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Groundwater Sapping Process and Runoff of Old River Systems in the Great Sand Sea and the Gilf El Kebir Plateau, Western Desert of Egypt

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ABSTRACT

The present work delineates two main patterns of drainage in the Western Province of the Western Desert. The first pattern was formed by runoff of old river systems and has a restricted geographic distribution on the top surface and slopes of the scarps of the Gilf El Kebir Plateau but it is generally low, intermittent, having a limited duration in the westernmost part of the Great Sand Sea along the Egyptian-Libyan borders. The second pattern was and still formed by groundwater sapping process which has a widespread distribution along the slopes of the Gilf El Kebir Plateau, the Nubia Sandstone hills distributed in the Dakhla Basin and the slopes of the widely distributed longitudinal Nubia Sandstone ridges in the Great Sand Sea between the Gilf El Kebir in the south and Siwa Oasis in the north. The phenomenon of lateral flowing of groundwater and its emergence as seeps at the edges of the scarps was and still today the main erosion process that produces major landforms with unique characteristics in the Great Sand Sea. It causes disintegration and breakdown of the Nubia Sandstone bedrock and erosion of the sandstone from the slopes, causing the slopes to be undermined and undergo mass wasting. It is also the predominant mechanism of the growth of the amphitheater-headed valleys, and the flat-topped surfaces of the upraised plateaus as well as the exploitation of joints and fractures in the Nubia Sandstone bedrock. In addition it is responsible of formation of different types of alcoves in headwalls, spring sites and seepage zones in many valley flanks. Moreover, vast areas of the Nubia Sandstone bedrock of the flat-topped plateaus, flat tracks and depressions are found to be eroded, well exposed, clean, and covered by silica debris as a result of intense erosion by the groundwater seepage.

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KEYWORDS: *Groundwater sapping process, runoff of old river systems, alcoves, amphitheater-headed valleys, Great Sand Sea, Gilf El Kebir Plateau, Western Desert*

1. Introduction and Previous related work

1.1. Groundwater Sapping Process

Groundwater sapping is an erosional process that produces major landscape features with unique characteristics (Higgins, 1982). The idea had previously been attributed to Peel (1941) based upon observations in the Gilf Kebir plateau of Libya. In this region he identified wadis with flat floors and steep sides which terminated in a headward cliff and appeared to have been 'cut out from below' rather than 'let down from above'. This description succinctly summarizes the key difference between erosion by exfiltrating water and the operation of surface incision by river erosion (Nash, 1996). Since that time terrestrial valleys, gullies and depressions suggested to have been formed by groundwater erosion have been identified across a wide range of climatic settings, including systems in Hawaii (e.g. Baker, 1988, 1990; Kochel and Piper, 1986), the Colorado Plateau (e.g. Pieri., 1980; Laity, 1983; Laity and Malin, 1985; Howard et al., 1988), Massachusetts (Uchupi and Oldale, 1994), Japan (Onda, 1994), Libya (Peel, 1941), Egypt (Luo et al. 1997), New Zealand (Schumm and Phillips, 1986), Botswana (Nash, 1992, 1995; Nash et al., 1994a,b) and England (Hackness Hills, North Yorkshire, Nash,1996).

Laity and Malin (1985) identified two populations of valleys with markedly different features in the Glen

Canyon region of the Colorado Plateau where canyons occur in the Navajo Sandstone, a highly transmissive aquifer underlain by essentially impermeable rocks. Within this formation, the first group formed by ground-water (sapping) processes exhibits theater heads, longitudinal profiles with high, step-like discontinuities and commonly asymmetric, structurally controlled patterns. The second group formed by overland-flow and is characterized by tapered terminations; a relatively smooth, concave-up profile; and a more arborescent network.

Kochel and Piper, 1986 pointed out that principal components analysis of morphometric data clearly separate runoff valleys from sapping valleys in Hawaii. The Hawaiian sapping valleys are characterized by: (1) steep valley walls and flat floors, (2) amphitheater heads, (3) low drainage density, (4) paucity of downstream tributaries, (5) low frequency of up-dip tributaries, and (6) strong evidence of structural and stratigraphic control on valley patterns.

Valleys developed by sapping and seepage erosion are suggested by Howard et al. (1988) and Baker (1990) to have a number of distinctive morphological features which, to a certain extent, may be diagnostic of the operation of groundwater processes in their formation. These include abrupt valley initiation with amphitheater headwalls and little evidence of surface flow above the valley head, alcoves and springs in the headward region, steep valley flanks with an abrupt angle to a flat valley floor, a long valley with a constant valley width, short first-order tributaries with possible hanging valleys and a paucity of tributaries downstream.

In the Western Desert of Egypt, Luo et al. (1997) pointed out that the scallop-shaped escarpment edges and stubby-looking channels that cut into the limestone plateau units which surround the Kharga, Farafra and Kurkur in southeastern Western Desert are suggestive of slumping of limestone by ground-water sapping at the limestone-shale interfaces, removal of slump blocks by weathering and fluvial erosion, and consequent scarp retreat. According to these authors the spring-derived tufa deposits found near the limestone escarpments provide additional evidence for possible ground-water sapping during previous wet periods.

On the other hand, no information was given about the groundwater sapping process in the Great Sand Sea and the southwestern Western Desert of Egypt. Since 1931 the Great Sand Sea has been described as being formed of many parallel longitudinal sand dunes which cover ~72000 km² and are bounded in the south by the Gilf El Kebir Nubia Sandstone Plateau and in the north by Siwa Oasis (e.g. Bagnold 1931,1941; Said 1962; Gifford et al. 1979; Hereher, 2010). However, the data given by Ouda et al.(2011, 2012) and; Ouda (2021) indicate that the Great Sand Sea is essentially made up of a series of parallel longitudinal sandstone ridges belonging to the younger members of the fluviatile Cretaceous Nubia Sandstone Group. The ridges are structurally controlled, extending north northwest- south-southeast and not covered by younger marine consolidated deposits but only with a thin veneer of accumulations of free sands originating from the disintegration and breakdown of the underlying Nubia Sandstone bedrock, thus obscuring the original bedrock. The area of the Great Sand Sea exhibits a long history of predominantly continental sandstone accumulation and continuous subsiding followed by a long period of active erosion since the uppermost Cretaceous. This is indicated by the great thickness of the Paleozoic-Mesozoic sequence of the Nubia Group which reaches up 3500 m in the subsurface of the Great Sand Sea (Foram-1 at the northwestern rim 10 km west of the Libyan borders).

1.2. Runoff of Old River Systems

Not much attention has been paid to the drainage pattern of old river systems in the Great Sand Sea. This part of desert has been considered for a long time as being devoid of well-marked drainage lines due to its arid climate. However, in the southwestern part of the Western Desert McCauley et al (1982), using Landsat images, were able to delineate several drainage networks extending well beyond the Gilf El Kebir Plateau margin. Moijzsis and El Baz (1992) recorded numerous dry wadis running northward from the southern part of the Western Desert and also dry courses of streams in the central region trending westward from the Farafra Oasis toward the area of the Great Sand Sea.

The age of the palaeodrainage system is a matter of conjecture. Interpretation of Shuttle Imaging Radar (SIR) images by McHugh et al. (1988) has led to the idea that a paleodrainage system of regional and perhaps transcontinental proportions crossed southern Egypt and northern Sudan prior to the onset of Quaternary aridity. According to these authors development of an integrated, regional river system probably occurred in the late Paleogene or early Neogene. The river courses eventually were disrupted by tectonism, volcanism, and stream piracy. Their broad valleys were almost fully aggraded long before the middle Pleistocene appearance of man in the area. Some of the large paleovalleys on the radar images are believed by McHugh et al. (1988) to represent the last episodes of running water in the valleys during the Quaternary pluvials.

Issawi and McCauley (1992) proposed that the paleodrainage in SW Egypt formed as far back as Tertiary times. Robinson et al (2006), however, makes no inferences about the ages of these channels. They only maintained that these channels must have received water from a continuous supply of rainfall at the time they were created.

The present work concerns with both phenomena of overland flow of old rivers on the flat-topped surface and slopes of the Gilf El Kebir Plateau, and the lateral flowing of groundwater and its emergence as seeps at the edges of the scarps of the Gilf El Kebir and the Nubia Sandstone hills distributed in the Dakhla Basin as well as the slopes of the widely distributed longitudinal Nubia Sandstone ridges in the Great Sand Sea between the Gilf El Kebir in the south and Siwa Oasis in the north (Fig.1).

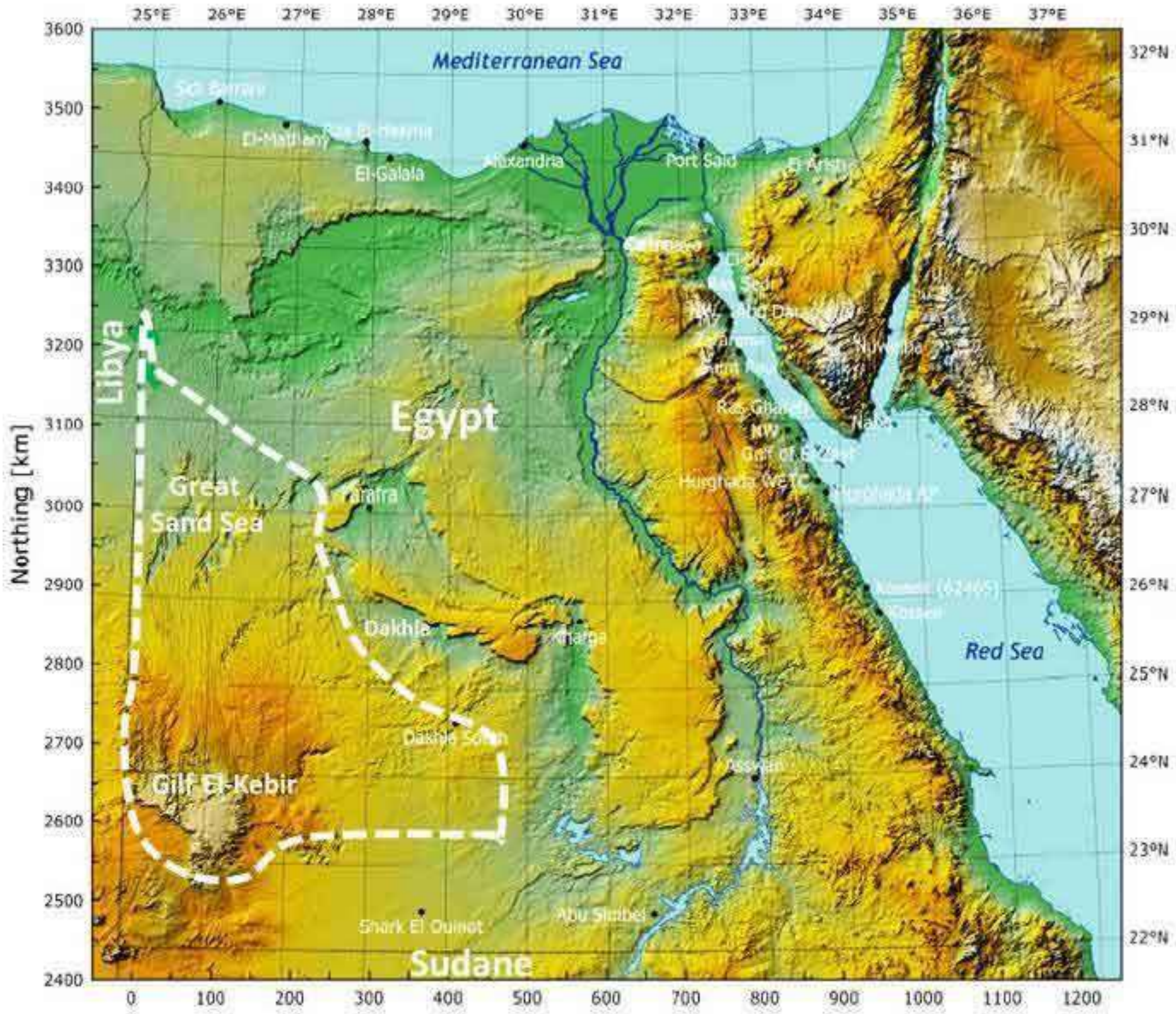


Fig. 1: Satellite SRTM map of Egypt showing the area of the present study

2. Method of Study

The present study concerns with the groundwater sapping process in the Western Desert of Egypt including both the Gilf El Kebir Plateau at south and the Great Sand Sea at north. The study based on both field work (Great Sand Sea) and remote sensing studies (both Great Sand Sea at north and the Gilf El Kebir Plateau at south), using the Digital Elevation Data brought by the Shuttle Radar Topographic Mission (SRTM) of NASA's Space, 3-arc-second Resolution, version 4, satellite images and surface photography. The data covered large areas of the topographic surface of this inhospitable and inaccessible desert of the Great Sand Sea, including geologic structures (New wide depressions, plains and plateaus with flat surfaces) and showing evidences of Recent groundwater seepage process beside paleodrainage networks.

Two field expeditions were made to the Great Sand Sea in June 2011 and March 2012, in order to assure, investigate and study the new topographic features and landforms in this area which could help in understanding the Geologic history and economic value of the area known as the Great Sand Sea in Egypt. The final results have been summarized in Ouda et al. (2011, 2012).

In this study the phenomenon of lateral flowing of groundwater and its emergence as seeps at the edges of the scarps which is widely distributed along the slopes of the Gilf El Kebir Plateau, the Nubia Sandstone hills distributed in the Dakhla Basin and the slopes of the widely distributed longitudinal Nubia Sandstone ridges in the Great Sand Sea are studied in details. Modern international mapping programs were used, the most important of which is the International Mapper Program (Global Mapper ver. 14) to design topographic and contour maps and make detailed and accurate measurements in the Western part of the Western Desert of Egypt, based on the information and digital data (ver. 4) of the ground elevations. received from The Shuttle Radar Topography Mission of NASA's space agency.

The geological and environmental phenomena in the areas under investigation have been determined by direct and accurate electronic projection of modern satellite images onto topographic maps designed with high accuracy. Satellite images from Google Map imagery, Google Earth Pro, Digital Globe World-Wide high-resolution imagery, Bing Map Imagery and World imagery were used. Cross sections via satellite SRTM images across the Gilf El Kebir Plateau and the Great Sand Sea are obtained. In addition, a detailed field study and surface photographs as well as results of study of petrography of the Nubia Sandstone ridges in the Great Sand Sea are given.

3. Results and Discussion
3.1. Geology and Geomorphology of the studied area
3.1.1. The Gilf El Kebir Plateau
Geomorphologically, the Gilf Kebir can be divided into two parts separated by Wadi Assib which is an offshoot of the Great Sand Sea (with the passage Aqaba which is an small eroded valley near Lat. 23º 30′ N) separating visually a northwestern part (Abdel-Malik plateau) from a southeastern part (Kamal-el-Din plateau) (Fig. 2).

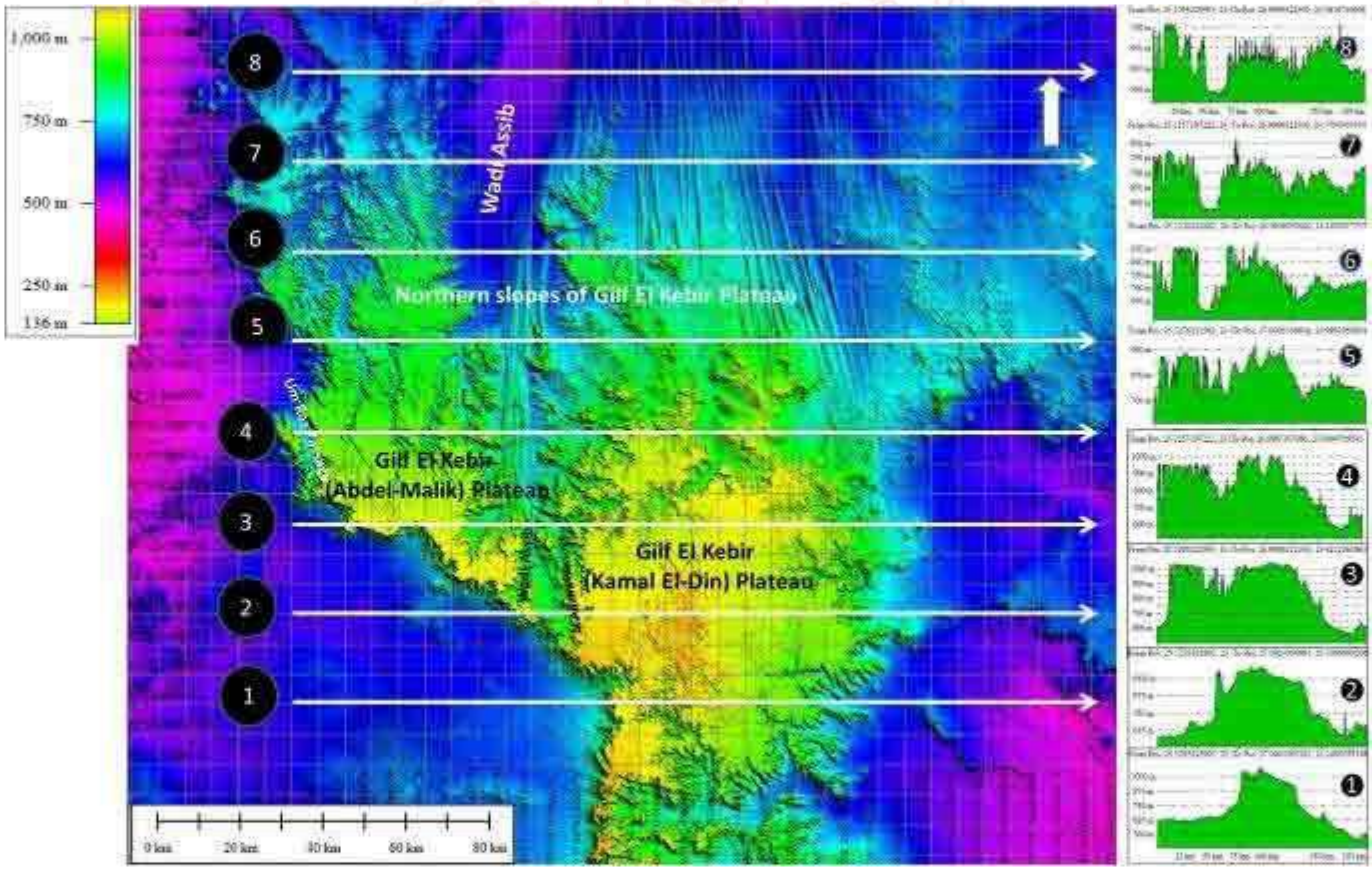


Fig.2: Cross sections showing via satellite SRTM image the topography of the area of the Gilf El Kebir Plateau

The Kemal El-Din plateau (Figs. 2-5) extends over 120 km in a north-south direction and 80 km in the east-west direction and gradually tapering toward south until becoming terminated at nearly Lat. 22º 40′ N. The elevation of the plateau varies from 700 m at the southern part to 1064 m near Al Aqaba Pass. The top surface of the plateau is entirely flat except of few localities which are disturbed by the rise of basaltic cones and flow sheets. Many wadis dissect the plateau particularly in its eastern side (Fig. 6), and several scarps and ridges overhang the main plateau and overlook the wide depressions north and northwestward of the plateau (Figs 4-5). Several networks of drainage pattern of old river systems originating from the hilocks on the flat-topped surface of the plateau and running north and northeast are detected. Many wadis cut its east and south sides. They are from north to south the named Wadi Mashi, Dayiq Wadi, Wadi Maftuh, Wadi Bakht, Gazayir Wadi, Wadi Wassa, Wadi Akhdar, Wadi Firaq. The Jebel Almasy is an isolated structure of the Gilf Kebir, lying in the southernmost part of the Great Sand Sea. The Nubia Sandstone sequence in this Jebel reaches a maximum height of about +870 m above sea level and exceeds the desert floor by about 150 m (Brügge, 2017).

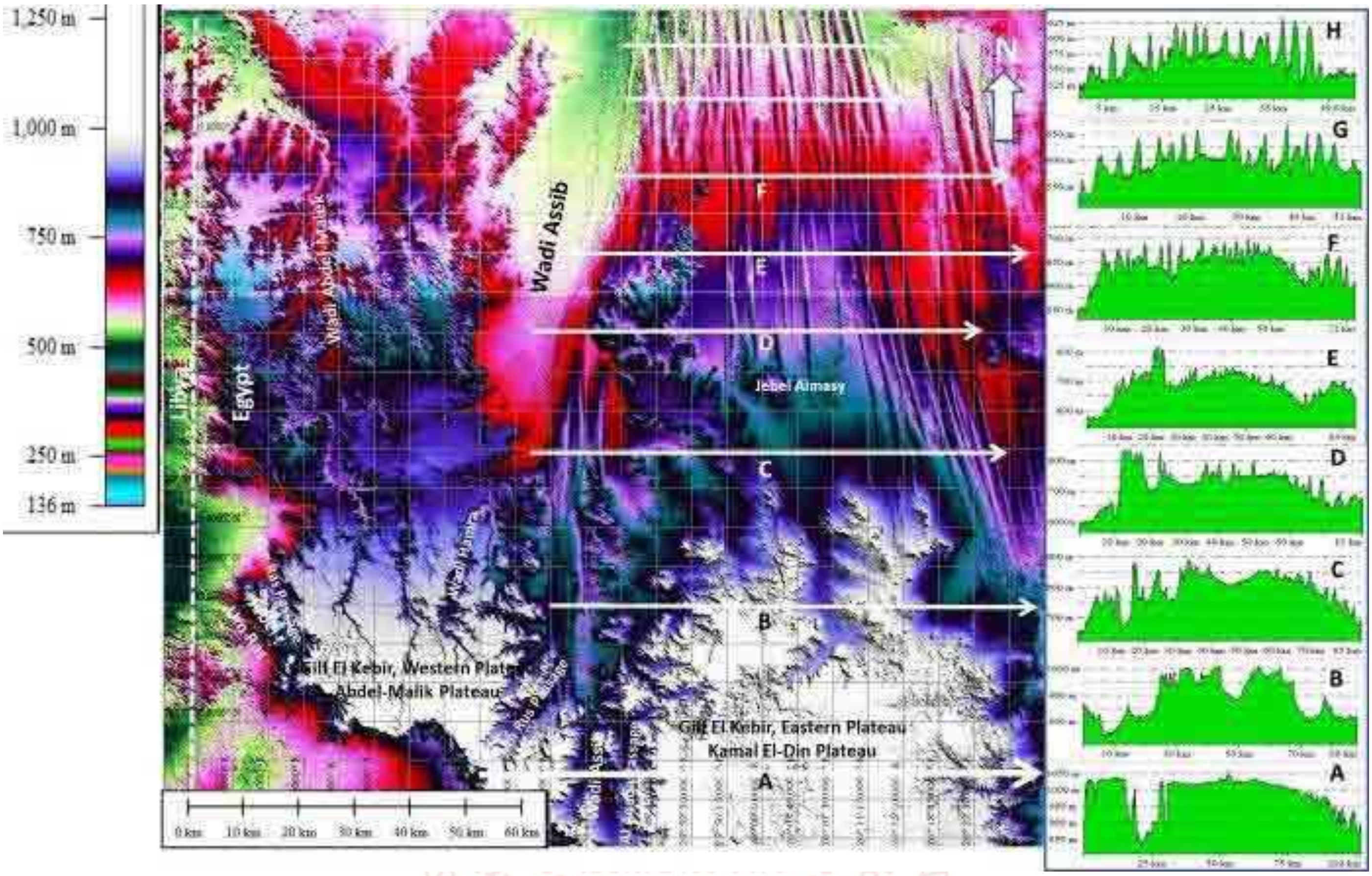


Fig. 3: Cross sections showing via satellite SRTM image the topography of the eastern part of the Gilf El Kebir Plateau (Kamal El Din Plateau) and its northern slopes towards the Great Sand Sea.

The Abdel-Malik plateau (Figs. 2-4 and 7) extends over 140 kilometers from north to south and about 40 kilometers from west to east. It is cut by two gigantic wadis, the approximately 100 km long Wadi Abdel Malik and the Wadi Hamra. On the southwestern edge of the Abdel-Malik plateau continues to Libya (Jabal Um Ras, Jabal Rukn and Jabal Asba). The morphological separation is effected by the Um-Ras passage. A special feature in the Abdel-Malik Plateau are marine Carboniferous deposits with plants imprints, which are widely spread in the so-called Wadi Talh, and above a heavily eroded relief of older Paleozoic sandstones lie. The Kemal-el-Din Plateau has a simple structure, but has a subvolcanic overprint that also spread is in the surrounding ranges (e.g. Clayton Craters and Gilf Kebir Crater Field).

Lithologically, the Gilf El Kebir Plateau is made up exclusively of Mesozoic fluviatile Nubia Sandstone sequence composed mainly of Six Hills and Sabaya Formations (Fig.8). According to Klitzsch and Schandelmeier (1990), the lower half to two thirds of this plateau is formed of predominantly fluviatile sandstone equivalent to both Six Hills and Abu Ballas Formations, whereas the upper half or one-third of the Gilf Plateau is made up of fluviatile sandstone equivalent to the Sabaya and the Maghrabi Formations.

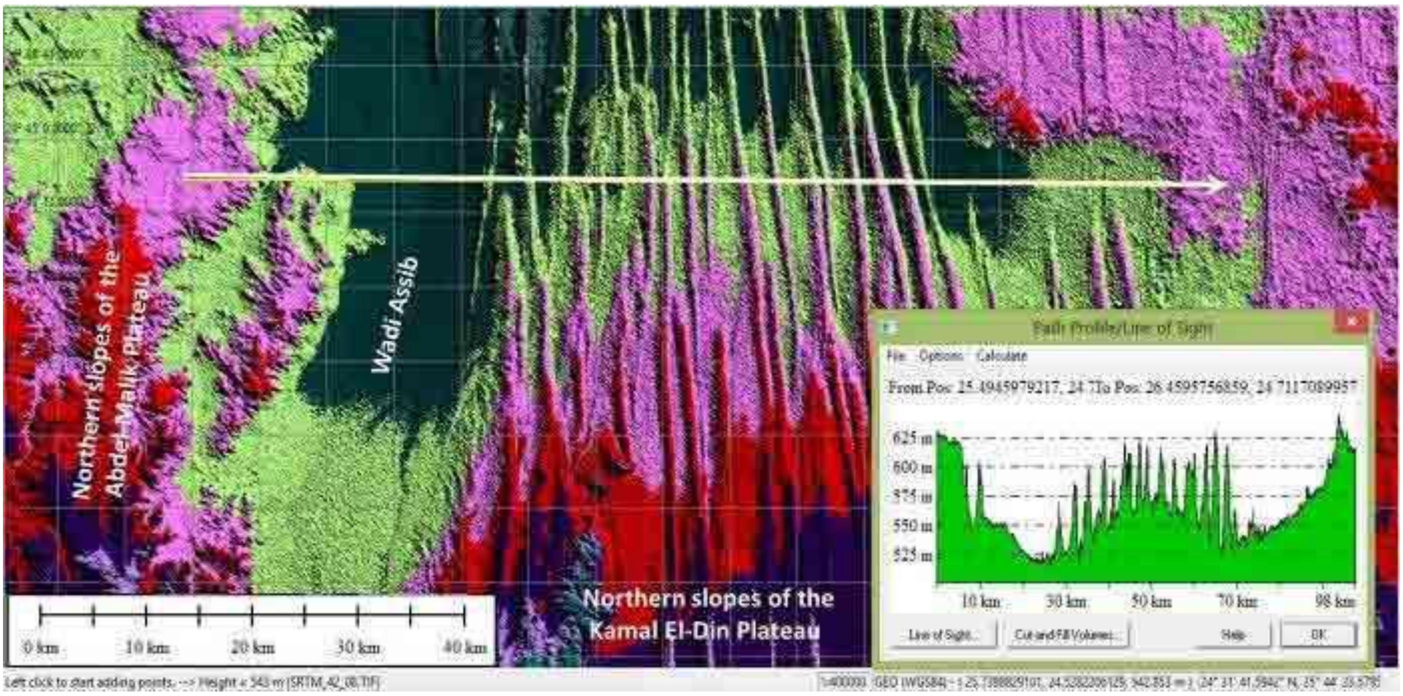


Fig.4: A cross section of the topography of the northernmost slopes of the Gilf El Kebir Plateau showing via satellite SRTM image how the sediments of the Nubia Sandstone sequence in the low-lying area between the Gilf El Kebir and Siwa (the Great Sand Sea) were subjected to a low-strain close to surface immediately following the regional uplifting movement in the Western Desert during the Late Cretaceous (Late Turonian- Santonian), and which resulted in the formation of gentle open folding made up of N-NW/S-SE longitudinal series of parallel up-folded ridges separated by troughs.

