

## ORIGINAL ARTICLE

# Regional view of a Trans-African Drainage System

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## ABSTRACT

Despite the arid to hyperarid climate of the Great Sahara of North Africa, pluvial climates dominated the region. Radar data shed some light on the postulated Trans-African Drainage System and its relationship to active and inactive tributaries of the Nile basin. Interpretations of recent elevation data confirm a source of the river water from the Red Sea highlands did not connect the Atlantic Ocean across Tushka basin, highlands of Uwinate and Darfur, and Chad basin, but northward to the ancestral Nile Delta. Elements of topography and climate were considered. They show that the former segments of the Nile closely mirror present-day tributaries of the Nile basin in drainage geometry, landscape, and climate. A rainfall data interpolation scenario revealed that this basin received concurrent runoff from both flanks such as Gabgaba-Allaqi to the east and Tushka basin to the west, similar to present-day Sobat and White Nile tributaries, respectively. Overall the western tributaries such as those of Tushka basin and Howar lead to the Nile, which was (and still is) the biggest river system in Africa.

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**Introduction**

Modern rivers in Africa (e.g., Nile, Niger, Congo, Orange, Chari, Cubango, Senegal, among others) receive water from its Equatorial belt (Fig. 1). These rivers head in different directions and controlled by topography and structure. Understanding the modern fluvial processes is significant in

revealing past paleohydrological processes [1], considering that modern processes might have occurred in the past, as the present is a key to the past. The comparison between past and modern processes is important when both occur in a similar landscape [2]. The Nile basin, in particular, represents an archive of active and inactive streams nearly of the same landscape and longitude.

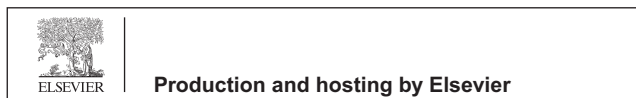
Regional field investigations of the Nile basin are hampered by political boundaries, difficult access, and expensive cost, among other factors. Remote sensing techniques provide an automated, cost effective data of fine temporal, spatial, and spectral resolution. The last few decades experienced major evolution of imaging systems. This allowed detecting paleodrainage courses and proposing new concepts of the Saharan paleorivers. For example, SIR-A data revealed segments of paleocourses covered by sand, and are thought to be tributaries of a major river [3–5]. This allowed proposing the “Trans-African Drainage System” (TADS). This term defined the

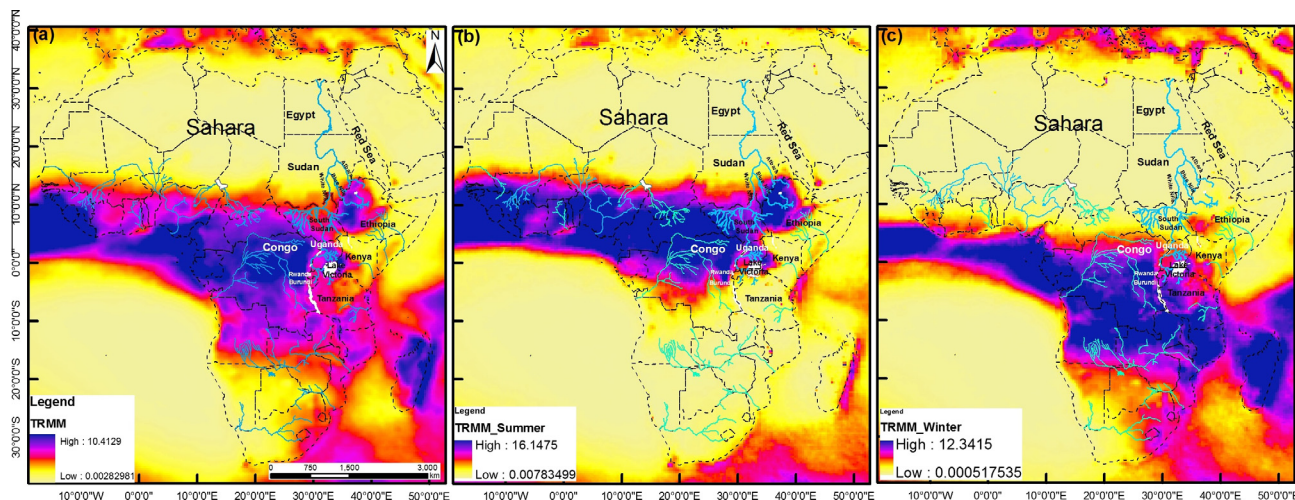
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**Fig. 1** Tropical Rainfall Measuring Mission (TRMM) data of Africa (January 1, 1998 to November 30, 2013) with the digitized modern-day rivers marked by blue lines; (a) spatially distributed TRMM data of Africa, representing the average of the four seasons; (b and c) spatially distributed TRMM data of Africa, representing the average of summer, and winter seasons, respectively. In (b) the rainfall belt migrates northward relative to the Earth Equator; in (c) it migrates southward relative to the Earth Equator.

