International Journal of Trend in Scientific Research and Development (IJTSRD)
Volume 8 Issue 1, January-February 2024 Available Online: www.ijtsrd.com e-ISSN: 2456 – 6470

The Pleistocene Delta of the Old Al Balatah River System, Northeastern Libya and its Eastern Extension in Egypt

Khaled Abdel-Kader Ouda

Geology Department, Faculty of Science, Assiut University, Assiut, Egypt

ABSTRACT

The present article concerns with the topography, geomorphology and morphotectonic features of the vast Pleistocene inland delta of the paleoriver system of the Al Balatah Valley in northeastern Libya and its eastern extension in the Great Sand Sea of Egypt where it constitutes what is known as Nahda Plain immediately east of the Libyan-Egyptian borders. The paleodelta was formed as a result of northward flowing of the old Al Balatah river streams into a huge Pleistocene freshwater lake occupying the area lying between latitudes 26º 30’ and 28° 30’, and longitudes 23º 15' and 25º 26’. It was previously described as belonging to the ancient Al Kufrah Paleoriver, however, evidences from the paleo-drainage patterns show that this ancient delta is belonging to the Al- Balatah Paleoriver, not to the Al Kufrah Paleoriver.

The paleoriver basin of the Al Balatah Valley is bounded along its both eastern (Egyptian) and western (Libyan) sides by two intersecting groups of structurally controlled Nubia Sandstone landforms. The older group is made up of a parallel series of longitudinal ridges trending NW/SE and representing bended (up-folded), cross-bedded to horizontally Nubia Sandstone layers separated by low-lying (down-folded) tracks formed as a result of the Upper Cretaceous (Turonian) folding movement which affected the Western Desert of Egypt and Eastern Desert of Libya. The younger group is extending NE/SW and consisting of a parallel series of huge mountain ranges of Nubia Sandstone made up of new plateaus/depressions and dome-like structures/troughs formed as a result of the Late Oligocene refolding movement and dissecting the older Nubia Sandstone ridges. The results are fundamentally significant to the establishment of new agricultural communities in the inhospitable place known as the Great Sand Sea along both sides of the Egyptian/Libyan borders especially when considering the threat of fresh water scarcity in both countries.

***How to cite this paper**:* Khaled Abdel-Kader Ouda "The Pleistocene Delta of the Old Al Balatah River System, Northeastern Libya and its Eastern Extension in Egypt" Published in International Journal of Trend in Scientific Research and Development (ijtsrd), ISSN: 2456-6470, Volume-8 | Issue-1, February 2024, pp.775-804, URL: www.ijtsrd.com/papers/ijtsrd63511.pdf

IJTSRD63511

***KEYWORDS:** Al Balatah Paleoriver system, Al Balatah Paleodelta, Northeastern Libya, Great Sand Sea, Western Desert of Egypt*

1. INTRODUCTION

Climatic change during the Quaternary has led to the widespread formation of vast plains on both sides of the Libyan-Egyptian borders such as the Sarir Tibisti, Sarir Kalanshiya, the easternmost part of the Libyan Desert (Al Waha Plain), the westernmost of the Great Sand Sea of the Western Desert of Egypt (the North Gilf Plain and Nahda Plain (Ouda et al., 2011,2012).

The fluviatile characteristics of the sediments in these plains at Libya have been documented by Desio (1943), Capot-Rey (1960), Fürst (1966), Wendorf et al. (1976) and Pachur (1980). According to the latter author lake formation took place in two humid phases around 13000-17000 B.P., and around 5000 B.P. and rock from Tibisti was transported fluvially in water-bearing river systems with a length of ~1000 km which flowed only periodically and drained into the Mediterranean Sea. The lakes finally dried out around 1900 B.P. and prior to this sabkhas were formed in some plains. Rognon (1980),on the basis of radiocarbon data, reported that the late Pleistocene-early Holocene interval includes the downcutting of the cliffs due to both runoff and groundwater seepage, giving way to widespread accumulation of silts and clays which are in contrast to the coarse, poorly sorted deposits left after wind erosion. According to Rognon (1980) this pluvial interval was followed by a short but intense dry interval in the southern Sahara towards about 8000-7500 leading to the deposition of Aeolian sands on the northwest piedmont B.P. A summer rainfall pluvial of Middle Holocene age is considered by Rognon to be responsible of several lakes which reappeared along the northern and southern borders of Tibisti at this time. According to him the central Sahara plains had a favorable vegetation cover between 5700 and 4100 B.P.. This conclusion is confirmed by some skeletal remains of elephants, giraffes, buffalos (Gabriel, 1977).

Climatic fluctuation during the Quaternary in northeast Africa has also been re-emphasized by various authors (Geyh and Jäkel, 1977; Rognon, 1980; El Ramly, 1980). During the Late Pleistocene and Early Holocene there was alternation of arid and humid cycles in the northeastern part of Africa. According to Geyh and Jäkel (1977), favorable climatic conditions prevailed and development of vegetation occurred at 12500 years B. P. This humid period was followed by a relatively arid interval between 11700 and 1055 years B. P., then a remarkably humid phase suitable for the growth of vegetation followed at 8700 years B. P. According to the same authors an arid phase began at 7100 years B. P., followed by a more humid conditions around 6000 years B.P. which was later succeeded by arid conditions during 4700-3700 years B.P. Since this date alternation of humid and arid phases each of 700-800 years followed until 1000 years B. P.

The climate of Al Kufrah region in Libya also underwent repeated oscillation in the Late Pleistocene and during the Holocene. According to El Ramly (1980) the clayey and silty layers found within the top 30 m of the examined lithologic logs of the drilled wells in Al Kufrah are assigned to relatively humid conditions. When this humid climate prevailed many lakes were found in the wadis and along extensive alluvial plains. El Ramly (1966, 1973) showed similarities in the paleoclimatic conditions in several sites of Quaternary lakes in the Middle East region. These lakes were formed under similar environments during the Late Pleistocene. Additional evidence is also afforded by the presence of *Melania tuberculata* in the Late Pleistocene terraces. These gastropod fossils were observed by El Ramly (1980) along the eastern side of Lake Buwaymah in the Al Kufrah region. Moreover indications of climatic variation which brought by El Ramily include the great variation of the water level, the extension of Lake Chad during the Quaternary and the presence of various levels of the marginal terraces within the valleys of south and north Tibisti and other locations within the Al kufrah basin. The same gastropods were recorded by Ouda (2023) in the Late Pleistocene playas and fresh water-lake deposits in the tracks between Nubia Sandstone ridges and the new depressions in the Great Sand Sea north of the Gilf El Kebir and along the Libyan-Egyptian borders

2. Previous Related Work

Robinson et al. (2006), using the Radar Data, were able to delineate two mega watersheds in southeastern Libya, covering 13,628 km2 and 4232 km2 in area, include water ponding depressions and structurally-controlled mega fluvial features draining into the Al Kufrah Oasis from the south and southeast. These results offer some explanation for the amount of water that has been retrieved from the Al Kufrah wells for over four decades (Salem, 1991). According to Robinson et al. (2006) much of the drainage is structurally controlled (as indicated by its linearity and tributaries at right angles to the main path) and surface water can be expected to have recharged the Nubian aquifer along these structures. Further, the structures may connect several horizontal aquifers in the subsurface to form a mega watershed as is the case in SW Egypt (El-Baz, 1995). This effectively increases the volume of accumulated groundwater.

Gossel et al. (2008), using finite element numerical modeling confirmed that groundwater in the Nubia Sandstone Aquifer in the eastern Sahara is likely to have originated from infiltration during the wet periods of approximately 20–25 ka BP and 5–10 ka BP. Modern recharge of groundwater due to regional ground-water flow from more humid areas to the south is considered by these workers to be highly unlikely.

Using orbital radar satellite imagery, Paillou et al. (2009 and 2012) mapped a major paleo-drainage system in eastern Libya, that could have linked the Kufrah Basin to the Mediterranean coast through the Sirt Basin, possibly as far back as the middle Miocene. According to these authors Synthetic Aperture Radar images from the PALSAR sensor clearly reveal a 900 km-long river system, which starts with three main tributaries (north-eastern Tibesti, northern Uweinat and western Gilf Kebir/Abu Ras) that connect in the Kufrah oasis region. The river system then flows north through the Jebel Dalmah, and forms a large alluvial fan in the Sarir Dalmah. In 2012 Paillou et al. reemphasized the potential connection of between the terminal part of the Kufrah River and the Mediterranean Sea through the Wadi Sahabi paleochannel, which may have constituted the northern extension of the lower Kufrah River paleodrainage system.

Ghoneim et al. (2012) made a combined remote sensing and GIS analysis of the Al Kufrah Paleoriver, Eastern Sahara allowing mapping of the Al Kufrah Paleoriver of Libya and sheds light on its geomorphic evolution during the Neogene. According to these authors the Kufrah system, which is now largely buried beneath the windblown sands of the Eastern Sahara, drained an area of about 236,000km 2 in central and southern Libya. The river discharged across a large inland delta to the Al Jaghbub depression in northern Libya, and ultimately through the Sirt Basin to the Mediterranean Sea. Radar imagery reveals buried features of the landscape including drainage divides, locations of possible stream capture, deeply-incised valleys, and the distal margins of the inland delta.

According to Ghoneim et al. (2012) the drainage basin of Kufrah Paleoriver was composed of four major tributaries emerging from highlands to the west, south and east; the two largest tributaries (Ar-Ramlah and At-Tawilah) converged at the Kufrah Oasis, whereas the other two tributaries (Sura and Abd-El-Malik) emerged from the Gilf-Kebir Plateau in southwest Egypt to join the main stem of the Kufrah Paleoriver. Due to the same authors the lower reach of the paleoriver basin which is today called Wadi Al Balatah flows north until it exits the plateau at Jabal Dalma where it has deposited a large inland paleodelta.

3. Materials and Method of Study

Field studies have been made through an expedition to the Great Sand Sea in the Egyptian side, including geology and topography of the area, the stratigraphy and structural features of the exposed bed rocks as well as evidences of near-surface groundwater (Ouda et al., 2011,2012). Lab work has later been done in the Geology Department of Assiut University on petrography, mineralogy and fossil content of rock samples in order to establish the geologic history and paleoenvironment of the total area.

Modern international mapping programs were used, the most important of which is the International Mapper Program (Global Mapper ver. 13 and ver. 14) to design topographic maps, contour maps, and paleo-drainage maps. The study makes detailed and accurate measurements of the eastern Libyan Sahara and the western province of the Western Desert, including the Great Sea of Sand, based on the information and digital data of the ground elevations received from the Shuttle Radar Topography Mission of NASA's space agency (SRTM World-Wide Elevation Data, 3-arc-second Resolution).which established a ground-altitude information system with high resolution (Ver.4.1) and clarity for most of the Earth's surfaces and the terrestrial and marine boundaries of the globe..

The geological and environmental phenomena in the areas under investigation have been documented by direct electronic projection of modern satellite images onto topographic maps designed with high accuracy. Worldwide high resolution color imagery from DigitalGlobe were used and also the satellite images received from Google Earth Pro, Google Map imagery, Bing Map imagery and World imagery. Available geographic information systems were also used for positioning such as the World Street Map, Google Map Hybrid, Bing Map Hybrid, and USDA National Agriculture Imagery Program (NAIP).

4. Results and Discussion

The results of this study do not support the concept of Ghoneim et al. (2012) concerning the source of the vast inland paleodelta located in northeastern Libya. Evidences from the drainage patterns designated by the Global Mapper ver.15 based on the SRTM 90m Digital Elevation Database ver. 4.1 show that the vast ancient delta plain which lies in northeastern Libya south of Latitude 28º 00′ N and east of Longitude 23º 22′ E is belonging to the Al Balatah Paleoriver, not to the Al Kufrah Paleoriver (Figs. 1-3)

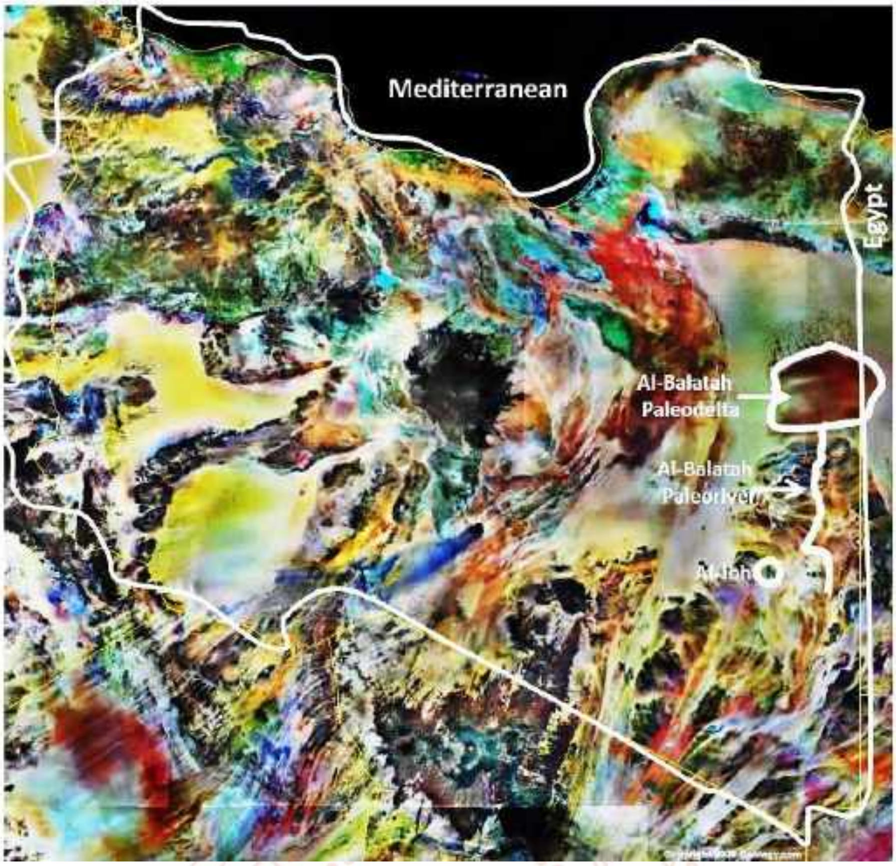

Fig. 1: Satellite image of Libya showing the location of the Al Balatah Paleoriver system and its northern inland delta plain

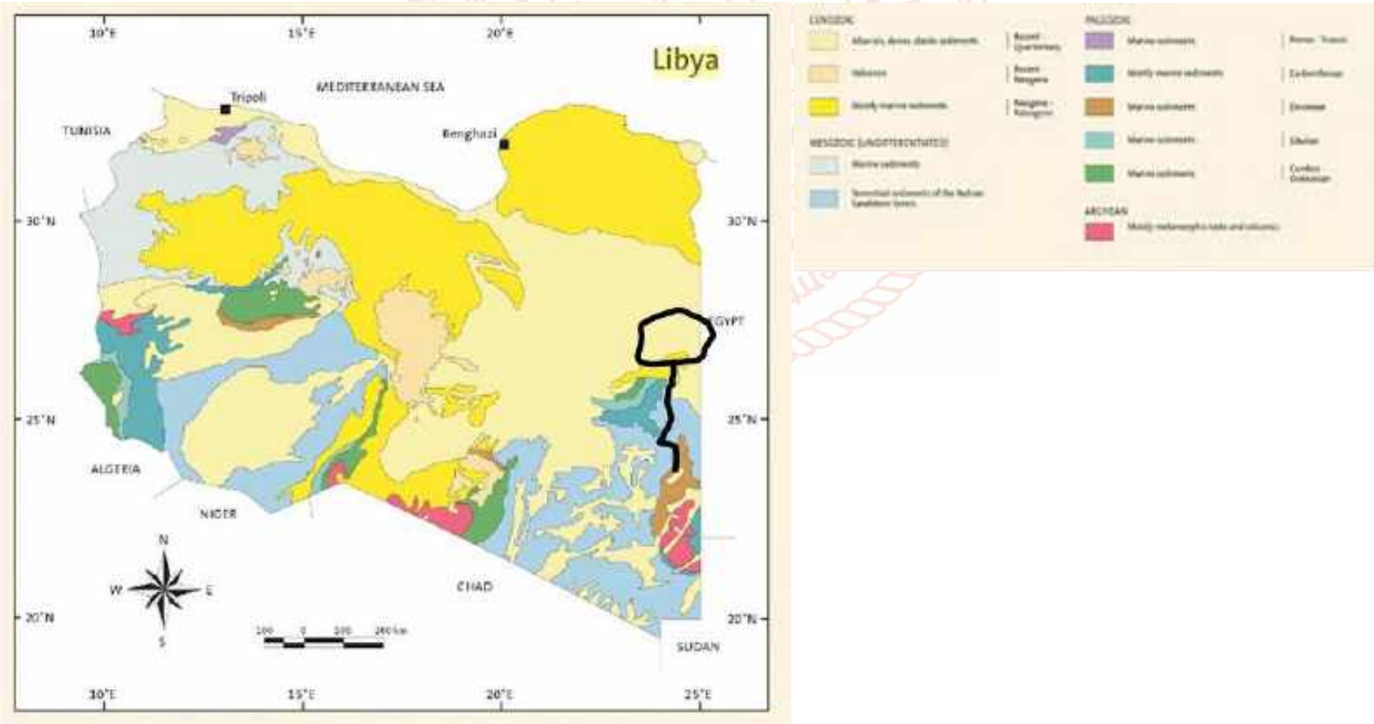

Fig. 2: Geological Map of Libya (from Geological Atlas of Africa with Notes on Stratigraphy, Tectonics, Economic. ..By Thomas Schlüter, 2006, Springer) showing the location of the Al Balatah Paleoriver system