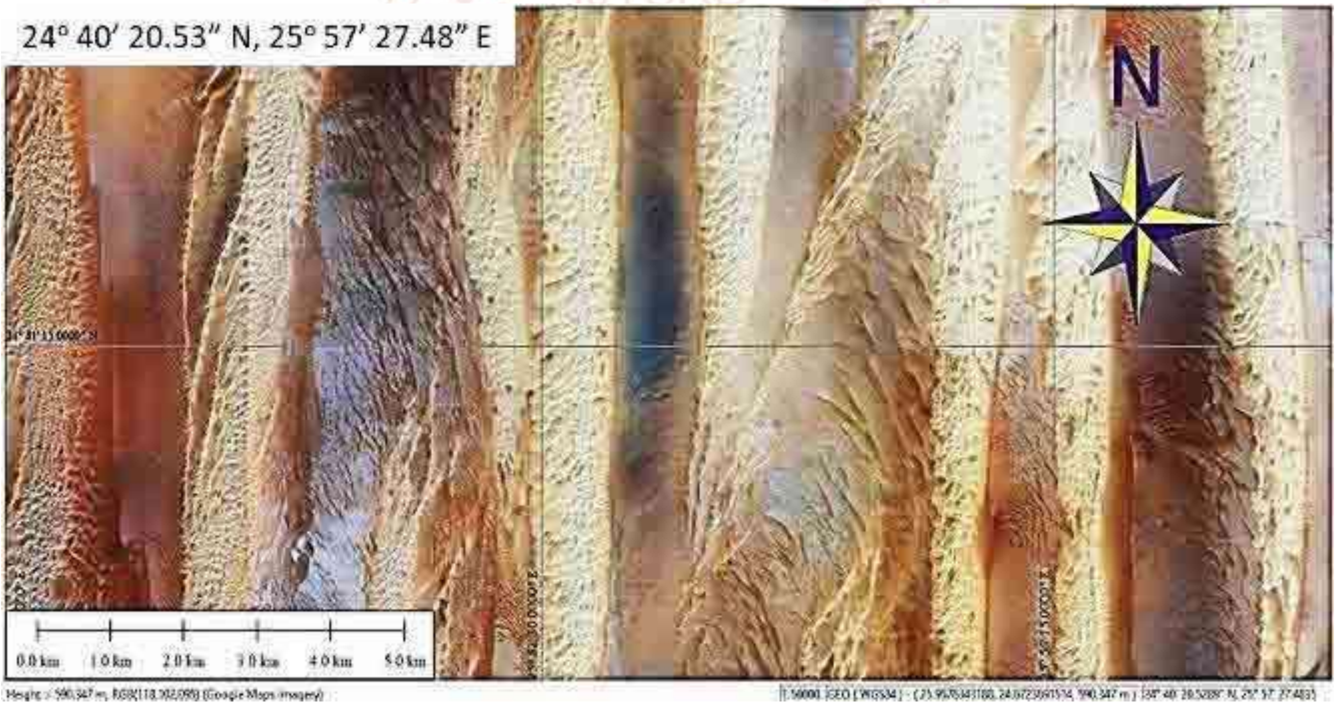


Fig. 5: Satellite SRTM image from Google Map imagery whose topography is given in Fig. 5, showing the extension of longitudinal series of bended (up-folded), cross-bedded to horizontally Nubia Sandstone ridges between the Gilf El Kebir at south and the Great Sand Sea at north. Note that the sandstone ridges are highly jointed, and intensively attacked by groundwater sapping process and overland flows of old river systems coming from south northward.

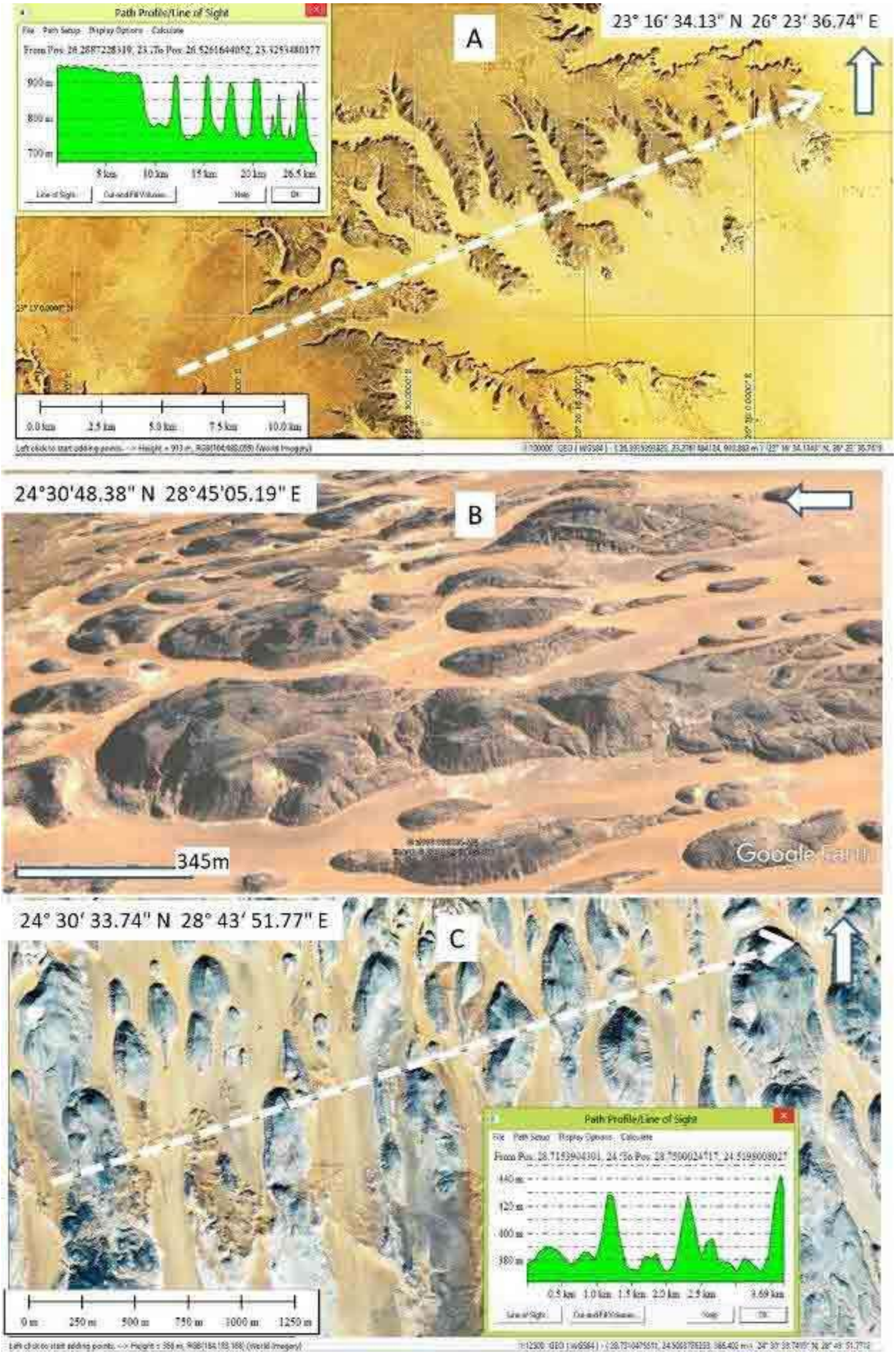


Fig.6. A and C: Satellite SRTM image from World Imagery showing longitudinal Nubia Sandstone ridges oriented N-NW/ S-SE and separated by canyons of different width developed along the scarps of the eastern edge of the Gilf El Kebir Plateau (A) and in the Dakhla Basin (C). B: A Google Earth image showing the same Nubia Sandstone ridges which are given in Fig. 6C.

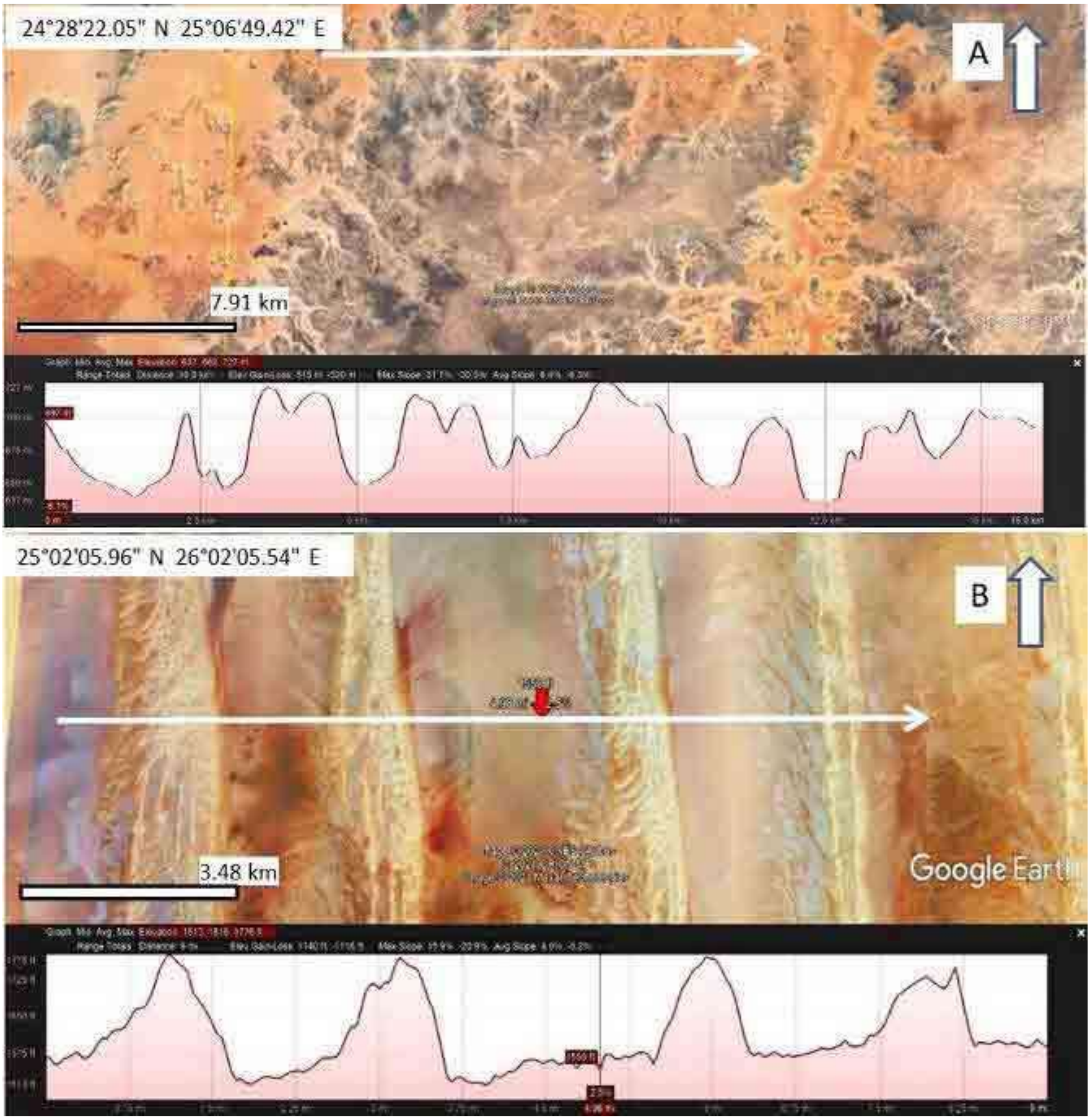


Fig. 7. A: A Google Earth image of the northernmost slopes of Abdel-Malik Plateau showing a cross section along complex network of runoff streams which are running along the intensively folded and fractured top surface of the plateau leading to the formation of a series of valleys dividing the plateau into a number of ridges and scarps of different dimensions. B: A Google Earth image of the Great Sand Sea showing a cross section of longitudinal series of parallel bended (up-folded) Nubia Sandstone ridges. Note that the ridges are intensively attacked by groundwater sapping process and overland flows of northward old river systems leading to the partial disintegration and breakdown of the sandstone ridges.

In Wadi Qubba, these sediments were found by the same authors to be overlain by fluvial and lacustrine sandstone and paleosol, equivalent to the Taref Sandstone (Awad and Ghobrial, 1965) of Turonian age (Fig 9; Ouda, 2021). However, some workers are inclined to apply other comparable geographic rock units in the Gilf El Kebir Plateau to express lateral changes in environment westward from continental sandstones changing gradually in the uppermost part into near-shore environment east of Long.27º, to exclusively continental sandstones west Long.27º

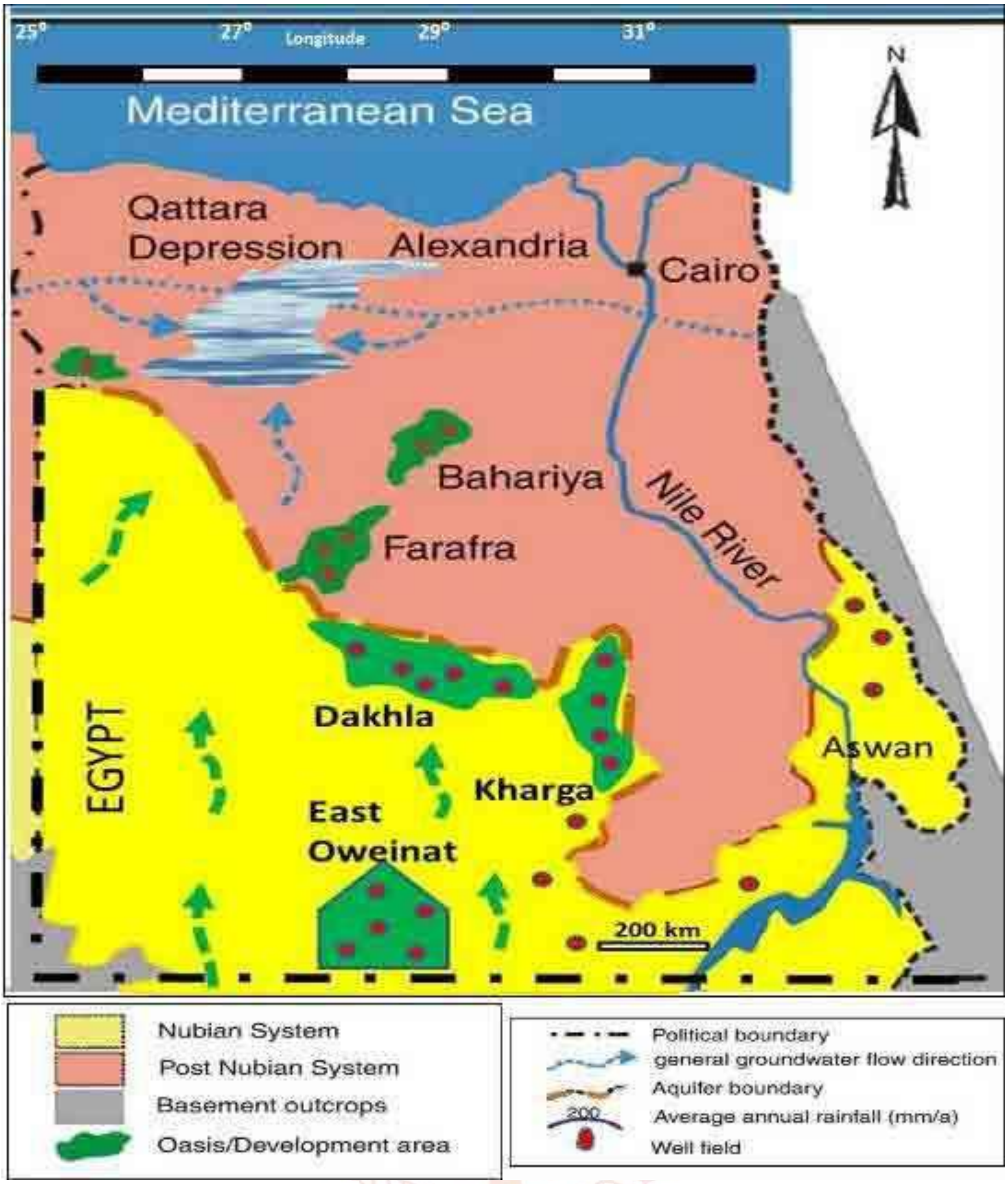


Fig.8: A- Regional surface exposures of the Nubia Sandstone in Egypt, Modified by Ouda (2021) after CEDARE (2002) and Bakhbakhi (2006).

The Six Hills Formation (Barthel and Boettcher, 1978 = Basal Clastics of Klitzsch, 1978 and Bisewski, 1982) attains a thickness of 600-700 m in the eastern part of the Gilf El Kebir Plateau (Kamal El-Din Plateau). The Formation is made up of fluviatile sandstone which is fine- to coarse-grained, tabular and trough cross-bedded with channel sediments representing upward-fining cycle of braided river systems (Hermina et al.1989). In the Abu Ras Plateau (western part of the Abdel-MaliK Plateau) the Six Hills formation represents the top part of the plateau and is eroded over large areas (Klitzsch and Schandelmeier, 1990). The sediments belonging to this formation cover unconformably older sandstone Paleozoic strata belonging either to the Silurian (Umm Ras Formation, Klitzsch and Lejal-Nicol, 1984), or the Carboniferous Wadi Malik Formation, Klitzsch, 1979 and Northern Wadi Malik Formation, Klitzsch and Lejal-Nicol, 1984) in Wadi Abdel Malik and its tributary wadis in the Abu Ras Plateau (Fig. 9). Along the eastern slopes of G. Uweinat, the Six Hills Formation overlies unconformably 250-300 m thick of unfossiliferous fluviatile sandstone of supposedly Permo-Lower Jurassic? age (Lakia Formation). On the basis of the detailed palynological study of Schrank and Mahmoud (1998), the entire Six Hills Formation should be regarded as belonging in age to the lower Cretaceous, from Berriasian to Early Aptian,

The Six Hills Formation is overlain directly by the Sabaya Formation (Barthel and Boettcher, 1978 =Desert Rose Beds of Klitzsch, 1978) which is made up mainly of fluviatile sandstone similar to those of the underlying Six Hills Formation, but both formations could be distinguished by a recognizable erosional surface characterized by a paleosol at the basal part of Sabaya Formation. The same erosional surface has been recognized at the base of

Sabaya Formation at its type locality and wherever it overlies the Abu Ballas Formation east of Long.27º. The formation is considered as one of the most productive beds in the Nubia Sandstone Aquifer System. The sediments belonging to this formation cover large areas south of Dakhla-Kharga road toward the Sudanese-Egyptian borders (= Abu Simbile Formation of Klitzsch, 1986 in the Lake Naser-wadi Halfa area) where they overly unconformably the Precambrian igneous rocks. They also extend west- and southwestward to the Gilf El Kebir where identical lithologic sediments of the same environment and the same age were described under the name of Gilf Kebir Formation (Klitzsch, 1978) covering unconformably Paleozoic sandstone of different ages northwest and south of the Gilf El Kebir Plateau. The thickness of the Sabaya Formation is about 170 m in the Kamal El-Din Plateau (eastern plateau of the Gilf El Kebir Plateau, but it reaches up more than 200 m in more basinal areas of the Dakhla Basin (Bisewski, 1982). The Sabaya Formation has a great extension towards the western part of the Western Desert where it constitutes the main bedrock in the desert surface of the Great Sand Sea (Ouda, 2021) and the irregularly low-scarped sandstone plains between Dakhla-Kharga road and the Gilf El Kebir Plateau (Figs, 6B-C). In Wadi Qubba the Sabaya Formation is overlain by continental sandstone and paleosols equivalent to Taref Sandstone (Klitzsch and Schandelmeier, 1990).

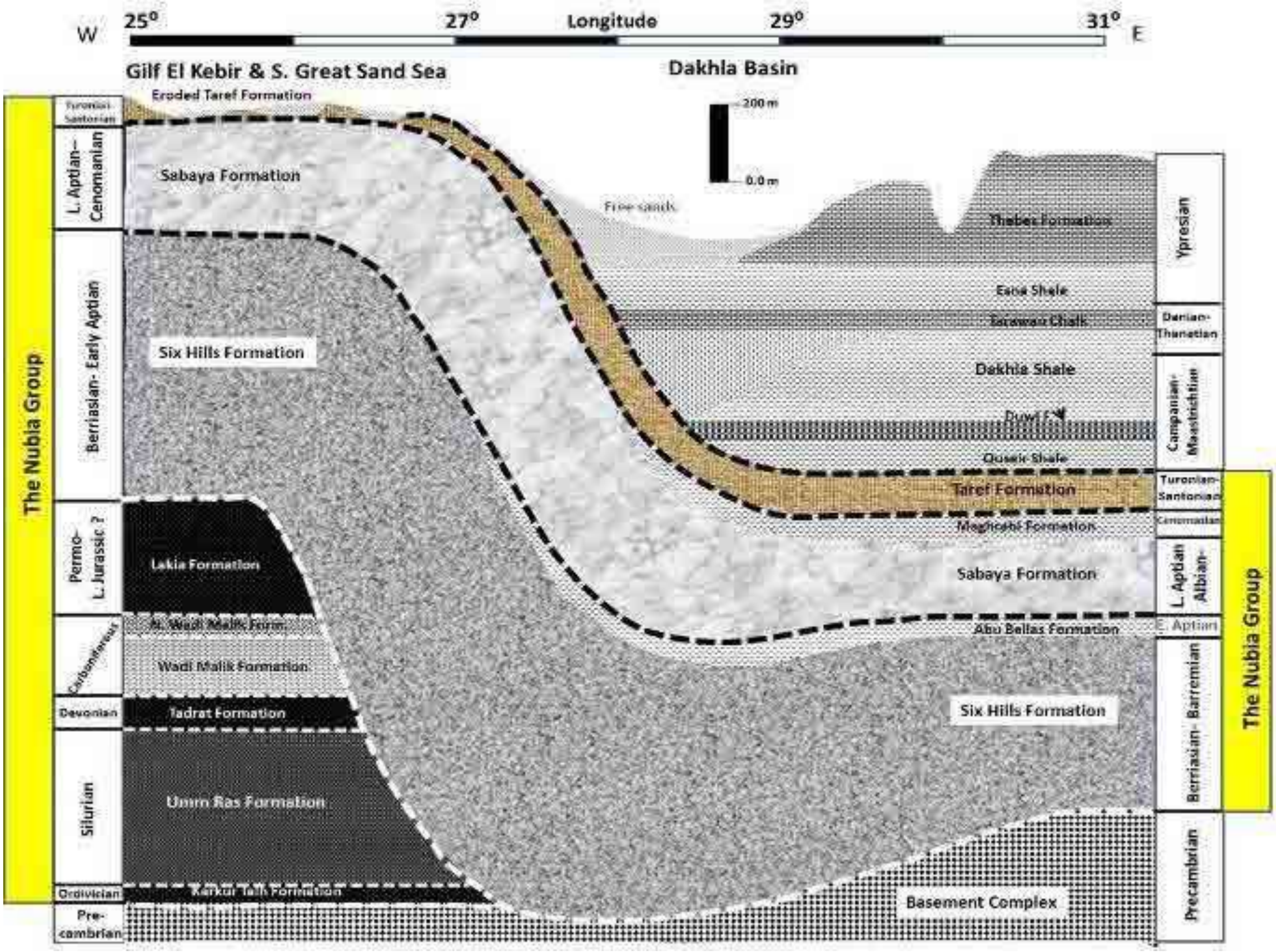


Fig. 9: Stratigraphic correlation of the different Paleozoic-Mesozoic rock units belonging to the Nubia Group between the Gilf El Kebir Plateau-southern Great Sand Sea at West (West of Long. 27⁰) and the Dakhla–Kharga stretch at east (East of Long. 27⁰ (After Ouda, 2021). Note the younger marine rock units belonging to the Campanian-Ypresian age which overly the Nubia Group in the Dakhla-Kharga regions. Note also that the uppermost rock unit of the Nubia Group (Taref Formation) is almost eroded in the Great Sand Sea.

On the basis of the detailed palynological study of Schrank and Mahmoud (1998), the entire Six Hills Formation should be regarded as belonging in age to the lower Cretaceous, from Berriasian to Early Aptian, not Late Jurassic-Aptian as previously proposed. The overlying Abu Ballas is regarded as Early Aptian in age, while the succeeding Sabaya Formation could range down into the Aptian, instead of Albian-Early Cenomanian as previously proposed. The Maghrabi Formation is Albian to Early Cenomanian in Dakhla area and Late Cenomanian-Turonian in Kharga area, thus indicating an eastward shift of the depocentre from West in Early Cretaceous time to East in Albian-Late Cretaceous time (Fig. 9).

The Taref Formation (Awad and Ghobrial, 1965) is made up of 100 m thick of mainly fluviatile cross-bedded sandstone with thin local intercalations of clay and shale containing leef impressions and fragmentary wood of possible near-shore marine influence northward at Abu Tartur (Hermina 1967; Dominik, 1985; Mansour et al., 1979). The sediments overly unconformably the Maghrabi Formation with an erosional contact and underlie unconformably the Quseir Shale. They are comparable in composition to the older fluviatile sandstone belonging to the Sabaya and Six Hills formations (Hermina, 1990). No index plant fossils have been encountered from this unit in the Western Desert. Its stratigraphic position between the underlying Cenomanian Maghrabi and the overlying Campanian Quseir Formation has led Hermina (1990) to postulate deposition of this unit in the south during the northern uplifting phase of the Bahariya area which started in the Turonian and continued on to the early-middle Campanian. Taref Formation is equivalent to the Turonian Abu Aggag Formation of El-Naggar (1970) in northeast of Aswan.

Eastward of the Gilf El Kebir Plateau toward the Kharga-Dakhla stretch, and southeastward (toward Gebel Kamel) the Paleozoic sediments are entirely missing, and the Lower Cretaceous sediments belonging to the Six Hills Formation overly unconformably the Precambrian basement rocks (Fig. 9). A vast flat plain of undulated Mesozoic sandstone bed rock with continuously decreased ground elevation (500 m to 400 m above sea level) extends from the eastern slopes of the Kamal El-Din Plateau toward the Kharga depression. The plain is dissected by longitudinal sandstone ridges made up of Six Hills and Sabaya Formations where they assume N/NW-S/SE trend (Figs.6B- C). Directly to the east of Long. 27º at Abu Ballas, the uppermost 60 m thick of the Six Hills Formation passes into near-shore, ferruginous clastic (silty sandstone, siltstone, shale and sandstone) belonging to the Abu Ballas Formation. The latter unit is unconformably overlain (with the formation of thick paleosol) by a fluvial sandstone more than 200 m thick belonging to Sabaya Formation.