mid-Tertiary westward-flow of paleorivers from the Red Sea highland to drain southwestward across Selima region and Chad basin before discharging into the Atlantic Ocean. The proposed drainage developed during late Eocene, reached its maximum during early Miocene, however, disconnected by late Miocene resulting intraplate doming and volcanism. Further studies [e.g., 6–10] disagreed with that interpretation. Burke and Welles [6] provided several evidences doubtful the existence of postulated TADS.

In addition to the evidences that challenging the southwestward flow of the proposed paleoriver [6], also raised a question: Was the Nile a Trans-African Drainage System? Subsequently [11,12] proposed that Egypt drained by three major drainage systems during the Cenozoic era from younger to older: the Nile, Qena and Gilf river systems [see sketches in [12,13]]. Prior to the northward-draining Nile, the Gilf system drained the Red Sea highlands during the late Eocene, and northwestward through the Western Desert of Egypt to Tethys shoreline at the present-day Siwa Oasis. Following the Gilf system, tectonic activity north of the Red Sea caused a southward tilting and runoff of Wadi Qena.

Paleorivers of the Selima Sand Sheet drained NE and ENE to Kharga depression instead southwestward to Chad basin [7]. Based on hydrological modeling results, the tributaries of the Tushka basin drained NE to the present location of Tushka lakes [8]. Further studies related the Nile basin to the geometry of the African continent in space and time versus the rainfall belt of Equatorial Africa [9]. Considering onshore and offshore evidence it was proposed that a large river west of the present-day Nile system from Oligocene to early Miocene received water from Red Sea highlands in Eritrea [10]. Since late Miocene the river in Egypt nearly mimicked its present setting and linked to Equatorial Africa in the Quaternary.

The objectives of this paper were to: (1) shed some light on the notion of the postulated Trans-African Drainage System (TDAS) based on interpretations of Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) and Tropical Rainfall Measuring Mission (TRMM) data of active and inactive tributaries of the Nile; and (2) present an overview

of the past climate of the inactive arid valleys of the Nile basin, based on rainfall data interpolation. A key aspect is to find a relationship to drainage pattern, landscape, and regional tectonic setting.

#### Data and methods

The TRMM satellite radar was launched in 1997. Since that time, it yielded a wealth of global rainfall data. It recorded the tropical rainfall by repeated observations. Fifteen years of data from January 1, 1998 to November 30, 2013 of global TRMM-3B42 version 7 satellite radar rainfall were used to understand the spatial and temporal coverage of the rainfall belt over Africa. Using a grid covered by more than 100,000 points, with a spatial resolution of about  $0.25 \times 0.25$  deg. The TRMM data represent the average value of the recorded daily precipitation in the basin. Kriging interpolation the tool of ArcGIS software package was used to visualize the spatial distribution. In this distribution, the geometry of both tropical rainfall belt and the arid Sahara region of North Africa is consistent with the interpolation of mean annual rainfall data over Africa (1950–1999) [14]. This comparison validates the modern-day TRMM data. Analyses of TRMM data and stream networks provide information on the catchment areas, runoff of modern rivers and possible areas that may be subject to frequent floods. Superimposing the stream networks on the TRMM data gives valuable information. The correlation approach was established by shifting some of the inactive tributaries to place them within a similar environment, about 10 deg southward to be nearest from the present-day rainfall belt. This assumes that the present-day arid tributaries of the Sahara were located south of the present-day latitude, and that the prevailing climate conditions were similar to those of present-day Equatorial Africa. Considering plate tectonics, Africa was south of its present geometry [15]. Use of such an approach would visualize some of the processes that might have happened during past pluvial conditions, supposing that the Sahara existed under climate conditions that were similar to the present-day tropical to semi-tropical Africa.