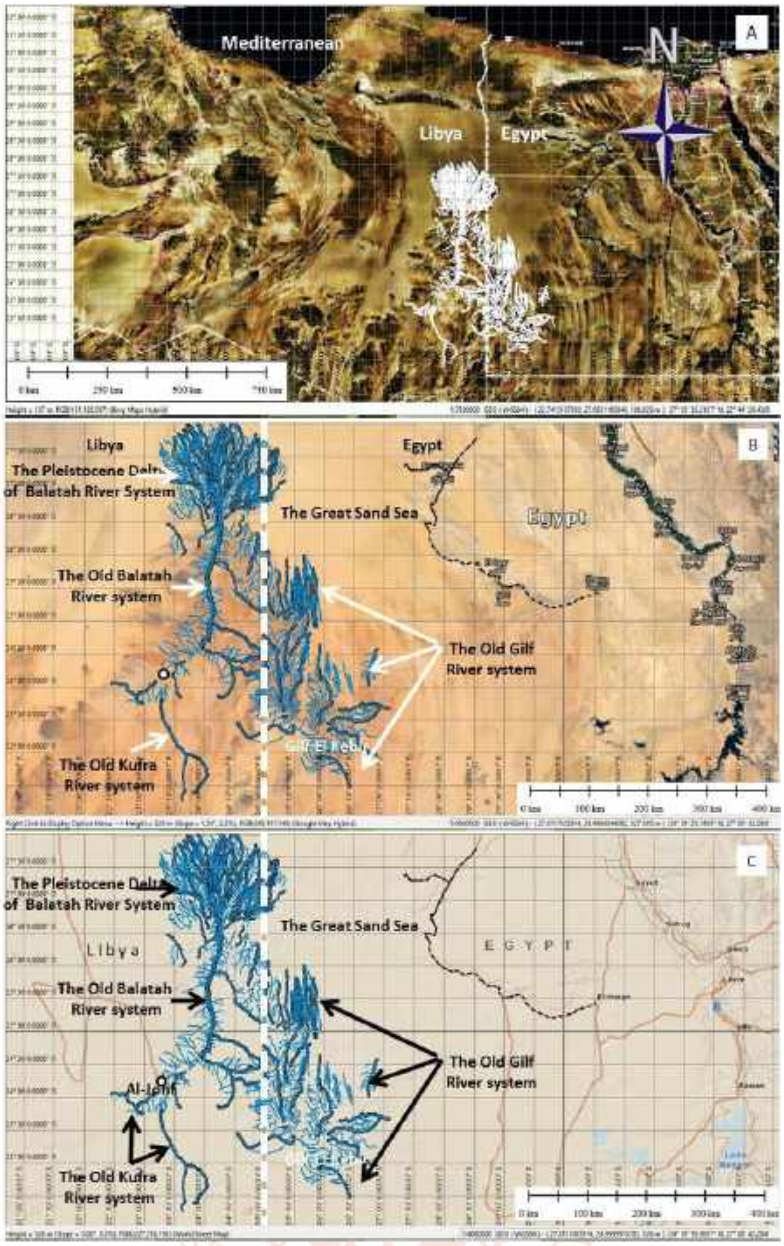

Fig. 3A-C: Satellite images of eastern Libya and western Egypt showing the paleo-drainage pattern of the Libyan Al Balatah Paleoriver system and its relation to the paleo-drainage pattern of the old rivers of the Gilf El Kebir Plateau in Egypt. A: from Bing Maps Hybrid; B: from Google Map hybrid; C: from World Street Map.

This ancient delta plain covers a total area of ~ 24218 Km², thus being more or less equal in size to the Present Nile Delta in northern Egypt (Ouda, 2010). Its maximum length (N-S) is ~150.86 km whereas its maximum width (E-W) is ~202 km. It was formed when the old River system of Wadi Al Balatah in northeastern Libya discharged northward into a huge, freshwater Late Pleistocene lake occupying the area lying northeast of Libya between latitudes 26º 30’ and 28° N, and longitudes 23º 22' and 25º 22’ E (Figs. 4-5)

The delta plain is bounded by disturbed and distorted Nubia Sandstone ridges which show the effect of delta progradation, thus supporting an exclusively inland delta resulted from the flowing of Pleistocene river streams into a quite water body occupying the lowest lands in northeastern Libya. The northernmost progradation of the delta distributaries onto the tracks between the sandstone ridges reached ~75 km long and 171.8 km wide, assuming an additional encroaching area of ~14142 km². The easternmost part of this old delta plain lies in Egypt immediately east of the Libyan-Egyptian borders where it constitutes what is known by Ouda et al. (2011 and 2012) as Nahda Plain (Figs. 4-5). The bed rock of the latter plain is belonging to the Nubian Aquifer System, being represented by the Early Cretaceous Sabaya Formation. The surface floor of the Nahda plain is entirely flat and dissected by rows of radiating draining lines running northeastward on the erodible Nubia Sandstone bed rock which in turn covered by a thin veneer of free silica debris. The draining lines represent the down northeastern streams of the complex draining system of the Al Balatah Paleoriver basin and its distributaries in Egypt.

4.1. The Al Balatah Paleoriver System

The Al Balatah Paleoriver system is made of a long S-N single, gently sinuous stream which is markedly meandering in its upper (southern) part. and running northward through Wadi Al Balatah during post Oligocene time for a distant of about 245 km (Bearing 7° 10′ 55.2″) before the entrance of the huge Pleistocene lake (Fig. 6). The ground of the area occupied by the Al Balatah Paleoriver is gradually sloping to the north, from elevation of 345 m a.s.l. northeast of Al Kufrah to elevation of 238 m a.s.l. at the mouth of the main river stream (south of the Paleodelta Plain). Near the mouth of the Al Balatah Paleoriver the main river channel was distributed into 22 second order distributaries, 19 of which range in length from 100 km to 250 km, while 3 of which range from 75 to 99 km. The distributaries are running north, northwest and northeast (Fig.7). In addition there are hundreds of small third order streams which are less than 74 km in length running in the same directions.

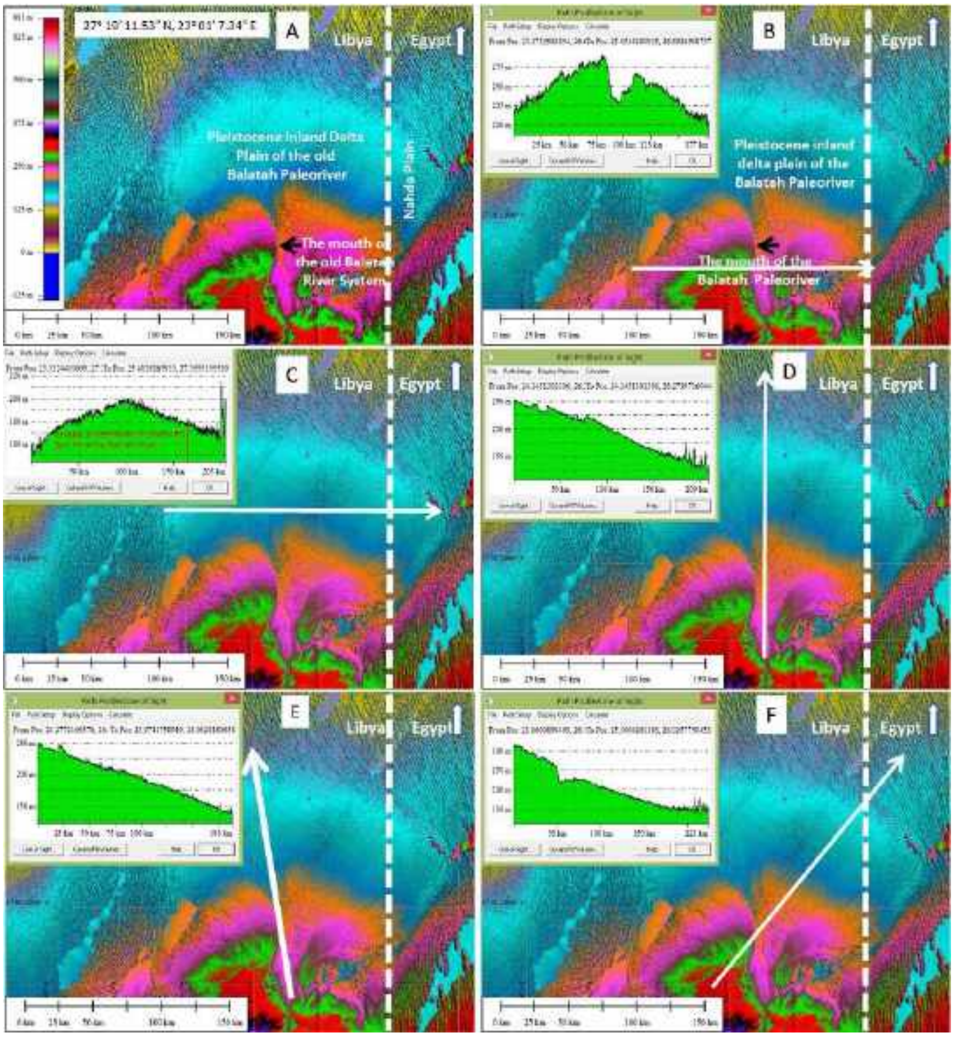

Fig. 4A-F: SRTM topographic maps of the Al Balatah Paleodelta and its eastern extension in Egypt showing different horizontal, vertical and oblique cross sections along the flat floor of delta plain. Note in A that the. paleodelta prograded northward affecting the older Nubia Sandstone ridges which bound the delta plain from north and northeast.

The main channel of the ancient river extends inside the paleodelta for a distance of 186 km where it slopes north- northwestward from ground level 222 m asl at the mouth of the river to ground level 126 m asl at the maximum northern progradation of the delta (Fig. 6). The major distributaries join the main river channel near its mouth forming a dendritic V-shaped pointing downstreams. They carry water away from the main river channel and distribute it over the surface of the delta in a triangular shape. High velocity and large volume of water in the distributaries seem to have led to strong flood erosion of the Nubia sandstone ridges which surround the delta plain (Fig. 8A-B). High water covered the tracks between the ridges and invaded the slopes of the ridges and acted together with the groundwater sapping process as a strong erosional agent of the Nubia Sandstone ridges. The weathering process involved widening of the tracks between ridges and removing of rocks from surrounding ridges. This is together with in-situ deep weathering which occurred due to the flowing of the groundwater both vertically and horizontally along faults and fractures which in turn acted as linear aquifers due to enhanced permeability of the Nubia Sandstone (Fig. 8C-D).

Two major distributary channels of the Al Balatah Paleodelta flowed northeastward into Egypt (Fig. 7) where they contributed a trellis pattern of parallel draining lines running NE down slopes of the delta towards the Egyptian flat sandy plain of the Nahda Plain and separating the main delta plain from the Egyptian longitudinal Nubia Sandstone ridges. Thus, the Nahda Plain on the eastern side of the Egyptian/Libyan borders represents the eastern extension of the Libyan Late Pleistocene inland delta of the Al Balatah Paleoriver system.

No sand dunes are encountered within the flat plain of the Paleodelta of the Al Balatah Paleoriver along both sides of the Libyan-Egyptian borders. However, topset beds made up of coarse grained clastic sediments (sand and conglomerate) were deposited in a network of prograding distributary channels transversing the top of Delta in the Nahda plain which represents the eastern extension of the Libyan Paleodelta Plain in Egypt (Fig. 9). The sand sediments of the distributary bodies are usually porous and exhibiting good criteria of recent groundwater seepage of the underlying Nubia Sandstone bedrock particularly during the winter season (Fig. 8D) where the evaporation rates are low in such dry desert.

On the other hand, the northward margin of the delta is bounded by a series of pre-existing, structurally controlled, Early Cretaceous Nubia Sandstone ridges forming barrier islands trending northwestward and bounding the northern margin of the delta (Fig. 8). The distributary channels of the delta attack these sandstone ridges when the delta prorgraded northward. This attack caused violation , bifurcation , distortion and disintegration of the sandstone ridges leading to in-situ deep weathering and bedrock dissolution of the ridges. The resultant disintegrated sands accumulated over the top surface of the sandstone ridges where they became not able to move for a long distance due to the wet nature of the Nubia Sandstone bedrock.

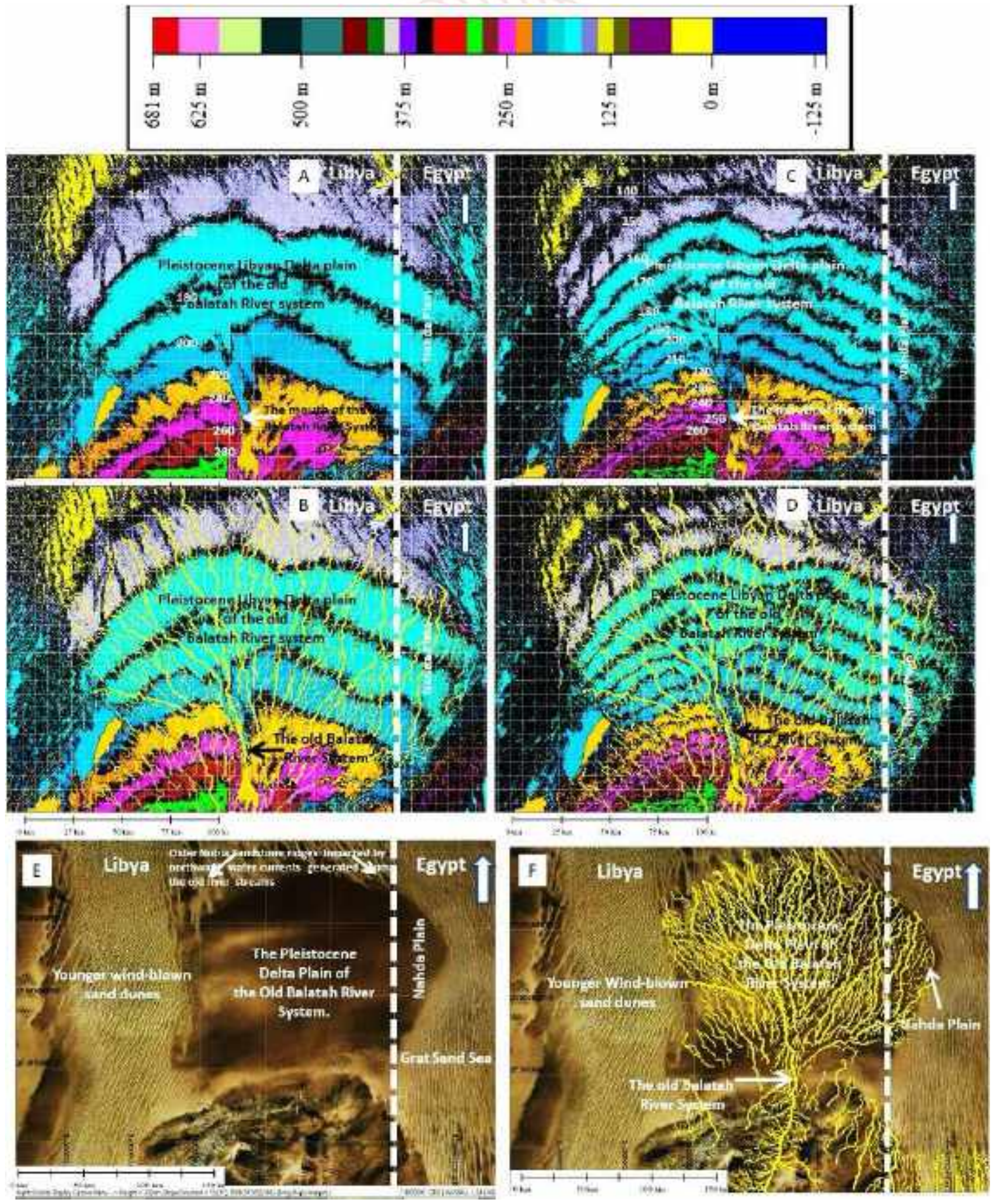

Fig. 5A-F : SRTM topographic maps (A-D) showing topography and contour maps of the Al Balatah Paleodelta in northeastern Libya and its eastern extension (Nahda Plain) in Egypt. Note that the

contour lines are 20 m apart in A - B, and 10 m apart in C - D above sea level and the slope of the floor is directed northward. B and D: are the same figures of A and C after downloading of the main distributaries of the Al Balatah Paleodelta. E and F: Satellite images from Bing Maps Imagery showing the Al Balatah Paleodelta in northeastern Libya and its eastern extension (Nahda Plain) in Egypt before (E) and after (F) downloading of the main distributaries of the paleodelta.

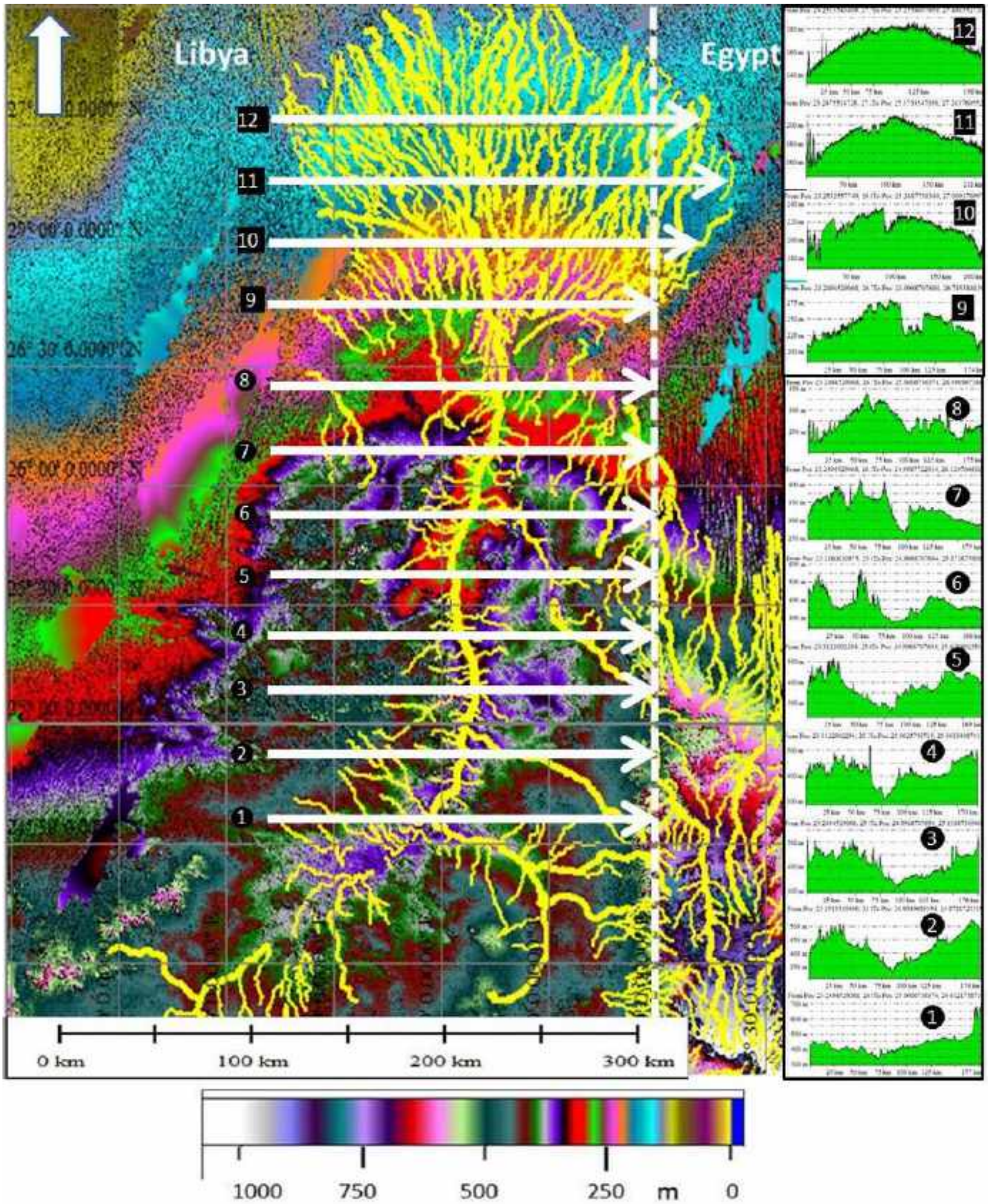

Fig.6: SRTM topographic map showing the paleo-drainage pattern of the Al Balatah Paleoriver system in Libya as well as the cross sections along its course from source to mouth and its northern delta. Note the paleogeographic relation of the Al Balatah Paleoriver to the old rivers of the Gilf El Kebir at south and the Nahda Plain at north of the western province of the Western Desert of Egypt.