3.1.2. The Great Sand Sea

In the Great Sand Sea (~72000 km² bounded in the south by the Gilf El Kebir Plateau and in the north by Siwa Oasis) the Paleozoic rocks become only known from the subsurface where they overlain by thick Early Cretaceous sediments which extend upward until becoming exposed on the surface. To the north of Lat. 24º 30′ the Six Hills Formation becomes subsurface while Sabaya Formation becomes exposed on surface where it forms a series of longitudinal Nubia Sandstone ridges running north northwest- south-southeast. The ridges are running parallel, straight and almost regularly spaced. They represent a series of bended (up-folded), cross-bedded to horizontally Nubia Sandstone layers belonging to the Sabaya Formation (Figs.10-12).

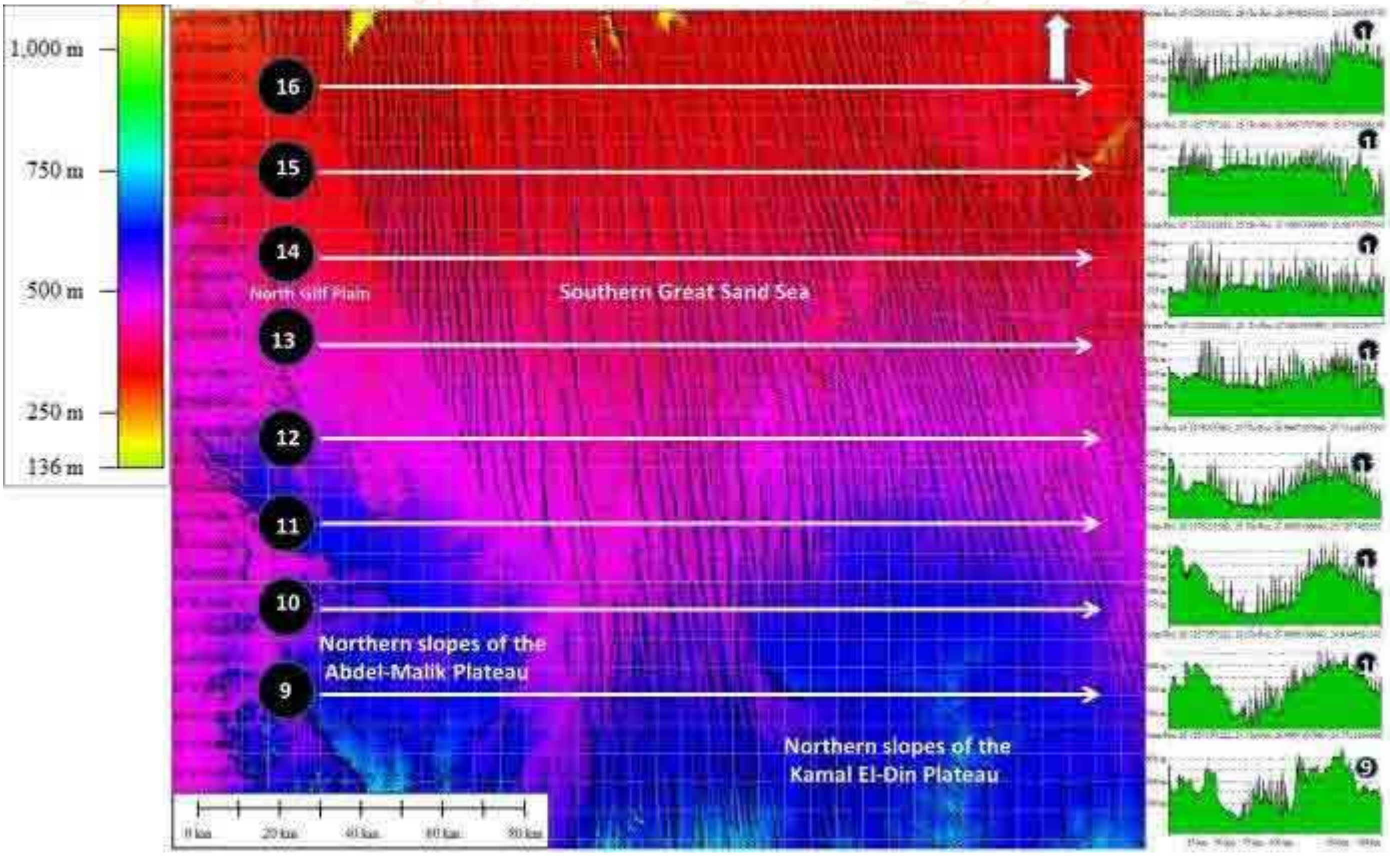


Fig.10- Cross sections showing via satellite SRTM image the topography of the transitional area from northern slopes of the Gilf El Kebir Plateau at south to the southern Great Sand Sea at north

Historically, the sediments of the Nubia Sandstone sequence in the low-lying area between the Gilf El Kebir and Siwa (the Great Sand Sea) were subjected to a low-strain close to surface immediately following the regional uplifting movement in the Western Desert during the Late Cretaceous (Late Turonian- Santonian), and which resulted in the formation of gentle open folding made up of N-NW/S-SE longitudinal series of parallel up-folded ridges separated by troughs. This uplifting movement which belongs to the Alpine orogeny has led to the formation of a series of major domes and anticlines in the Nubia Sandstone sequence in several places of the Western Desert including the Gilf el Kebir uplift (WWD Province) at south, the Bahariya arch (EWD Province), the Qattara uplift and the Sidi-Barrani-Matruh coastal area (NWD Province) at north. The folding movement was contemporaneously followed by intense fracturing and cracking, followed by a long period of erosion by groundwater sapping process and overland flows of old river systems leading to the partial disintegration and breakdown of the sandstone ridges. The sandstone ridges extend for a long distance ranging between 80 and 240 km and are uniformly separated by parallel tracks or corridors of varied width ranging between 500 m and 2500 m (Figs. 11A-D, 12A-E). The difference in ground elevation between the top of ridges and the floor of tracks are varying between 30 m and 70m, but averaging between 40 and 50 m. The sandstone ridges are highly jointed, and intensively attacked by groundwater sapping process. They become twisted and corrupted near the Egyptian/Libyan as a result of invasion of old (Pleistocene) river systems.

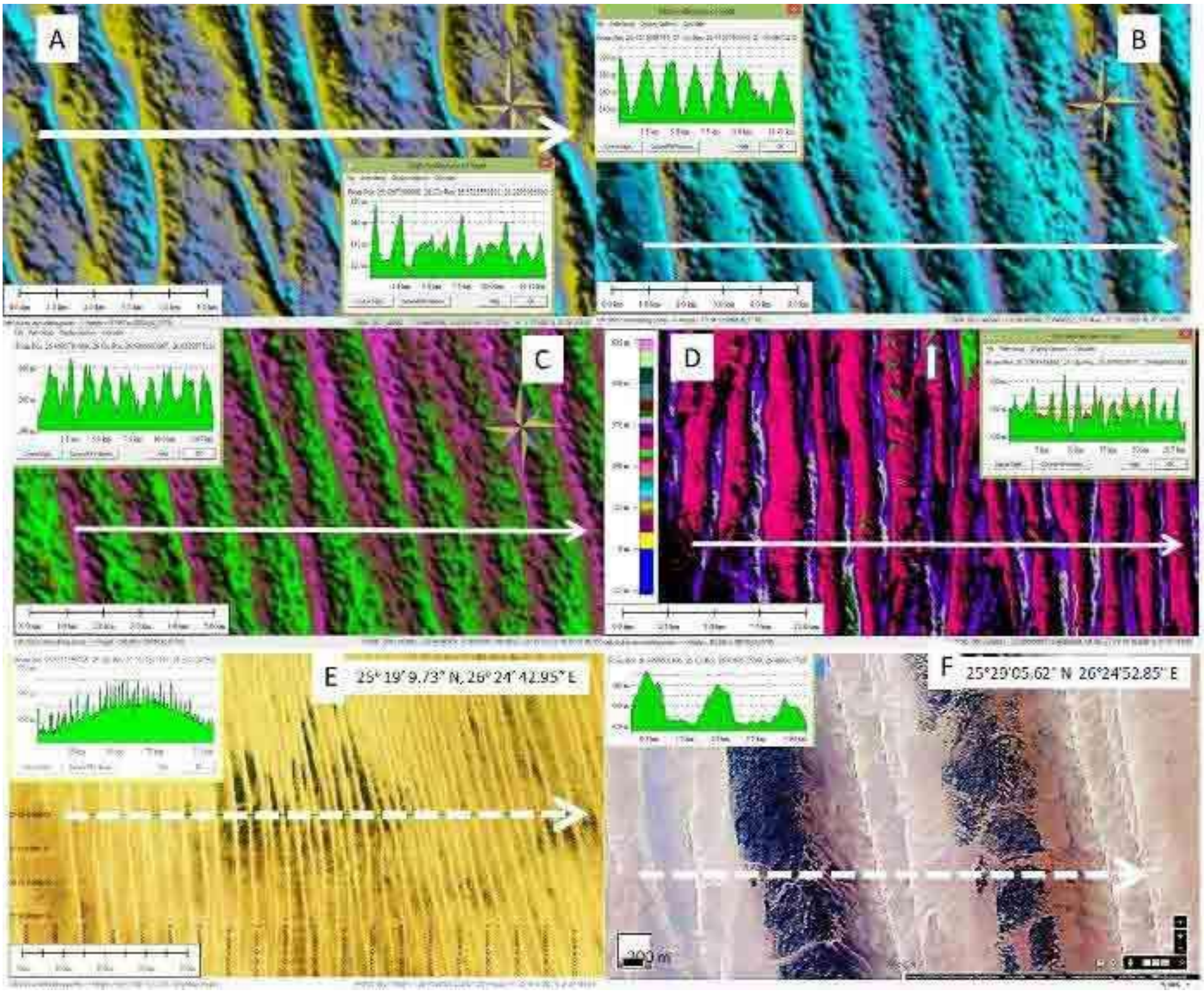


Fig. 11. A-D: Satellite images based on SRTM data showing cross sections of parallel series of up-folded longitudinal Nubia Sandstone ridges oriented N-NW/S-SE direction in northernmost (A), northern (B and C) and western (D) Great Sand Sea. See Legend in D. E: A Bing Map image showing cross section along the same ridges in the southern Great Sand Sea. F: A Google Map image (enlarged view of Fig. 11E) showing that the troughs between the Nubia Sandstone ridges are intensively attacked by groundwater sapping process and overland flows coming from south northward.

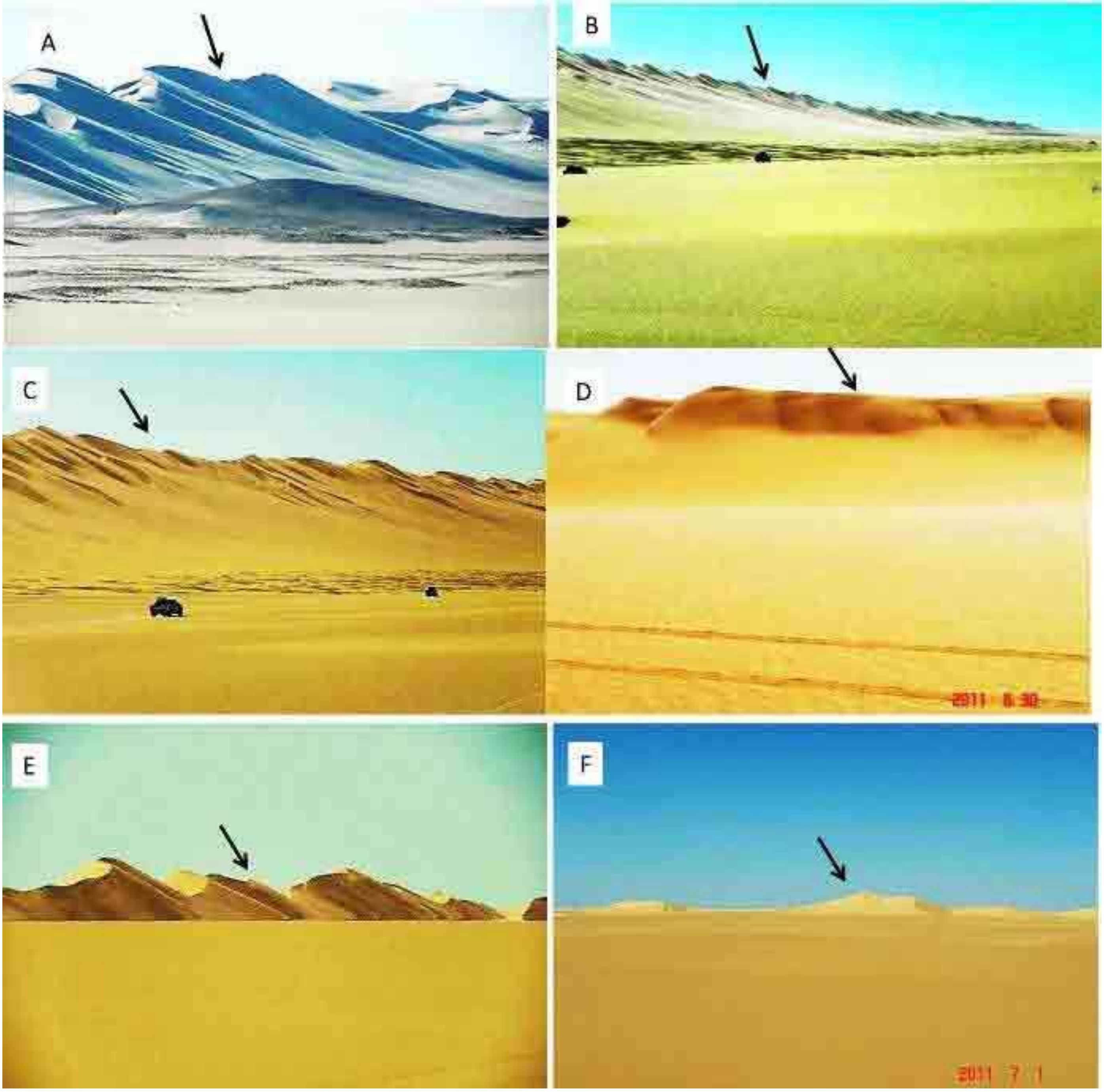


Fig.12. A - E: Photographs showing longitudinal cross- bedded sandstone ridges of Sabaya Formation (black arrows) extending N-NW/S-SE in the middle part of the Great Sand Sea (between latitudes 27º and 28º). F: -Interrupted Sabaya Sandstone ridges in the northern part of the Great Sand Sea (North of Lat. 28°). The ridges are well-bedded, short in length, narrow in width and less highly elevated compared to those southwards, and showing the phenomenon of groundwater sapping process which plays the main erosional agent of the bed rock in this area. Note the wide wet tracks between the sandstone ridges due to groundwater seepage Note also in Fig. C cars are running easy over the compact and flat depression due to saturation of the underlying Sabaya bedrock by groundwater.

The studies of Ouda et al. (2011, 2012) and Ouda (2021) on the bedrock of different landforms in the Great Sand Sea including sandstone ridges, tracks between ridges, plateaus, domes, mesas, buttes, depressions, troughs and plains between latitudes 26º 30′ to 28º 30′ N and longitudes 25º 30′ to 27º E have shown that all bedrock of these new landforms belongs to the Sabaya Formation of Barthel and Boettcher (1978). The Nubia Sandstone ridges and intervening low-lying tracks are not overlain by younger consolidated deposits, but only covered by a thin veneer of free, brownish to yellowish sands originating from the disintegration and breakdown of the underlying Nubia Sandstone bedrock. The sand veneer attains a thickness of 3-5 cm, sometimes reaching up 10-15 cm, thus obscuring the original sandstone bedrock, but do not hinder the movement of cars over it (Fig. 13A-B). The Sabaya bedrock below the drifted sands is hard, white, highly porous quartz sandstone composed of rounded and translucent quartz grains which are well to moderately sorted, coarse to medium grained, partly kaolinitic and entirely barren of fauna (Fig. 13C-D).

Fig. 13. A-B: Photographs showing Sabaya Sandstone lying directly below a thin veneer (3-5 cm thick) of loose brown sand grains formed as a result of disintegration and breakdown of the underlying Sabaya Sandstone bedrock. C-D: Sandstone ridges of White quartz sandstone belonging to Sabaya Formation which made up of white to translucent quartz sandstone, with rounded quartz grains well to moderately sorted, coarse to medium grained, partly kaolinitic and entirely barren of fauna.

In the area between latitudes 26º N and 28º N the sandstone ridges have subjected to intense uplifting and faulting during the Oligocene leading to the development of two parallel sandstone mountain ranges; each one is made up of broad flat-topped plateau or dome (up to 180 m thick and 60 km long) and wide flat depressions (63 km² to 1616 km² in area) running northeast-southwest in parallel lines which are oblique (~45º) to the long axes of the pre-existing sandstone ridges (Ouda et al. 2012; Ouda, 2021). The depressions and plateaus are exclusively made up of Nubia Sandstone and show well-marked evidence that they are all structurally controlled, thus being different from the previously known depressions in the western Desert (Figs. 14-16).

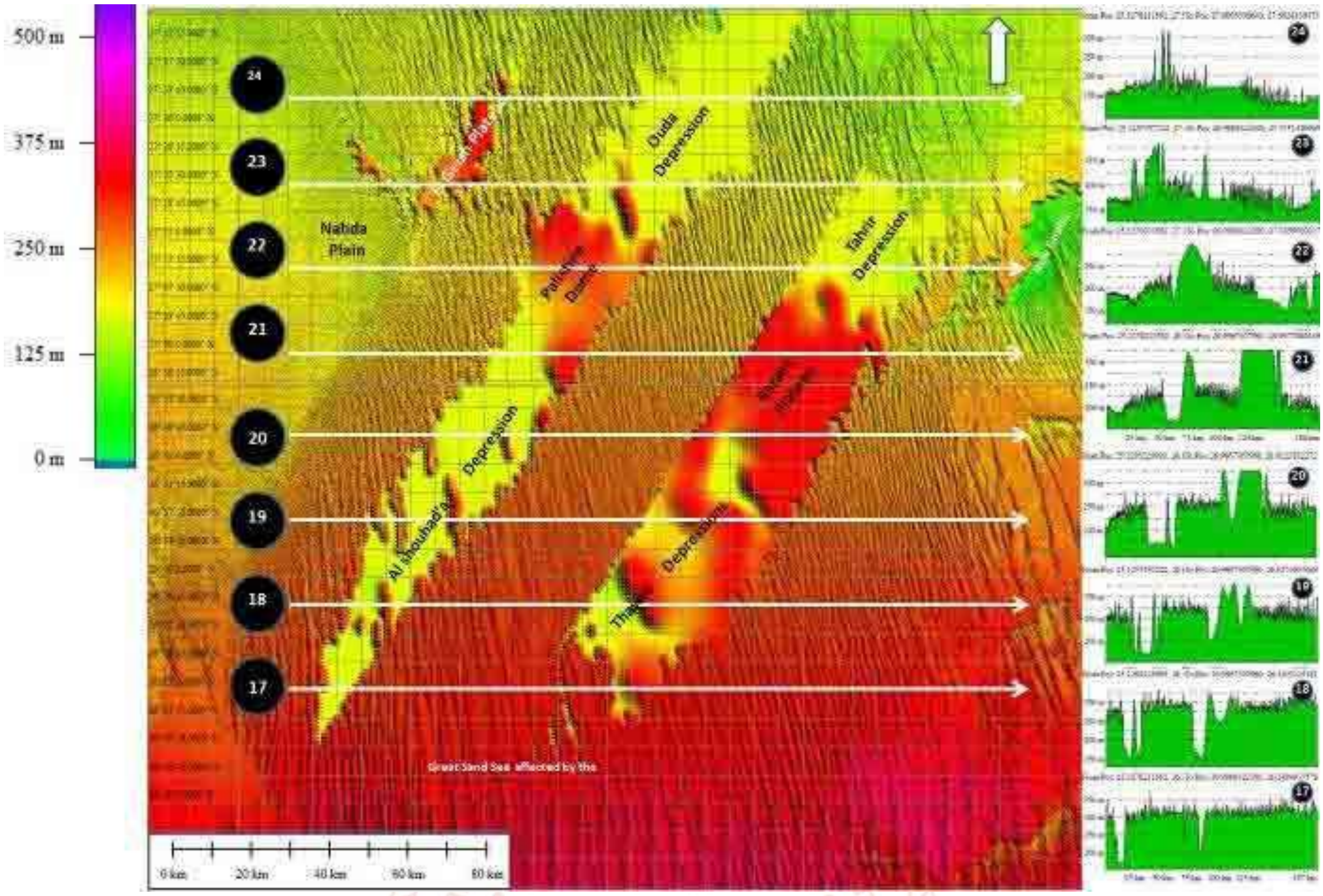


Fig. 14: Cross sections showing via satellite SRTM image the topography of the central area of the Great Sand Sea between latitudes 26º N and 28º N. Note that the sandstone ridges were subjected to intense uplifting and faulting during the Oligocene leading to the development of two parallel sandstone mountain ranges; each one is made up of broad flat-topped plateau or dome (up to 180 m thick and 60 km long) and wide flat depressions (63 km² to 1616 km² in area) running northeast-southwest in parallel lines which are oblique (~45⁰) to the long axes of the pre-existing sandstone ridges. All depressions and plateaus being exclusively made up of Nubia Sandstone and show well-marked evidence that they are all structurally controlled.

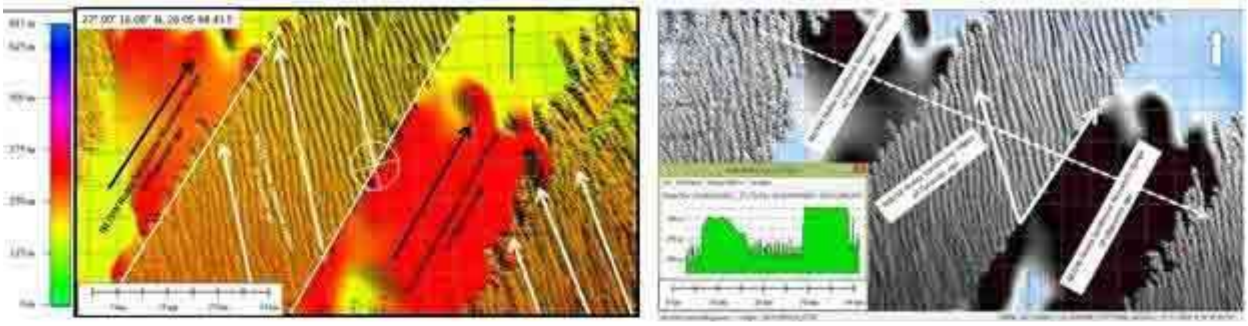


Fig. 15: Enlarged Satellite images based on SRTM data showing that the fault-block mountain ranges were formed as a result of intersection of two major fault systems, one is running north-northwest parallel to the long axes of the pre-existing sandstone ridges while the other is oriented northeast parallel 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).

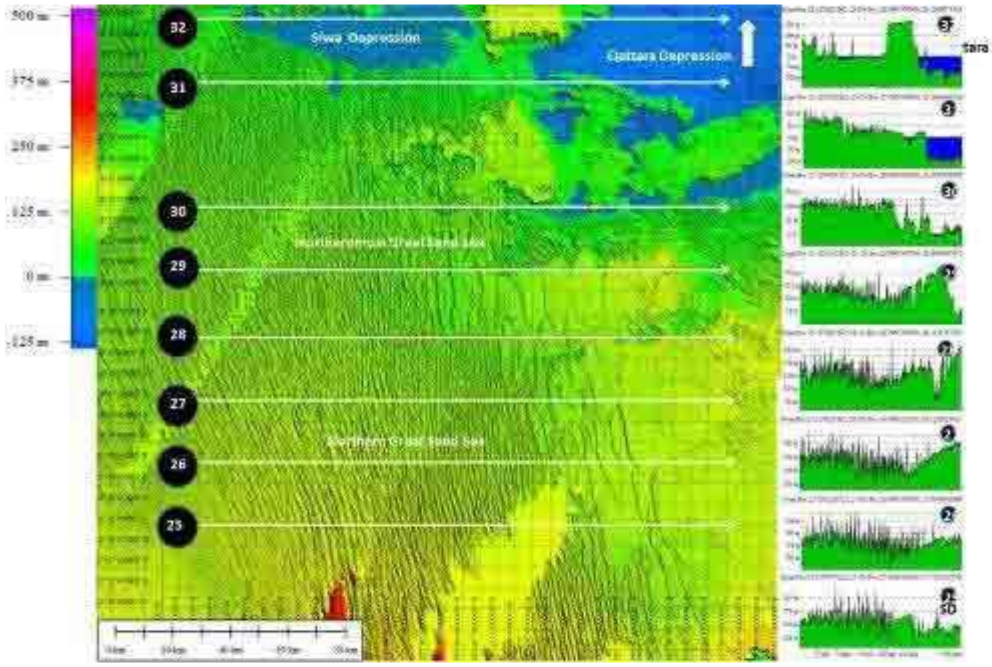


Fig. 16: Cross sections showing via SRTM data the topography of the northern area of the Great Sand Sea up to the southern limits of Siwa-Qattara depressions.

The fault-block mountain ranges are formed as a result of intersection of two major fault systems, one is running north-northwest parallel to the long axes of the sandstone ridges while the other is oriented northeast parallel to the long axes of the depressions and plateaus (Fig.15). 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) (Fig.17).

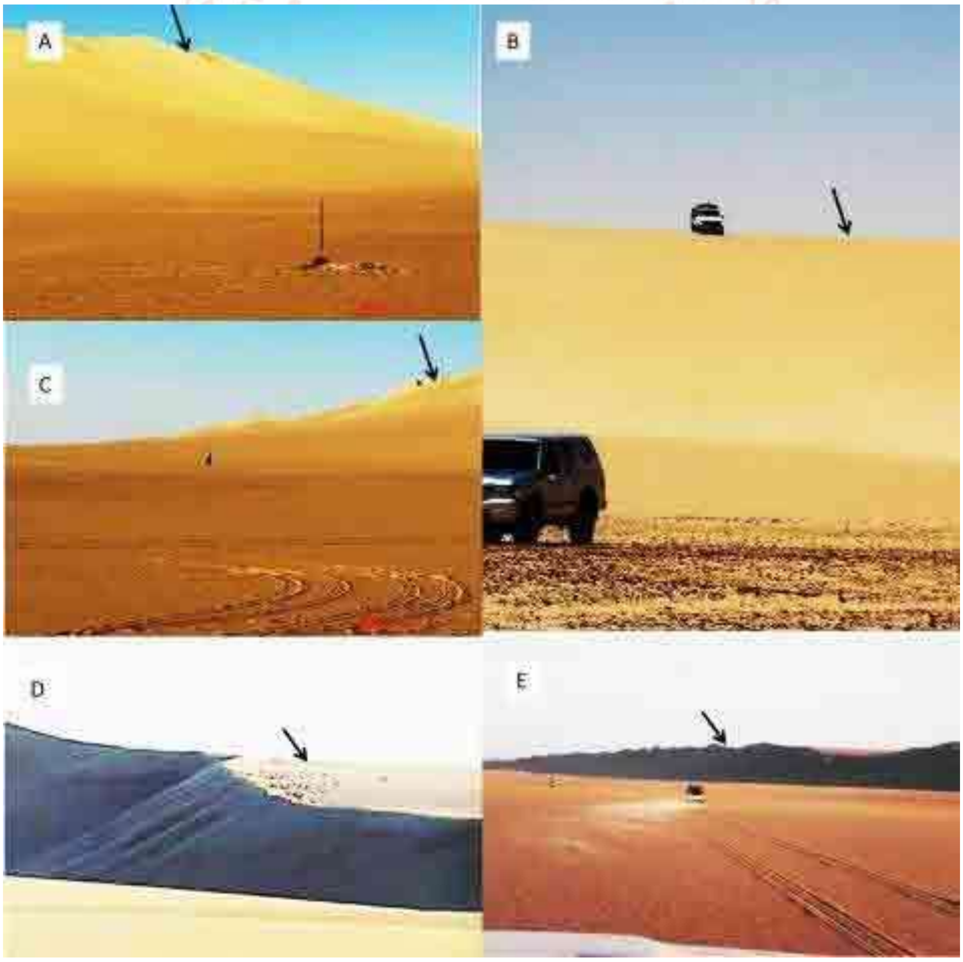


Fig. 17. A-E: Photographs showing the flat-topped plateau (black arrow) made up of Sabaya Sandstone rising 180 m above floor and running northeast-southwest for 60 km in the Great Sand Sea. Note in B and D that cars (black arrows) running easy over the top surface of the plateau and the

flat depression to the north of the sandstone plateau due to saturation of the underlying Sabaya bedrock by groundwater. Note the thin veneer of brown loose sands which obscure the underlying Sabaya bedrock

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.14). It is topographically made up of a major plateau in the middle part of the range (namely by Ouda et al., 2012 as Baraka Plateau), uprising against a major depression at the northeast (namely by the same authors as Al-Tahrir Depression), and three small depressions at the southwest (namely as 25 January Depressions). The total area of Baraka Plateau is 1020 km² and has an elevation varying between 310m and 330m (with most area lying around 325m above sea level. The plateau 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 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. The ground elevation of this depression varies from 150 m to 175 m with most values lying around 173m above sea level.