The rainfall represents the daily average precipitation of the period from January 1, 1998 to November 30, 2013. Perhaps, the data represent a very short interval as opposed to the Holocene, or Pleistocene, they visualize the present-day climate conditions of Africa. It also represents the average rainfall of the year's seasons (Fig. 1a) that ranges from 10.4129 to 0.00282 mm/day. Such values reveal wide variation in the climate of Africa. The spatial distribution of TRMM data also shows that the modern tropical rainfall belt seasonally oscillates between the northern and the southern equatorial zone in summer and winter, respectively (Fig. 1a and b). The tropical belt migrates northward during the northern hemisphere's summer seasons (Fig. 1b), however, it shifts southward during the winter seasons (Fig. 1c). This southward migration is probably related to the coldness of the North Atlantic region [14].

The Nile basin was previously classified based on geomorphology, structures, and hydroclimate conditions. Said [18] characterized five regions of the Nile based on structure and geologic history, including, Lake plateau, the Sudd and Central Sudan, the Ethiopian highlands, the cataracts, and the Egyptian region. Abteu and Melesse [19] summarized six zones based on hydroclimate conditions including, Lake plateau territory, Sudd fresh water swamp (southern Sudan), Ethiopian highlands, Sudan plains (central Sudan), northern Sudan and Egypt, and Mediterranean zone. The spatially distributed TRMM data confirm that the Nile basin, in general, classifies into three zones (Fig. 3), which are: (1) arid to hyper-arid zone, which nearly contributes neither sediments nor runoff in most seasons. It covers approximately 1750 km of the Nile basin length (~45%) that occupy the northern part. All of the present-day inactive streams occupy the northern portion of this basin, including Gabgaba-Allaqi, Tushka and Howar, among others; (2) semi-arid zone which contributes sediments and runoff during the summer season, covering about 1150 km of the basin length (~30%). This zone includes, for example, Atbara, Blue Nile, parts of Sobat and White Nile, receiving much runoff during the northern hemisphere summer season; and (3) tropical zone, nearly perennial and covers ~1000 km (~25%) of the Nile basin length, including equatorial lakes. The Equatorial and southernmost tributaries of the Nile occupy the tropical zone that represents a small segment of the total Nile basin length, representing the main source of the White Nile.

Much of the catchment areas that are inactive today were active resulting wetter conditions and reasoned, for example, by: (1) the presence of Nilotic fauna such as crocodiles and/or fish remains in some of the former valleys and basins such as in Tushka [20–22] and Kom Ombo [23], and Mollusca shells in the now-inactive Wadi Howar, northwestern Sudan [24]; (2) abundance of sizable fluvial deposits of mainly sand covering northern Egypt from Suez to the Qattara Depression [25,26], and abundance of paleolake deposits that distributed through eastern Sahara e.g., [27–29]; (3) frequent rainfall is necessary to form the valley courses and fluvial deposits, and for the denudation and differential erosion of the landscape; and (4) plate tectonics provide an explanation of Africa's drift northward through geologic time, this geometry of Africa favored wetter condition over most of North Africa including the Nile basin when it was south of its present position [9].

It is noteworthy that the three zones of tropical, semi-arid and arid to hyper-arid are located at the same longitude, but different latitudes. This clearly supports the notion of the subsequent changes of the rainfall belt based on changes of

the African continent position in space and time [9]. This is an important factor to answer the question: are the former and modern fluvial processes of the Nile basin related? For further verification, it is important to shed some light on some of the past climate conditions by copy the modern-day rainfall data to the inactive streams of the Nile basin or vice versa.