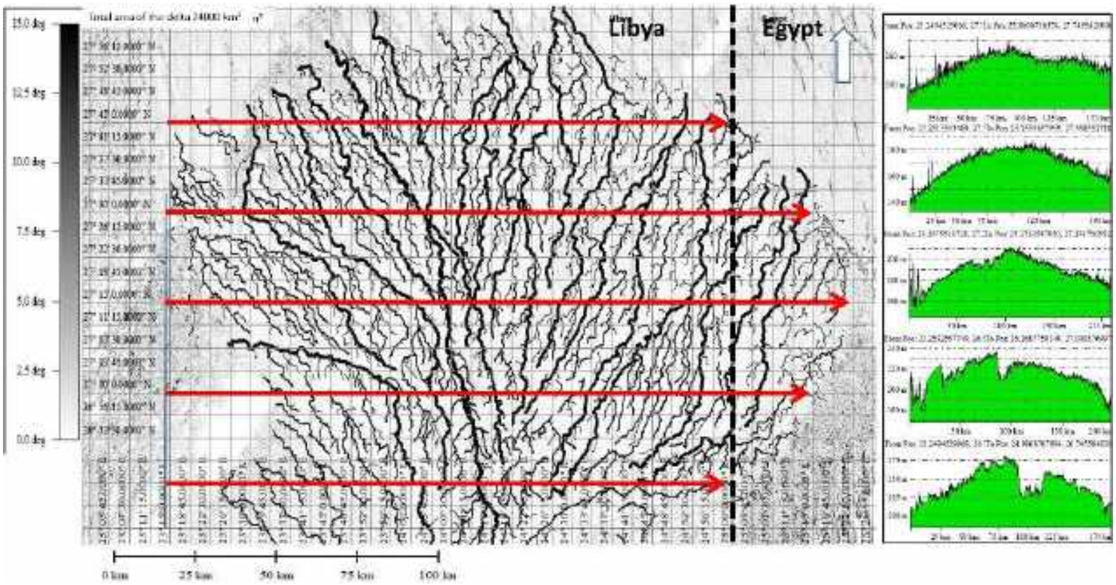

Fig. 7: SRTM paleo-drainage map (Slope Shader) showing distributary channels of the Pleistocene delta of the Al Balatah river system and horizontal (East-West) cross sections along the delta plain. Line Width of the Balatah river streams: 1 pixel: streams first order lower than 25 km; 2 pixel: high order streams from 25 to 75 Km ; 3 pixel: high order streams from 75 to 100 Km 4 pixel: high order streams from 100 to 250 Km; 5 pixel: The main river stream (450 km).

The argument that the inland Paleodelta of the Al Balatah Paleoriver system is highly potentially containing economic quantities of oil and/or gas (Ghoneim et al. 2012) cannot be substantiated. This is simply because the delta plain was originated during precious wetter periods of the Late Pleistocene when the paleoriver streams of Wadi Al Balatah flowed into a huge freshwater lake occupying the area lying northeast of Libya. Thus, it is expected that no enough thickness of coarse deltaic alluvial sediments were buried in the plain during this short time. On the other hand, enormous quantities of water of the Pleistocene inland delta were stored in the subsurface of the underlying Nubia Sandstone bedrock due to its high porosity and permeability along both sides of the Libyan-Egyptian borders. During the periods of very arid climate the Libyan delta plain (including its northeastern extension in Egypt) became apparently dry but the groundwater occurred very near the surface and the groundwater infiltration occurs intermittently in the plain, just enough to support existing vegetation (Fig. 8C-D).

Older deltas such as the present Nile Delta contain vast thickness of coarse alluvial sands and silts (up to 2500 m thick, Ouda and Obaidalla,1995) ranging in age from the Middle Miocene (~15 Ma ago) to the Recent and, thus, containing vast amounts of reserves of oil and gas.

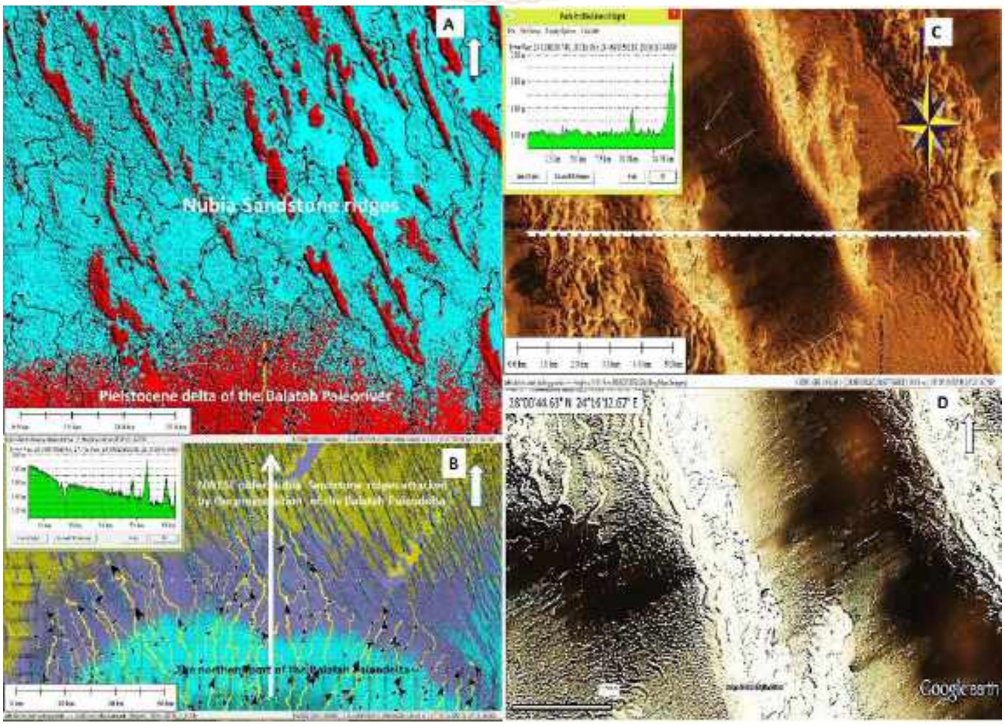

Fig. 8A-D: A and B- SRTM topographic map showing violated Nubia Sandstone ridges separated by wide flat tracks as a result of the attack of the northern progradation of the Al Balatah Paleodelta. C- Satellite image from Bing Map Imagery showing the northward margin of the Al Balatah Paleodelta which is bounded by a series of pre-existing, structurally controlled Nubia Sandstone ridges forming barrier islands trending northwestward where they attacked by the prorgradation of the delta. Note in figs B and C that the attack caused violation , bifurcation , distortion and disintegration of the sandstone ridges leading to the flatness of most of the northern margin of the delta plain. D- Satellite image from Google Earth showing that the attacked sandstone ridges are later affected by groundwater sapping process where the groundwater emerges through joints and pores at the free slope surfaces of the sandstone ridges, then flows downslope of the flat surface of the tracks.

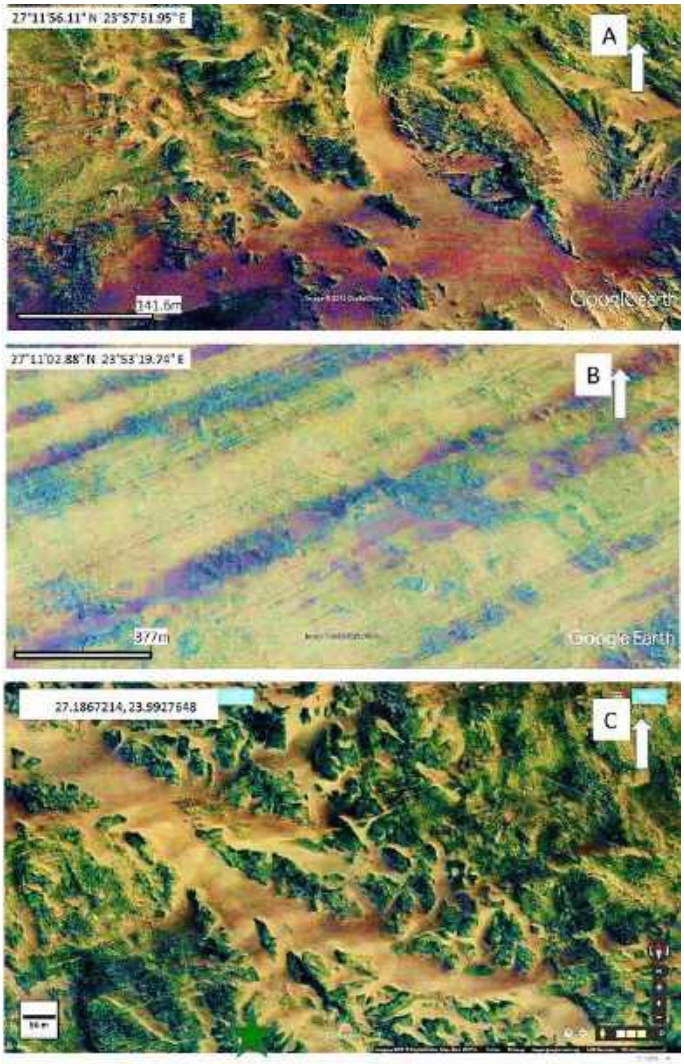

Fig. 9 (A-C): Satellite images from Google Earth (A and B) and Google Map imagery (C) showing topset beds on the floor of the Al Balatah delta plain made up of coarse grained clastic sediments (sand and conglomerate) deposited in a network of prograding distributary channels transversing the top of Delta. During the periods of very arid climate the Libyan delta plain (including its northeastern extension in Egypt) became apparently dry but the groundwater occurred very near the surface and the groundwater infiltration occurs intermittently in the plain, just enough to support existing vegetation

4.2. Source of the Al Balatah Paleoriver

The source of the Al Balatah Paleoriver is independent from the Al Kufrah Paleoriver system, and consequently the Pleistocene Lake of the Al Balatah Paleoriver is independent from the Pleistocene Lake of Al Kufrah Paleoriver. According to Fisk and Pennington (1976), there is an ancient stream channel ""Wadi Kufrah" extends for about 50 km NE and SW of Al Kufrah town. El Ramly (1980), based on LANDSA imagery for Kufrah region described a Pleistocene lake following the same course as that mentioned by Fisk and Pennington (1976). According to him the Al Kufrah river system seems to drained into the Kufrah Lake which is a Pleistocene Lake located in a depression at Al Jawf (Al Kufrah Oasis) and is about 100 km long in NE/EW direction and attain a width of about 60 km.

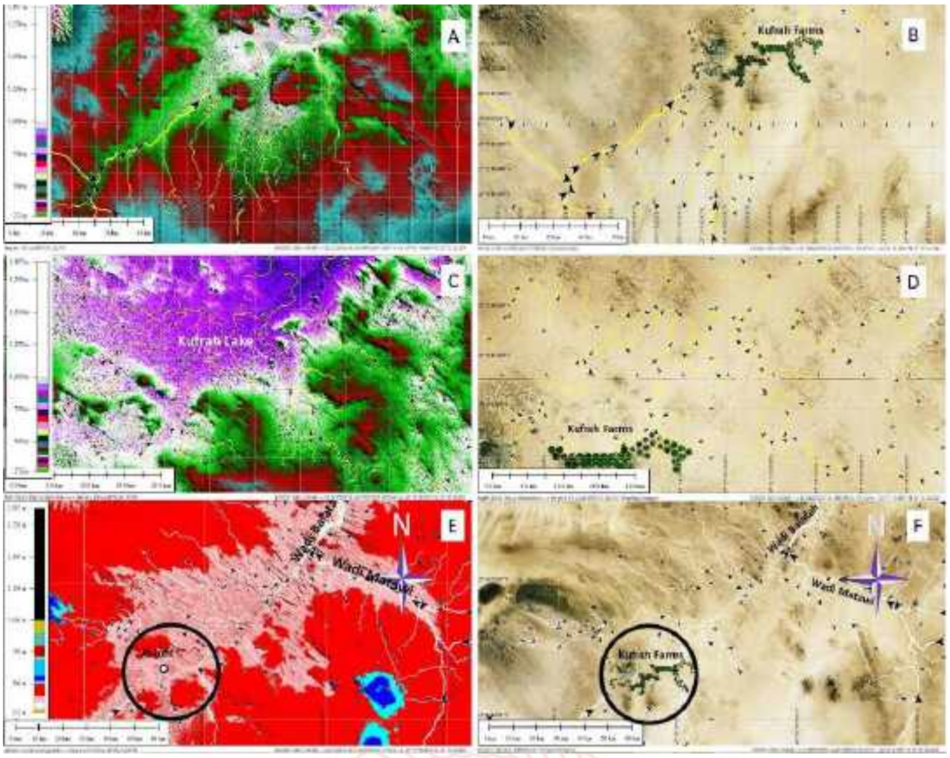

Fig. 10A-F: SRTM topographic maps of the Al Kufrah Basin (A,C and E) and their corresponding Satellite images from Bing Map Imagery (B and D) and World Imagery (F) showing the paleo-drainage pattern of the Al Kufrah Paleoriver system. Black arrows point to the direction of flow of streams. Note in E and F that the drainage pattern of the Al Kufrah Paleriver is independent from the drainage pattern of the Al Balatah Paleoriver as deduced from direction of streams.

Three prominent Jabals are located within the Lake depression: Jabal al Bahr north of Al kufrah town, Jabal az Zurg and Jabal at Tullä. The latter two jabals are located on the southern rim of the Al Kufrah Production Project (KPP). The three jabals were islands during the evolutionary stages of the Pleistocene Kufrah Lake. El Ramly (1980) also showed that along the southern piedmont slopes of Gebel az Zalmah, overlooking Al Kufrah depression in a SE direction, the other limb of the divide flows towards the northwest.

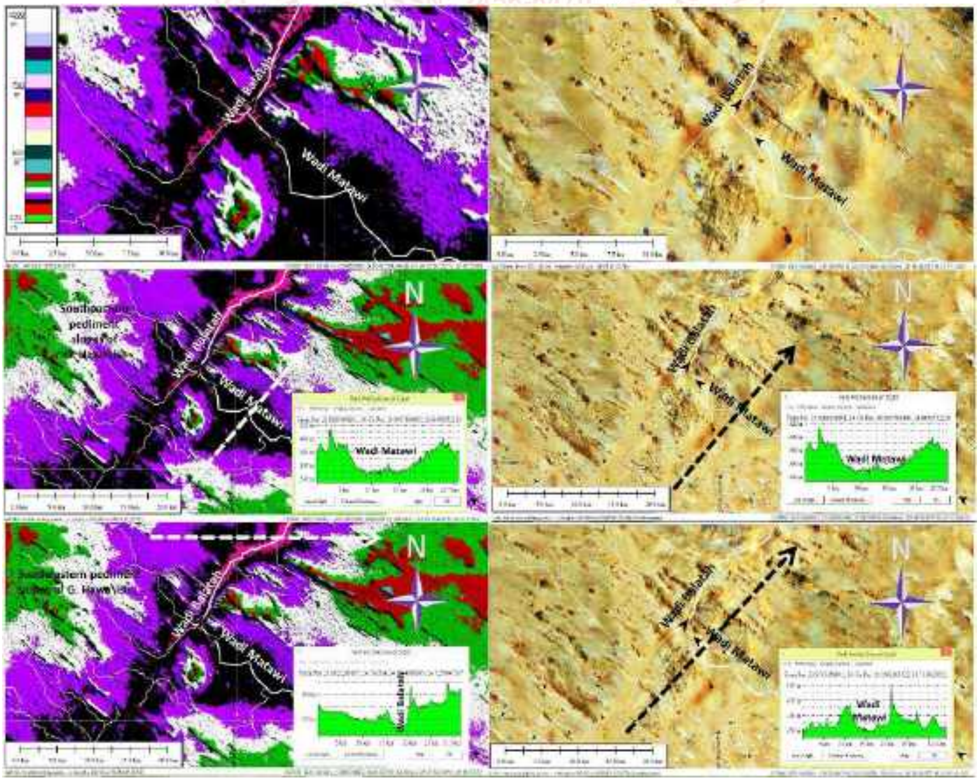

Fig. 11 A-F: SRTM topographic maps (A, C and E) and corresponding Satellite images from World Imagery (B, D and F) showing that the Al Balatah Paleoriver originates from the intersection of two opposed E-W systems of streams. The first and major eastern stream ran into Wadi Matawi from

East to west. It is a long sinuous channel, 150 km long, with a broadly looping curve starting at Lat. 23º 51′ 38″ N, and Long. 24º 14′ 56″ E, ~40 km NE of Gebel Zurg and 70 km NW of Gebel Rukn and extending northward , then westward through Wadi Matawi where it met the western system of streams which are coming from the southeastern piedmonts of Gebel Hawa'ish at the beginning of Wadi Al-Balatah..