The bedrock of all these new landforms is white unfossiliferous highly permeable fluviatile quartz sandstone belonging to the Lower Cretaceous Sabaya Formation. The top and limbs of the sandstone plateaus as well as the flat depressions between have all a compact and hard surface due to saturation of the bedrock with groundwater, thus making car travel easy and fast (Fig. 17B). The southern scarp of the Baraka plateau suffered a tectonic deformation and subsequent erosion by combined wind action and groundwater sapping process leading to the formation of four broad flat-topped (mesas-like) cliffs (namely here as 25 January Cliffs) with a total surface area of 387 km² that are separating four small depressions and troughs in between (namely by Ouda et al., 2012 as 25 January Depressions and Troughs) with a total surface area of 410 km².

The second parallel mountain range 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 (Figs. 14-15). It occupies an area of about 4550 km² and is topographically composed of a strongly eroded domelike cliff (Palestine Dome, Ouda et al., 2012) uprising in the central part of the range against two major long depressions, a northeastern one (namely as Ouda Depression by Ouda et al., 2012) and a southwestern depression (namely by the same authors as El Shohad'a Depression). The eroded central cliff 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 this range extends northeast the central plateau for 70 km long, with an average width of 23 km (maximum width 27 km), and assuming a total area of 1616.5 km². 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 a total area of 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 toward the north/northwest, coincident with the general longitudinal trend of the sandstone ridges which are surrounding the depression. The floor of depressions also shows evidence of groundwater sapping process as indicated by the discontinuous appearance of intermittent channels of clean and eroded quartz sandstone bed rock running near the foot of the steeper walls of the cliffs and hills.

The lower limit of the Sabaya Formation is not exposed and therefore its total thickness below the surface is not definitely known. Unfortunately no wells have been drilled in the Great Sand Sea except of Ammonite -1 at the eastern rim (~80 km west of Abu Minqar) and Foram-1 at the northwestern rim (10 km west of the Libyan borders). In the Ammonite 1 the Mesozoic sequence of the Nubia Group (Six Hills, Abu Ballas, Sabaya, Maghrabi and Taref Formations) attains ~1170 m, overlying unconformably the Precambrian Basement complex and underlying 170 m thick of marine Campanian-Masstrichtian sediments. In Foram-1 the Mesozoic sequence (both Six Hills and Sabaya Formations) attains ~1200 m covering unconformably ~2300 m thick of Paleozoic sediments (Shrank, 1984)

The Taref Formation is almost entirely eroded leaving remnants and elongated yardangs (up to 6 meters high) of bedded, highly jointed sandstone formed by differential erosion and wind abrasion in the flat depressions near the steep walls of the plateaus (Figs.18A-D). The Taref outcrops attain a maximum height of 6 meters and are made up of a thin (0.3-0.4 m thick) basal brown bed of clayey sandstone containing poorly sorted quartz grains mingled with brown rock debris of gravel size, and an upper thick-bedded white yellowish to greyish quartz sandstone made up of rounded, coarse to medium translucent quartz grains with erratic silica debris.

Northward of Latitude 28^{o} and west of Long, 27^{o} the Nubia Sandstone ridges decrease in length to 23-35 km until becoming very short and intensively interrupted south of Siwa-Oasis (Figs.11A and 16). The width of the tracks increases generally in this area due to connection or branching of the sandstone ridges meanwhile the ridges are becoming shorter. The Nubia Sandstone bedrock of the floor of the tracks between sandstone ridges is composed of quartz sandstone, brown in color due to disseminated iron oxides, but the quartz grains are still well sorted and having rounded edges. The area shows evidence of attack by the northeastern distributaries of the old river delta of Wadi Balatah in northeastern Libya, thus leading to the destruction or distortion of the Sandstone ridges and the development of wide intertwined or branched plains. The surface floor in some tracks between ridges becomes wet during winter seasons so that plants become more common and almost situated in parallel arrangement around the exposed bed rock, thus suggestive of near-surface groundwater seepage (Figs.18E-F).

Fig. 18: A-D- Photographs showing small yardangs of bedded, highly jointed sandstone up to ~6 meters height belonging to Taref Formation are sporadically exposed over the Sabaya bedrock in the flat depressions near the steep walls of the plateaus. These outcrops are made up of a thin (0.3-0.4 m thick) basal brown bed of clayey sandstone containing poorly sorted quartz grains mingled with brown rock debris of gravel size, and an upper thick-bedded white yellowish to greyish quartz sandstone made up of rounded, coarse to medium quartz grains with erratic silica debris. E: Desert plants become much more dense and structurally controlled, being almost arranged in rows along the sides of the tracks at the northernmost limit of the Great Sand Sea. F: Wedges and thin sheets of the Middle Miocene Marmarica Formation overlying unconformably the Nubia Sandstone bedrock (Sabaya Formation) in the northernmost part of the Great Sand Sea to the north of Lat. 28^{o} 30.

Further northward of Lat. 28º 30′, The desert plants become much more dense and structurally controlled, being almost arranged in rows along the sides of the tracks. The floor of the tracks become well exposed, fully made up of eroded and washed Nubia Sandstone which in turn becomes discontinuously covered by wedges and thin sheets of hard grey shiny unfossiliferous limestone (Fig.18F) belonging to the lower part of the Middle Miocene

Marmarica Formation of Said (1962). The limestone sheets show a progressive increase in both thickness and areal distribution northward towards Siwa where they change into fossiliferous limestone rich in echinoides belonging to the middle part of Marmarica Formation at the vicinity of Siwa Oasis.

4. Patterns of Drainage

4.1. Groundwater Sapping Process

The present investigation points out to the fact that the groundwater sapping process produces major landscape features with unique characteristics in the western Desert of Egypt. The process is the main erosion agent in the Gilf El Kebir Plateau, the Dakhla Basin and the Great Sand Sea where it causes disintegration and breakdown of the Nubia Sandstone ridges and erosion of the sandstone from the slopes, causing the slopes to be undermined and undergo mass wasting (Figs. 19-21). It is also the predominant mechanism of the growth of the theater-headed valleys (Fig.22), and the flat-topped surfaces of the upraised plateaus and domes as well as, the exploitation of joints and fractures in the Nubia Sandstone bedrock due to laterally flowing of ground water, so that the drainage pattern of the valleys reflects that of the regional jointing pattern of the Nubia Sandstone (Fig. 23). In addition it is responsible of formation of alcoves in headwalls, spring sites and seepage zones in many valley flanks (Figs. 24-28). Moreover, vast areas of the Nubia Sandstone bedrock of the flat-topped plateaus, flat tracks and depressions are found to be eroded, well exposed, clean, and covered by silica debris as a result of intense erosion by the groundwater seepage.

In the Great Sand Sea both the tectonic movements and the groundwater sapping process were responsible of the formation of long tracks and wide depressions with steep walls, flat floors, "theater-shaped" headwalls, and short stubby tributaries Fig.20). In addition vast areas of the Nubia Sandstone bedrock of the flat-topped plateaus, flat tracks and depressions are found to be eroded, well exposed, clean, and covered by silica debris as a result of intense erosion by the groundwater seepage. Emergence of groundwater from the soil along an extensive line of surface is also found on a large scale in the wide tracks between the sandstone ridges in the northernmost part of the Great Sand Sea tracks, south of Siwa Oasis.

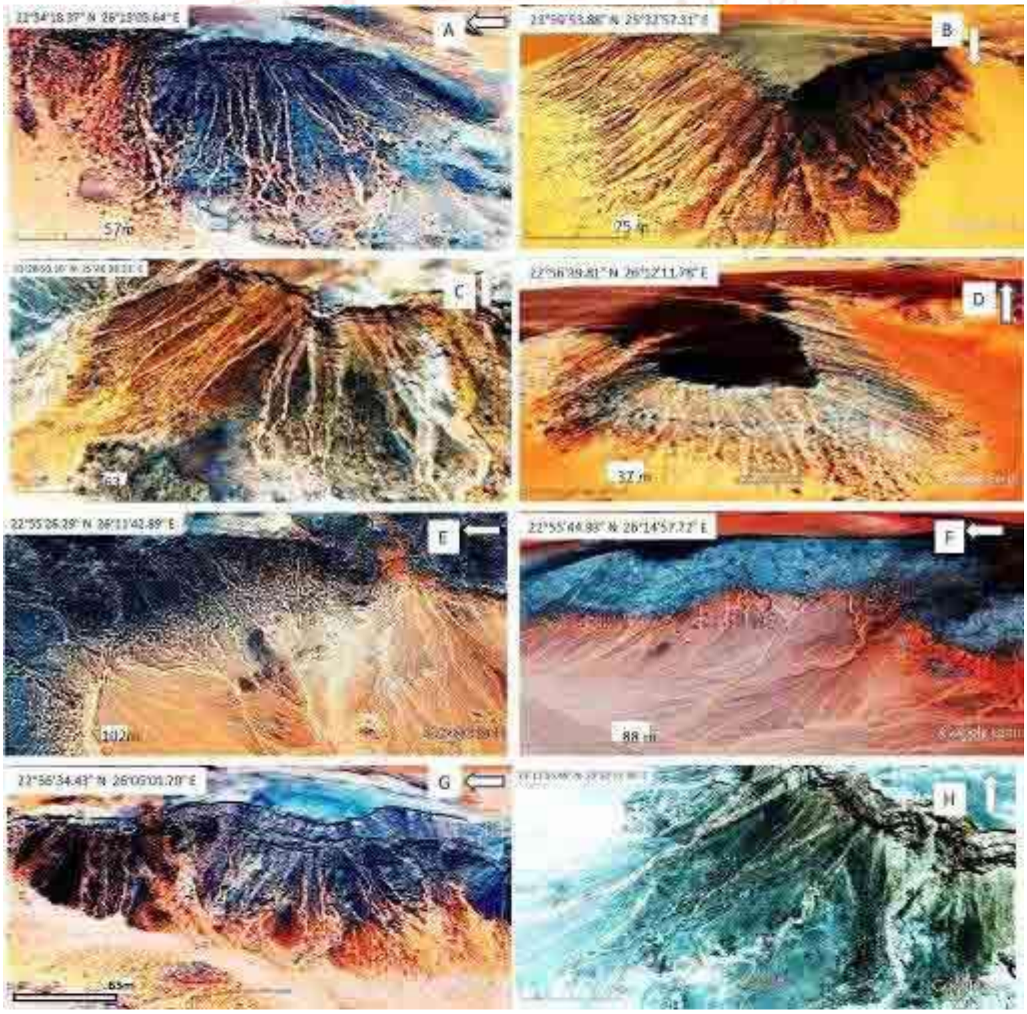


Fig. 19. A-H: Google Earth images of Nubia Sandstone scarps in the Gilf El Kebir Plateau showing headwater streams made up of first to third order, more or less parallel tributaries emerged from seepage zone made up of horizontal headwall alcoves. A, D, E and F from southeastern Kamal El-Din

Plateau. B from north of Wadi Hamra, Abdel-Malik Plateau. C from western Kamal El-Din Plateau. G and H from southwestern Kamal El Din Plateau.

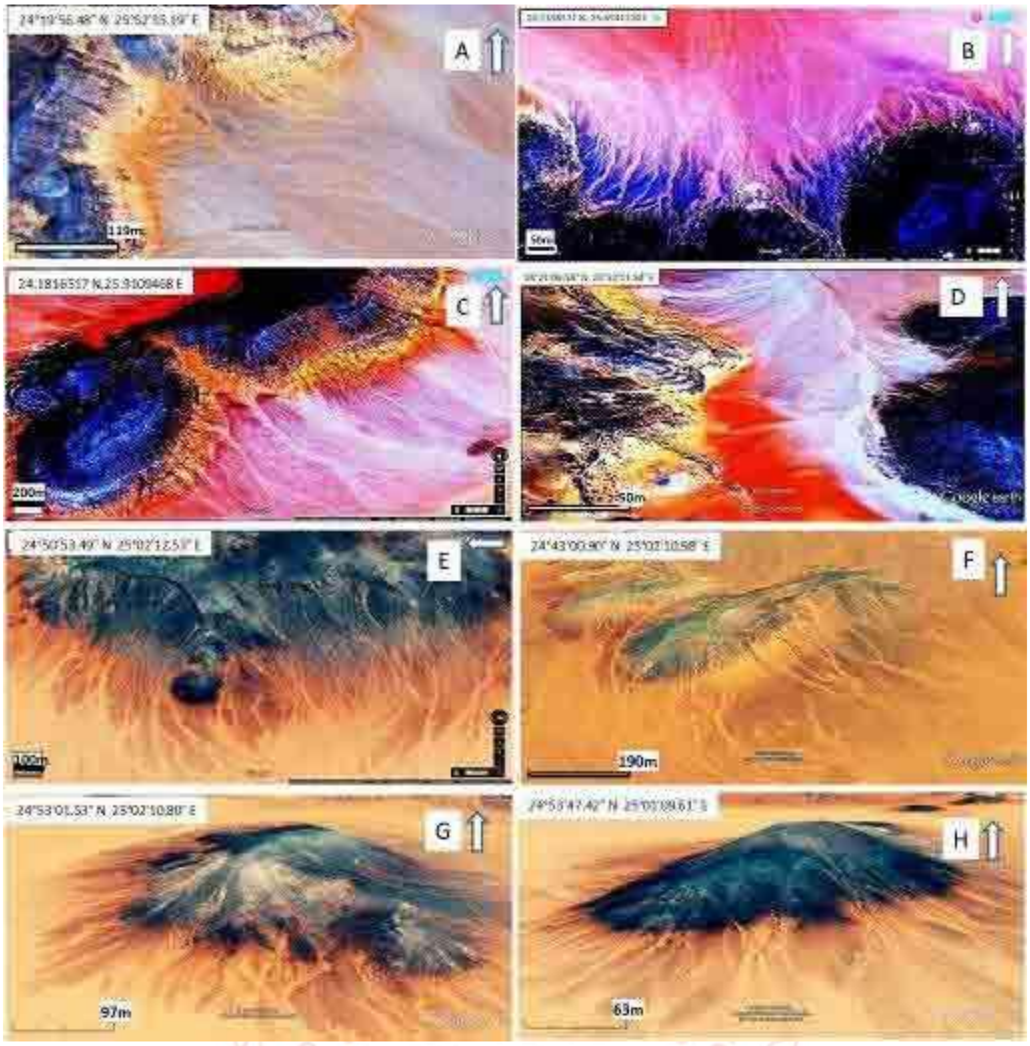


Fig. 20. A-H: Google Earth images of Nubia Sandstone scarps in the Great Sand Sea showing headwater streams made up of first to third order, more or less parallel tributaries emerged from seepage zone made up of horizontal headwall alcoves. A, B, G and H: from southwestern Great Sand Sea. C and D: from southern Great Sand Sea. E and F: from northwestern slopes of Abdel-Malik Plateau, adjacent to the Libyan/Egyptian borders.

Both field and remote sensing (SRTM data) studies support that the groundwater sapping process played the major role in the erosion, disintegration and breakdown of the sandstone bedrock of the Gilf El Kebir Plateau (Figs. 19 and 21) and the Great Sand Sea (Fig. 20), thus, producing vast amounts of loose, well sorted sand grains covering the bedrock of the hill-slopes along the entire length of the longitudinal sandstone ridges and consequently obscuring its consolidated identity. This is not surprising if we know that the bedrock of all topographic features in the Great Sand Sea is composed of highly porous, well permeable sandstone rock units saturated with groundwater i.e. the Sabaya Formation which is widely known as the most productive aquifer of the Nubia Sandstone sequence in the Western Desert. The sapped drainage system in this area differs in morphology, pattern and rate of erosion from their fluvial counterparts in the western portion of the Great Sand Sea near the Libyan borders.

The bedrock of all these new landforms is white unfossiliferous highly permeable fluviatile quartz sandstone belonging to the Lower Cretaceous Sabaya Formation. All these landforms have latter been attacked by the groundwater sapping which acted for a long time as an erosional process leading to headward erosion of the scarps of plateaus and ridges, wideness of the sides of the troughs through the formation of amphitheater-like valley heads along the slopes of the ridges and plateaus, flatness of the top surface of plateaus and surface floor of troughs and disintegration of the bed rock at the slopes (Fig. 22). The top and limbs of the sandstone plateaus as well as the flat depressions between have all a compact and hard surface due to saturation of the bedrock with groundwater, thus making car travel easy and fast.

The action of the groundwater sapping process creates a particular drainage pattern which is markedly different from that produced by runoff. This pattern is considered to be the most widespread in the in the Gilf El Kebir Plateau and the Great Sand Sea. It is made up of an intermittent channels without known distributaries resulted from the flowing of groundwater and its emerging from the porous sloping sides of the sandstone ridges or the scarp faces of the sandstone plateaus at the free slope surface of the tracks or depressions (Figs,19-20). This process produced channels that migrate headward into the structurally controlled plateaus or ridges with steep sides, flat floor and amphitheater-like heads that lack well-developed tributaries (Fig.23). This contrasts with the dendritic pattern of V-shaped valleys in the area lying north of Abdel-Malik Plateau near the Libyan borders (see later) where drainage patterns produced mainly by overland flows that become wider with distance from their source.

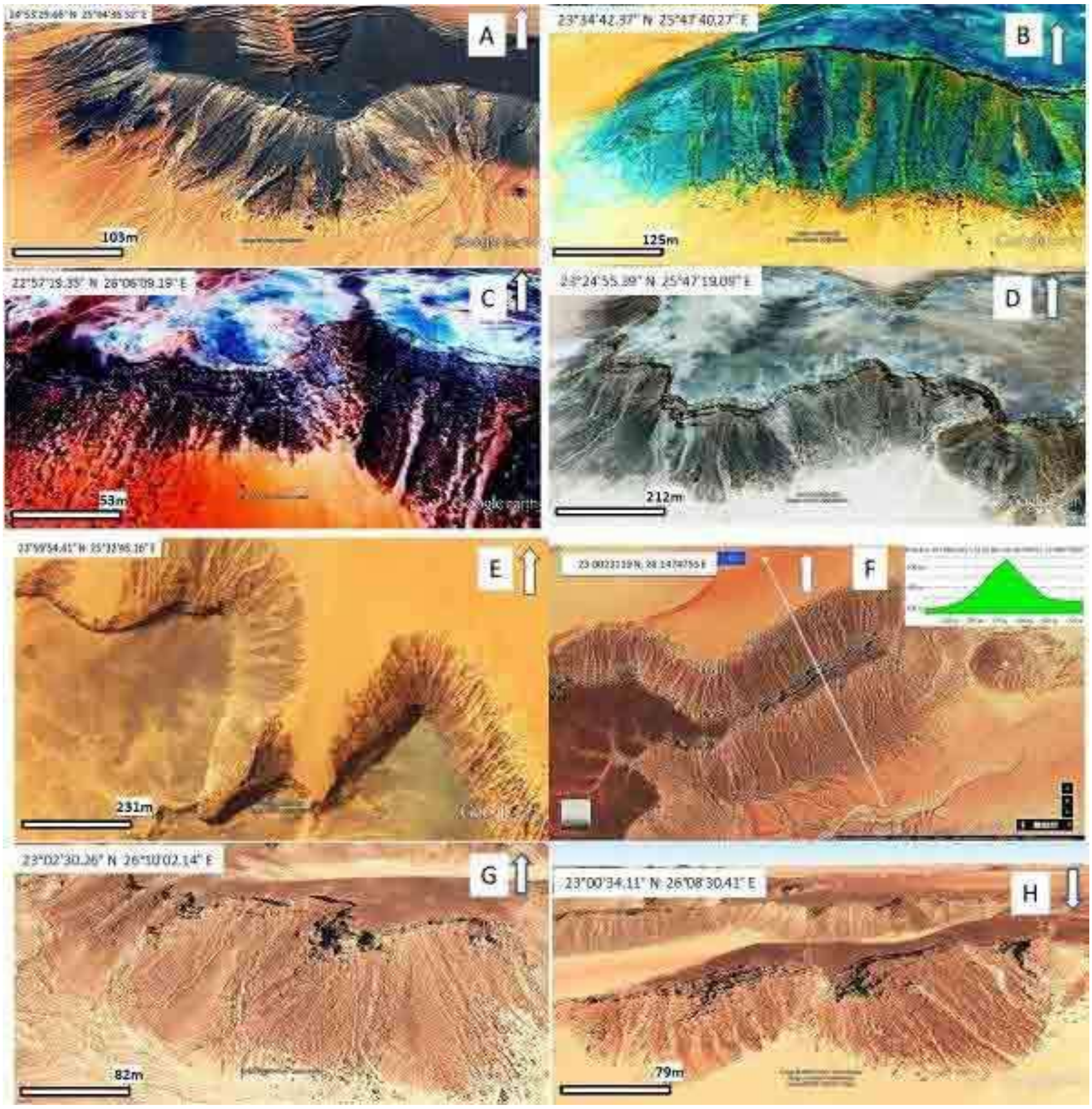


Fig.21. A-H: Google Earth and Google Map images showing broad belt of rills, gullies and ephemeral streams along the slopes of the Nubia Sandstone scarps formed by combined overland flows and groundwater sapping emerged from alcoves at the valley headward. A: from the southwestern Great Sand Sea. B-D: from the Kamal el-Din plateau. E-F: Broadly and densely rilled slopes of the Sabaya scarps at the northern slopes of Wadi Abdel-Malik Plateau. G-H: Nubia Sandstone scarps with steep valley wall showing headwall streams made up short tributaries of first-three order emerged from a seepage zone made up of horizontal headwall alcoves in the southern Kamal El-Din Plateau. The rilled slopes are attacked by short first order tributaries flowing from alcoves at the headward downward into the valley.

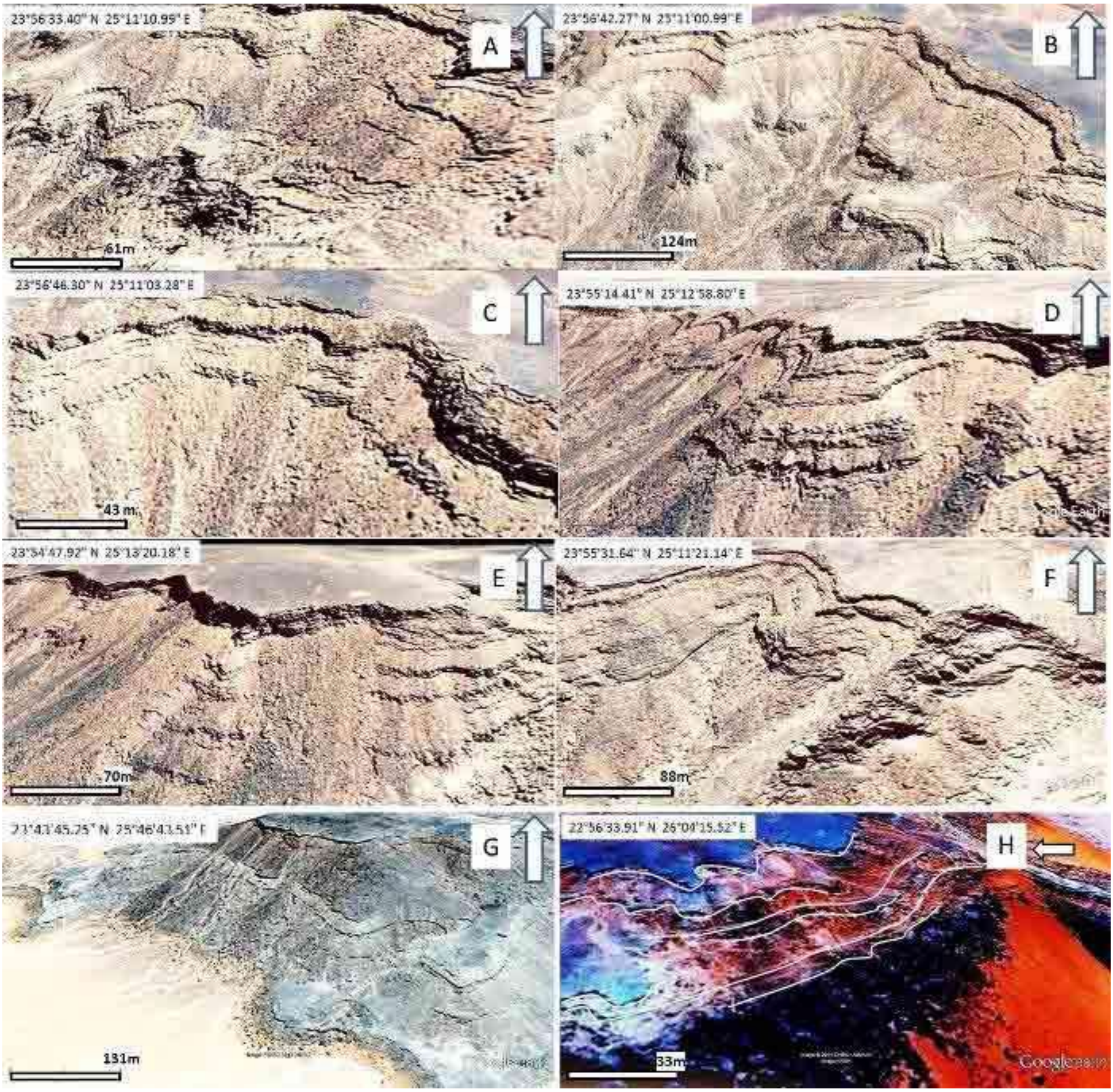
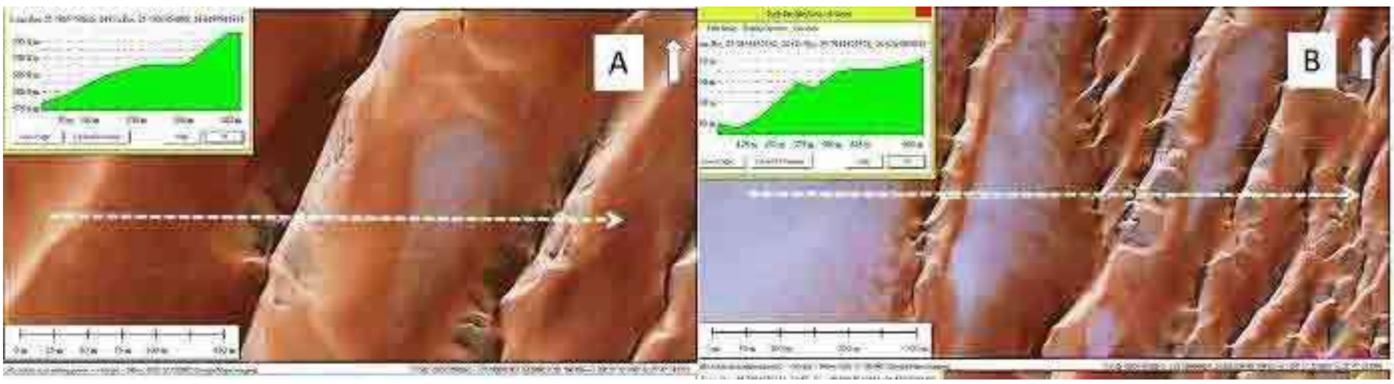


Fig.22. A-H: Google Earth images showing the predominant mechanism of the growth of the theater-headed valleys as one of the major landscape features of the groundwater sapping process. The process causes disintegration and breakdown of the Nubia Sandstone ridges and erosion of the sandstone from the slopes, causing the slopes to be undermined and undergo mass wasting. The continuous emerging of the groundwater at seeps gradually removes materials from the headwall and slopes, thus leading to the undermining of the overlying sediments which will cause retreat of the scarp face (canyon head). A-F: from the northern slopes of Abdel-Malik Plateau. G-H: from Kamal El-Din Plateau.