The results of shifting the Tushka and Gabgaba-Allaqi tributaries about 10 deg closer to the location of the White Nile and Sobat region (Fig. 3d) show that the area likely occupied a semi-arid zone. Accordingly, the rainfall belt recharged both eastern (e.g., Gabgaba-Allaqi) and western tributaries (Tushka and Howar basins). The rainfall in the summer recharged Kufra, Tushka, Lake Darfur, Chad, and Gabgaba-Allaqi basins (Fig. 3e). In the winter season, the tropical zone probably migrated southward leaving the northern tributaries arid and recharging the southern tributaries of Howar, Chad and Lake Darfur (Fig. 3e). The frequent northward and southward migrations at the phase of tropical rainfall are coincident with variations in the fluvial deposits, which reveal frequent rainfall conditions, such as the several cycles of the fluvial sand and gravel deposits in Wadi Qena, and wadis east of Qena and Kom Ombo in the Eastern Desert of Egypt.

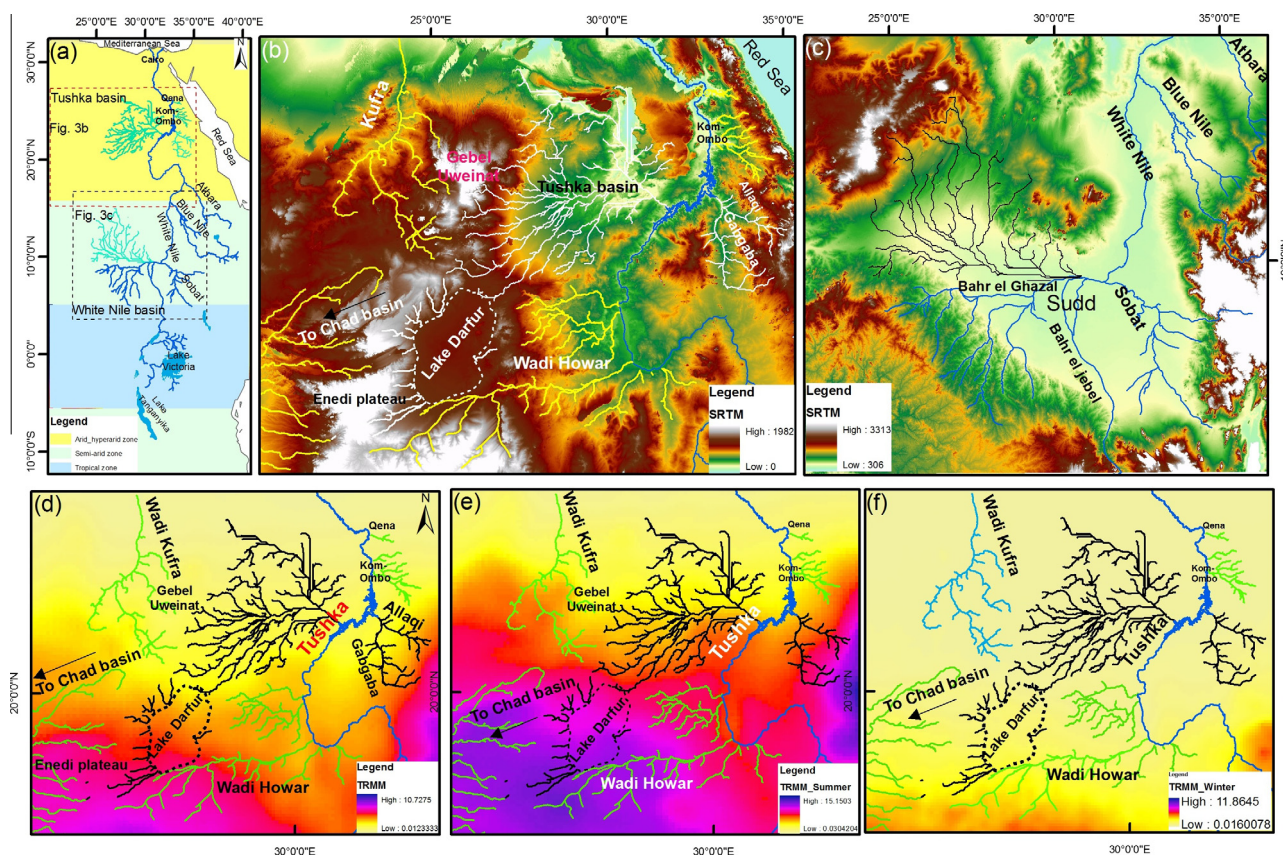
The interpolated data also suggest that during the past pluvial events, Tushka basin probably joined the Nile, receiving water from southwest closely match the modern-day White Nile tributaries. A prior study [27] suggested that Tushka was a tributary of the Nile. This is consistent with drainage network system extracted from SRTM DEM's and landscape gradient (Fig. 2). When the water in Tushka lakes reached its upper level, in response to increase of runoff during the summer seasons, it spilled and drained into the Nile basin. The magnitude of rainfall is responsible for the velocity of runoff from Lake Darfur to Tushka/and or Howar. These processes are close to the relationship between the Equatorial lakes and their surroundings. This lake received seasonal flooding, because frequent flooding and water accumulation were necessary for forming such a mega-lake. Further investigations using SRTM and TRMM also suggest that the headwater for Kufra, Tushka, Howar, Chad, and Gabgaba-Allaqi concurrently received runoff from the past rainfall belt (Fig. 3). Despite the present-day condition that Tushka and Gabgaba-Allaqi basins contribute neither runoff nor fluvial deposits to the Nile basin, their landscape gradient and the predicted inactive stream networks represent evidence of past runoff to the Nile basin that was necessary to form such basins.