The present investigation, based on paleo-drainage patterns designated by SRTM data SRTM data showed clearly that the Al Balatah Paleoriver system drained northward into an independent vast fresh water lake located ~ 400 km north-northeast of Kufrah Oasis (Fig.. 10). It also confirms the existence of a divide line running in a NW direction between: the piedmont slopes which is running SW towards the Kufrah Basin and those running NE towards the Al Balatah Valley. It showed that the Al Balatah Paleoriver started at Lat. 24º 37′ 2″ N and Long. 23º 56′ 46″ E, ~78 km NE of Al Johf (Kufrah), and ~108 km west of the Libyan/Egyptian boundary where it originates from the intersection of two opposed E-W systems of streams. The first and major eastern stream ran into Wadi Matawi from East to west. It is a long sinuous channel, 150 km long, with a broadly looping curve starting at Lat. 23º 51′ 38″ N, and Long. 24º 14′ 56″ E, ~40 km NE of Gebel Zurg and 70 km NW of Gebel Rukn and extending northward , then westward through Wadi Matawi where it met the western system of streams which are coming from the southeastern piedmonts of Gebel Hawa'ish at the beginning of Wadi Al Balatah(Fig. 11).. The major eastern stream of Wadi Matawi was also charged from two subsidiary streams, 55 km and 78 km long, which flowed northwestward from the western slopes of Wadi Talh area in Egypt (Fig. 12). The western streams are short but dense and flowing southeastward. Both systems were met to discharge into the Al Balatah Valley at the point of its intersection with Wadi Matawi.

The paleo-drainage patterns along the western side of the Al Balatah Valley indicate that the upper part (southern part) of the main river channel of Wadi Al Balatah received overland flows from the southeastern piedmont slopes of Gebel Hawa'ish, whereas the lower part (northern part) of the main river channel received vast quantities of overland flows from the eastern and northeastern piedmont slopes of Gebel Az Zalmah. The running water of the old Al Balatah river moved downward toward the north under the influence of gravity, from ground elevation of 345 m a.s.l. at the beginning of Wadi Al Balatah to 151 m a.s.l. at the northern limit of the delta plain (Fig.6).

The divide (topographically high areas) which separates the drainage basin of the Al Balatah Paleoriver system from the adjoining Al Kufrah Paleoriver system is running NW-SE ~8 km before the entrance of Wadi Al Balatahat Lat. 24º 33′ 45.17″ N and Long 23º 53′ 43.6″ E where it extends from the southeastern piedmont of G. Hawa'ish (Lat. 24º 32′ 10.7″ N and Long. 23º 28′ 13.7″ E) towards the SE (south of Wadi Matawi) for a distance of 95.31 km assuming a bearing of 128º 37′ 13.7″, then veers towards the south for 56.8 km and a bearing of 178º 30′ 47.3″, then towards the ENE for a distance of 32 km and a bearing of 178º 30′ 47.3″ before taking the NE direction for 68.44 km and a bearing varying from 25º 01′ 1.5″ to 68º 30′ 45.2″ until it reaches the Libyan-Egyptian borders at Lat. 24º 16′ 4″ and Long. 25º where it meets the divide coming from the Gilf El Kebir Plateau (Figs. 12-13).

This divide separates drainage in opposite directions of the Al Balatah Paleoriver basin from the Kufrah Paleoriver basin; drainage to the southwest of the divide goes to the Kufrah basin, whereas drainage to the north and northeast of the

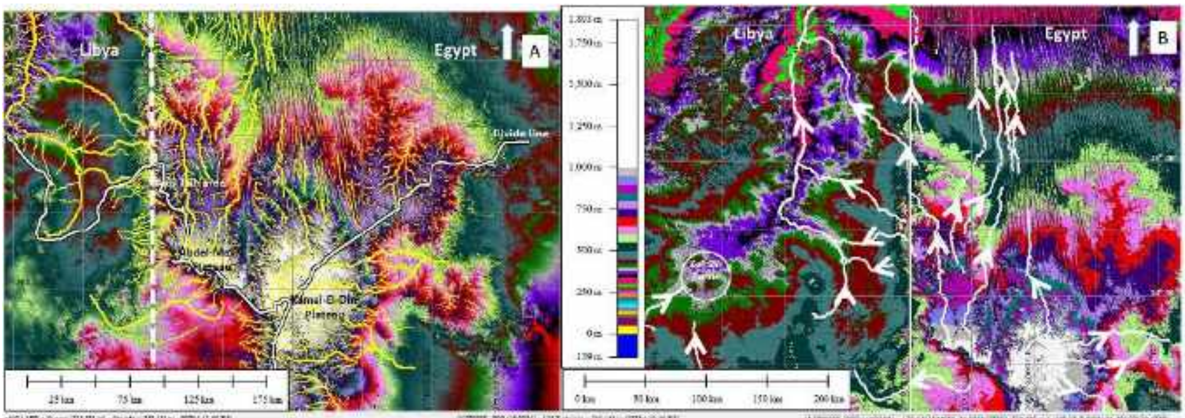

Fig. 12 A-B: A- SRTM topographic map showing divide line separating between different directions of paleo-drainage systems in the Gilf El Kebir Plateau (Both Kamal El-Din and Abdel-Malik Plateaus). Note that the majority of streams is flowing northward and northwestward north of the

divide line. B- Enlarged SRTM topographic map showing that the drainage in the Abdel-Malik Plateau (western part of the Gilf El Kebir Plateau) is oriented north- and northwestward where it charges the eastern stream of Wadi Matawi via two subsidiary streams, 55 km and 78 km long, which flowed northwestward from the western slopes of Wadi Talh area in Egypt.

divide eventually goes to the Wadi Al Balatah basin and then to the Al Balatah delta plain (Figs. 13-14). The drainage of the eastern and southeastern piedmont slopes of the Az Zalamah (Delma) mountain (west of the Al Balatah Valley) goes directly to the Al Balatah Paleoriver basin. However the drainage of the northeastern piedmont slopes of Gebel Zurg goes indirectly to the Al Balatah Valley via a long sinuous channel stream (150 km long) extending northwestward through Wadi Matawi where it meets with those coming from the southeastern piedmont slopes of Gebel Az Zalmah at the entrance of Wadi Al Balatah, thus contributing to form the main stream of the old Al Balatah river at Lat. 24º 37′ 2.31″ N and Long. 23º 56′ 45.91″ E (Figs 11,13 and 14).

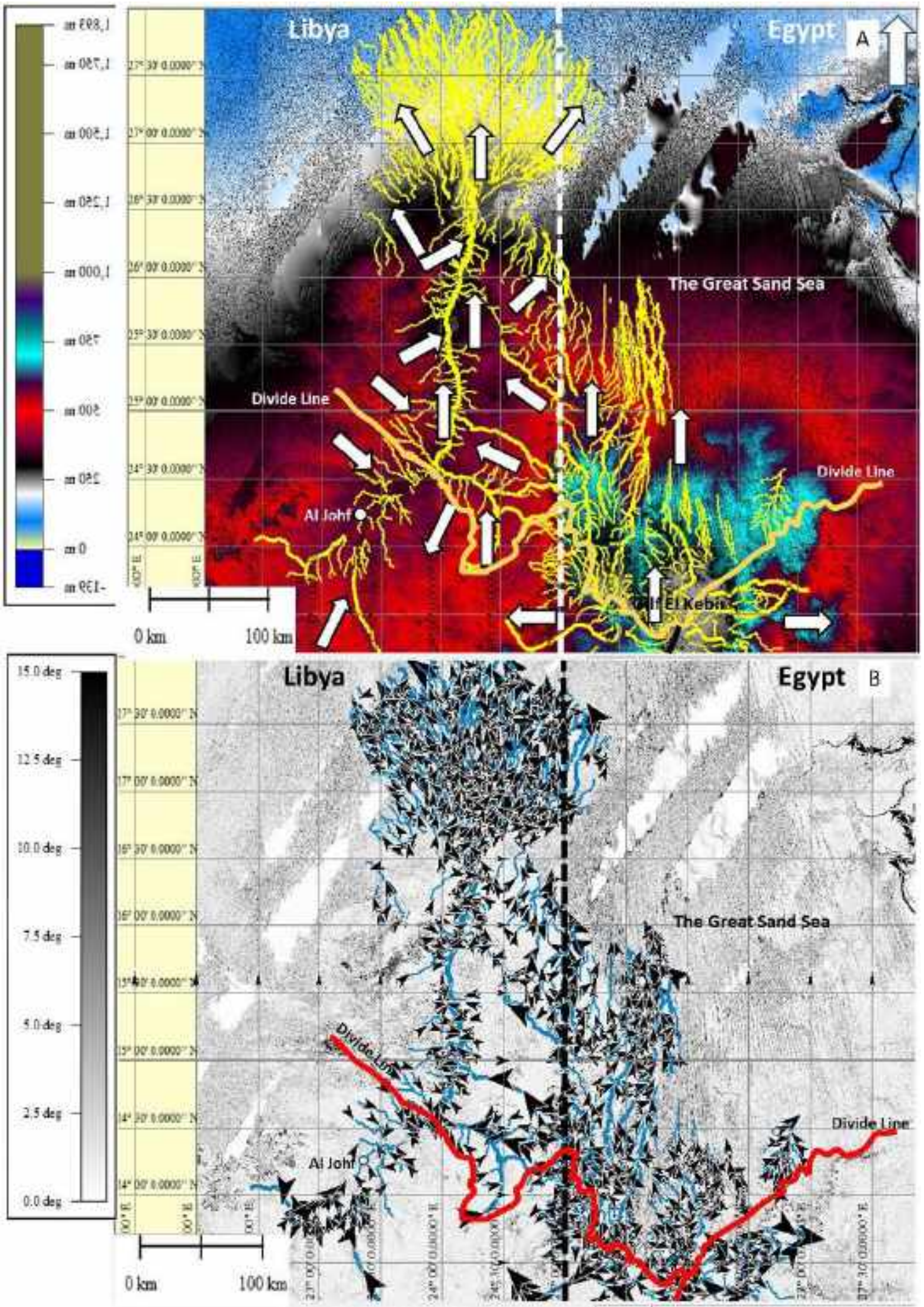

Fig. 13A-B

Fig. 13A-B: SRTM topographic maps showing the divide (topographically high areas) which separates the drainage basin of the Al Balatah Paleoriver system from the Al Kufrah Paleoriver. This divide (orange line in A and red line in B) separates drainage in opposite directions of the Al Balatah Paleoriver basin from the Al Kufrah Paleoriver basin; drainage to the southwest of the divide goes to

the Al Kufrah basin, whereas drainage to the north and northeast of the divide eventually goes to the Wadi Al Balatah basin and then to the Al Balatah paleodelta. Note the direction of paleo-drainage (white arrows in A and black arrows in B) relative to the divide line in both the Gilf El Kebir Plateau and the Al Balatah Paleoriver.

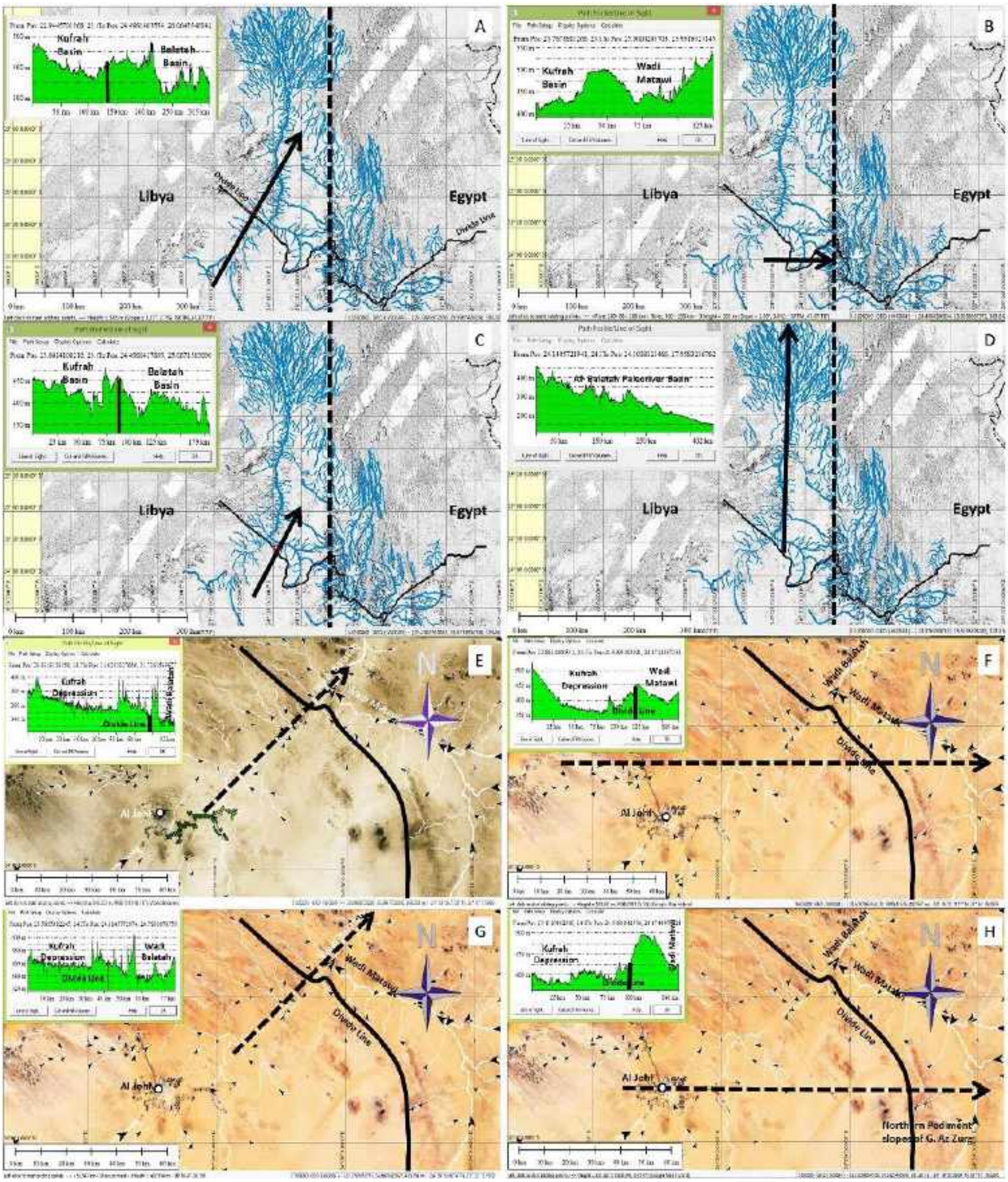

Fig. 14A-H: SRTM topographic maps (Slope Shader A-D) , and Satellite images from World Imagery (E) and Google map hybrid (F-H) showing different cross sections along the divide line which separates the paleo-drainge pattern of Al Balatah Paleoriver system from those of the Al Kufrah Paleoriver.

4.3. Morphotectonic Features of the Al Balatah Paleoriver Basin

The paleoriver basin of the Al Balatah Valley is bounded along its both eastern and western sides by steep scarps and longitudinal ridges of Paleozoic- (almost Carboniferous) Mesozoic (almost Early Cretaceous) Nubia Sandstone. Along both sides of the Egyptian-Libyan borders, the continental Mesozoic sandstone sediments overly unconformably the Paleozoic sediments on both surface (Western Abdel-Malik Plateau, northwest of the

Gilf El Kebir Plateau), and in the subsurface of the Great Sand Sea (Foram-1 Well) in the Egyptian side, as well as in the whole central part of the Kufrah Basin in the Libyan Side (Bellini and Massa, 1980). These sediments which belong to the Nubia Aquifer System show a markedly groundwater sapping process up to the present time due to the highly permeable Nubia Sandstone scarps and ridges and by which groundwater can transmit in substantial quantities along bedding planes (Fig. 15).

Historically, these longitudinal Nubia Sandstone ridges are the oldest landform in the Great Sand Sea along both sides of the Egyptian/Libyan borders. They are structurally controlled, trending NW/SE direction and representing a series of bended (up-folded), horizontally Nubia Sandstone layers separated by low-lying (down-folded) tracks formed as a result of the Upper Cretaceous folding (Turonian) movement (analgous to the Laramide) which affected the Western Desert of Egypt and the Eastern Desert of Libya and led to the uplift of the Gilf El-Kebir Plateau at south and the Bahariya area, the Qattara and the Sidi Barrani-Matruh coastal area at north. Trellis drainage is the most common one where hundreds of short tributaries flowing from the nearby ridges join the main channel of the Al Balatah Paleoriver at right angles. During precious wetter periods of the Late Pleistocene these scarps and ridges received vast amounts of rainfall which exceeded the rate of infiltration and thus both the effluent groundwater and rain water then contributed to overland flow downhills and the main channel of the Al Balatah Valley became water bearing along its course.

The Al Balatah Paleoriver Basin and its Delta Plain is also bounded on both sides of the Libyan- Egyptian borders by a series of younger Nubia Sandstone landforms extending NE/SW and consisting of parallel series of huge, structurally controlled mountain ranges which are dissecting the older Paleozoic and/or Mesozoic Nubia Sandstone ridges (Fig.16). These mountain ranges were first identified in the Egyptian side by Ouda et al. (2011, 2012, 2023) and this is the first identification of these landforms in the Libyan side. They include plateaus, depressions, domes and troughs extending northeast-southwest in parallelism with the New Farafra Oasis (Ouda et al. 2011), Gus Abu Said plateau (west of classic Farafra Oasis) and the Bahariya Oasis. The bedrock of all these new landforms are exclusively made up of Nubia Sandstone and show well-marked evidence that they are all belonging to the Late Oligocene refolding movement. The depressions and plateaus cover wide areas and show well-marked evidence that they are all structurally controlled, thus being different from the previously known depressions in the western Desert (Kharga, Dakhla and Farafra Oases).