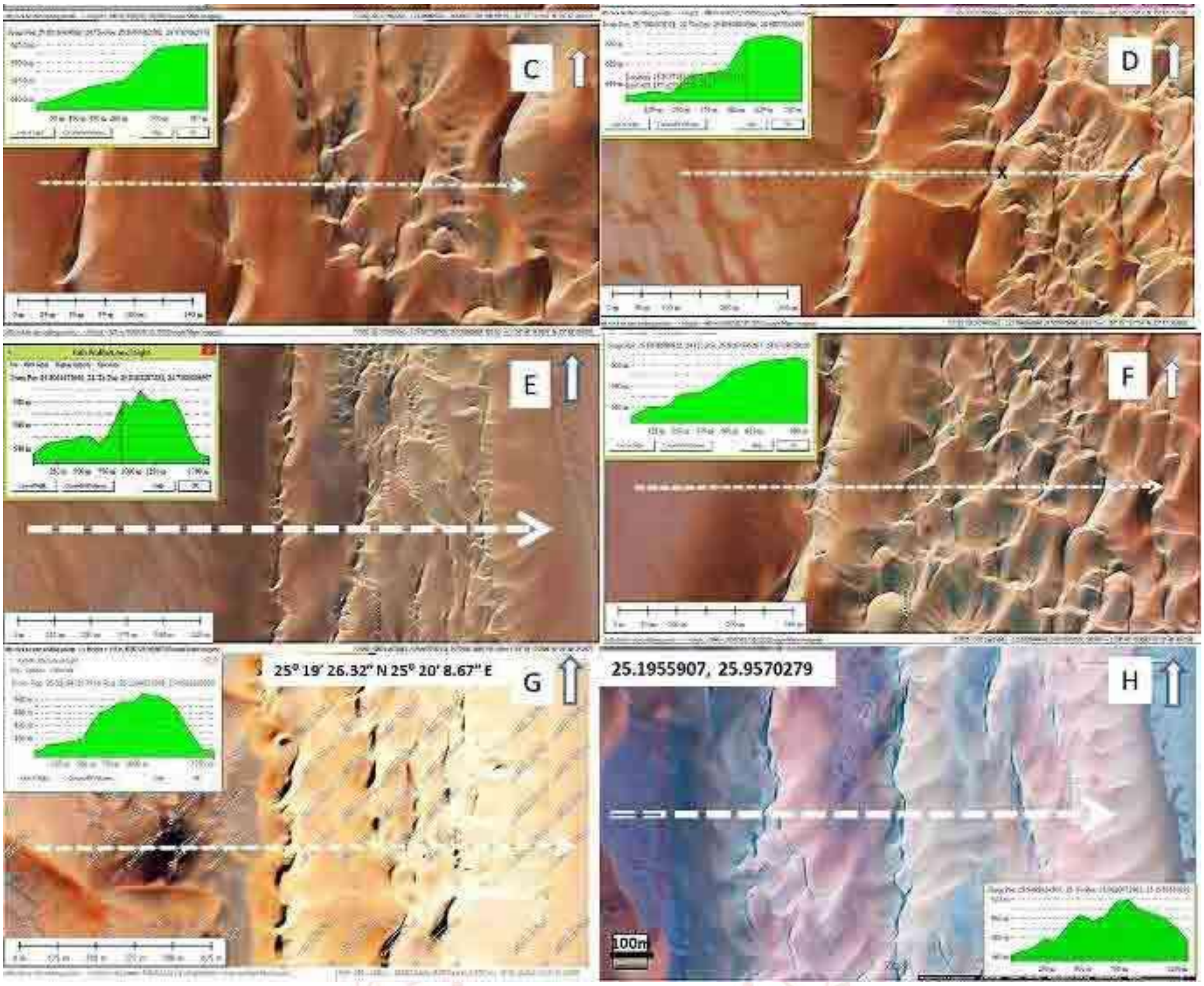


Fig. 23. A-H: SRTM Satellite images from Google Map imagery (A-F) DigitalGlobe World-Wide high resolution imagery (G) and Google Earth Pro image (H) showing cross sections across theater-headed valleys exhibited by the Nubia Sandstone ridges which are eroded by the groundwater sapping process in the southern Great Sand Sea. Note in Figs. E,G and H that the ridges have sharp steep slopes on one side and theater-like heads with flat floor on the other side. Note also in B-F that the Nubia Sandstone ridges exhibit well preserved current three- dimensional ripple marks of linguoid shape that resulted from weathering and disintegration of the ridges by groundwater sapping process along fractures and joints. Note also the frequency of alcoves along the bedding planes in Fig. G.

Because the Nubia Sandstone bedrock is highly jointed (structurally controlled) the drainage pattern is characterized by branching of channels at nearly right angles (Figs.23A-F). This type of drainage pattern is called rectangular pattern or U shaped-pattern (Easterbrook, 1999).and usually forms in jointed horizontal sedimentary beds with well-developed jointing or intersecting faults. In case of absence of known distributaries, this type of drainage pattern on highly jointed porous sandstone bedrock could be used as indicator of groundwater sapping.

The drainage lines are running north-northwestward, coincident with the general trend of the sandstone ridges and the general slope of the ground towards the Mediterranean. In the tracks between sandstone ridges the draining lines are almost confined to the steeper walls of the "theater-shaped" valleys forming discontinuous channels on the sloping floor of tracks, with a width varying from 250m to 1000m

4.1.1. Alcoves, Arches and Tunnels

A series of groundwater sapping alcoves or eyes (25-200m width) are recorded along the theater-shaped heads of each sandstone ridge (Figs.24-28), so that the total number of these groundwater landforms may reach enormous number in the Great Sand Sea. The alcoves are formed as result of concentrated seepage along bedding planes, joints and faults. For the appearance of these alcoves in a sedimentary layered rock, it is required that the sedimentary layer be porous and permeable and lie on an impermeable layer.

Alcoves formed by groundwater sapping process in the western Desert of Egypt are common in both sandstone and limestone layered rocks. According to Luo et al. (1997) the scallop-shaped escarpment edges and stubby-looking channels that cut into the limestone plateau units which surround the Kharga, Farafra and Kurkur in southeastern Western Desert are suggestive of slumping of limestones by ground-water sapping at the limestone-shale interfaces. The wide alcoves which gave rise to scallop-shaped escarpment edge are here recorded by the writer using satellite images in the northern scarps of Abu Tartur and Dakhla Oasis beside the eastern scarps of kharga and Farafra Oasis (Figs. 25G-H). In these regions. the partial removal of the less resistant material of the underlying shale (Dakhla Shale in Dakhla or Esna shale in Kharga and Farafra Oases) by groundwater sapping led to the creation of an overhanging ledge with protected wide alcoves above the impermeable contact between the shale and limestone.

Fig. 24. A-C: Satellite Google Earth images showing alcoves along bedding planes of the longitudinal ridges of Sabaya Formation. A: The alcoves may be developed separately in small openings along the contact between ridges and the ground surface in the Dakhla Basin. B: The alcoves could be developed along successive bedding planes in horizontally-bedded Nubia Sandstone, some of which became connected together along the bedding planes to form tunnel or natural arches particularly in the Dakhla Basin. C: The alcoves form at the head and on the side walls of canyons in many other sandstone scarps north of the Abdel-Malik Plateau. Note in Fig. C that exfoliation may play a major role in the development of natural sandstone arches

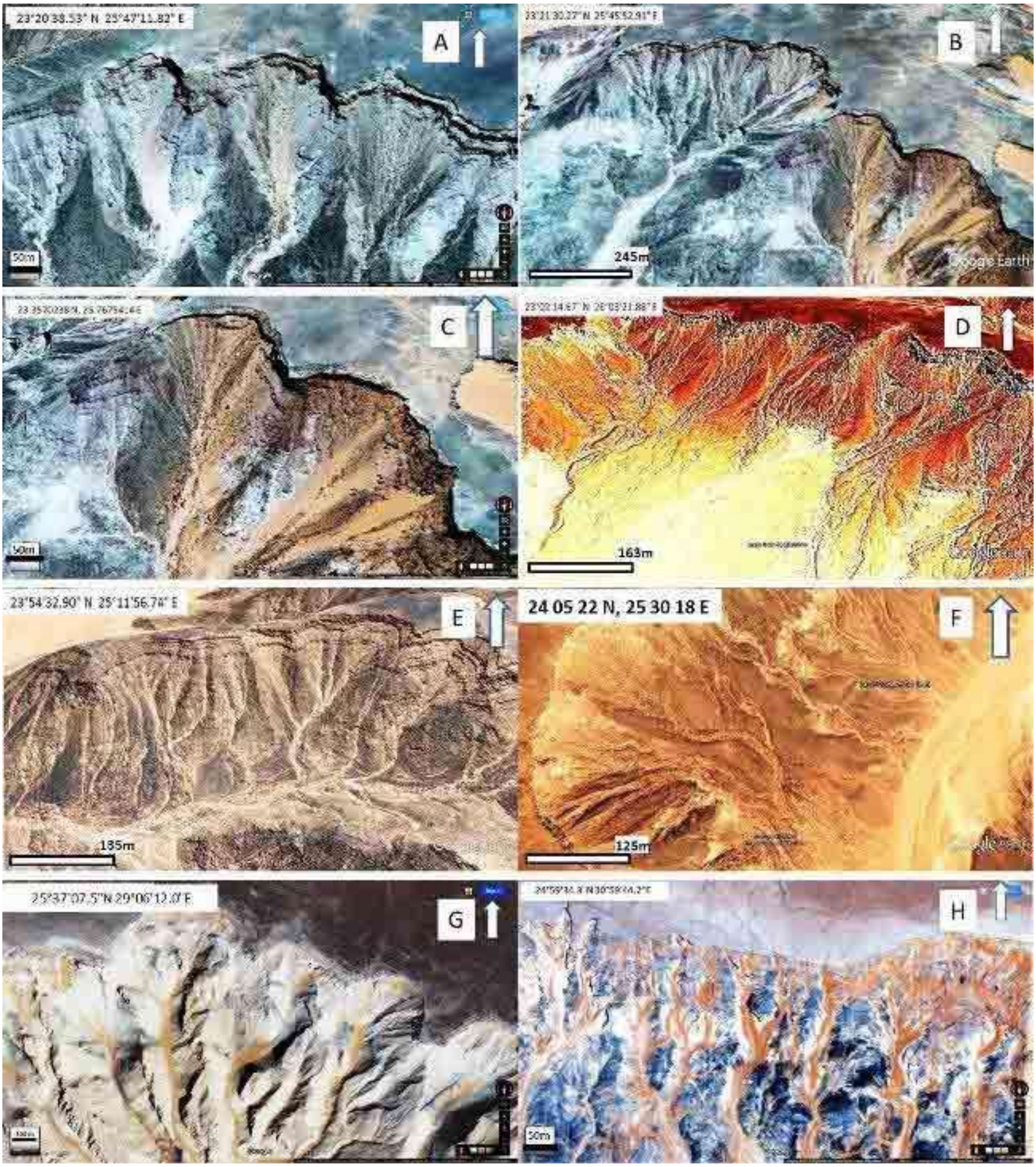
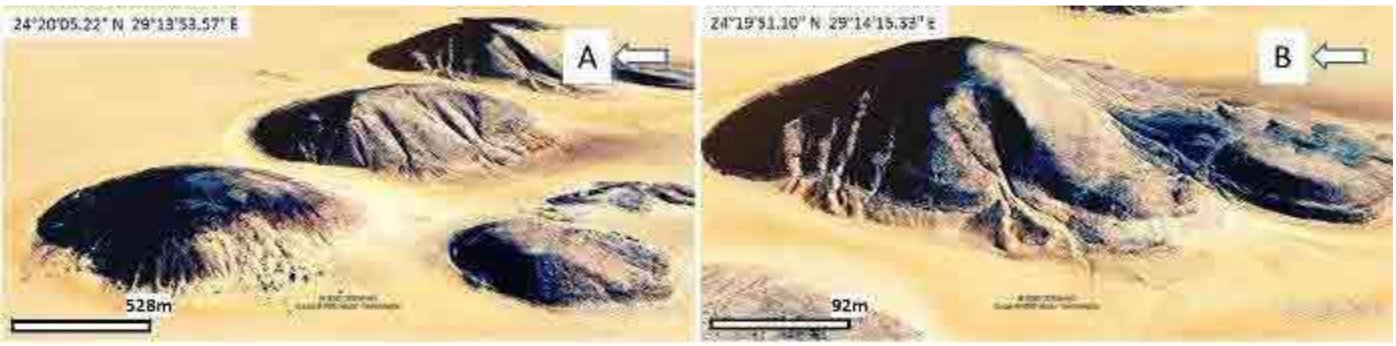


Fig. 25. A-H: Satellite SRTM images from Google Map imagery (A, C, G and H) and Google Earth images (B, D, E and F) showing wide alcoves and scallop-shaped escarpment edges that are commonly distributed in the Nubia Sandstone sequences which include silty or clayey horizons underlying the highly permeable massive sandstone beds along the western (A-C) and southern (D) scarps of Kamal El Din Plateau, northern scarps of Abdel-Malik Plateau (E-F), northern scarp of Dakhla Oasis (G) and eastern scarp of Kharga Oasis (H).



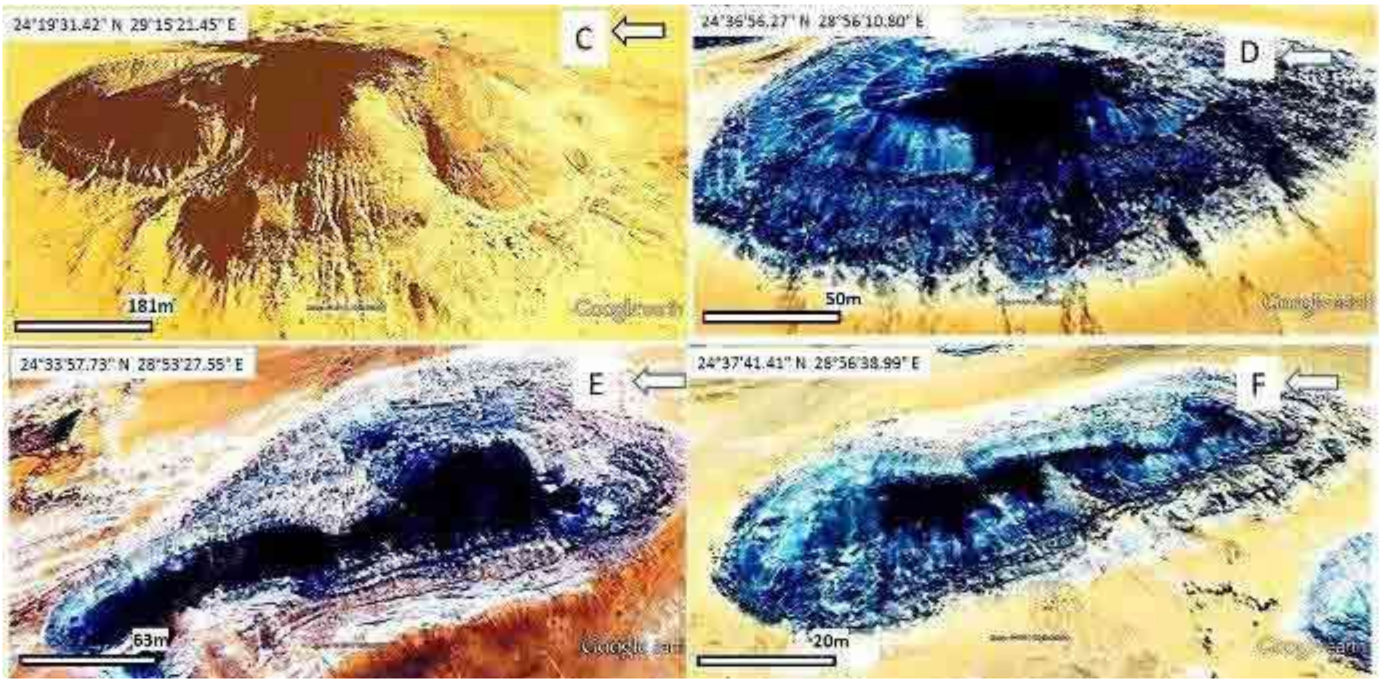


Fig. 26. A-F: Satellite Google Earth images showing Natural arches and tunnels through the horizontal (A-D) or gentely dipping (E-F) beds of the Nubia Sandstone cliffs (A-C: Six Hills Formation and D-F: Sabaya Formation) in the Dakhla Basin, southern Western Desert. The arches and tunnels were formed in these formations due to mass collapse of slabs of the highly permeable massive sandstone beds as a result of groundwater sapping that promotes weathering along bedding planes and which have enough cohesion for an arch to develop. The length of the arches ranges between 80m and 200m and thus considered to be the broadest known arches in the sandstone beds. Note in D-F that the arches in Sabaya Formation have a classic elongate arch shape and all appear to be formed when the massive sandstone undermined mainly by seepage of groundwater (blue color) and associated salt weathering processes (white color).

This type of wide alcoves and scallop-shaped escarpment edges is also commonly distributed in the Nubia Sandstone sequences which include silty or clayey horizons underlying the highly permeable massive sandstone beds along the southern and northern scarps of the Gilf El Kebir Plateau (Figs.25A-F). The removal of the underlying weakened shale materials by groundwater sapping has led to the development of scallop-shaped cliff faces formed by thinning of the alcove roof near the slope face of the overlying permeable massive sandstone beds. In some localities the wide alcoves seem to be formed as a result of convergence of runoff streams and streams generated by groundwater seepage along the slope of the same scarp. In the Great Sand Sea, the wide alcoves are missing while the small individual alcoves are frequently occurring as eyes in sandstone outcrops. Sometimes the alcoves are connected together along the bedding planes to form tunnel or natural arches particularly in the northernmost part of the Great Sand Sea.

However, The natural arches or tunnel are well developed in the type sections of the Six Hills and Sabaya Formation south of the Dakhla-Kharga road (Fig. 26). In these type sections the groundwater exits along the weathered bedding planes which represent the most weakened parts of the sequence and the resultant alcoves may connect together along the bedding plane to form a wide tunnel or natural arches through the horizontal (Figs. 26A-D) or gently dipping beds (Figs. 26 E-F) of the Nubia Sandstone cliffs. The arches and tunnels were formed due to mass collapse of slabs of the highly permeable massive sandstone beds as a result of groundwater seepage that promotes weathering along bedding planes and which have enough cohesion for an arch to develop. The length of the arches ranges between 80 m and 200 m and thus considered to be the broadest known arches in the sandstone beds (see Goudie, 2013). The arches have a classic elongate arch shape and all appear to be formed when the massive sandstone formation undermined mainly by seepage of groundwater and associated salt weathering processes.

In some longitudinal ridges made up of horizontally-bedded Nubia Sandstone the alcoves are often developed separately in small openings along the contact between ridges and the ground surface (Fig.24A). In many other sandstone scarps the alcoves form at the head and on the side walls of canyons (Figs.24B-C). These are formed by weakening cement by groundwater solution at the basal contact with an impermeable shale or siltstone layer.

Weathering of the sandstone at and along the seep area is induced due to concentrated moisture. According to Campbell (1973) the flowing groundwater exploits the major joints which act as conduits and subsequently emerged at seepage zone along the cliff face. However, the present writer noticed that most alcoves and hence their seepage areas are aligned horizontally along bedding planes in normally horizontal Nubia bedrock while the natural arches (wide arched seepage zone) show a preferable distribution in gently-curved Nubia Sandstone bedrock.

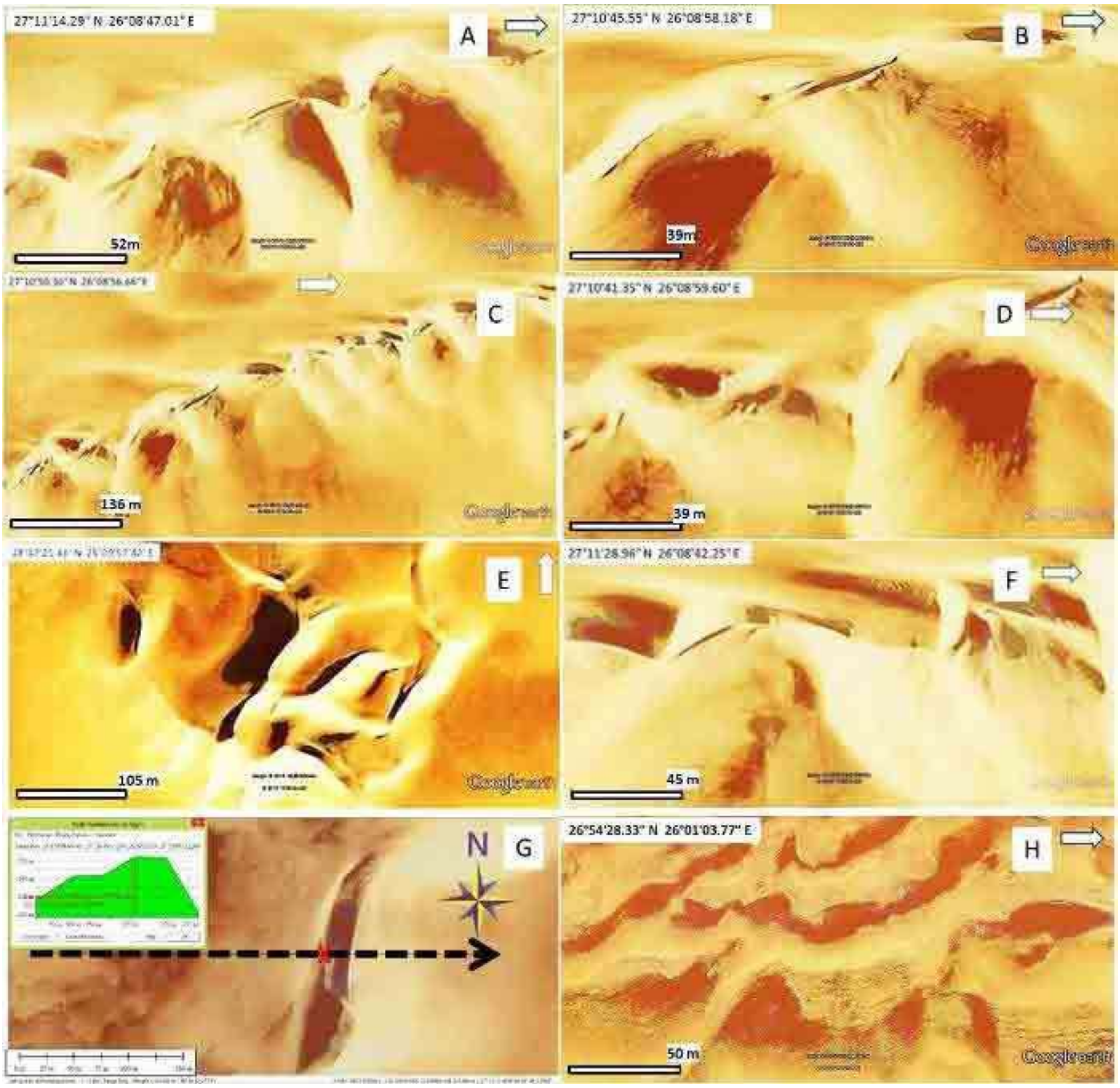


Fig. 27. A-H: Satellite Google Earth images (A-f and H) and Satellite SRTM image (G) showing alcoves in the headwall of longitudinal sandstone ridges in the Great Sand Sea. A-F: Individual alcoves which are frequently occurring as eyes with a cross section across the bedding plane (G). Sometimes the alcoves are connected together along the bedding planes to form tunnel or natural arches (H), particularly in the northernmost part of the Great Sand Sea.

The drainage pattern developed by the groundwater seepage is totally different from those formed by fluvial overland flows. According to Morisawa (1964) and Parker (1977) the fluvial network rapidly evolves into a branched network that fill a drainage basin and undergoes slow changes thereafter. However, in the Western Desert the network developed by sapping is generally stubby and made up of short, first- order tributaries (headwall tributaries) which flow slowly in parallelism from the seepage zone downward the theatre-headed valley where they go into second and may be third –order tributaries before going to the mainstream at the plain floor of a narrow canyon (Figs.19-20). As recognized in the Navajo Sandstone (Latiy and Malin, 1985), the canyon network in the western part of the Western Desert lack the randomly branching space-filling dendritic pattern common to fluvial stream system.

The emerging of the groundwater at seeps gradually removes materials from the headwall and slopes, thus leading to the undermining of the overlying sediments. The undermining of the overlying sediments of the sandstone cliff will cause retreat of the scarp face (canyon head). The resultant week sandstone debris shatter readily upon impact then becoming easily affected by weathering process and ultimately accumulated at the foot of the cliff. Repeated seepage due to recharge accompanied by removal of talus accumulated at the base of the slope will lead to successive retreat of the canyon head and sidewalls hence the development of an amphitheater-headed valley before eventual collapse (Figs.22-23). The groundwater sapping process is facilitated by exfoliation joints that develop parallel to the canyon sidewalls and headwalls (Fig.24C). The widening of valleys by the successive collapse of massive slabs, developed by exfoliation jointing and undermining by seepage has been discussed by Bradley (1963), Robinson (1970) and Laity and Malin (1985).

The seepage is ephemeral as deduced from different summer and winter field trips and from high resolution satellite images produced during the last 10 years for the same localities (Fig. 29). In the Gilf El Kebir area there is good indication that the groundwater is re-charged during winter seasons as deduced from the annual progressive enlargement of alcoves and extension of the seepage zone associated by progressive retreat of the scarp face of the cliffs and increase of undermining of the sandstone beds overlying the seepage zones (Figs 29A-D- 29A'-D'). As recognized by Latiy and Malin (1985) in the Navajo Sandstone, the pervasive fracturing of the Six Hills and Sabaya Sandstone bed rock in the Gilf El Kebir and the Great Sand Sea greatly increases the over-all permeability of their bedrock surface. The joints and faults also act at depth of increase the transmissivity of the bedrock.

The author has observed during his visits to some sites in the Great Sand Sea during winter (March) that the sand accumulations on the floor of the low-lying areas west of Farafra and also on the flat floor of several tracks between the sandstone ridges in the northern part of the Great Sand Sea, are saturated by groundwater to the point that it could fill bags of water when squeezing sands (Figs. 30-31). While during the summer (June-July) the floor of the same sites were found dried out but reflecting a dark color and often desiccated with a networks of short drainage channels or contain inclusions of dispersed coarse- grained sands, gravels and iron rods (Fig. 32). Sometimes they show thin white layers of sodium carbonate indicating the high evaporation rate of the pre-existing leaked water during the summer.