Based on rainfall data interpolation and landscape gradients, the past processes in Tushka and Gabgaba-Allaqi basins postformation of the present topography are nearly consistent with the present processes of the White Nile and Sobat tributaries, considering that the area was at or near the present-day rainfall belt. This is because the geometric alignments of Tushka and White Nile basins are of the same landscape and longitude.

#### *Implications to the Trans-African Drainage System (TADS)*

The stream networks (Fig. 2a) and transverse profile using recent topography (SRTM) reveal that highlands of Uweināt–Darfur–Ennedi represent a water divide for Nile (Tushka, and Howar), Chad, and Kufra basins. SRTM DEMs also show Lake Darfur at ~600 m elevation is separated from Chad basin by the Ennedi plateau (700 m). However, the plain of





**Fig. 3** (a) Drainage networks of the Nile Basin in eastern Africa. The basin is classified into three zones, based on rainfall precipitation data of TRMM, from north to south: arid-hyper-arid zone, semi-arid zone, and pluvial zone; (b) drainage networks of the predicted paleorivers in the Eastern Sahara. The Uwinate-Darfur highlands probably served as the source of water for the Tushka, Kufra, Howar, and Chad basins, as depicted from the stream gradient and topographic elevations; (c) western tributaries of White Nile and Sobat River concurrently link to the main channel of the Nile. They compare to the Tushka and Gabgaba-Allaqi basins, respectively as shown in the upper and middle segments in (a); (d) interpolated Tropical Rainfall Measuring Mission (TRMM) data covering the Tushka basin and its surroundings. This view represents an average of four seasons rainfall precipitation based on the notion that the area was south of its present-day geometry; (e) predicted rainfall precipitation during summer seasons; (f) predicted rainfall precipitation during winter seasons.

Tushka basin is much lower at low topographic level ( $< 200$  m above sea level). The topographic profile (Fig. 2b) also shows that Tushka and Chad basins are separated by highlands about 600 m (above sea level) and that Lake Darfur would be linked to Tushka and Wadi Howar basins. This profile also depicts separate basins borders by prominent water divides. Therefore, the connection of drainage from the Red Sea highlands across Tushka, and Chad basin into the Atlantic Ocean via Benue valley was difficult to connect because of topography [6] (see Fig. 2, profile A–B). This is, for example, because much of the present topography of Africa whether due to uplift or subsidence initiated since about  $\sim 30$  Ma [6,30–34]. The surface and subsurface processes were crucial to shaping the African topography, and the most important factor that shaped the continent is the dynamic force as influenced by the underlying mantle [34 and references therein]. The Nile basin, the Benue valley (in its present geomorphology) and the interior Chad basin have all formed along with the new swells [33] (see Fig. 2, 33) during the past 30 My. These issues cast doubt on the existence of the postulated TADS of late Eocene–early Miocene.