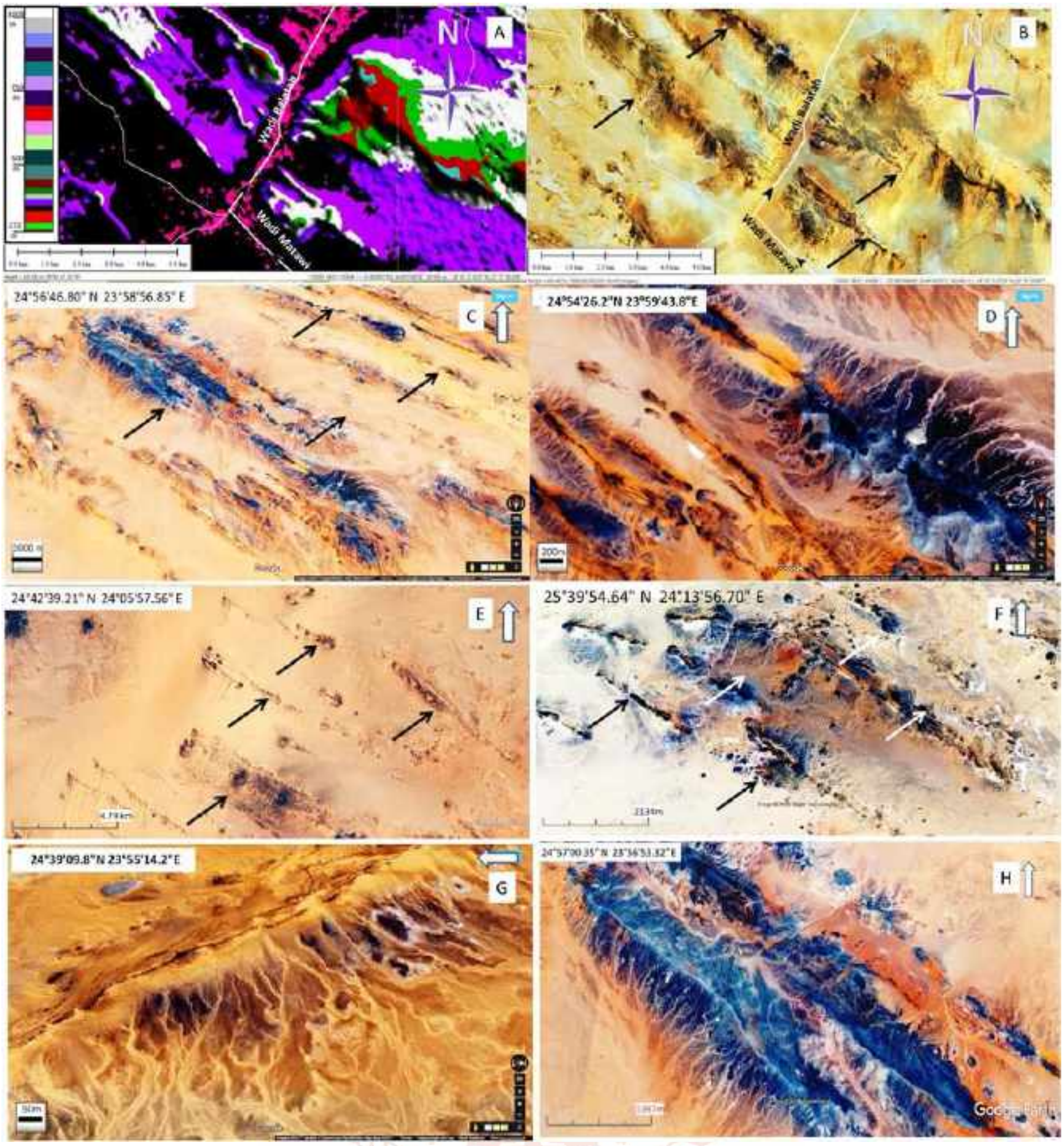

Fig. 15 A-H: SRTM topographic map (A) and Satellite images from World Imagery (B) Google Map Imagery (C , D and G) and Google Earth (E, F and H) showing older Nubia Sandstone ridges (Paleozoic –Mesozoic) in the Libyan side which are trending NW/SE and exhibiting broad belt of rills, gullies and ephemeral streams along the slopes of the Nubia Sandstone scarps formed by combined overland flows and groundwater sapping emerged from alcoves at the valley headward.

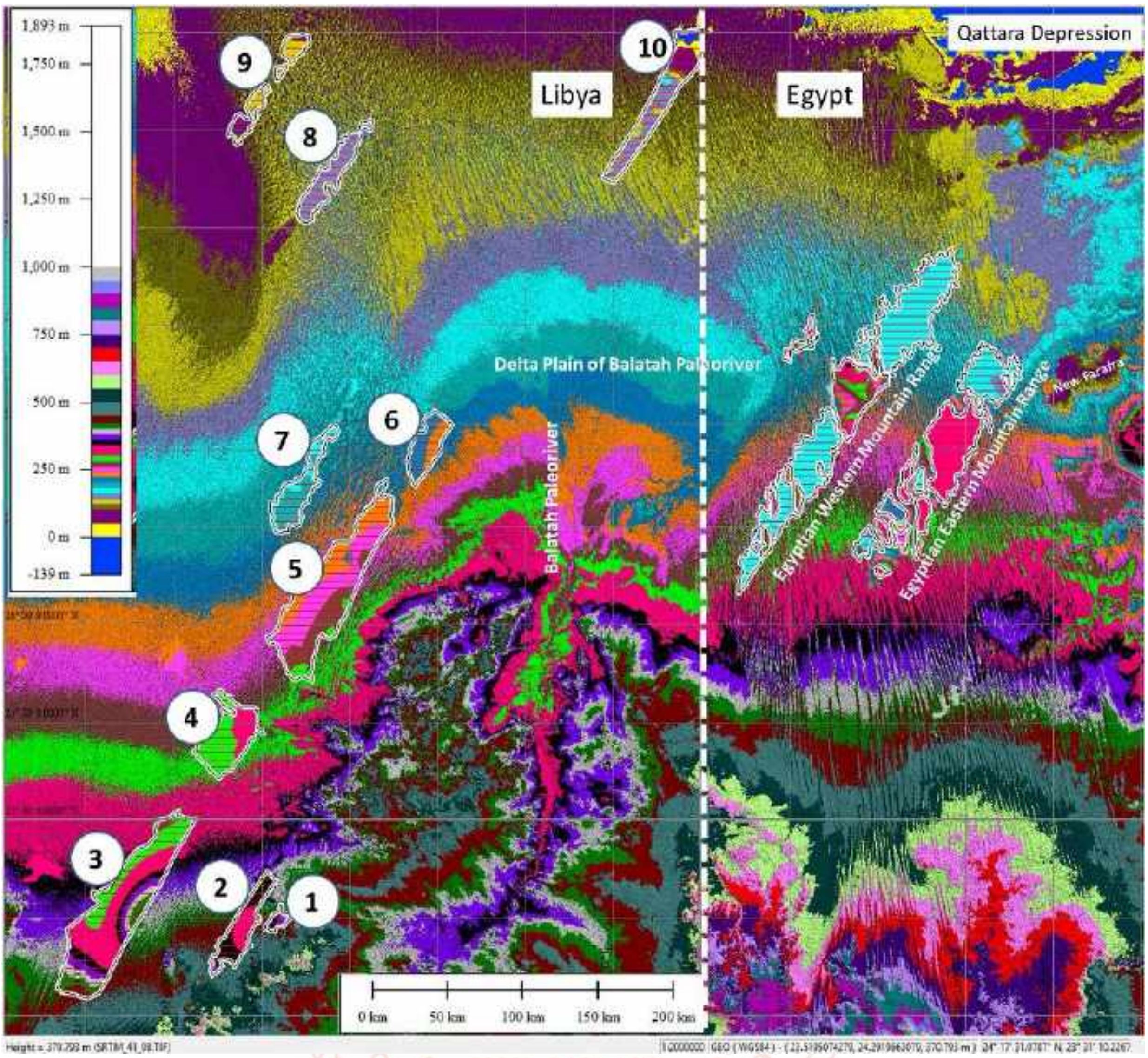

Fig. 16: SRTM topographic map showing that the Al Balatah Paleoriver Basin and its Delta Plain is bounded along both sides of the Libyan- Egyptian borders by a parallel series of huge, structurally controlled younger mountain ranges (two in the Egyptian side and ten in the Libyan side) including plateaus, depressions, domes and troughs extending northeast-southwest. These younger landforms are wholly made up of Nubia Sandstone which was subjected to a major refolding movement during the Oligocene. They are dissecting the older Paleozoic and/or Mesozoic Nubia Sandstone ridges which are belonging to the Turonian folding movement.

They are formed as a result of intersection of two major fault systems, the older one is running north-northwest parallel to the long axes of the pre-existing sandstone ridges while the younger is oriented northeast parallel to the long axes of the depressions and plateaus Fig. 17). Both systems have previously

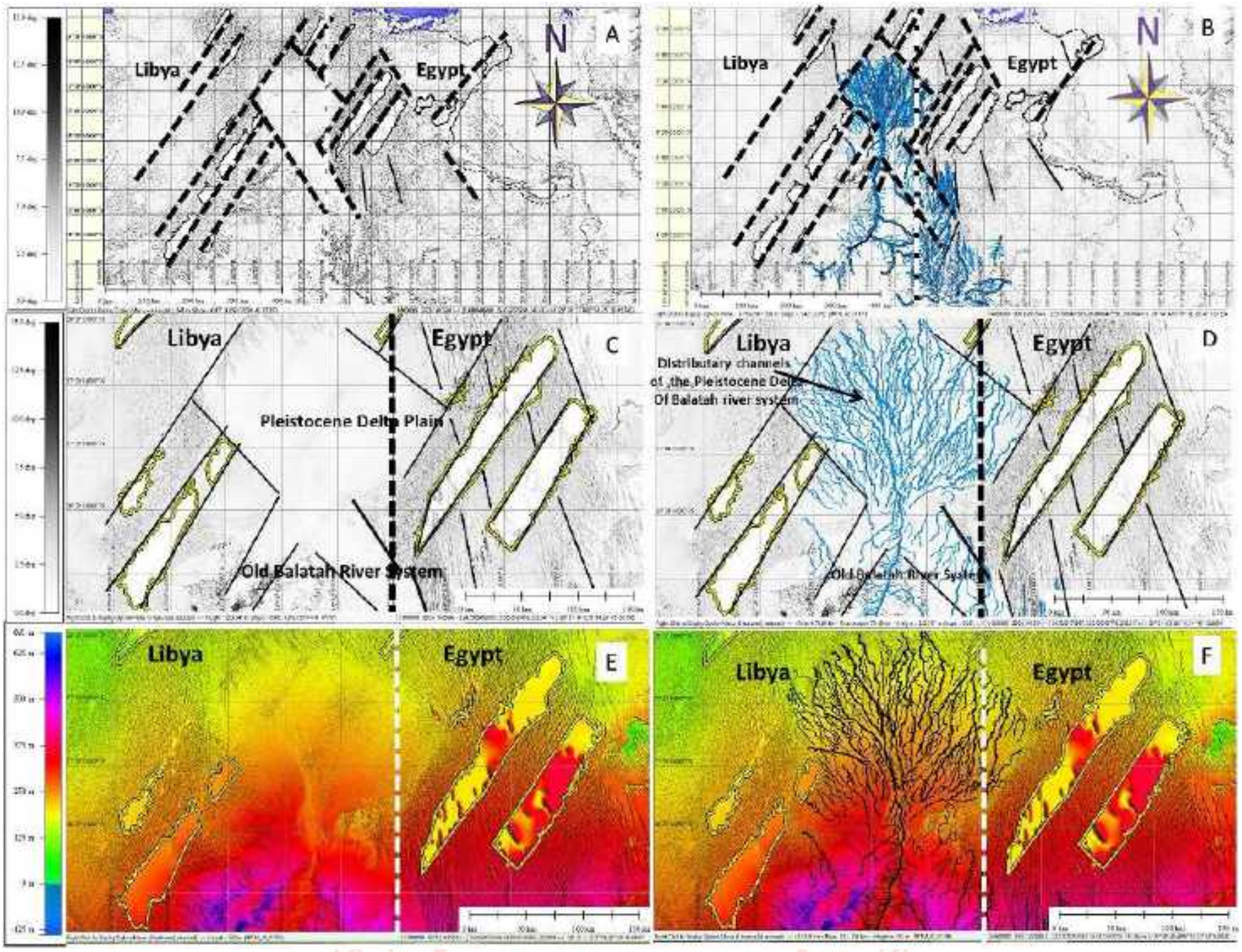

Fig. 17A-F: SRTM topographic maps of the delta plain of the Al Balatah Paleoriver system showing two different fault systems affecting the area before the running of the AL Balatah Paleoriver (A-D Slope Shader). The older system (Upper Cretaceous) is trending NW/SE whereas the younger one (Late Oligocene) is trending NE/SW. Both opposing fault systems have led to the formation of the basinal area that later became the course of the old Balatah river system during the time interval from the Early Miocene to the late Pleistocene (A, C and E). Note in B, D and F the same basinal area after downloading the paleo-drainage pattern of the old Al Balatah river and the distributaries of its delta plain. Note also that the younger mountain ranges which represent refolded landforms during the Late Oligocene bound the paleoriver system along both sides of the Libyan-Egyptian borders.

recognized by Goudarzi (1980) in Libya where they intersect near the center of the Great Sand Sea. According to this author the Sirt embayment is tectonically a NW basin belonging to the older faulting system in which the major structural features trend NW, whereas the Cyrenaica uplift is a NE trending anticline produced by orogenic movements that probably began in the Oligocene and continued into the Miocene.

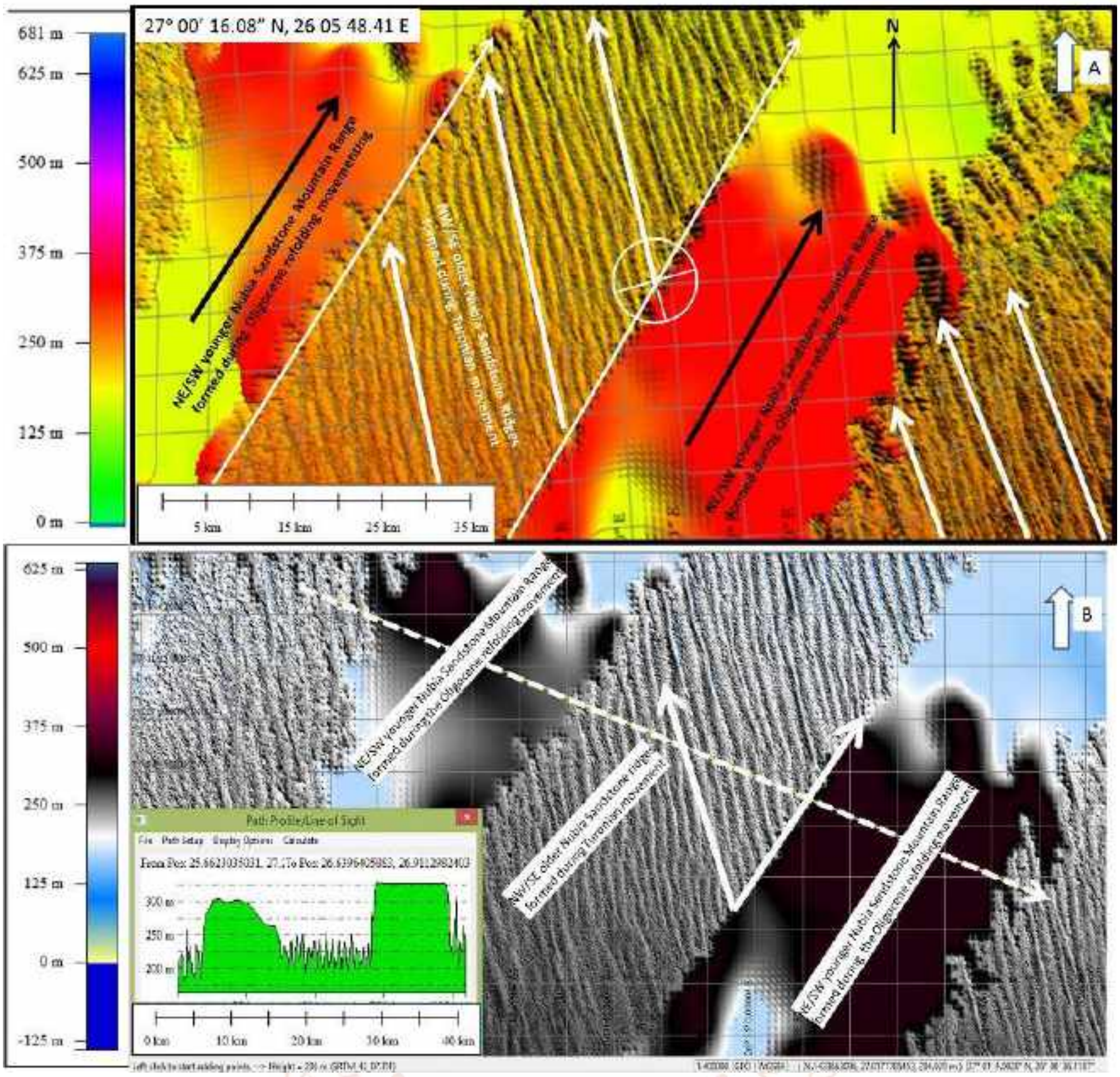

Fig. 18A-B: SRTM topographic maps of the Egyptian side showing that the younger fault-block mountain ranges were formed as a result of intersection of two major fault systems, one is running north-northwest parallel to the long axes of the pre-existing older sandstone ridges while the other is oriented northeast parallel to the long axes of the depressions and plateaus. The depressions represent down faulted blocks sliding towards the Northeast and Southwest and extend for many kilometers long and wide while the plateaus form uplifted flat-topped blocks between the depressions, thus constituting fault-block mountain ranges (horsts). Note in B the cross section along both older and younger sandstone landforms.