It is, thus, clear that groundwater seeps in abundance in the Great Sand Sea during the winter season where the evaporation rates are low in such dry desert. This leads to increase the volume of groundwater which seeps through alcoves and exits frequently at and along the whole seep area leading to the retreat of the scarp face and thus undermining of the overlying sandstone which falls to the valley floor below. This would lead ultimately to increases the rate of the collapse of the walls of sandstone hills. Thus, it can be stated that the difference in volume of the water which seeps out from alcoves seem to be not only controlled by porosity and permeability of the wall rock of the hill, or quantity of water soaked into ground in the hill but also by the climatic regimes and rates of evaporation which are minimized in winter and maximized in summer.

Additional phenomenon which occurs frequently in the northern part of the Great Sand Sea is the vertical emergence of groundwater from the Nubia sandstone bedrock along extensive flat surfaces of wide tracks, depressions and plains (Fig. 32). This phenomenon is termed "groundwater seepage" (Wikipedia, the free encyclopedia) which differs from the term "groundwater sapping process" that the latter has a more précised definition (see above). The present day groundwater discharge and rates of retreat of cliffs in the Gilf El Kebir Plateau and the sandstone ridges in the Great Sand Sea may be less than during Pleistocene water periods. Surface flows during former periods of wetter climate (Pleistocene) seem to be more prevalent as deduced from the common detection of complex drainage patterns of high tributaries grades on the top surface of the Gilf El Kebir plateau (see later).

The retreat of the scarp face causes undermining of the overlying sandstone which falls into the alcove or to the valley floor below. The scarp retreat proceeds as the weaker underlying sandstone beds are eroded, undermining the more resistant caprock and leading to cliff development, rock falls and back wasting of the scarp. Loose debris tends to be removed from the slopes as fast as it is produced by weathering, so that little or no loose residuum covers the bedrock surface. Schmidt (1989) estimated the rates of the scarp retreat varied between 0.5 to 6.7 km per million years. He believed that these rates were sufficient for scarp retreat, operating simultaneously and independently at different levels to remove great proportions of sedimentary cover of the

Colorado Plateau during the Cenozoic. Similar rates (0.4 m and 0.7 m ky) were obtained by Matmon et al., 2005) along the margins of the Dead Sea by means of cosmogenic dating of rockfalls in Cambrian sandstones.

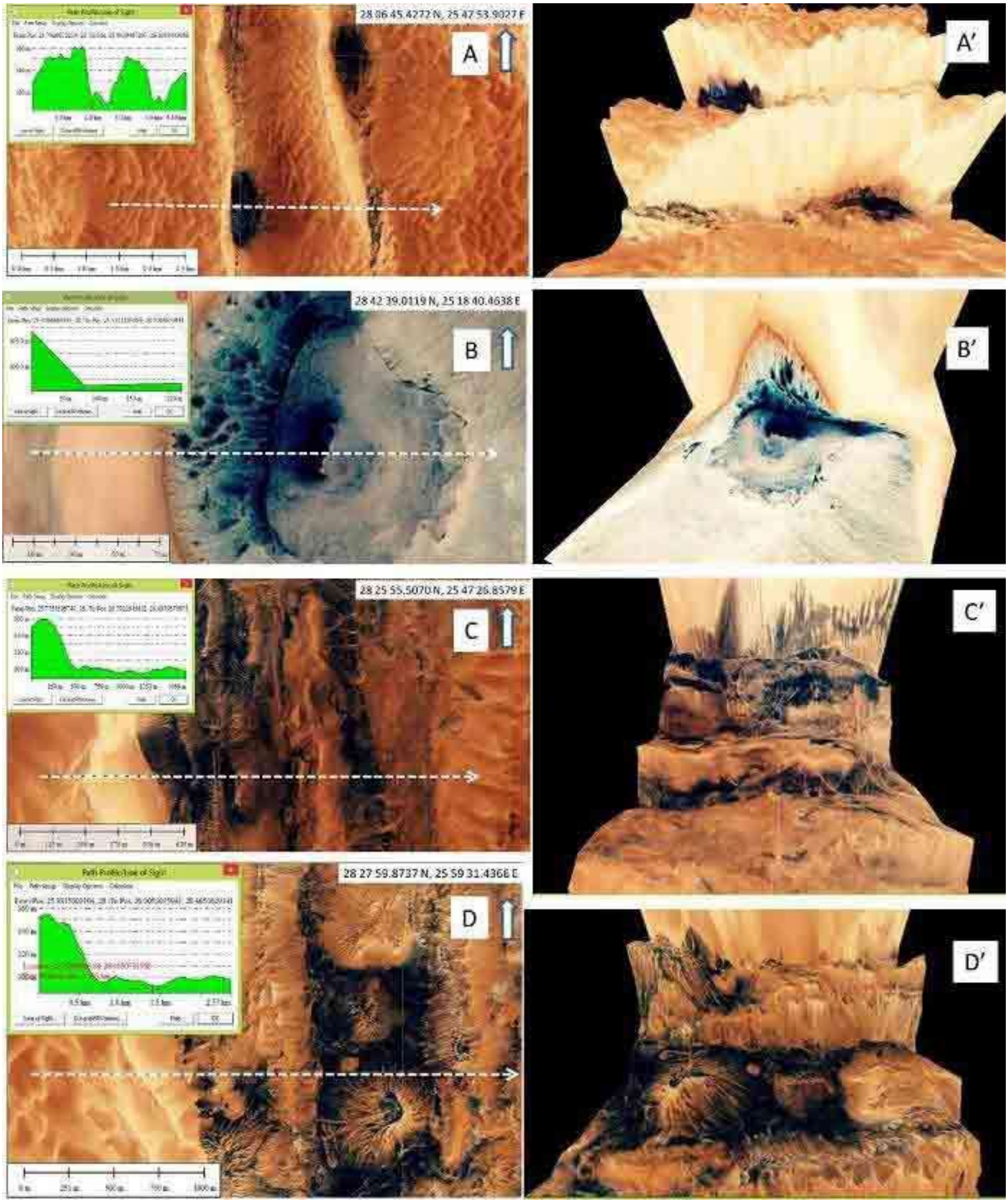


Fig. 28. A-D: SRTM Satellite images from Bing Map imagery showing cross sections along alcoves which are occurring in the northernmost Great Sand Sea, south of Siwa Oasis along bedding planes or at the base of the Nubia Sandstone ridges. A-A': small individual alcoves (eyes) intercalated along bedding planes of the ridges. B-B': a large circular alcove along the contact between the sandstone ridge and the ground surface. C-C' and D-D" connected alcoves forming tunnels along the successive bedding planes.

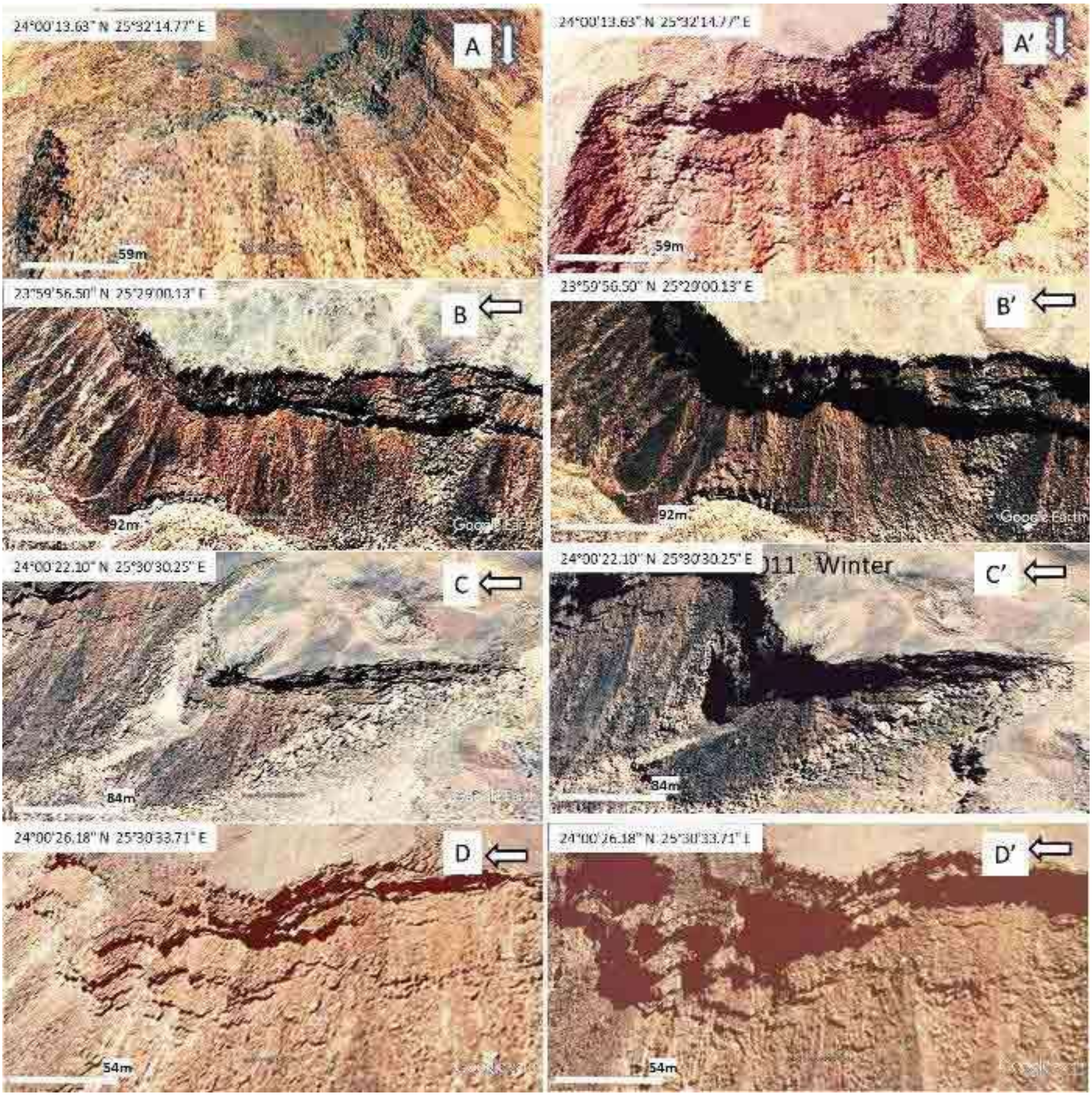


Fig. 29. A-D: Satellite Google Earth images in both summer (left column A-D) and winter (right column A'-D'). showing the difference in volume of the groundwater which seeps out from alcoves along the bedding planes of the Nubia Sandstone scarps of the northern Abdel-Malik Plateau to the north of Wadi Hamra., The difference in volume of the water which seeps out from alcoves seem to be not only controlled by porosity and permeability of the wall rock of the hill, but also by the climatic regimes and rates of evaporation which are minimized in winter and maximized in summer. During Summer (June-July, figs. A-D) there is minor short horizontal alcoves which are developed headward below the scarp edge. During winter (November, figs. A'-D') the groundwater exits frequently at and along the whole horizontal seep area at the headwalls of the same Nubia Sandstone scarps leading to the retreat of the scarp face and thus undermining of the overlying sandstone which falls to the valley floor below.

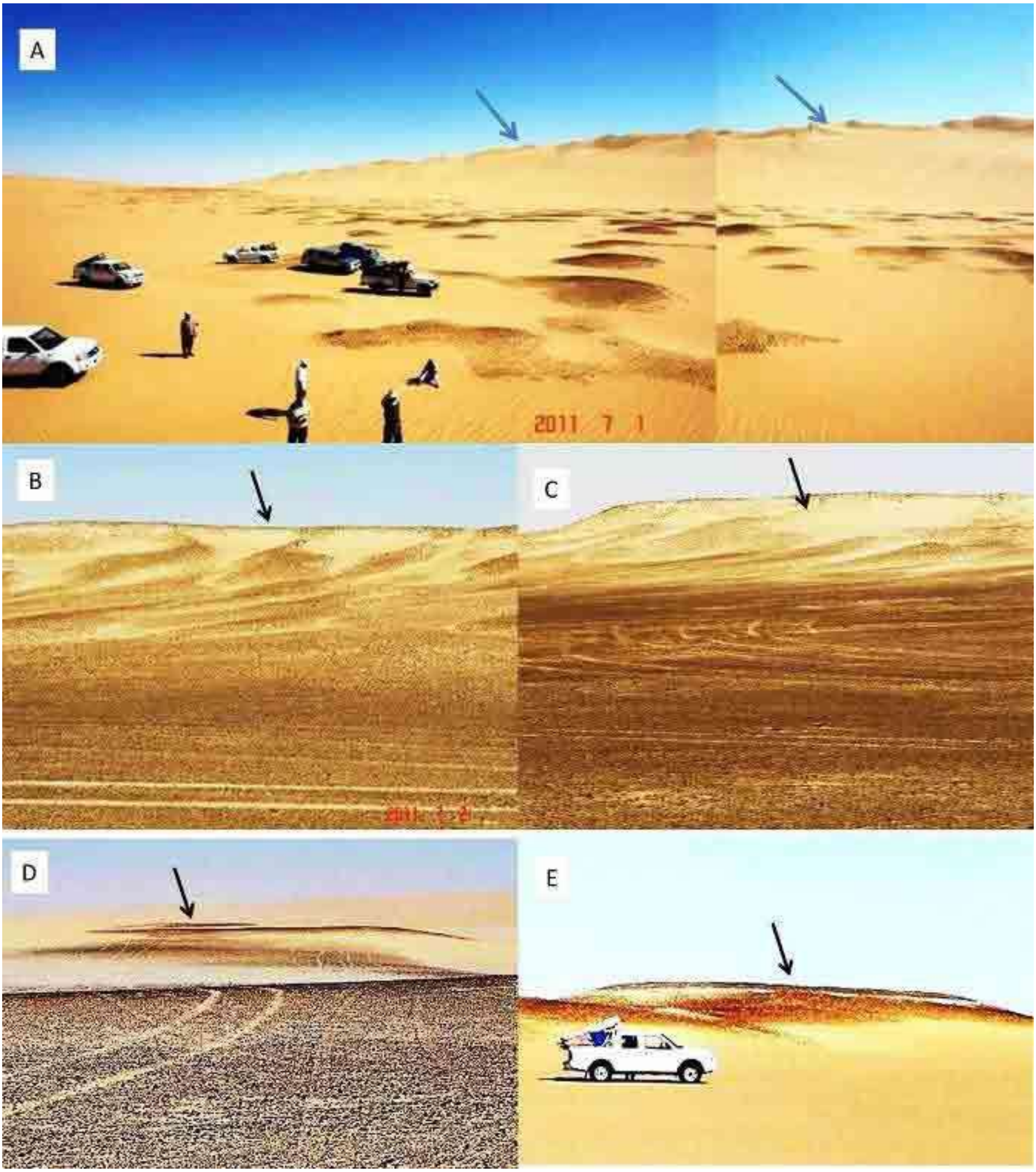


Fig. 30. A-E: Photographs showing groundwater sapping process along bedding planes of the longitudinal sandstone ridge in the Great Sand Sea. Note that the longitudinal Nubia Sandston ridges (black arrows) are made up of Sabaya Formation extended northwest-southeast. Note also the wide, flat and compact tracks between the sandstone ridges which are covered by a thin veneer of loose, brown sands so that cars can move fast and easy

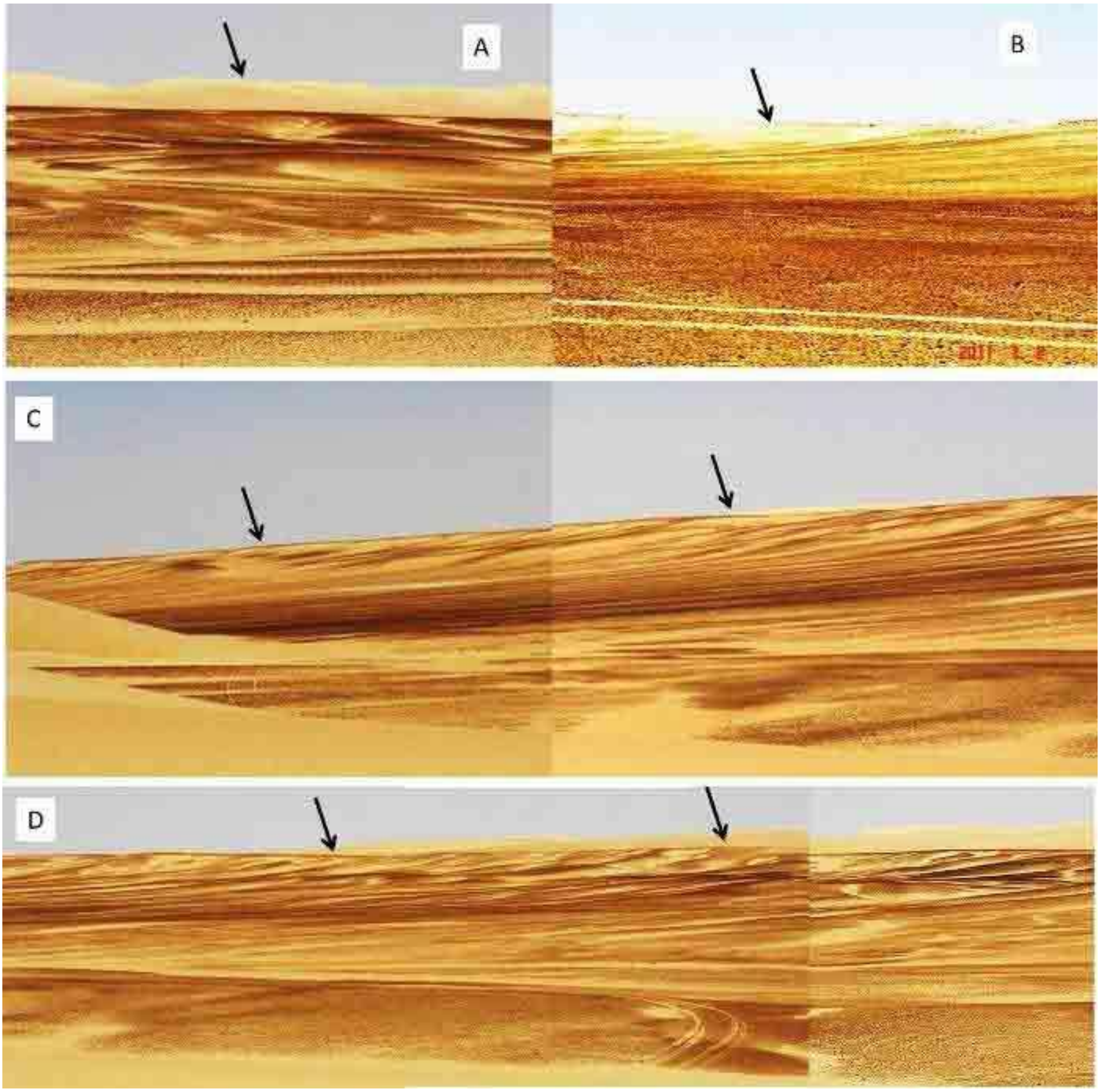


Fig. 31. A-D: Photographic panorama showing wide distribution of groundwater sapping process along bedding planes of the longitudinal sandstone ridge in the northern Great Sand Sea. Note that the longitudinal Nubia Sandstone ridges (black arrows) are made up of Sabaya Formation extended northwest-southeast. Note also the increase in the volume of groundwater which seeps through alcoves and exits frequently at and along the whole seep area leading to the retreat of the scarp face

Fig. 32. A-F: Photographs showing vertical emergence of groundwater from the Nubia sandstone bedrock along extensive flat surfaces of wide tracks, depressions and plains (white arrows) in the Great Sand Sea, particularly its northern part. This phenomenon is termed "groundwater seepage" which differs from the term "groundwater sapping process" that the latter has a more précised definition; it is a geomorphic process by which groundwater exits a hillslope laterally as seeps at the edges of the scarps and erodes soil from the slope. This often causes the slope to be undermined and undergo mass wasting, hence the word sapping.

In the Gilf El Kebir area the rates of scarp retreat appear to have been rapid because groundwater seepage and salt weathering were highly effective in undermining slopes and causing alcoves, natural arches and box canyons to develop. The sedimentary sequence of the Nubia Sandstone Group favors slope retreat because of alternations of sandstone and siltstones. Moreover, the sandstone of Six Hills and Sabaya Formations which constitute the main plateau of the Gilf El Kebir is generally soft and breaking down to produce easily removed fine-grained debris and producing limited amounts of talus.

Schumm and Chorley (1966) attributed the absence of talus at the cliff bases in southern Jordon that the talus blocks are rapidly disintegrated and removed leaving the foot of the scarp relatively free of rock accumulations. Goudie (2013) also maintained that the sandstones are mechanically weak so that many blocks disintegrate when they fall from any great height. Rockfall debris appears to suffer rapid weathering on desert floor in the Gilf El Kebir area during the Cenozoic.

Northward of Latitude 28º 18' in the area lying in the northern part of the Great Sand Sea (El-Kheir Plains, Ouda et al. 2012), which is characterized by wide tracks between the sandstone ridges, groundwater seepage increases and sapping process becomes much more active (Figs, 28 and 32). The sandstone ridges in this area are corrupted, less highly elevated and discontinuous. The draining channels show a complex U-shaped pattern, often branching out along joints to surround the slightly elevated quartz sandstone bed rock then meat again. Desert plants appear along these draining lines and increase progressively toward the north. Further northward toward the Siwa-Qattara depressions the sandstone ridges lose their identity and the draining channels become more connected and cover wide valleys of "theater-shaped" slopes that are almost bounded by dense rows of desert plants.

4.2. Surface Runoff of Old River Systems

Drainage patterns of old river systems in the Western Province of the Western Desert are all endoreic, i.e. flowing towards the center and end up in closed basins). Some of them may be due to high evaporation but most of them are due to high rate of transmission losses into the highly transmissive permeable Nubia Sandstone (Six Hills and Sabaya Formations) bedrock. Overland flows of old rivers are generally low, intermittent, having a limited duration and mainly localized along the Egyptian-Libyan borders and on the top of the main two parts of the Gilf El Kebir (Kamal El Din Plateau and Abdel Malik Plateau).

4.2.1. Surface Runoff on top and slopes of the Gilf El Kebir Plateau

The drainage pattern formed by runoff at the top surface of the western part of the Gilf El Kebir Plateau (Abdel Malik Plateau) is represented by a high complex network of dendritic streams flowing northwards toward the Great Sand Sea(Fig. 33). Some of these streams are running down slopes in opposite direction drainage to the west toward Libya whereas to the north and northeast eventually reached to the Great Sand Sea at Lat. 26º 03' 45” N and Long. 25º 22' 30” E. These streams are parts of larger paleoriver systems consisting of four main parallel channels flowed northward between the passage of Um Ras at west and the Aqaba Passage at east (Fig.34).

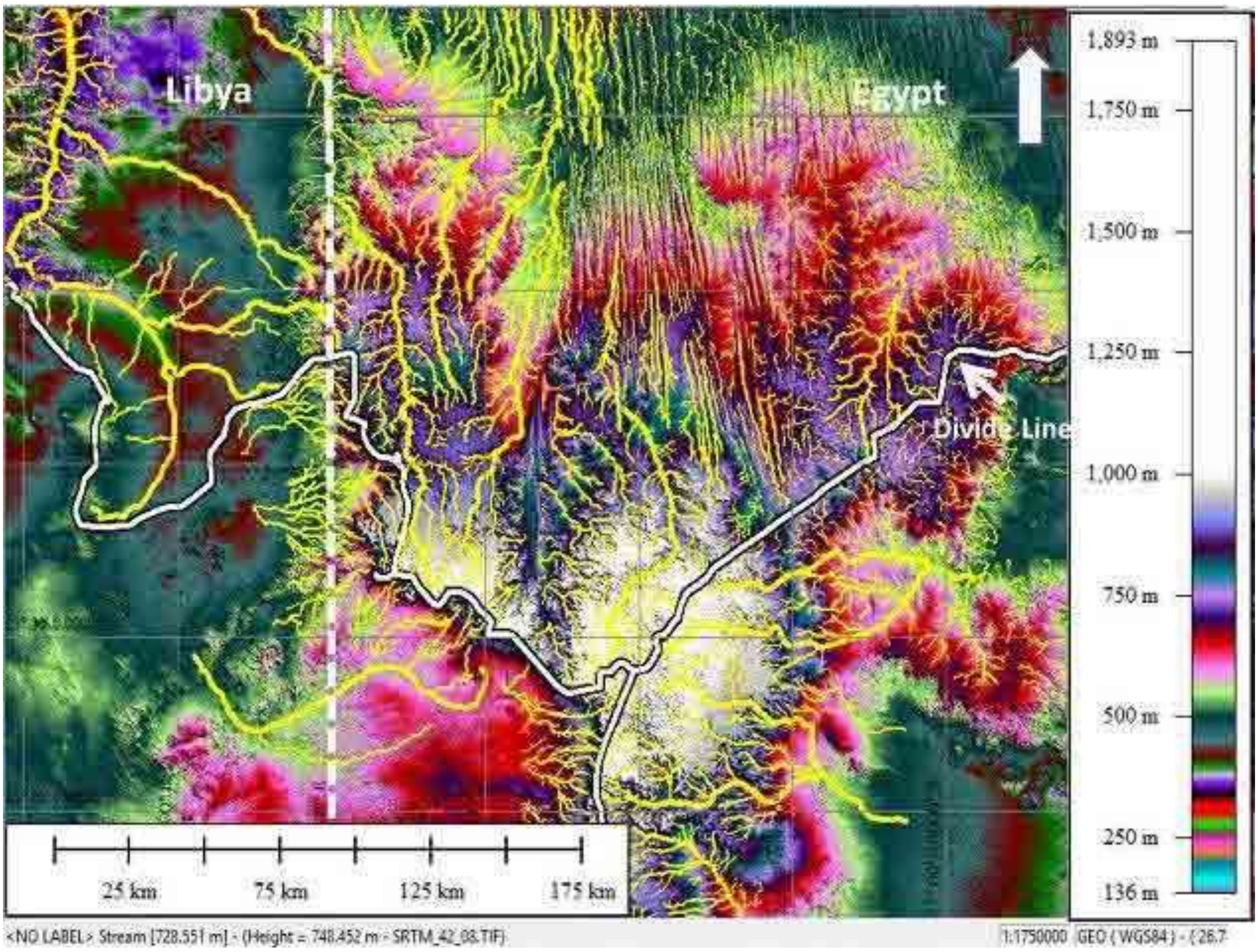


Fig. 33: SRTM Satellite image showing drainage pattern of old river systems in the Gilf El Kebir Plateau. Note the divide line (white line) which separates between different directions of drainage systems in the Gilf El Kebir Plateau. The drainage in the majority of the plateau is oriented north- and northwestward (north of the white line).

The longest paleoriver (Channel 1) started at the top of the western part of the Gilf El Kebir Plateau (at ground elevation ~1000 m a.s.l.) and flowed northwards for a distance of ~ 359 Km throughout Wadi Abdel-Malik east of the Um Ras Passage. This channel extended up to Lat. 24 33 N, and Long. 25 14 E where it twisted westwards then northwards along the Libyan/Egyptian borders between latitudes 24 46 and 25 05, until Wadi Quba, and finally heading toward west through the Libyan desert where it drained in the upper part of of the Balatah Paleoriver.

