluvial fans*. In: Thomas D. (ed.), Arid Zone Geomorphology: Process, Form and Change in Drylands: 333-371. Wiley, Chichester.

Hassan M.A., Marren P.M., Schwartz U., 2009. *Bar structure in an arid ephemeral stream*. Sedimentary Geology, 221: 57-70. doi:10.1016/j.sedgeo.2009.07.012

Hunt C.B., Mabey D.R., 1966. *Stratigraphy and structure, Death Valley, California*. U.S. Geological Survey Professional Paper 494-A, Washington.

Iacobucci G., Delchiaro M., Troiani F., Nadali D., 2024. *Land-surface quantitative analysis for mapping and deciphering the construction processes of piedmont alluvial fans in the Anti-Lebanon Mountains*. Geomorphology 453: 109148. doi.org/10.1016/j.geomorph.2024.109148

Kelly S.B., Olsen H., 1993. *Terminal fans – a review with reference to Devonian examples*. Sedimentary Geology 85: 339-374.

Kleinhans M.G., Ferguson R.I., Lane S.N., Hardy R.J., 2013. *Splitting rivers at their seams: bifurcations and avulsion*. Earth Surface Processes and Landforms 38: 47-61.

Lang S.C., Payenberg T.H.D., Reilly M.R.W., Hicks T., Benson J., Kassan J., 2004. *Modern analogues for dryland sandy fluvial-lacustrine deltas and terminal splay reservoirs*. APPEA Journal 329-356.

Lecce S.A., 1990. *The alluvial fan problem*. In: Rachocki A.H., Church M. (eds), Alluvial Fans: A Field Approach: 3-24. Wiley, Chichester.

Lecce, S.A., 1991. *Influence of lithologic erodibility on alluvial fan area, western White Mountains, California and Nevada*. Earth Surface Processes and Landforms 16: 11-18.

Leopold L.B., 1994. *A View of the River*. Harvard University Press, Cambridge.

Mather A., Harvey A., Stokes M., 2000. *Quantifying long-term catchment changes of alluvial fan systems*. Geological Society American Bulletin 112: 1825-1833.

Merla G, Abbate E, Azzaroli A, Bruni P, Canuti P, Fazzuoli M, Sagri M, Tacconi P., 1979. *A geological map of Ethiopia and Somalia*. Consiglio Nazionale delle Ricerche, Firenze.

Milana J.P., Ruzycki L., 1999. *Alluvial-fan slope as a function of sediment transport efficiency*. Journal of Sedimentary Research 69: 553-562.

Mokarram M., Seif A., Sathyamoorthy D., 2014. *Use of morphometric analysis and selforganizing maps for alluvial fan classification: case study on Ostorankooh altitudes, Iran*. In: IOP Conference Series: Earth and Environmental Science. IOP Publishing, 012003.

Nanson G.D., Knighton A.D., 1996. *Anabranching rivers: Their cause. character and classification*. Earth Surface Processes and Landforms 21: 217-239.

Nichols G.J., 1987. *Structural controls on fluvial distributary systems–the Luna System, Northern Spain*. In: Ethridge F.G., Florez R.M., Harvey M.D. (eds), Recent Developments in Fluvial Sedimentology: 269-277. Society of Economic Palaeontologists and Mineralogists, Special Publication 39.

Nichols G.J., Fisher J.A., 2007. *Processes, facies and architecture of fluvial distributary system deposits*. Sedimentary Geology 195: 75-90. doi:10.1016/j.sedgeo.2006.07.004

Nilsen T.H., Moore T.E., 1984. *Bibliography of alluvial-fan deposits*. Geo Books, Norwich.

North C.P., Warwick G.L., 2007. *Fluvial fans: myths, misconceptions, and the end of the terminal-fan model*. Journal of Sedimentary Research 77: 693-701. doi: 10.2110/jsr.2007.072

Olariu C., Zhou C., Steel R., Zhang Z., Yuan X., Zhang J., Chen S., Cheng D., Kim W., 2021. *Controls on the stratal architecture of lacustrine delta successions in low-accommodation conditions*. Sedimentology, 68(5), 1941-1963. doi.org/10.1111/sed.12838

Özpolat E., Yildirim C., Görüm T., Gosse J.C., Şahiner E., Akif Sarikaya M., Owen L.A., 2022. *Three-dimensional control of alluvial fans by rock uplift in an extensional regime: Aydın Range, Aegean extensional province*. Scientific Reports 12: 15306.

Parkash B., Awasthi A.K., Gohain K., 1983. *Lithofacies of the Markanda terminal fan, Kurukshetra district, Haryana, India*. In: Collinson J.D., Lewin J. (eds), Modern and Ancient Fluvial Systems: 337-344. International Association of Sedimentologists, Special Publication 6.

Reitz M.D., Jerolmack D.J., Swenson J.B., 2010. *Flooding and flow path selection on alluvial fans and deltas*. Geophysical Research Letters 37, L06401. http://dx.doi.org/10.1029/2009GL041985.

Sadler S.P., Kelly S.B., 1993. *Fluvial processes and cyclicity in terminal fan deposits: An example from the Late Devonian of southwest Ireland*. Sedimentary Geology 85: 375-386.

Saito K., Oguchi T., 2005. *Slope of alluvial fans in humid regions of Japan, Taiwan and the Philippines*. Geomorphology 70: 147-162. doi:10.1016/j.geomorph.2005.04.006

SCHUMM S.A., 1956. *Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey*. Geological Society of America Bulletin 67 (5): 597-646.