This would indicate that both major fault systems which reflect two different tectonic movements during the Cretaceous and the Oligocene have led to uplift, subsidence, tilting, faulting and refolding of the Mesozoic Nubia Sandstones in the Great Sand Sea on both sides of the Egyptian/Libyan Borders. The vast depressions which resulted from the Late Oligocene tectonic movement represent down-faulted blocks sliding towards the Northeast and extend for many kilometers long and wide while the plateaus form uplifted flat-topped blocks between the depressions, thus constituting fault-block mountain ranges (horsts in the Egyptian side); sometimes being bounded by a fault along one side of its boundaries, thus forming half grabens or asymmetrical dome-like structures in the Libyan Side. The plateaus and domes in the mountain ranges in the Egyptian side of the Great Sand Sea rise 300-350m above sea level, whereas the depressions assume 150-175m asl. In the Libyan side the plateaus/domes rise 425-475 m asl in the south, decreasing to 230-305 m asl northwards and then 137-170 m northmostwards, whereas the depressions/troughs assume 280-350 m asl in the south decreasing to 165-250 m asl northward, then 65-100 northmostward and finally become partly below sea level south of Al Jaghbub Oasis.

The tectonic origin of the younger plateaus and depressions could be achieved by the permanently parallel orientation of the mountain ranges and the parallel northeast-southwest orientation of the long axis of all depressions intersecting the pre-existing sandstone ridges. The parallel orientation of the long axes of the NE/SW structurally controlled Nubia Sandstone plateaus and depressions in the Great Sand Sea with the axis of the calcareous Plateau of Gus Abu Said west Farafra and Bahariya Oasis would substantiate a regional post lower Eocene tectonic event, most probably occurred during the Oligocene leading to the formations of all these new landforms synchronously. According to Said and Issawi (1964) a folding episode took place in Bahariya in the post Middle Eocene-Pre Oligocene time resulting in the formation of domes of small sizes and steep dips. These domes are aligned along a line which extend in an east-west direction in the Darb El Bahnasawi area and the area was affected by a faulting system trending mainly in the same direction, then displaced by a younger set of faulting which had a NE/SW trend. The latter fault system which runs parallel to that of the plateaus and domes of the Great Sand Sea is connected with basalt flows in the nearby regions of Bahariya and Bahnasawi. Thus, an Oligocene age is more likely to be proposed for the second major tectonic movement affecting the Great Sand Sea along both sides of the Egyptian/Libyan borders.

During the time interval from the Early Miocene to the late Pleistocene the old river system of the Al Balatah Valley, northeastern Libya ran through the basinal area lying between the younger mountain ranges on both sides of the Libyan-Egyptian borders where it built a vast inland delta plain as a result of flowing of the river streams into a huge freshwater Pleistocene lake occupying the area lying northeast of Libya and northwest of the Great Sand Sea (Fig.17). The old river system of Al Balatah Valley and its delta plain intruded the pre-existing longitudinal sandstone ridges and drained in the area lying between latitudes 26º 30' and 28° 30', and longitudes 23º 15' and 25º 26'. Also the old river system of the Gilf El Kebir which ran during the same time from south to north and northeast along the Libyan-Egyptian border intruded the surrounding sandstone ridges and drained northward in the Great Sand Sea along both sides of the Egyptian/Libyan borders (Ouda, 2023).

Not less than 12 elongated NE/SW younger Nubia Sandstone mountain ranges are discovered by using SRTM Data on both sides of the Egyptian-Libyan borders where they arrange in parallelism between latitudes 24º and 29º, and longitudes 21º 15' and 27º, two major of which are situated in the Egyptian side and 10 of which are situated in the Libyan side (Fig.16). The movement of the depressions is usually down parallel to the dip of the inclined fault surface suggestive of a dip-slip normal faults which dip northeast at angle ranging from 45: to 50: whereas the plateaus are uplifted sufficiently (140 -190 m with an average value of 170 m) to form a horst in the Egyptian side. In the Libyan side most of these landforms are almost bounded by a fault along one side of its boundaries, with sloping walls ranging from 125 m to 150 m in the south and from 70 m to 140 m in the north. The slopping walls of the plateau along fault planes in the mountain range are marked in Egypt by the transformation of the quartz sandstone into hard siliceous sandstone as a result of thermal effect of sliding of depressions.

Both fault-block mountain ranges in the Egyptian side are localized in the western part of the Great Sand Sea (east of the Al Balatah Paleoriver System), running northeast-southwest; each one is made up of upraised Nubia Sandstone plateaus or domes against Nubian Sandstone depressions or troughs whose allover axes are running NE/SW oblique to the general N-NW/S-SE direction of the pre-existing longitudinal Nubia Sandstone ridges (Fig. 18). The first eastern range is located 53 km west of Ain Dalla, ~117 km west of Qasr Farafra and 312 km northwest of Mut. It extends NE-SW across Sakhret El-Amoud for more than 140 km long, and 30 km wide, assuming a total area of ~4100 km² (Fig. 19A-B). It is topographically made up of a major plateau in the middle part of the range (namely by Ouda et al., 2011, 2012 as Baraka Plateau), uprising against a major depression at the northeast (namely by the same authors as Tahrir Depression) (Fig. 19C -D).

The total area of Baraka Plateau is 1020 km² and has an elevation varying between 310m and 330m asl (with most area lying around 325m above sea level). It is almost flat-topped and consisting of horizontally bedded sandstone layers covered by a thin veneer of drifted brown loose sand that contrast in color

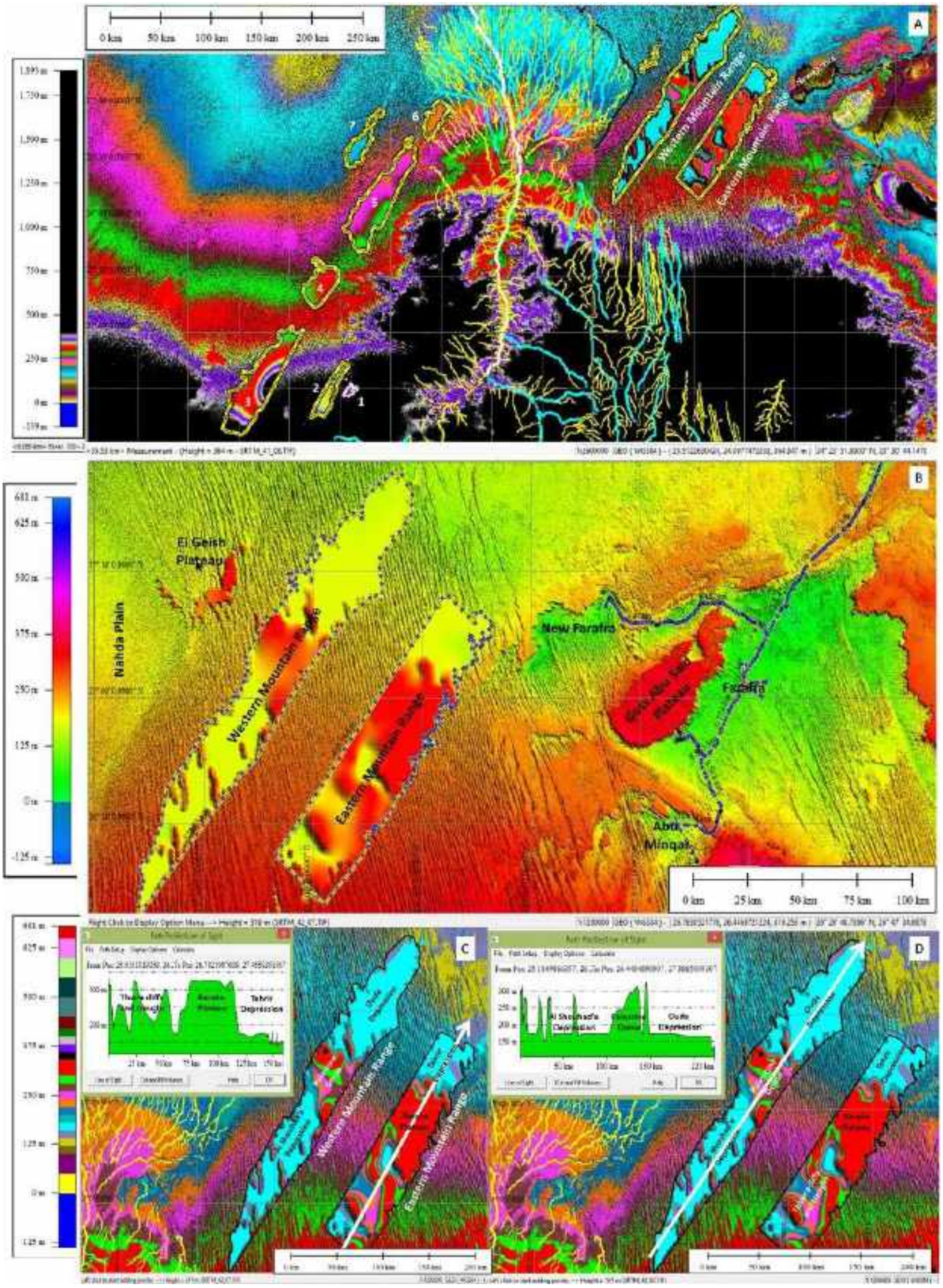

Fig. 19A-E: SRTM topographic maps showing: A - the Al Balatah Paleoriver system lying between the younger mountain ranges of Nubia Sandstone which belong to the Oligocene refolding movement along both sides of the Libyan-Egyptian borders. Note that yellow streams are from 75 to 99 km; green streams are from 100 to 250 km; white stream is the main stream of the paleoriver 450 km. B-Two main fault-block mountain ranges in the Egyptian side are localized in the western part of the Great Sand Sea (east of the Al Balatah Paleoriver System). C-E- Cross sections along the Egyptian mountain ranges showing that each one is made up of upraised Nubia Sandstone plateaus or domes against Nubian Sandstone depressions or troughs whose allover axes are running NE/SW oblique to the general N-NW/S-SE direction of the pre-existing longitudinal Nubia Sandstone ridges.

with the underlying white quartz sandstone bed rock. The Tahrir Depression is semi-quadrate in shape and extending northeastward with a maximum length of 33 km (average length is 26 km) and a maximum width of 28.5 km (average width is ~25 km), assuming a total surface area of 647 km² (Figs. 19D). The ground elevation of this depression varies from 150 m to 175 m with most values lying around 173m above sea level. The floor of the depressions is identical to that of the top of the plateaus , being flat and made up of white compact Nubia Sandstone belonging to the Lower Cretaceous Sabaya Formation.

The southern part of the Baraka Plateau suffered a subsequent erosion by combined wind action and ground water sapping process leading to the formation of four broad flat-topped (mesas-like) cliffs (namely by Ouda et al. (2012) as 25 January Cliffs) with a total surface area of 387 km² that are separating four small depressions and troughs in between (namely by the same authors as 25 January Depressions and Troughs) with a total surface area of 410 km² (Fig. 19D). The cliffs bound the troughs from three directions, thus suggesting an eroded dome-like structure. All evidences point to a combination of tectonic, wind action and groundwater sapping process during the formation of these landforms (See Ouda, 2023).

The second parallel mountain range in the Egyptian side is located 35 km west of the first range, extending northeast from 19 km to 138 km east of the Egyptian-Libyan borders, with a total length of 224 km and a width increasing northward up to 25 km (Fig. 19A-B). It occupies an area of about 4550 km² and is topographically composed of a strongly eroded domelike cliff uprising in the central part of the range up to 350 m asl (Palestine Dome, Ouda et al., 2011, 2012) against two major long depressions, a northeastern one and a southwestern depression (namely by Ouda et al., 2011, 2012 as Ouda Depression and Shohad'a Depression respectively) (Figs. 19C and E). The eroded central cliff is marked by steep walls north-, south- and northeastward whereas southwestward it slopes gradually to the surface ground of the Shohad'a Depression (173m asl). It seems to have suffered intense combined erosion by wind action and groundwater sapping process leading to its splitting into three small dome-like hills of asymmetrical sides.

The northern depression of the western mountain range is a flat depression of elongate rectangular shape extending northeast the central plateau for 70 km long, with an average width of 23 km (maximum width 27 km), thus assuming a total area of 1616.5 km² (Fig. 19E). Its ground elevation is 172 m asl, with small areas lying at 180m in the south and 160m in the north above sea level. The southern depression extends southwest of the central plateau for 105 km, with an average width of 12.5 km (maximum width is 23 km) and assuming 1311.5 km². The latter depression encloses remnants of the original eroded cliff represented by a number of narrow isolated hills with a flat top and very steep sides (buttes) running in parallel direction with the general longitudinal trend of the pre-existing sandstone ridges which are surrounding the depression (Fig.19E). The bed rock of both depressions is exclusively made up of white compact quartz sandstone belonging to the Sabaya Formation

Similar ten parallel Nubia Sandstone mountain ranges including plateaus/ dome-like structures, half grabens and depressions/troughs trending NE are recorded to the west, north and northwest of the Al Balatah Paleoriver Basin and its delta plain where they structurally intersect the older longitudinal Nubia Sandstone ridges (Fig. 16). The bedrock of all these landforms is made up of Nubia Sandstone (Nubia Group in its wide stratigraphic meaning including Paleozoic and/or Mesozoic fluviatile sediments.as given by Ouda, 2021). Parallel fault system running northeast-southwest could be recognized on both sides of the Al Balatah Paleoriver Basin and its delta plain separating them from these mountain ranges originated in the quartz sandstone on both sides of the Libyan-Egyptian border (Fig. 17). This would support the influence of a major tectonic movement affecting the area north of the Gilf El Kebir Plateau during the Late Oligocene leading to the uplifting of plateaus and domes intersecting the pre-existing longitudinal ridges and tracks of the Nubia Sandstone on both sides of the Libyan-Egyptian border before the runoff of the Al Balatah Paleoriver and formation of the Al Balatah Paleodelta Plain. The flat depressions/troughs in these mountain ranges were developed subsequently due to the combination of different factors including structural slip-fault movement, wind action and groundwater sapping process. Prolonged erosion by both wind and groundwater sapping have led to flatness of the surfaces of plateaus and floors of depression (Figs. 20-22), while deflation was resulted in the accumulation of a thin cover of drifted loose sand on the slopes of the plateaus and floor of the depressions obscuring the original bedrock. The Libyan Nubia Sandstone mountain ranges related to the younger refolding movement of the Late Oligocene vary in area from 111 km² to 2809 km², covering a total area of 10430 km². they can be distinguished from south to north as follow:

Mountain Range1: 73 km northwest of AL Johf Village It is a half-graben, located around latitudes 24º 29' 4.5971" N and 22º 35' 34.2083" E, with a maximum length 20 km oriented NE at bearing 62º 07' 18.9" and sloping rapidly SW from 390 m to 350 m asl; with an average width of 5.6 km and total area of 111 km² (Fig. 20A-A').

Mountain Range 2: 88 km northwest of AL-Johf Village. It is a faulted-down depression (graben), located around latitudes 24º 27' 11.6519" N and 22º 23' 32.0437" E, extending NE with a maximum length of 61 km at bearing of 32º 11’ 30.3”; varying in elevation from 350 m to 337.5 m asl ; with an average width of 10.47 km and a total area of 638.66 km² (Fig. 20B-B’).

Mountain Range 3: 147 km northwest of Al-Johf Village, southwest of of Buzaymah and 32 km west of Harrat Zuwayyah. It is a complex structure made up of a half-graben in the south changing northeastward into a vast asymmetrical dome-like structure, located around latitudes 24º 36’ 10.7084” N and 21º 43’ 8.005” E, extending NE with a maximum length of 115 km at bearing of 30º 58’ 33.9”; The half graben is sloping toward NE from 425 m to 312 m asl; the dome-like structure is sloping toward NW and NE from 425 m to 285 m asl; the average width of the structure is 24.42 km and its total area is 2809 km² (Fig. 20C-C’).

Mountain Range 4: 160 km west of the Al Balatah Valley, 10 km east of Zighan. It is a flat tilted plateau, located around latitudes 25º 24’ 21.0783” N and 22º 17’ 55.7750” E, extending NE with a maximum length of 43 km at bearing of 41º 41’ 31.4”; tilting slightly toward NW and SW from 305 m to 290 m asl and from 308 m to 284m respectively; with an average width of 21.3 km and a total area of 916 km² (Fig. 20D-D’).

Mountain Range 5: 120 km west of the Al Balatah Valley, 30 km east of Bosto Trucchi. It is a Double-lobed folded structure, located around latitudes 26º 10’ 11.2174 N and 22º 52’ 46.4968” E, extending NE with a maximum length of 119 km at bearing of 24º 59’ 54.7”; sloping rapidly toward NW from 290 m to 230 m asl; with an average width of 21.67 km and a total area of 2579 km² (Fig.21A-A’).

Mountain Range 6: 71 km west of the main stream of the Al Balatah Paleoriver. It is a flat plateau located around latitudes 26º 53’ 49.4920 N and 23º 26’ 3.5730” E, extending NE with a maximum length of 40 km at bearing of 21º 15’ 11.3”; tilting slightly toward NW from 222 m to 205 m asl ; with an average width of 11.8 km and a total area of 473 km² (Fig.21B-B’).