The second paleoriver (Channel 2) started also at the top of the western part of the Gilf El Kebir Plateau (at elevation ~1000 m a.s.l.) and flowed northwards for a distance of 155 km throughout Wadi Hamra west of Wadi Abdel-Malik, where it drained out in closed basins in the flat desert north of Wadi Assib

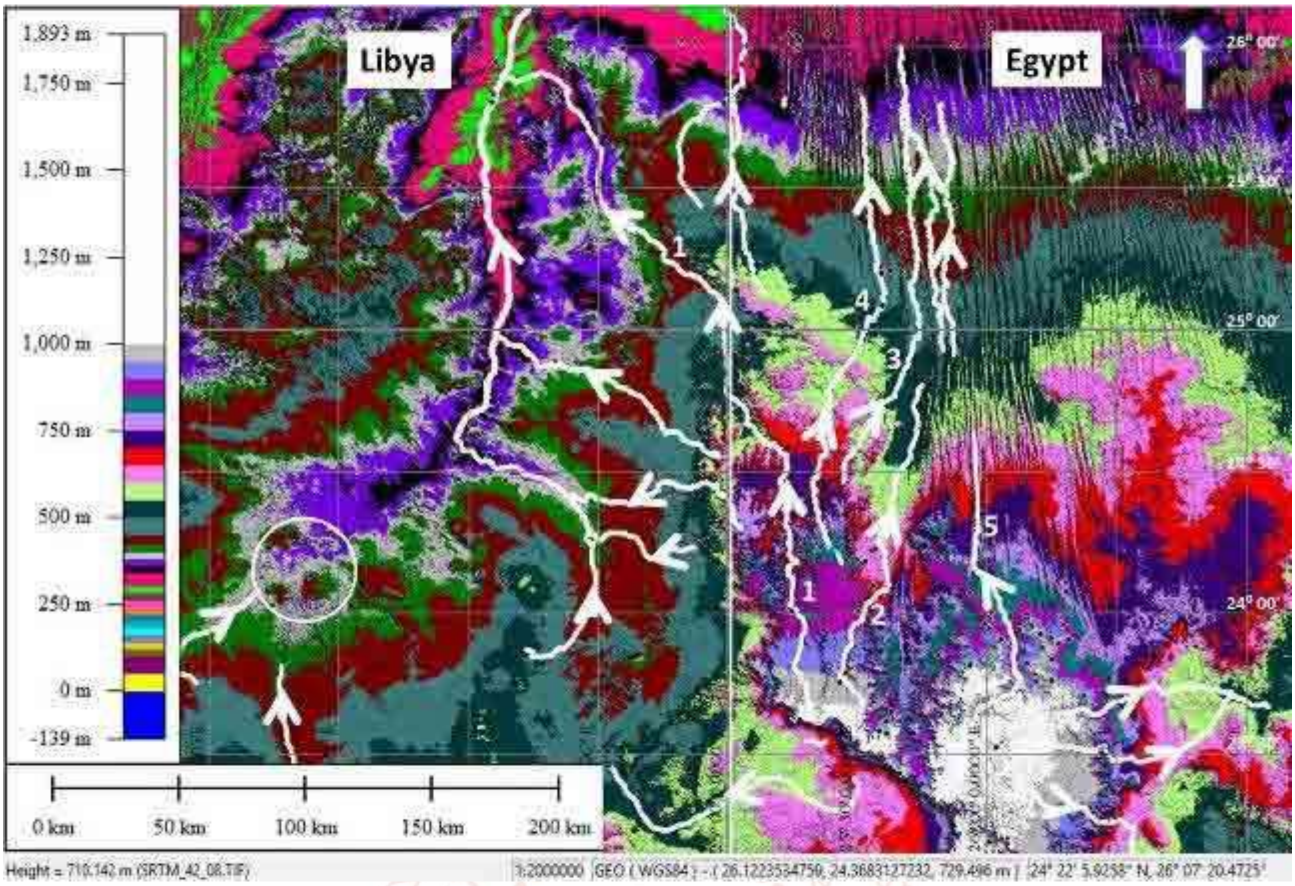


Fig. 34: SRTM Satellite image showing the major streams in the Gilf El Kebir Plateau that are parts of larger paleoriver systems (from 100 to 450 km) and consisting of five main parallel channels (1-5) flowed northward between the passage of Um Ras at west and the Aqaba Passage at east.

The third and fourth channels represent two parallel paleorivers ranging in length from 213 km (Channel 3) to 225 km (Channel 4). They started near the northern scarps between Channels 1 and 2 (at elevation 700-850 m a.s.l.) and flowed northward, then northeastward where they attacked the older Nubia Sandstone ridges in the Great Sand Sea and drained in closed basins within the tracks between the ridges.

On the top surface of the eastern part of the Gilf El Kebir Plateau (Kemal El-Din Plateau), east of the Aqaba Passage an independent drainage pattern started at elevation 1050 m a.s.l and the overall streams show a well-marked radial distribution characterized by flow of water outward in all directions from a more or less central point, thus indicating that this part of the plateau is merely an dome (Fig. 34). The longest main channel (Channel 5, 131.5 Km) extended northeastward towards the contrast Wadi, then twisted northward where it overpassed the northern pediment slopes of the Gilf El Kebir and drained out in closed basins in the tracks between Nubian Sandstone ridges to the north of Kemal El Din plateau. The other secondary channels (100-123 km long) flowed either eastward or southeastward through Wadi Mashi, Wadi Daying, Wadi, Winkel, Wadi Bakht, or Wadi Wassa.

Dendritic paleodrainage patterns made up of ephemeral streams (only carry water during storms) of paleorivers characterize the top surface of Kamal-El-Din Plateau and Abdel-Malik Plateau (Figs. 35-36). The surface flows suffer rapidly a north- and eastward decreasing discharge downstream due to increased rate of transmission losses. The runoff on slopes of the scarps and cliffs in the Gilf El Kebir PLateau can also be considered to be characteristically Hortonian flow (after Horton, 1945, Yaire and Lavee, 1985), that is, runoff is ultimately produced from circumstances in which the rate of supply of rainfall is greater than the infiltration capacity of the Nubia Sandstone bedrock of the Gilf El Kebir Plateau.

As a result of adding water via precipitation in the Gilf El Kebir area during the wet periods of the Pleistocene the infiltrating water started moving along underground layers that are porous enough (Six Hills and Sabaya Formations) to allow water to move through them. It moves both downward and horizontally along permeable layers and exits at seeps (alcoves) at the edge of the scarp. (see groundwater sapping process above). Transmission losses in the Great Sand Sea appear to be considerably high as deduced from the low integrated drainage networks and the high permeability rate of the Sabaya Sandstone which constitutes the entire bedrock of the Great Sand Sea.

A dense rill network made up of narrow water courses on sloping ground that is incised into the soil or the surface of easily eroded rock formed by combined overland flows and groundwater sapping emerged from alcoves at the valley headward are widespread on the sandstone slopes of the scarps of the Abdel-Malik Plateau (Figs. 21A-F and 37A-B). Prolonged rain during the Pleistocene caused almost complete surface sealing and overland flow in shallow rills.

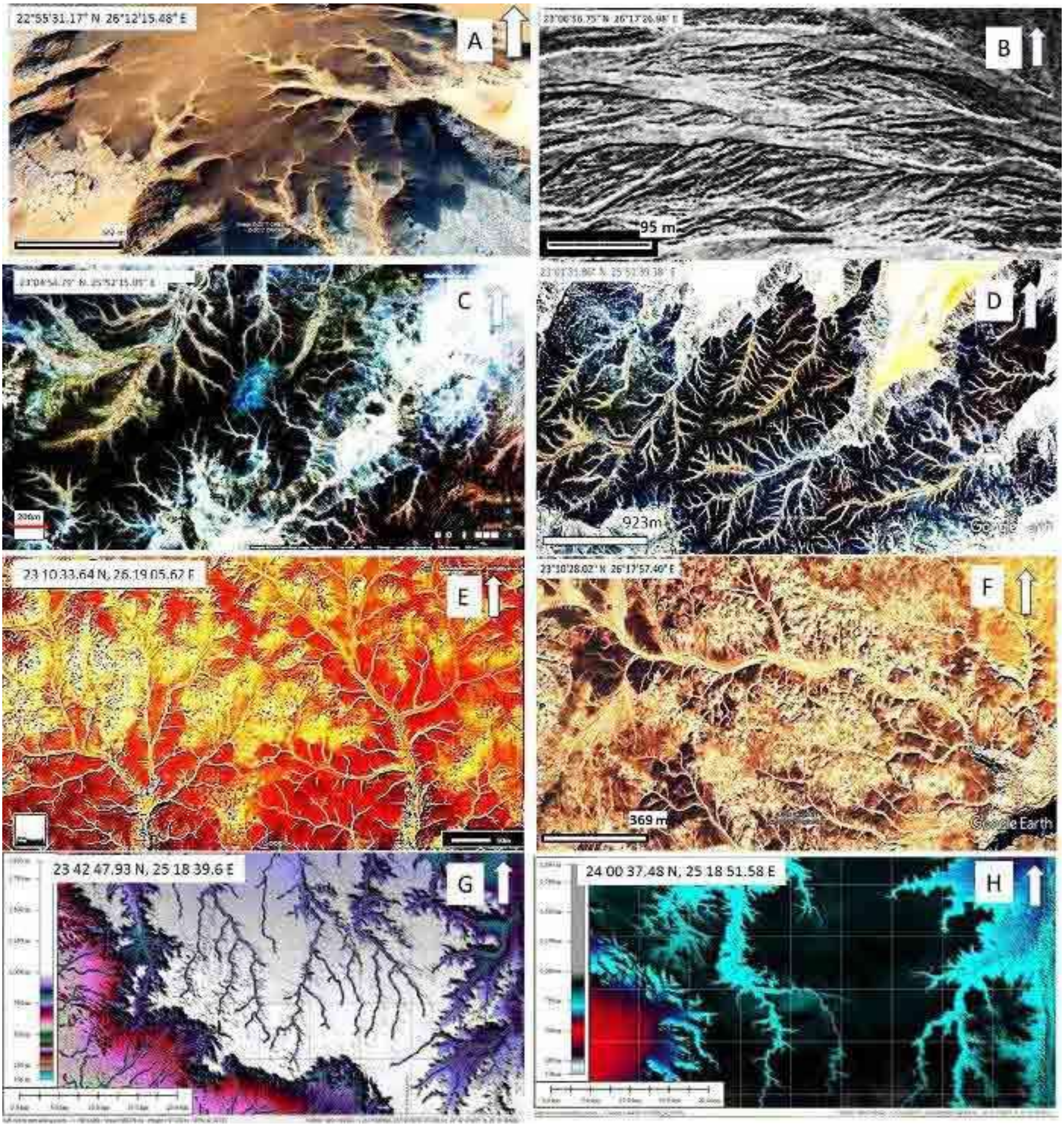


Fig. 35. A-H: Satellite images from Google Earth (A, B, D and F, Google Map Imagery (C and E), and Satellite SRTM topographic images (G-H) showing Dendritic drainage patterns made up of ephemeral streams of paleorivers formed by Hortonian overland flows at the top surface of the Gilf El Kebir Plateau. Fig. A from southeastern Kamal El-Din Plateau. Figs. B, E and F from eastern Kamal El-Din Plateau. Figs. C-D from southwestern Kamal El Din Plateau. Figs. G-H from Abdel Malik Plateau.

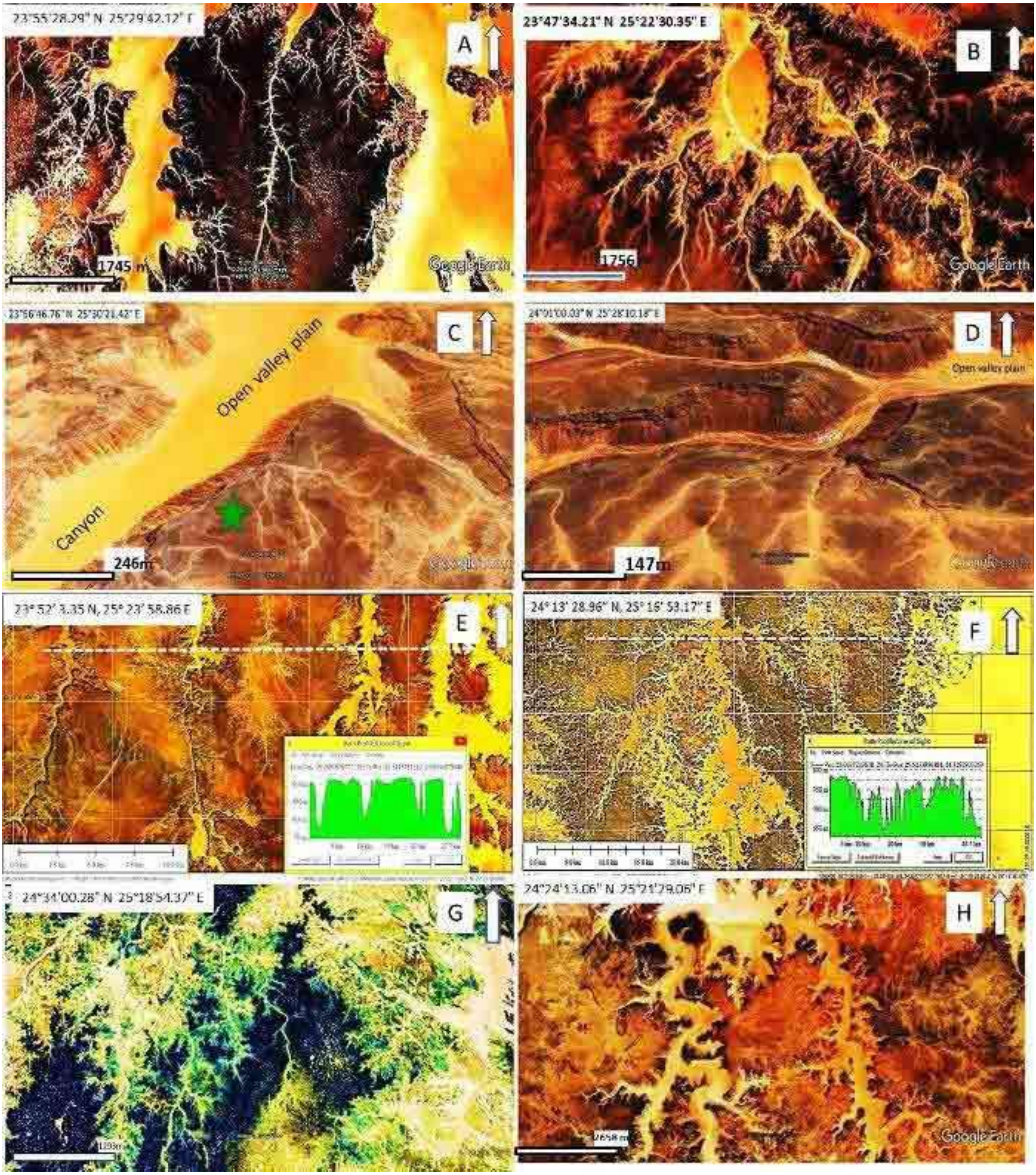


Fig. 36. A-H: Google Earth images (A-D and G-H), and SRTM World imagery (E-F) showing a complex network of runoff streams running northward along the intensively fractured top surface of the northern slopes of Abdel-Malik Plateau leading to the formation of a series of ridges and valleys of different dimensions. Note that the well exposed joints, pits and cavities on the plateau surface act to concentrate surface run-off and thus enlarge to form channels. Much of this surface water is lost due to infiltration while the remainder flows through narrow notches and falls as a small cascade to the canyon floor (C-D).

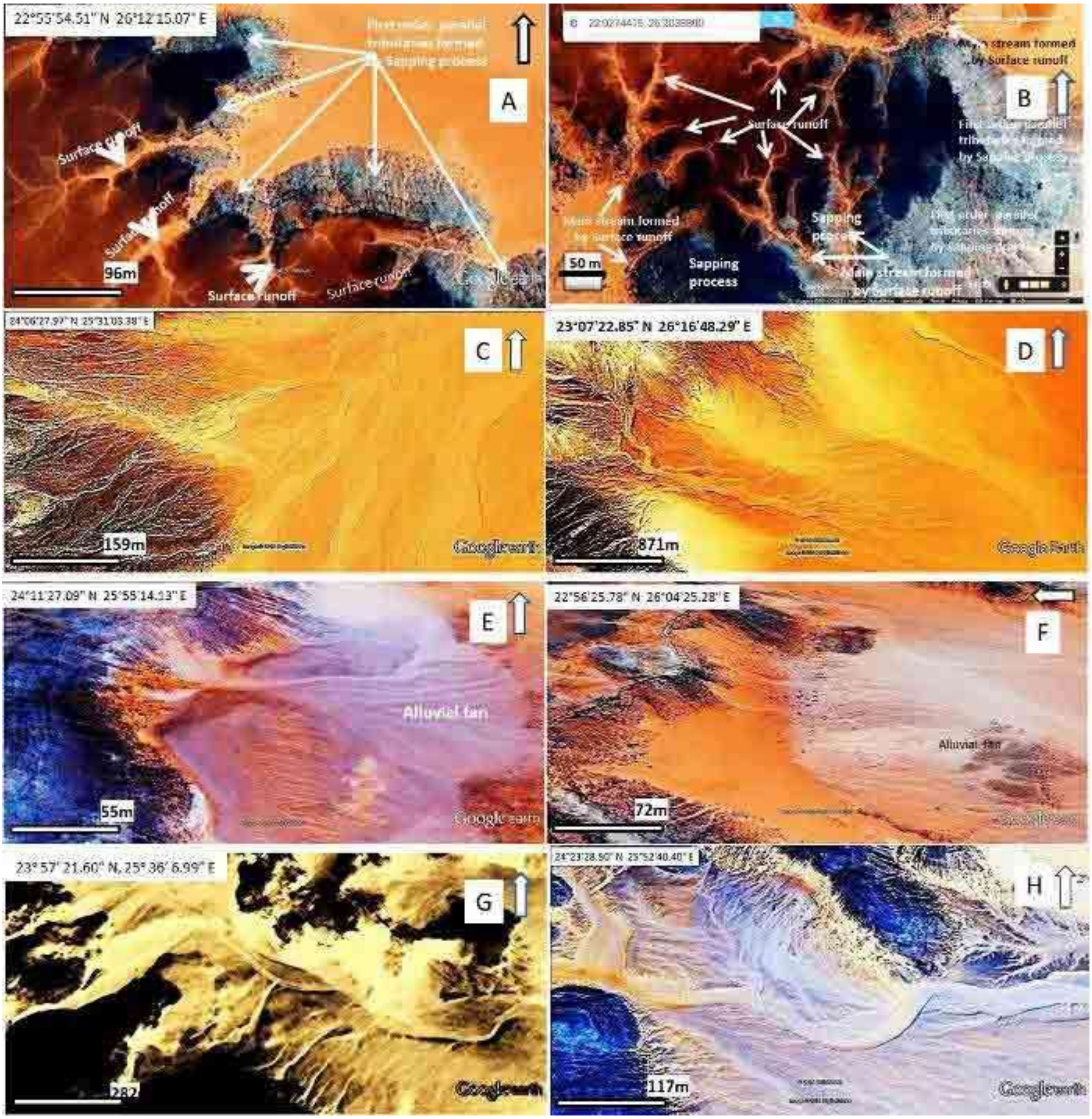


Fig. 37: Google Earth and Google Map Satellite images showing A-B: Combination of surface runoff on top of southeastern scarp of Kamal El-Din Plateau and first order parallel tributaries formed by groundwater sapping process along bedding planes at the same sloping scarp. C-D: Surface overflow along the eastern slopes of Abdel-Malik (C) and the southeastern slopes of Kamal El-Din Plateau (D) originated from both groundwater sapping process and runoff of old rivers. Much of this surface water is lost due to infiltration in the Nubia bedrock while the remainder flows through narrow notches and falls as a small cascade to the canyon floor. E-F: Broad alluvial fans (fan-shaped piles of coarse sandstone and conglomerate) bound the scarps of Gebel Almasy (E) and southern Kamal El-Din Plateau (F) where they formed by old river streams emerged from the top of the plateau onto flatter valley plains. The streams are now dried as indicated by their white color while groundwater sapping is currently flowing through the horizontal bedding planes, joints and faults forming natural arches alcoves and seepage zones at the headwalls of the valleys. G-H: Anabranching channels are not uncommon among the main channels of the drainage pattern in Wadi Aqaba (G) and southernmost Great Sand Sea (H).

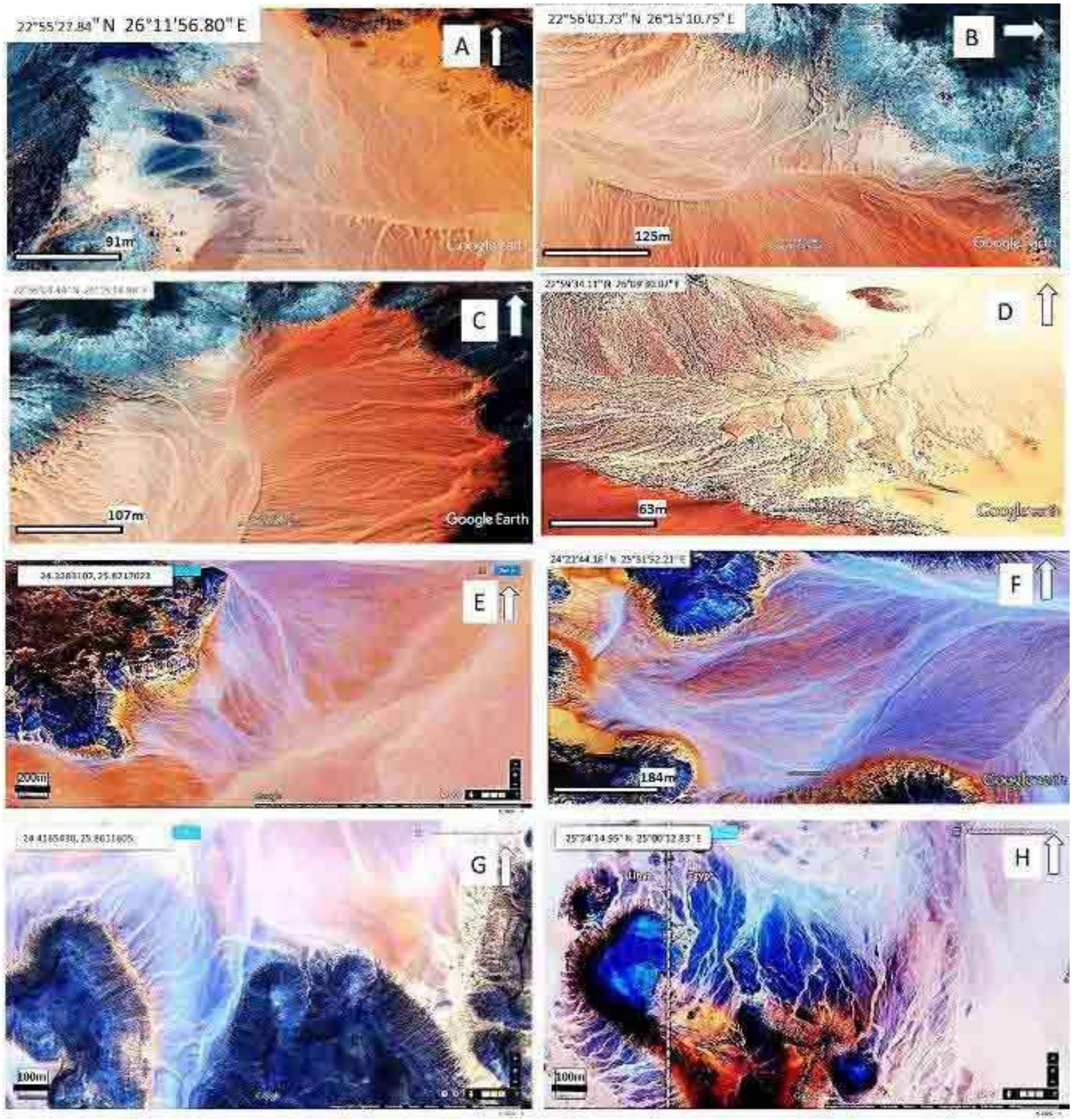


Fig. 38A-H: Satellite images from Google Earth and Google Map imagery showing convergence of runoff streams and streams generated by groundwater seepage in the main canyon streams in southeastern Kamal El-Din Plateau (A-D), Gebel Almasy, north of Kamal El-Din Plateau (E-G) and northwestern Abdel-Malik Plateau (H).

Gullies which develop from the runoff of a violent torrent that bits deeply into top soil and soft sediments are common on valley sides. When gullies dominate along the edge of the escarpments they act together with alcoves to form unsupported roof and the side materials collapse. Continued groundwater sapping processes remove the collapse debris (Fig 37A-B).

The widespread distribution of a network of drainage pattern on the top surface of the Gilf El Kebir Plateau indicates that the well exposed joints, pits and cavities on the plateau surface acted to concentrate surface run-off and thus enlarged to form channels. However, much of this surface water is lost due to infiltration in the Nubia bedrock while the remainder flows through narrow notches and falls as a small cascade to the canyon floor (Fig.37C-D). Joint-controlled drainage network are also a characteristic feature of the Gilf El Kebir Plateau. Some channels follow a NE-SW and NW-SE orientation which is probably reflecting orthogonal joint sets which are roughly parallel and normal to the main structural trend of the sandstone ridges. Anabranching and anastomosing channels are not uncommon among the main channels of the drainage pattern (Fig.37G-H).

According to Gibling et al. 1998, rivers in arid-region have a diversity of channel type including both anabranching and anastomosing forms**.**

The valleys formed by surface run-off differ from those formed by groundwater sapping by having a valley width that almost increases downstream and usually with increasing tributary order. The valleys formed by the groundwater sapping, on the other hand, are generally narrow, with more or less constant widths and with a small drainage area made up of short, more or less parallel first-order tributaries and with a paucity of downstream tributaries (for differences between valleys formed by runoff and those formed by groundwater seepage see Laity and Malin, 1985 and Nash, 1997). Convergence of runoff streams and streams generated by groundwater seepage in the main canyon streams are frequently recorded in southeastern Kamal El-Din Plateau (figs. A-D) Gebel Almasy, north of Kamal El-Din Plateau and northwestern Abdel-Malik Plateau (Fig. 38)

4.2.2. Surface Runoff in the Great Sand Sea

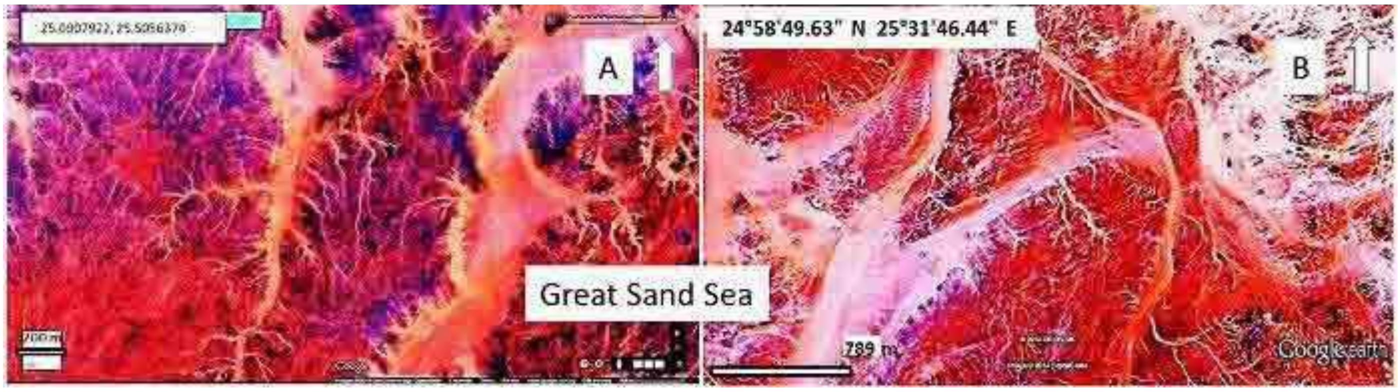
An Additional but less complex network of dendritic streams of runoff started north of the Abdel-Malik Plateau at or near Lat. 25º (at elevation of 600 m a.s.l.) and flowed northward in the Great Sand Sea (Fig. 39). The network is made up of three main channels varying in length from 120-137 km. One of these channels were flowed northwards and drained out in the North Gilf sandy plain which is situated along the Egyptian-Libyan borders between latitudes 25º 22' 30" and 26º 07' 30" N and longitudes 25º and 25º 22' 30" E, whereas the other two channels ran down slopes towards northeast where they attacked the older Nubia Sandstone ridges in the Great Sand Sea and drained out in closed basins within the tracks between the sandstone ridges Fig. 34).