Prior to the present topography ( $\sim 30$  Ma), back to  $\sim 100$  Ma (apart from the Santonian disturbances [31], or at

least during an interval 65–30 Ma [32], the continent of Africa, in general, was low-lying topography and nearly flat [32,33 and references therein]. Since that time some rivers drained from the interior toward the continental margin [review in 33]. Rivers in northeast Africa probably drained into the Tethys shoreline before initiation of the Nile in its present geomorphology [e.g., 10,25,26,29]. This is proven by the presence of the fluvial sediments that extend from Suez to Qattara depression [26], and might be extended to the Gulf of Sirt in Libya as it represents an intracontinental rift (180–130 Ma) that might have hosted major rivers until 30 Ma [32,33]. It had a deltaic pattern of late-Eocene to early Miocene, e.g., [25] Oligocene [26,29]. Said [26,29] attempted to depict drainage lines that drained north-northwestward into Tethys shoreline during the Oligocene, prior to the present Nile in its geomorphology and structure. Macgregor [10] also displayed a drainage pattern from the south to the north since the Oligocene, and related the base of Nile cone clastic deposits to about 30 Ma. Thus, no part of the previously proposed TADS system [4] is compatible with drainage drained northward or NNW to the Tethys shorelines. In addition, no part of what was interpreted as “Mid-Tertiary” was older than the present topography. Moreover, analysis of DEM and TRMM data shows that the concurrent runoff from

both Nile flanks in present-day tropical Africa suppose that the Red Sea highlands were not only the source of water into the Nile basin during the postulated TADS, but basins such as Tushka and Wadi Howar, among others, might have contributed to the Nile. As the rise of Red Sea highlands was more or less contemporaneous with the new swells of Africa (30 Ma), this negates the TADS hypothesis.

The postulated segments of TADS in northwestern Sudan that were revealed by SIR-A [3] were tributaries of Wadi Howar that drained into the ancestral Nile basin [6]. Such segments most likely drained into Lake Darfur and out of it to the Tushka basin by spillways into the Nile basin as indicated by SRTM DEM's landscape gradient and extracted stream networks (Fig. 2). Such streams of the Nile basin currently contribute no sediments to the Nile because of climate. However, they would have prevailed by frequent cycles of runoff and erosion during much of the Tertiary [29], and frequent short intervals during Pleistocene and Holocene. During much of the Tertiary [29] pluvial conditions promoted runoff and erosion of highlands that surround much of North African basins such as Tushka, Howar, Chad, Gabgaba-Allaqi and Kufra since about ~30 Ma. Evidences of fauna, flora, and lithologic remains indicate that the interval of late Eocene to early Miocene hosted wet conditions [29, and references therein]. Although, the advent of Pleistocene period characterized by arid conditions [29], frequent wetter intervals through this period prevailed in North Africa as indicated, for example, by the presence of buried channel of the Pleistocene filled with gravels in Egypt [27,29]. Furthermore, several evidences of recent (Holocene) pluvial conditions were recorded throughout North Africa such as an interval 9800–5000 BP [28] in southwestern Egypt and northwestern Sudan. During this interval in northwestern Sudan [24] shells of early Holocene age (about 6500 BP) were found that reflect rainfall patterns similar to those in present-day East Africa. Therefore, much of North African basins and streams, in its topography, received frequent runoff and fluvial deposits during the past ~30 Ma.

## Conclusions

Past tributaries of the Nile basin can be thought of as a mirror of the pluvial paleoclimate. Integrated SRTM DEMs and rainfall data present evidence that the drainage pattern of the now-arid Tushka and Gabgaba-Allaqi basins is similar to the modern White Nile and Sobat, respectively. Thus, Tushka and Gabgaba-Allaqi basins were at the present-day geometry of Equatorial Africa. Coupling the rainfall and geometry simulations, the rainfall belt recharged the northern tributaries of Tushka (at Kharga), Kufra, Chad, and Gabgaba-Allaqi basins during summer seasons. However, they migrated southward in winter seasons, recharging the southern tributaries as those in the Selima region. Considering the shifts in the ITCZ and the African drift in space and time allows a better perception of variations in rainfall patterns, and the resulting fluvial cycles that affected the eastern part of the continent.

## Conflict of interest

*The authors of this paper and their institutions have no conflict of interest issues.*

The authors are academics affiliated with educational institutions that have no other interests.

## Compliance with ethics requirements

*Nothing in this paper requires review by an Ethic Committee. It does not deal with any human subjects.*

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