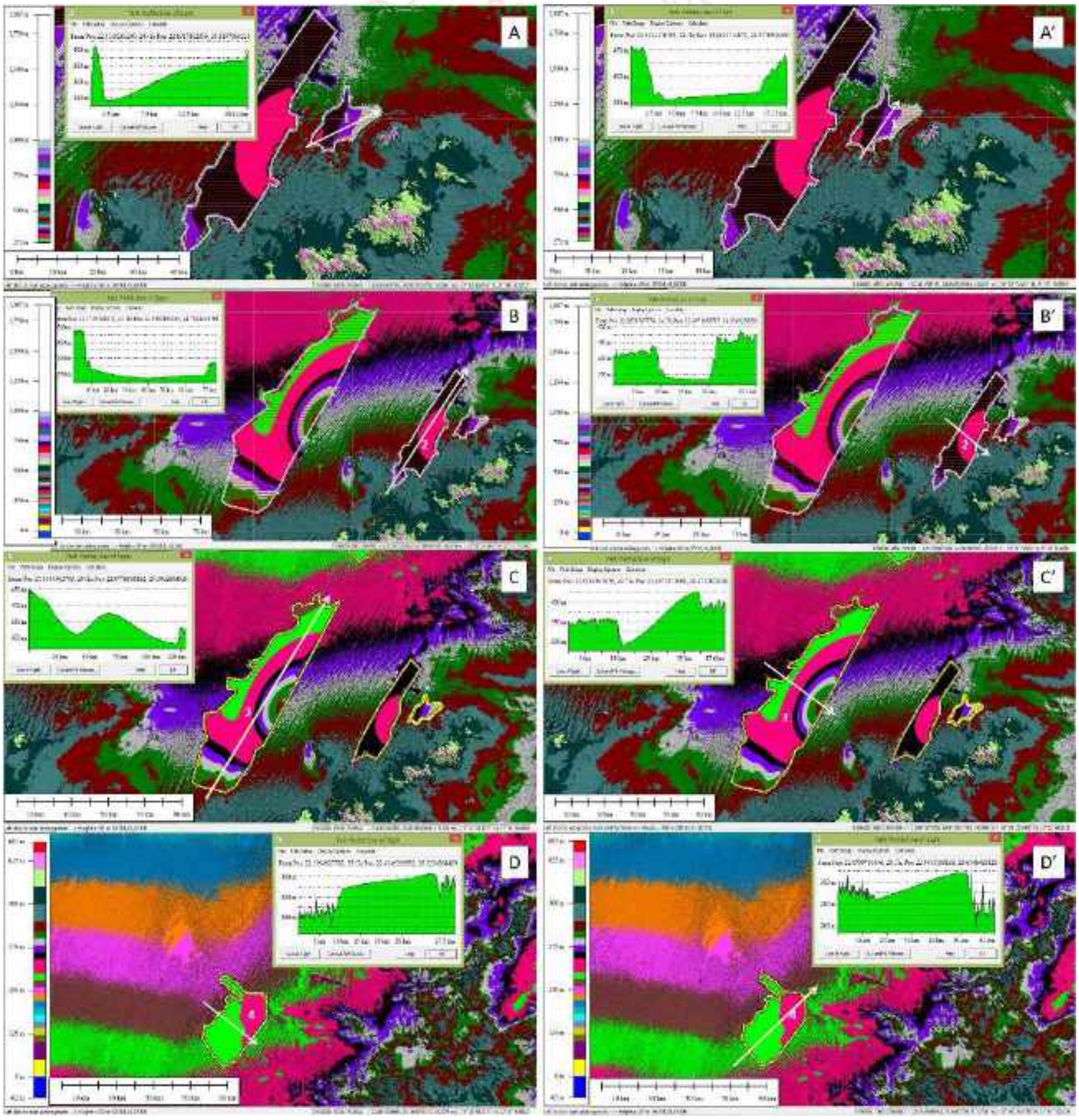

Fig. 20 A-D: Cross sections upon SRTM topographic maps showing the morphology of the Libyan Nubia Sandstone mountain ranges related to the younger refolding movement of the Late Oligocene.

These landforms vary in area from 111 km^2 to 2809 km^2, covering a total area of 10430 km^2. Ten parallel Nubia Sandstone mountain ranges are recorded to the west, north and northwest of the Al Balatah Paleoriver Basin and its delta plain where they structurally intersect the older longitudinal Nubia Sandstone ridges. The cross sections indicate that these landforms are made up of plateaus/ dome-like structures, half grabens and depressions/troughs trending NE. Figures A-D show the mountain ranges No. 1 (A-A'), No. 2 (B-B'), No.3 (C-C') and No. 4 (D-D') arranged from south to north.

Mountain Range 7: 143 km west of the main stream of the Al Balatah Paleoriver. It is a series of alternative folded dome-like structures separated by troughs, located around latitudes 26º 41' 40.4822 N and 22º 43' 30.3274" E

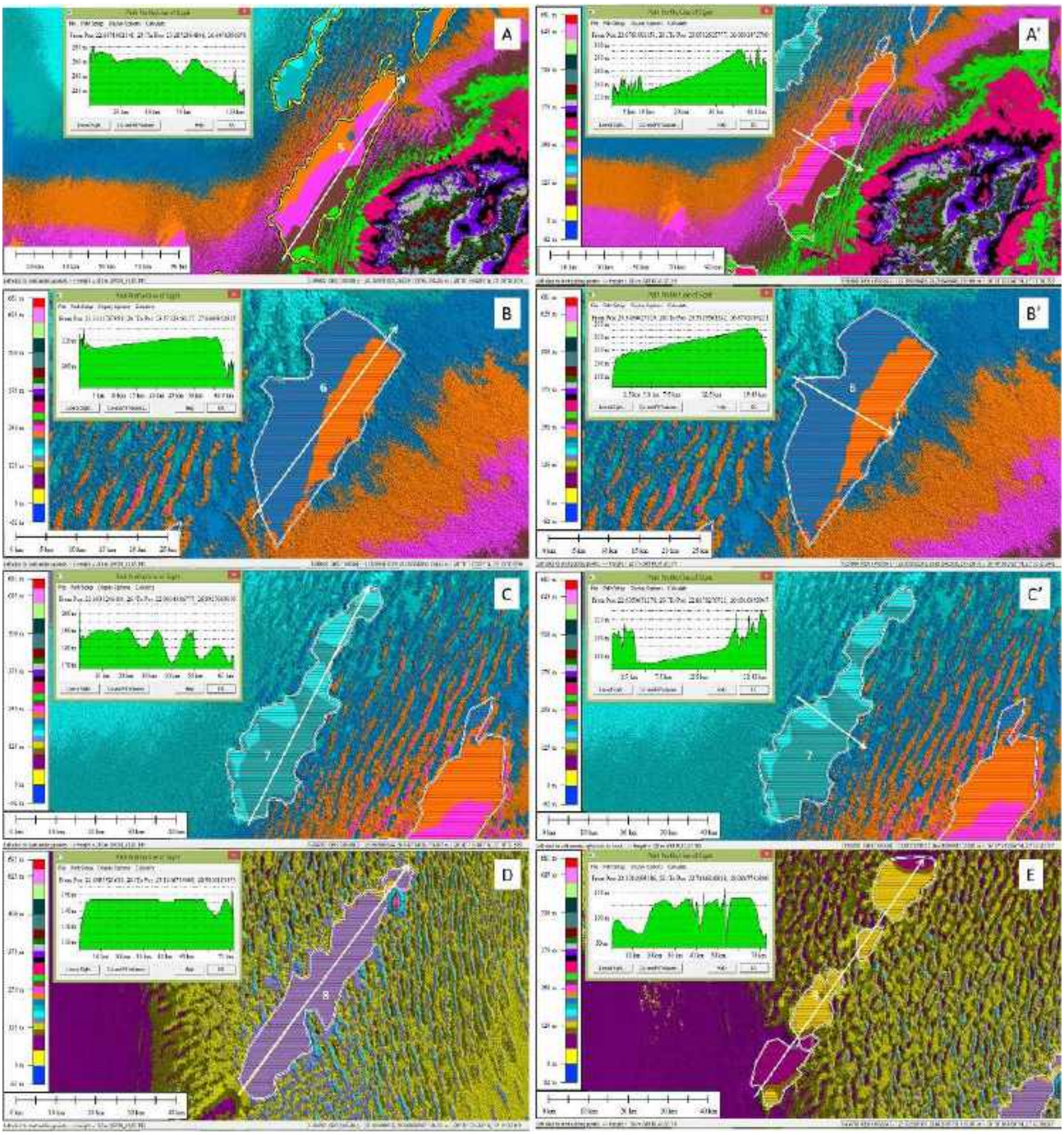

Fig. 21 A-D Continuation of Fig. 20: Cross sections upon SRTM topographic maps showing the morphology of the remaining Libyan Nubia Sandstone mountain ranges Nos. 5 (A-A'), No. 6 (B-B'), No.7 (C-C'), No.8 (D) and No. 9 (E) arranged from south to north.

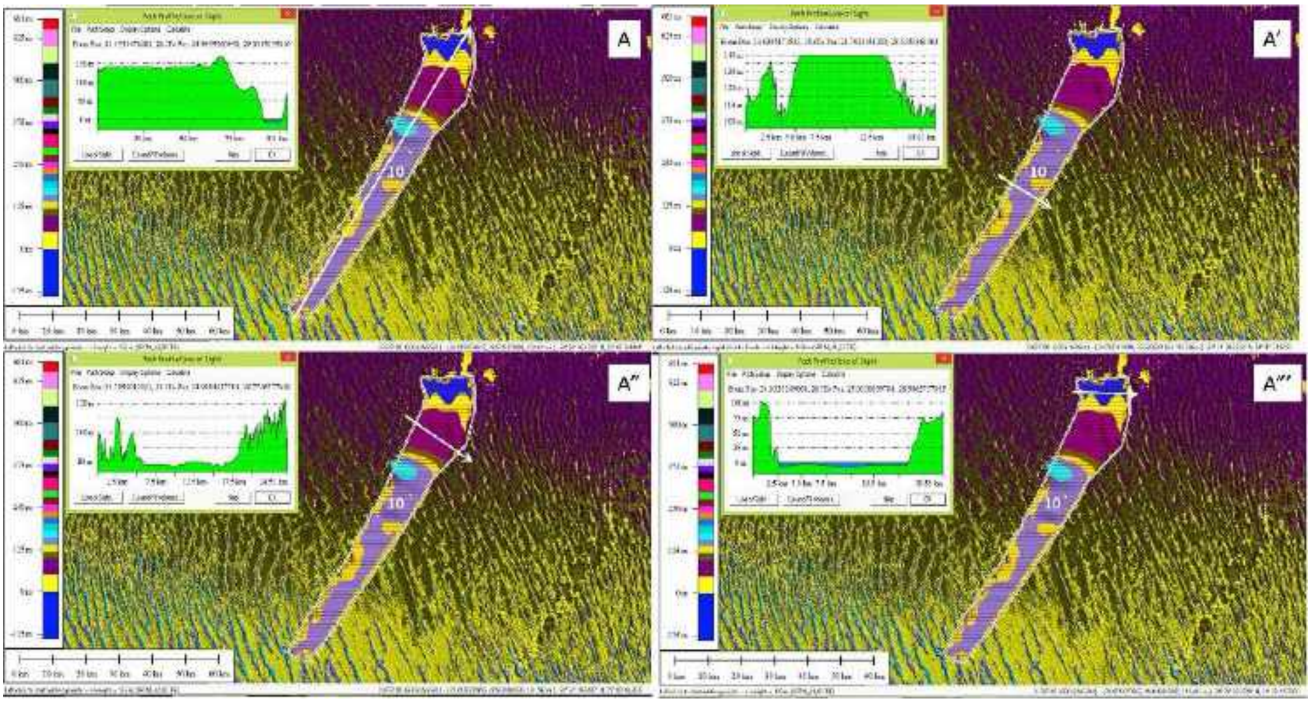

Fig. 22 A-D Continuation of Figs. 20 and 21: Cross sections upon SRTM topographic maps showing the morphology of the remaining Libyan Nubia Sandstone mountain ranges No 10. (A-A''') which lies south of Al Jaghbub Depression at the northernmost of the Delta Plain of the Al Balatah Paleoriver. Note that it is a vast plateau with a northern down-faulted depression (A, A') extending NE with a maximum length of 100 km at bearing of 30º 59' 1.4"; the surface of the plateau rises 140 m asl at south and then subsiding northeastward to 80 m asl (A") before the northern depression which lies below sea level downward of -7.0 m (A''').

extending NE with a maximum length of 66 km at bearing of 28º 34' 16.6"; sloping gradually toward NW from 230 m to 170 m asl; with an average width of 10 km and a total area of 658.33 km² (Fig.21C-C').

Mountain Range 8: 82 km northwest of the delta plain of the Al Balatah Paleoriver. It is a flat plateau located around latitudes 28º 17' 6.4606 N and 22º 53' 53.2372" E; extending NE with a maximum length of 60 km at bearing of 32º 18' 53.8"; rising 147 m asl ; with an average width of 10.2 km and a total area of 611.0 km² (Fig. 21D).

Mountain Range 9: 144 km northwest of the delta plain of the Al Balatah Paleoriver. It is a strongly fractured plateau with a southern down- faulted depression; located around latitudes 28º 42' 26.0867 N and 22º 31' 24.7401" E; extending NE with a maximum length of 71 km at bearing of 32º 18' 6.7"; the floor of the southern depression is sloping toward NW from 120 m asl to 65 m asl whereas the surface of the plateau rises 137-140 m asl ; with an average width of 6.65 km and a total area of 472.0 km² (Fig. 21E).

Mountain Range 10: 20 km north of delta plain of the Al Balatah Paleoriver and 67 km south of Al Jaghbub Oasis. It is a vast plateau with a northern down-faulted depression; located south of the Al Jaghbub Depression around latitudes 28º 37' 26.6108 N and 24º 45' 2.1367" E. It extends NE with a maximum length of 100 km at bearing of 30º 59' 1.4"; the surface of the plateau rises 140 m asl at south and then subsiding northeastward to 80 m asl before the northern depression. The latter attains an area of 103² km; its floor is flat and lying below sea level downward of -7.0 m. The average width of the total structure is 11 km and the total area of the plateau and depression is 1096 km² (Fig. 22A-D).

4.4. The Nahda Plain (The Eastern part of the Pleistocene Delta Plain of the Al Balatah Paleoriver)

The eastern part of the delta plain of the Al Balatah Paleoriver lies in Egypt immediately east of the Libyan-Egyptian borders where it constitutes what is known by Ouda et al. (2011 and 2012) as Nahda Plain. The latter plain is a large triangular flat plain situated along the Egyptian-Libyan borders between altitudes 26º 38' 21" N and 25° E in the south , 27º 43' 08" N and 25º E in the north and 27° 15' 03" N and 25º 24' 56" E in the east (Figs.5-7 and 23). The longest side of this triangular plain coincides with the Libyan borders where it extends ~120 km from Latitude 26° 38' N in the south to Latitude 27° 43' N in the north, then decreasing eastward until altitude 27° 15' N and 25° 26' E where it attains a maximum width of 41 km. The total covering area of this plain is 3030 km². Its ground elevation is sloping gradually from 220m above sea level in the south to 150m in the north, with an average level of 180m above sea level (Fig. 23A-D).

The bed rock of the Nahda Plain is belonging to the Nubian Aquifer System, being represented by the Early Cretaceous Sabaya Formation. The surface floor of the plain is entirely flat and dissected by rows of radiating draining lines running northeastward on the erodible Nubia Sandstone bed rock which in turn covered by a thin veneer of free silica debris. The draining lines represent the down northeastern streams of the complex draining system of the Al Balatah Paleoriver basin and its distributaries in Egypt.

Two major distributaries of the Al Balatah Paleoriver system flowed northeastward into Egypt where they contributed a trellis pattern of parallel draining lines running NE down slopes of the delta towards the Egyptian flat sandy plain of the Nahda Plain and separating the main delta plain from the Egyptian sandstone ridges (Fig. 23E-F). The flatness of this sandy plain indicates

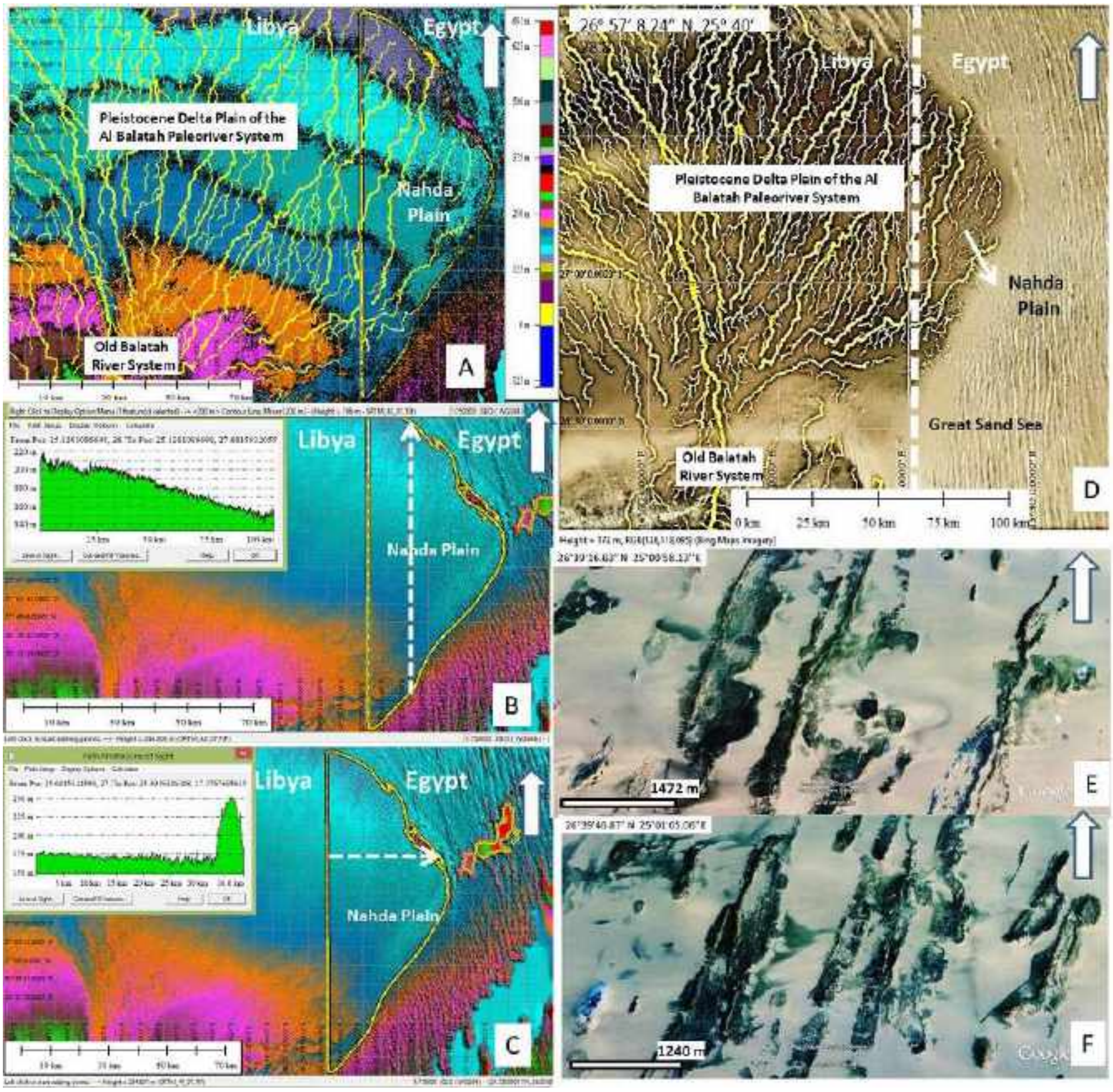

Fig. 23A-F : SRTM topographic maps (A, B and C) and Satellite images from Bing Map Imagery (D) and Google Earth (E and F) showing the Nahda plain in the north western part of the Great Sand Sea of Egypt. Note in A-B the paleographic relation of this plain to the northern delta plain of the Al Balatah Paleoriver where the distributary channels of the Pleistocene delta of Al Balatah Paleoriver system flowed northeastward into Egypt B-C- Cross sections across the Nahda Plain showing that the surface floor of the plain is entirely flat, thus indicating that it has a long history with periodic phases of flooding of the paleoriver of the Al Balatah valley during the Pleistocene leading to complete destruction and disintegration of the pre-existing Nubia Sandstone ridges. E and F showing that the surface floor of the Nahda Plain is dissected by rows of draining lines running northeastward on the erodible Nubia Sandstone bed rock which in turn covered by a thin veneer of free silica debris. The total covering area of the Nahda plain is 3030 km². Its ground elevation is sloping gradually from 220m in the south to 150m in the north above sea level.

that it has a long history with periodic phases of flooding of the paleoriver of the Al Balatah valley in northeastern Libya during the Pleistocene leading to complete destruction and disintegration of the Nubia Sandstone high ridges (Fig. 23C-D). The entire absence of sandstone ridges or sand dunes in the Nahda Plain would indicate that the older periodic or seasonal flooding during the Pleistocene prevent dune development of the weathered sands while the high water table acted as a base level to the action of the wind scour.