SHISHAYE H.A., TAIT D.R., BEFUS K.M., MAHER D.T., READING M.J., JEFFRE, L., TEWOLDE T.G., ASFAW A.T., 2020. *Development of an improved hydrogeological and hydro-geochemical conceptualization of a complex aquifer system in Ethiopia*. Hydrogeology Journal 28: 2727-2746. doi.org/10.1007/s10040-020-02229-4

SILVESTRINI V., 2011. *Che cos'è l'entropia*. Ed. Riuniti University Press, 130. Roma.

SLINGERLAND R., SMITH N.D., 2004. *River avulsions and their deposits*. Annual Review of Earth and Planetary Science 32: 257-285. doi: 10.1146/annurev.earth.32.101802.120201

SMITH D.G., 1991. *Lacustrine deltas*. The Canadian Geographer, 35 (3): 311-316.

STOCK J.D., SCHMIDT K.M., MILLER D.M., 2007. *Controls on alluvial fan long-profiles*. Geological Society of America Bulletin 120 (5-6): 619-640. doi.org/10.1130/B26208.1

STOKES M., MATHER A.E., 2015. *Controls on modern tributary-junction alluvial fan occurrence and morphology: High Atlas Mountains, Morocco*. Geomorphology 248: 344-362.

STOKES M., GOMES A., 2020. *Alluvial fans on volcanic islands: A morphometric perspective (Sao Vicente, Cape Verde)*. Geomorphology 368: 107356.

SYVITSKI J.P.M., KETTNER A.J., CORREGGIARI A., NELSON B.W., 2005. *Distributary channels and their impact on sediment dispersal*. Marine Geology 222-223: 75-94. doi:10.1016/j.margeo.2005.06.030

TOMCZYK A.M., 2021. *Morphometry and morphology of fan-shaped landforms in the high-Arctic settings of central Spitsbergen, Svalbard*. Geomorphology 392: 107899. doi.org/10.1016/j.geomorph.2021.107899

TOOTH S., 1999. *Floodouts in central Australia*. In: Miller A.J., Gupta A. (eds), Varieties of Fluvial Form: 219-247. Wiley, Chichester.

VENTRA D., CLARKE L.E., 2018. *Geology and Geomorphology of alluvial and fluvial fans: Terrestrial and planetary perspectives*. Geological Society of London, Special Publications 440: 1-21. doi.org/10.1144/SP440.16

VISERAS C., CALVACHE M.A.L., SORIA J.M., FERNANDEZ J., 2003. *Differential features of alluvial fans controlled by tectonic or eustatic accommodation space. Examples from the Betic Cordillera, Spain*. Geomorphology 50: 181-202.

WEISSMANN G.S., BENNETT G.L., LANSDALE A.L., 2005. *Factors controlling sequence development on Quaternary fluvial fans, San Joaquin Basin, California, USA*. In: Harvey A.M., Mather A.E., Stokes M. (eds), Alluvial Fans: Geomorphology, Sedimentology, Dynamics: 169-186. Geological Society of London, Special Publications 251.

WEISSMANN G.S., HARTLEY A.J., SCUDERI L.A., NICHOLS G.J., DAVIDSON S.K., OWEN A., ATCHLEY S.C., BHATTACHARYYA P., CHAKRABORTY T., GHOSH P., NORDT L.C., TABOR N.J., 2013. *Prograding distributive fluvial systems: geomorphic models and ancient examples*. In: Driese S.G., Nordt L.C., McCarthy P.J. (eds), New Frontiers in Paleopedology and Terrestrial Paleoclimatology: Palaeosols and Soil Surface Analog Systems: 131-148. SEPM, Special Publication 104.

WHIPPLE K.X., TRAYLER C.R., 1996. *Tectonic control of fan size: the importance of spatially variable subsidence rates*. Basin Research 8: 351-366.

WILLIAMS E.A., 2000. *Flexural cantilever models of extensional subsidence in the Munster Basin (SE Ireland) and Old Red Sandstone fluvial dispersal systems*. In: Friend P.F., Williams B.P.J. (eds), New perspectives on the Old Red Sandstone: 239-268. Geological Society, London, Special Publications 180.

WILLIAMS R.M.E., ZIMBELMAN J.R., JOHNSTON A.K., 2006. *Aspects of alluvial fan shape indicative of formation process: A case study in southwestern California with application to Mojave Crater fans on Mars*. Geophysical Research Letters 33: L10201. doi:10.1029/2005GL025618

WOOR S., THOMAS D.S.G., PARTON A., LEENMAN A., 2023. *Morphology and controls of the mountain-front fan systems of the Hajar Mountains, south-east Arabia*. Earth-Science Reviews 237: 104316. doi.org/10.1016/j.earscirev.2023.104316

ZANETTIN B., 1993. *On the evolution of the Ethiopian volcanic province*. In: Abbate E., Sagri M., Sassi F.P. (eds), Geology and mineral resources of Somalia and surrounding regions: 279-310. Istituto Agronomico per l'Oltremare, Firenze.

ZHANG Y., DAI X., WANG M., LI X., 2020. *The concept, characteristics and significance of fluvial fans*. Petroleum Exploration and Development 47 (5): 1014-1026.

(ms. pres. 15 marzo 2025; ult. bozze 15 giugno 2025)