The total area of the Nahda Plain is covered with a thin veneer (from 5cm to 15 cm thick) of free sands overlying directly the Nubia Sandstone bedrock. The sand sediments of the distributary bodies are usually porous and exhibiting good criteria of recent groundwater seepage of the underlying Nubia Sandstone bedrock particularly during the winter season where the evaporation rates are low in such dry desert (Fig. 23E-F).. The sand cover often shows well developed current ripple marks expressing periodic flooding and overland flow from west to east.

Enormous quantities of water of the Pleistocene inland delta are expected to be stored in the subsurface of the underlying Nubia Sandstone bedrock due to its high porosity and permeability along both sides of the Libyan-Egyptian borders. In Foram-1 which is drilled at the northern part of the Nahda Plain the thickness of the Nubia Sandstone Aquifer reaches 3500 m of which the Mesozoic sequence (both Six Hills and Sabaya Formations) attains ~1200 m covering unconformably ~2300 m thick of Paleozoic Nubia Sandstone sequence (Shrank, 1984). During the periods of very arid climate the Libyan delta plain (including its northeastern extension in Egypt, Nahda Plain) became apparently dry but the groundwater occurred very near the surface where Sabaya Formation is exposed and the groundwater infiltration occurs intermittently in the plain, just enough to support existing vegetation.

5. Conclusion

Evidences from the paleo-drainage patterns designated by the Global Mapper based on the SRTM 90m Digital Elevation Database ver. 4.1 indicate that the vast ancient delta plain which lies in northeastern Libya south of Latitude 28º 00′ N and east of Longitude 23º 22′ E is belonging to the Al Balatah Paleoriver, not to the Al Kufrah Paleoriver as previously proposed. This Libyan ancient delta plain covers a total area of ~ 24218 Km², thus being more or less equal in total area to the Present Nile Delta in northern Egypt. It was formed when the old River system of Wadi Al Balatah in northeastern Libya discharged northward into a huge, freshwater Late Pleistocene lake occupying the area lying northeast of Libya between latitudes 26º 30’ and 28° N, and longitudes 23º 22' and 25º 22’ E.

The delta plain is bounded northward by disturbed and distorted older Nubia Sandstone ridges which show the effect of delta progradation, thus supporting an exclusively inland delta resulted from the flowing of Pleistocene river streams into a quite water body occupying the lowest lands in northeastern Libya.

The eastern part of this old delta plain lies in Egypt immediately east of the Libyan-Egyptian borders where it constitutes what is known by Ouda et al. (2011 and 2012) as Nahda Plain. The bed rock of the latter plain is belonging to the Nubian Aquifer System, being represented by the Early Cretaceous Sabaya Formation. The longest side of this triangular plain coincides with the Egyptian/Libyan borders and extends ~120 km from Latitude 26° 38' N in the south to Latitude 27° 43' N in the north, then decreasing eastward until altitude 27° 15' N and 25° 26' E where it attains a maximum width of 41 km. The total covering area of this plain is 3030 km². Its ground elevation is sloping gradually from 220m above sea level in the south to 150m in the north, with an average level of 180m above sea level.

The surface floor of the Nahda plain is entirely flat and dissected by rows of radiating draining lines running northeastward on the erodible Nubia Sandstone bed rock which in turn covered by a thin veneer of free silica debris. The draining lines represent the down northeastern streams of the complex draining system of the Al Balatah Paleoriver basin and its distributaries in Egypt. The flatness of this sandy plain indicates that it has a long history with periodic phases of flooding of the paleoriver of the Al Balatah valley in northeastern Libya during the Pleistocene leading to complete destruction and disintegration of the pre-existing Nubia Sandstone ridges as well as preventing the formation of sand dunes.

The source of the Al Balatah Paleoriver is independent from the Al Kufrah Paleoriver system, and consequently the Pleistocene Lake of the Al Balatah Paleoriver is independent from the Pleistocene Lake of Al Kufrah Paleoriver.. The Al Balatah Paleoriver system drained northward into an independent vast fresh water lake located ~ 400 km north-northeast of Kufrah Oasis. It started at Lat. 24º 37′ 2″ N and Long. 23º 56′ 46″ E, ~78 km NE of Al Johf (Kufrah), and ~108 km west of the Libyan/Egyptian boundary where it originates from the intersection of two opposed E-W systems of streams. The first and major eastern stream ran into Wadi Matawi from East to west where it met the western system of streams which are coming from the southeastern piedmonts of Gebel Hawa'ish at the beginning of Wadi Al-Balatah. Both systems were met to discharge into the Al BalatahValley at the point of its intersection with Wadi Matawi.

The direction of streams within the paleo-drainage patterns of the AL Balatah Paleoriver confirms the existence of a divide line running in a NW direction between: the piedmont slopes which is running SW towards the Kufrah Basin and those running NE towards the Al Balatah Valley. This divide separates drainage in opposite directions of the Al Balatah Paleoriver basin from the Al Kufrah Paleoriver basin; drainage to the southwest of the divide goes to the Al Kufrah basin, whereas drainage to the north and northeast of the divide eventually goes to the Wadi Al Balatah paleoriver and then to the Al Balatah delta plain.

Morphotectonically, the paleoriver basin of the Al Balatah Valley is bounded along its both eastern (Egyptian) and western (Libyan) sides by two intersecting groups of structurally controlled Nubia Sandstone landforms The older group is made up of a parallel series of longitudinal ridges trending N-NW/S-SE and representing bended (up-folded), cross-bedded or horizontally Nubia Sandstone layers separated by low-lying (down-folded) tracks formed as a result of the Upper Cretaceous (Turonian) folding movement (analgous to the Laramide) which affected the Western Desert of Egypt and the Eastern Desert of Libya. The younger group is extending NE/SW and consisting of a parallel series of huge mountain ranges of Nubia Sandstone made up of new plateaus/domes and depressions/troughs formed as a result of the Late Oligocene refolding movement and dissecting the older Paleozoic and/or Mesozoic Nubia Sandstone ridges.

Not less than 12 younger NE/SW mountain ranges are identified by using SRTM Data on both sides of the Egyptian-Libyan borders where they arrange in parallelism between latitudes 24º and 29º, and longitudes 21º 15' and 27º. Two major mountain ranges of these younger landforms are situated in the Egyptian side; the first eastern mountain range in the Egyptian side is located ~117 km west of Qasr Farafra and extending NE-SW across Sakhret El-Amoud for more than 140 km long, and 30 km wide, thus, assuming a total area of ~4100 km². The second parallel mountain range in the Egyptian side is located 35 km west of the first range, extending northeast from 19 km to 138 km east of the Egyptian-Libyan borders, with a total length of 224 km, a width of 25 km and a total area of 4550 km². Each one of these mountain ranges in the Egyptian side is made up of upraised Nubia Sandstone plateaus or domes against Nubian Sandstone depressions or troughs. The movement of the depressions is usually down parallel to the dip of the inclined fault surface suggestive of a dip-slip normal faults which dip northeast at angle ranging from 45: to 50: whereas the plateaus are uplifted sufficiently (140 -190 m with an average value of 170 m) to form a horst in the Egyptian side. The bed rock of both mountain ranges is exclusively made up of white compact quartz sandstone belonging to the Sabaya Formation which is the most productive unit of the Nubia Sandstone Aquifer

In the Libyan side, ten younger parallel mountain ranges including new plateaus/ eroded dome-like structures, half-grabens and depressions/troughs trending NE, varying in area from 111 km² to 2809 km² and covering a total area of 10430 km² could be distinguished by remote sensing using SRTM data where they surround the Al Balatah Paleoriver Basin and its delta plain from west, north and northwest. However, most of these younger landforms are almost bounded by a fault along one side of its boundaries, thus constituting half grabens, tilted plateaus or dome-like folded structures, with sloping walls ranging from 125 m to 150 m in the south and from 70 m to 140 m in the north. This would support the influence of a major tectonic movement affecting the area of the Great Sand Sea on both sides of the Libyan-Egyptian borders during the Late Oligocene leading to the refolding and uplifting of the older Nubia Sandstone bedrock before the runoff of the Al Balatah Paleoriver and formation of the Al Balatah Paleodelta.

During the time interval from the Early Miocene to the late Pleistocene the old river system of the Al Balatah Valley, northeastern Libya ran through the basinal area lying between the younger mountain ranges on both sides of the Libyan-Egyptian borders where it built a vast inland delta plain as a result of flowing of into a huge freshwater Pleistocene lake occupying the area lying northeast of Libya and northwest of Egypt. Prolonged erosion by both wind and groundwater sapping have led to flatness of the surfaces of plateaus and floors of depression as well as erosion of domes, while deflation was resulted in the accumulation of a thin cover of drifted loose sand on the slopes of the plateaus and floor of the depressions obscuring the original bedrock.

Enormous quantities of water of the Pleistocene inland delta are expected to be stored in the subsurface of the underlying Nubia Sandstone bedrock in the Al Balatah Paleodelta and its eastern extension in Egypt (Nahda Plain) due to its great thickness, high porosity and permeability. The results become, therefore, fundamentally significant to the establishment of new agricultural communities in the Paleodelta Plain (24218 km²) of Al Balatah Paleoriver of northeastern Libya and its eastern portion in Egypt , the Nahda Plain (3010 km²) as well as the flat-topped plateaus, depressions and troughs of the younger mountain ranges which surround the Al Balatah Paleoriver System, (at least 5000 km² in Egypt and 6500 km² in Libya), especially when considering the threat of fresh water scarcity in both countries.

Acknowledgement

The author wishes to express his gratitude to the Management of Assiut University for providing Lab facilities necessary for the completion of this study. Deep thanks are also due to the reviewers for their insightful reviews and valuable comments on this manuscript.

Declarations:

Funding: No funding

Conflicts of interest: No conflicts

References

[1] Bellini E., Massa D. (1980). A stratigraphic contribution to the Paleozoic of the Southern Basins of Libya. In: the Geology of Libya, Eds. Salem M. J. and Busrewil, M. T.., Academic Press, Vol. I, pp. 3- 56.

[2] Capot-Rey R. (1960). Comptes rendus. Forschungen in der zentralen Sahara. Trav. Inst. Rech. Sahariennes, Alger. 19.

[3] Desio A. (1943). II Sahara Italiano. II Tebesti nord-orientale. R.Soc. Geogr.Ital., 232 p

[4] El-Baz F. (1995). Utilizing satellite images for groundwater exploration in fracture zone aquifers. In: Proceedings of the International Conference on Water Resources Management in arid countries12-16 March 1995, Ministry of Water Resources, Muscat, Oman, Vol. 2, pp.419-427.

[5] El Ramly I. M. (1966). New light on the origin of the natural lakes, south Qattara Depression. 5th Arab Sci. Congr., Baghdad.

[6] El Ramly I. M. (1973). Final report on geomorphology, hydrogeology, planning for groundwater resources and land reclamation in Lake Nasser region. Un-published report, Lake Nasser Res. Cent., Aswan, 474 p

[7] El Ramly I. M.(1980). Al Kufrah Pleistocene Lake-Its evolution and role in present-day land reclamation. In the Geology of Libya, Eds. Salem M. J. and Busrewil, M. T.., Academic Press, Vol. II, pp.659-670.

[8] Fisk E. P., Pennington W. D. (1976). Groundwater geology and hydrology of the Kufrah region, Libyan Arabic Republic. Libyan J. Sci., Vol. 6B, pp.39-54

[9] Fürst M. (1966). Bau und Entstehung der Serir Tibesti. Z. Geomorph., N. F., Vol. 10, pp.378-418.

[10] Gabriel B. (1977). Zum okologishen Wandel im Neolithikum derostlichen Zentralsahara. Berl. Geogr. Abb. 27, 111 p.

[11] Geyh M. A., Jäkel D. (1977). The climate of the Sahara during the Late Pleistocene and Holocene on the basis of available radiocarbon dates. Nat. Resour Dev. Inst. Scient. Coop., Hanover

[12] Ghoneim E., Benedettia M., El-Baz F. (2012). An integrated remote sensing and GIS analysis of the Kufrah Paleoriver, Eastern Sahara. Geomorphology, Vol. 139–140, pp. 242-257.

[13] Gossel W., Ebraheem A. A., Sefelnasr A. M., Wycisk P. (2008): A GIS-based flow model for groundwater resources management in the development areas in the eastern Sahara, Africa. In: Adelana, S. M. A, MacDonald, A. M. [Ed.]: Applied groundwater studies in Africa.

[14] Goudarzi G. H. (1980). Structure-Libya. In the Geology of Libya, Eds. Salem M. J. and Busrewil, M. T.., Academic Press, Vol. III, pp.879-892.

[15] Ouda, Kh. & Obaidalla, N. (1995): The geologic evolution of the Nile Delta area during the Oligocene-Miocene. Egypt. Journal Geology, vol. 39 (1), pp. 77-111.

[16] Ouda Kh. A. K. (2021). The Nubia Sandstone (Nubia Group), Western Desert, Egypt: An overview. International Journal of Trend in Scientific Research and Development (IJTSRD): ISSN: 2456 – 6470, Vol. 5 (3), Mars-April 2021, pp. 274-292, URL:www. ijtsrd.com/papers/ijtsrd38760.pdf.

[17] Ouda Kh. A. K. (2023). Groundwater Sapping Process and Runoff of Old River Systems in the Great Sand Sea and the Gilf El Kebir Plateau, Western Desert, Egypt. International Journal of Trend in Scientific Research and Development (IJTSRD): ISSN: 2456 – 6470, Vol. 7 (5),

October 2023, pp.181-234, UR. www.ijtsrd.com/papers/ijtsrd59885.pdf

[18] Ouda Kh., Senosy M., Gad M., Hassan G., Saber M. (2012). New Findings in Geology, Geomorphology and Groundwater Potentiality of the Great Sand Sea, Western Desert, Egypt. Proceedings of the Geology of the Nile Basin Countries Conference (GNBCC-2012): Geology and development challenges, Alexandria, Egypt, March 20th - 22nd, 2012, pp.98-103.

[19] Ouda Kh., Senosy M., Nasr I., Gad M., Hassan G., Saber, M. (2011). A final technical report about the results of the joint expedition of the Geology Department, Assiut University, Assiut and the Desert Research Center, Mattariya, Cairo, Egypt to the Great Sand Sea during July-August 2011, submitted to the Minister of Agriculture and Land Reclamation, Egypt, 36 p. The results were announced in a press conference in Al-Ahram newspaper in October 14/ 2011.

[20] Pachur H-J. (1980). Climatic history in the Late Quaternary in Southern Libya and the Western Libyan Desert. : In: the Geology of Libya, Eds. Salem M. J. and Busrewil, M. T.., Academic Press, Vol. III, pp.781-788.

[21] Paillou P., Schuster M., Tooth S., Farr T., Rosenqvist A., Lopez S. and Malézieux J.-M. (2009). Mapping of a major paleo-drainage system in Eastern Libya using orbital imaging Radar: The Kufrah River, Earth Planet. Sci. Lett., Vol. 277, pp. 327-333 (doi: 10. 1016/j. epsl. 2008. 10).

[22] Paillou P., Tooth S., Lopez S. (2012). The Kufrah paleo-drainage system in Libya: A past connection to the Mediterranean Sea?. Comptes Rendus. Géoscience, Vol. 344 (8), pp. 406-414.

[23] Robinson C. A., El-Baz F. Al-Saud T. S. M., Jeon, S. B. (2006). Use of radar data to delineate paleo-drainage leading to Kufra Oasis in the eastern Sahara.. J. Africa Earth Sci., Vol. 44(2), pp. 229-240, doi:10.1016/j.jafrearsci.2005.10.012pp. 1-12

[24] Rognon P. (1980). Comparison between the Quaternary Terraces around Atakor and Tibisti: In the Geology of Libya, Eds. Salem M. J. and Busrewil, M. T.., Academic Press, Vol. III, pp.815-821

[25] Said R. Issawi B. (1964). Geology of northern plateau, Bahariya Oasis. Egypt. Geol. Surv., paper 28, 41 p.

[26] Salem O. (1991). The great man-made river project. A partial solution to Libya's future water supply. Planning for groundwater development in arid and semi-arid regions. Research Institute for Groundwater, Cairo, Egypt, pp. 221-238.

[27] Schlüter T. (2006). Geological Atlas of Africa. Springer, Germany. Library of Congress Control Number: 2005933041.

[28] Shrank E. (1984). Paleozoic and Mesozoic palynomorphs from Foram 1 Well (Western Desert, Egypt. N. Jb. Geol. Paläont. Mh. H.2, pp.95-112, Stuttgart.

[29] Wendorf F., Schild R., Said R., Hayens V., Gautier A. and Kobusiewicz M. (1976) The prehistory of the Egyptian Sahara. Science, Vol.193 (42-48), pp. 103-114.