One of the most characteristic features of the Great Sand Sea is the flood breakouts through the cordon of the Nubia Sandstone ridges along the Egyptian-Libyan borders, sometimes as catastrophically large flows (Fig. 39G-H). This phenomenon which can be related to increasing aridity was termed floodout in Australia by Goudie (2013). It results from failing of the majority of channels to reach the lowest point in the drainage basin and the large overland flows become largely disappear. These floodouts have led to the distortion, deterioration and collapse of the Nubia Sandstone ridges due to infiltration of the surface flow through the sandstone beds along joints and faults. A similar feature has been reported by Svendsen et al. (2003) in Namibia. Alluvial sandy fans formed by floodouts are generally rare, small in size, only few tens of meters long and showing a decrease in grain size down fan.

The Nubia Sandstone ridges in the Great Sand Sea which surround the northern and eastern slopes of the Gilf El Kebir Plateau are greatly affected by the flowing/ floodout of the surface water of these channels. They are distorted, curved, partly or completely deteriorated and lose their consolidated identity and symmetry. The surface water flows through the joint system of the nearby highly fractured sandstone ridges where it forms branches of tributaries at right angles thus producing a rectangular or angular drainage pattern, similar to that produced by groundwater sapping process.

4.2.3. Surface Runoff in the northwestern sandy plains of the Great Sand Sea

As noted before, there are two main flat sandy plains in the western part of the Great Sand Sea situated along the Egyptian/Libyan borders between latitudes 25º 22′ and 27º 45′. The plains were identified by Ouda et al. (2012) as the North Gilf Plain in the South and the Nahada Plain in the North. These sandy plains seem to have a long history with periodic phases of flooding of the paleoriver systems coming from the northern slopes of the Abdel-Malik plateau and from the Balatah Valley in northeast Libya during the Pleistocene, leading to the complete destruction and disintegration of the pre-existing Nubia Sandstone ridges, thus contributing to the flatness of the plains. The bedrock of the plains is made up of Sabaya Formation covered by a thin veneer of loose sands. Current ripple marks formed mainly by wind blowing over loose sand, with small alternating ridges and troughs that having straighter crests characterize the surface of the sand veneer all over the area.



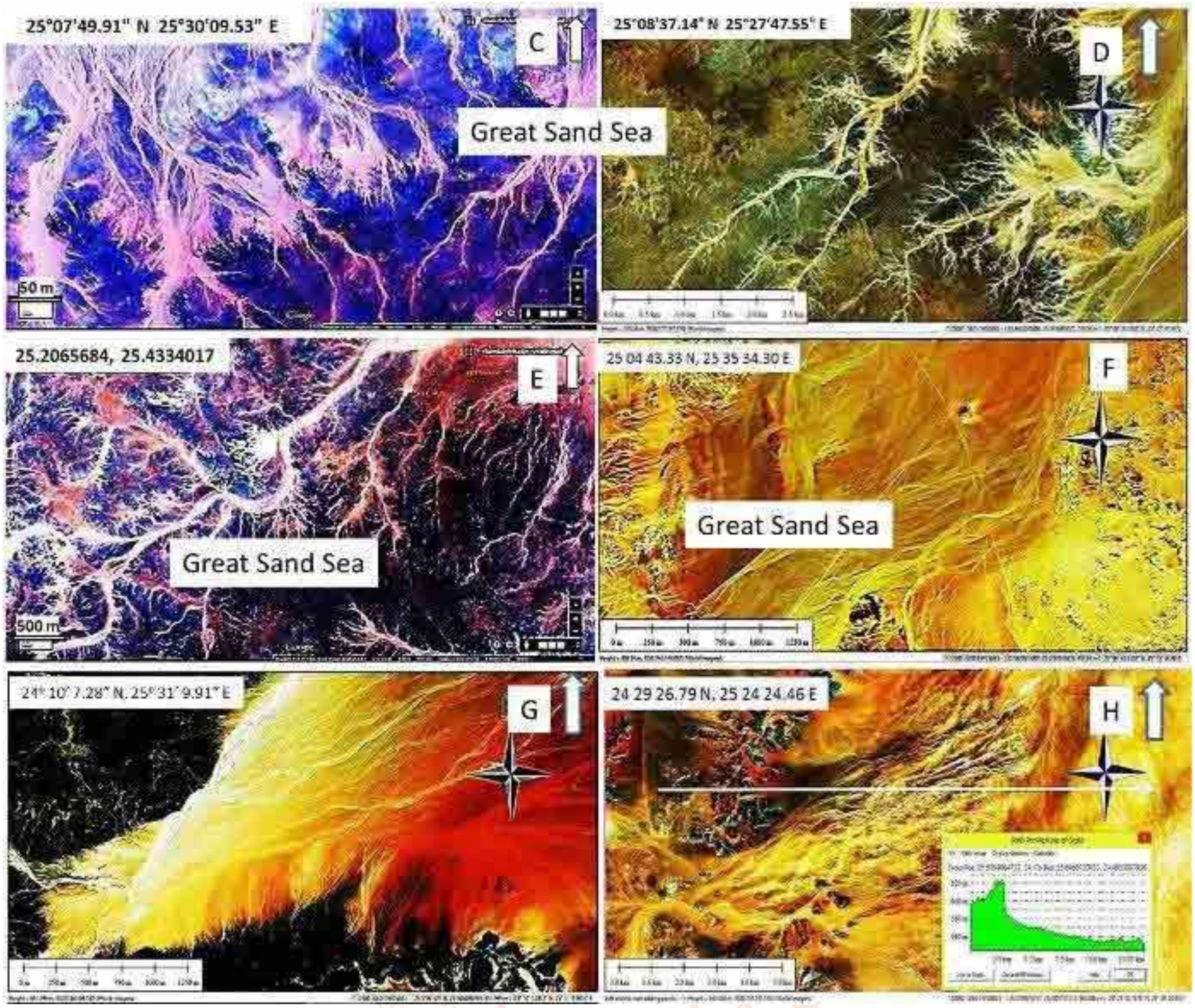


Fig. 39: Satellite Google Map imagery (A, C and E), Google Earth images (B) and World imagery based on SRTM data (D, F, G and H) showing dendritic drainage patterns formed by overland flow at the top surface of the Nubia Sandstone bedrock in open valleys and wide tracks between sandstone ridges in the Great Sand Sea. Some of the streams (G-H) are drained as catastrophically large flows (Floodout) in closed basins (e.g. Wadi Assib, in the southern part of the Great Sand Sea.

The total areas of these plains are covered with thin veneer (from 10cm to 15 cm thick) of free sands overlying directly the Nubia Sandstone bedrock. The sand cover often shows well developed current ripple marks expressing periodic flooding and overland flow from west to east and from south to north. Indications of near-surface groundwater table are evident in these plains where patches and shallow depressions are filled with groundwater seepage coming to the surface. This would mean that the older periodic or seasonal flooding 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 runoff streams in these plains are of low intensity and showing two different drainage patterns as delineated below:

4.2.3.1. Drainage Pattern of the North Gilf Plain

This is a Nubia Sandstone plain of trapezoid to sub-triangular shape lying along the Egyptian-Libyan borders north of Wadi Abdel Malik and the Wadi Talha area (Fig. 40). The plain extends for a length ranging between 68 km along the Egyptian-Libyan borders to 87 km eastwards, and a width decreasing from 35.6 km at the south to 10.2 km at the north, assuming a total area of 1678 km². It has a flat surface sloping gradually from an elevation of 435 m in the south to 290 m above sea level in the north. The bed rock of the plain is belonging to the Nubian Sandstone, being represented by fluviatile sandstone which is equivalent to the Sabaya Formation.

The plain is dissected by a dendritic drainage pattern running north and northeastward representing northward streams (75-135 Km long) flowed from the northwestern slopes of the Abdel-Malik Plateau near the Egyptian-

Libyan borders (Figs 41 and 42). Some of these streams drained out within the Northern Gilf Plain, whereas others are twisted towards northeast where they attacked the older Nubia Sandstone ridges in the southern part of the Great Sand Sea and drained in closed basins in wide valleys and among flat tracks between the sandstone ridges (Fig. 41A-B).

The drainage pattern of this plain is oriented N-NE/S-SW between latitudes 25º 22' 30" and 26º 07' 30" N and longitudes 25º and 25º 22' 30" E. The pattern is represented by a less complex network of dendritic streams and distributaries of an old river system flowing from two radiating central high points north of the Abdel-Mali Plateau. Some of these streams are running down slopes in opposite direction; drainage to the west toward Libya whereas to the north and northeast eventually reaches to Lat. 26º 03' 45" N and Long. 25º 22' 30" E. The streams and distributaries are parts of a larger system of drainage consisting of two main parallel channels with their distributaries flowed from the tops of the Abdel-Malik Plateau northward near the Libyan borders. The Nubia Sandstone ridges surrounding the northern and eastern slopes of the Abdel-Malik Plateau are greatly affected by the flowing of surface water from this old river system. They are distorted, curved, partly or completely deteriorated and lose their consolidated identity and symmetry (Fig. 42). The surface water flows through the joint system of the nearby highly fractured sandstone ridges where it forms branches of tributaries at right angles thus producing a rectangular or angular drainage pattern, similar to that produced by groundwater sapping process.

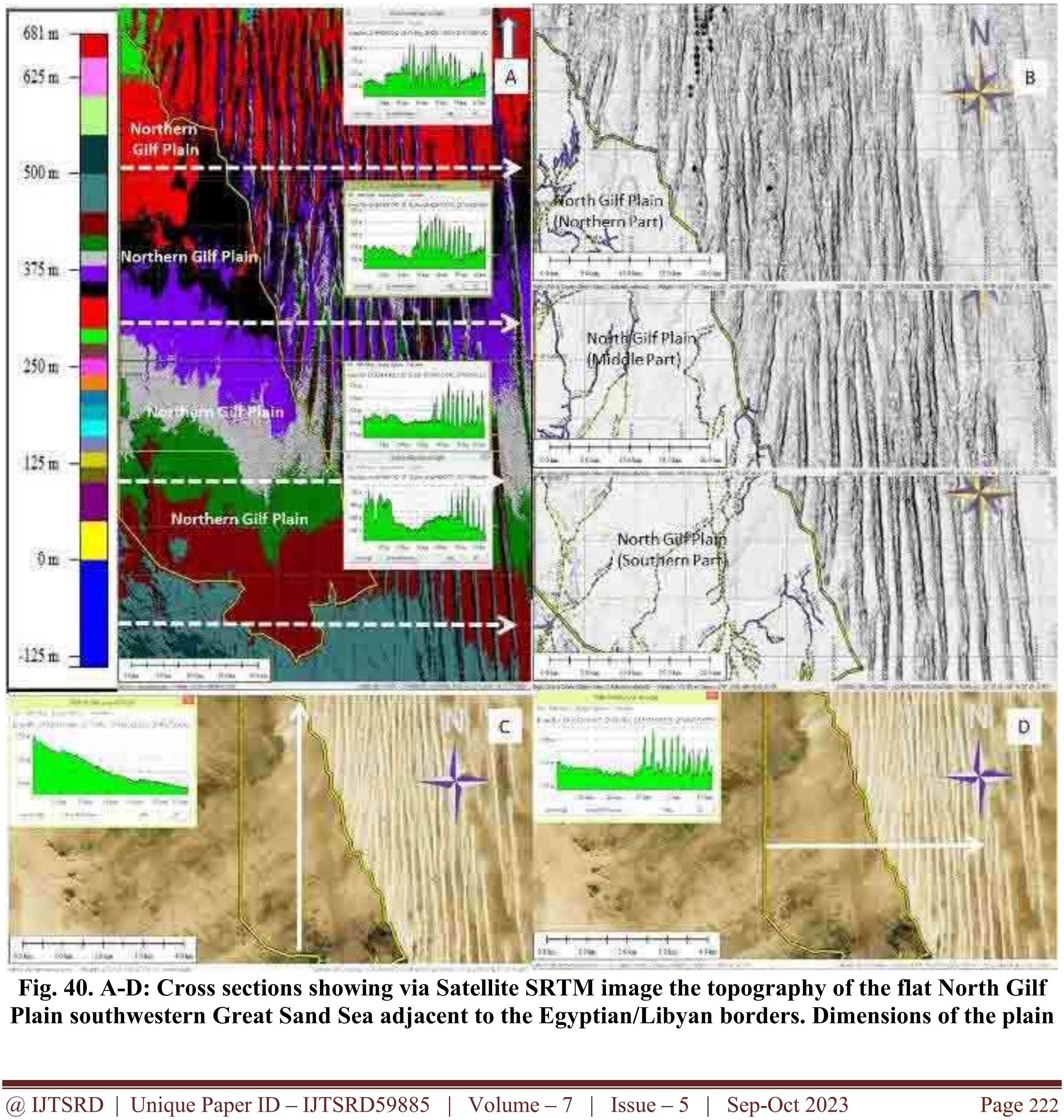


Fig. 40. A-D: Cross sections showing via Satellite SRTM image the topography of the flat North Gilf Plain southwestern Great Sand Sea adjacent to the Egyptian/Libyan borders. Dimensions of the plain

(length and average width) are given in C and D where a flat surface is sloping gradually from an elevation of 435 m in the south to 290 m above sea level in the north. The bedrock of the plain is made up of fluviatile Nubia Sandstone which is equivalent to the Sabaya Formation. Note in Fig. B that the plain is dissected by a dendritic drainage pattern representing northward streams (75-135 Km long) flowed from the northwestern slopes of the Abdel-Malik Plateau.

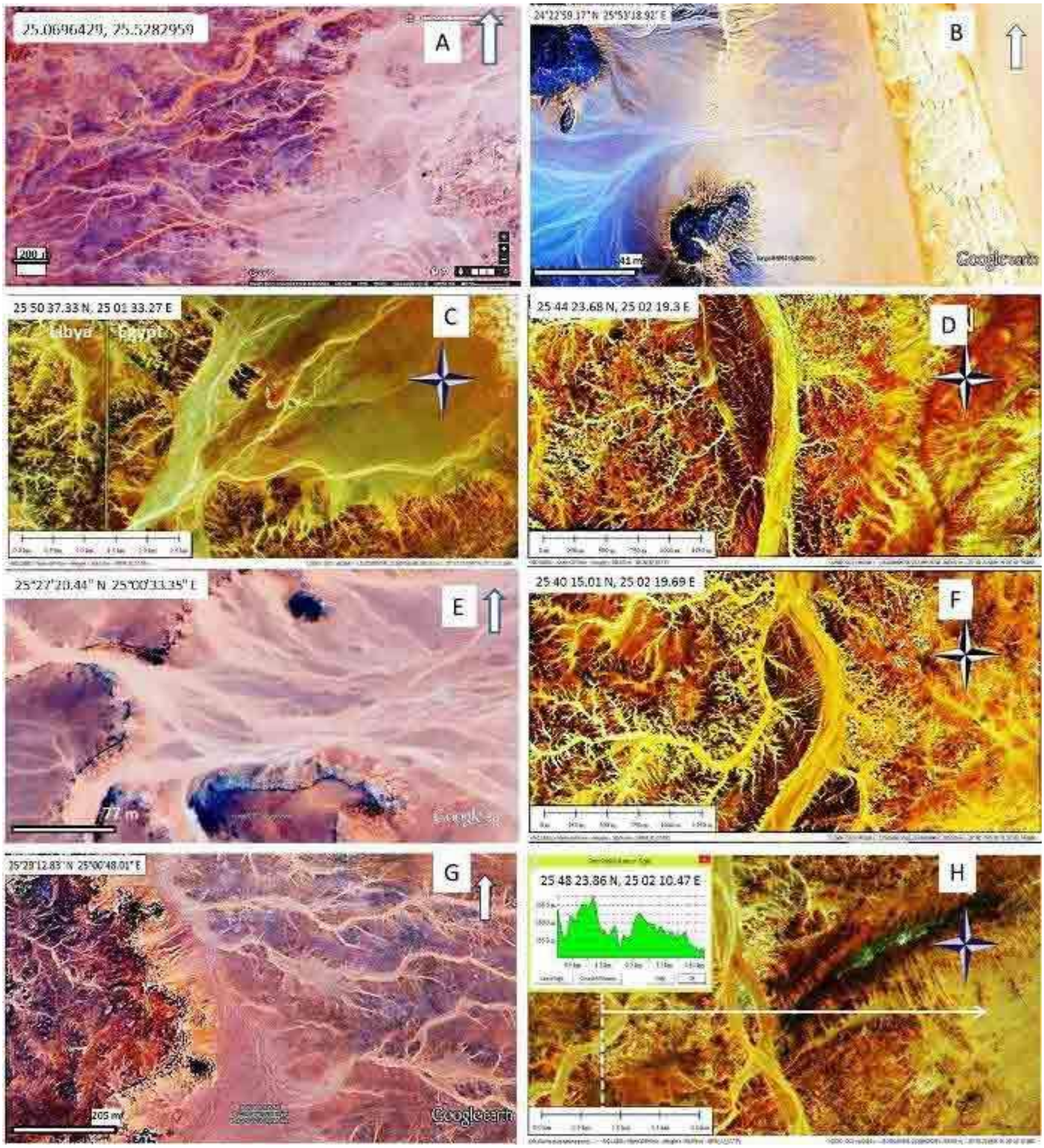


Fig. 41. A-H: Satellite images from Google Earth (B, E and G), SRTM images from World Imagery (C, D, F and H) and Google Map Imagery (A) showing less complex network of dendritic streams and distributaries of old rivers representing northward streams (75-135 Km long) flowed from the northwestern slopes of the Abdel-Malik Plateau and drained out within the Northern Gilf Plain near the Egyptian-Libyan borders (C-H). Note in B that the overland flows over northernmost hillslopes of Abdel-Malik Plateau (westward) are attacking the Nubia Sandstone ridges in the low land of the Great Sand Sea (eastward).

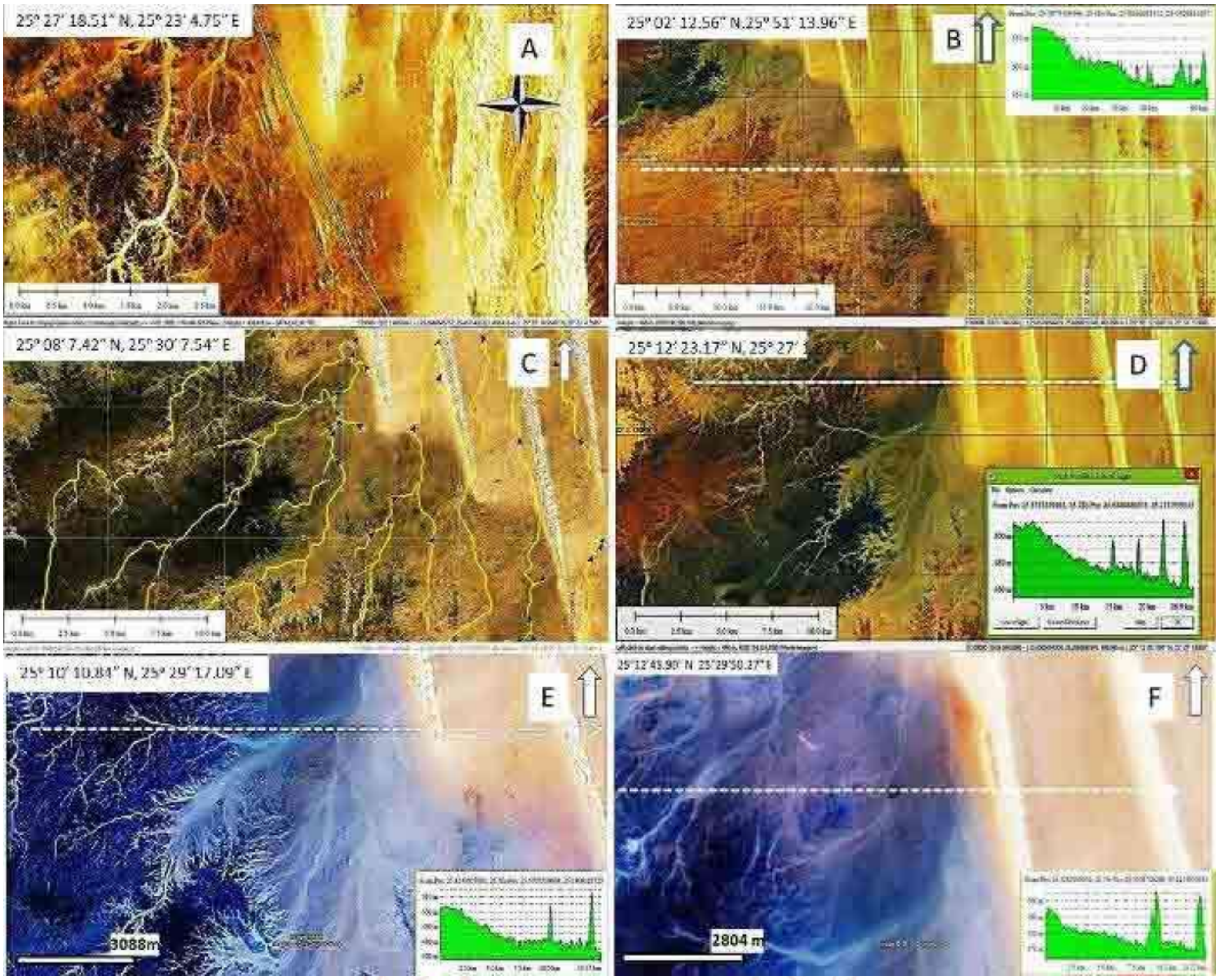


Fig. 42. A-F: Satellite World Imagery based on SRTM data showing overland flows of old rivers running northeastward over flat hillslopes of the North Gilf Plain along the Egyptian/Libyan borders (westward) and attacking the pre-existing Nubia Sandstone ridges (eastward) in the low lands of the Great Sand Sea. The overland flows were generated when the rainfall intensity during wet Pleistocene periods exceeded the rate of infiltration of the Nubia Sandstone bed rock. Water in this case was stored in small surface depressions until they overtopped when the water starts to flow downhills

4.2.3.2. Drainage Pattern of the Nahda Plain

The Nahda Plain is a large triangular flat plain whose floor is made up of a quartz sandstone bed rock belonging to the Sabaya Formation, covered by a thin veneer of loose sands and silts. It is 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. 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. 43)

The Nahda plain represents the eastern extension of a vast delta plain of the paleoriver system of the Balatah Valley in northeastern Libya which seems to have formed as a result of northward flowing of the old Balatah river streams into a huge Pleistocene freshwater lake occupying the area lying northeast of Libya between latitudes 26º 30' and 28° 30', and longitudes 23º 15' and 25º 26' (Figs 43-44). This Delta was originally described by Ghoneim et al. (2012) as belonging to the ancient Kufrah River which was flowed north with a very gentle gradient of about 0.6 m km−1 comparable to that of the adjacent modern Egyptian Nile.

However, the writer does not agree with the concept of Ghoneim et al. (2012) concerning the source of the vast inland paleodelta which lies in the northeastern part of Libya and its eastern extension in Egypt. Evidences from the drainage patterns designated by the Global Mapper 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 Balatah paleoriver, not to the Kufrah paleoriver as previously proposed. The delta was formed when the old River system of Wadi Balatah in northeastern Libya discharged northward into a huge, freshwater Pleistocene lake occupying ~ 24218 Km², between latitudes 26º 30' and 28° N, and longitudes 23º 22' and 25º 22' E. The delta plain being more or less equal in size to the Present Nile Delta in northern Egypt. Its maximum length (N-S) is ~150.86 km whereas its maximum width (E-W) is ~202 km.

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 most lowest lands in northeastern Libya.

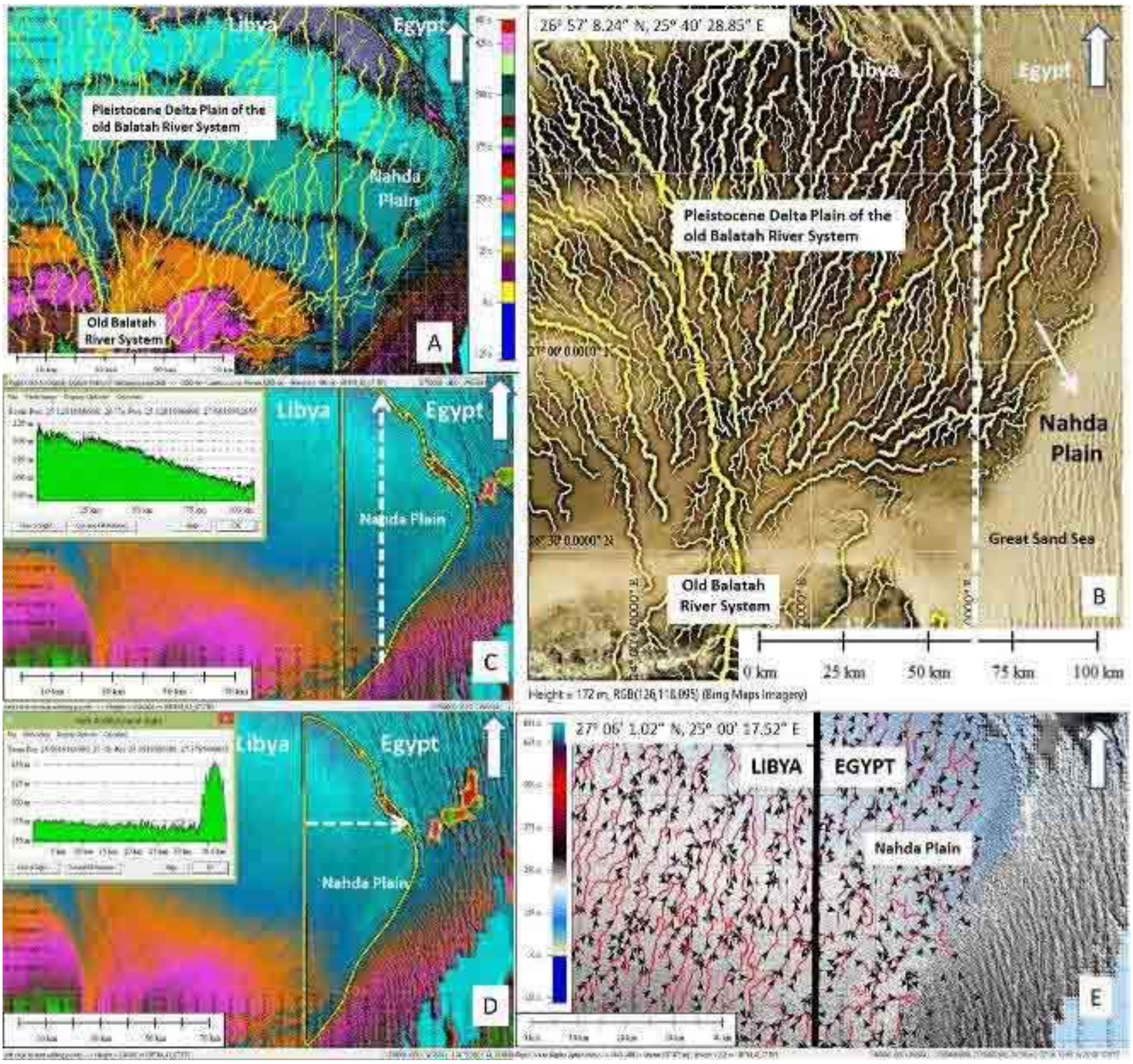
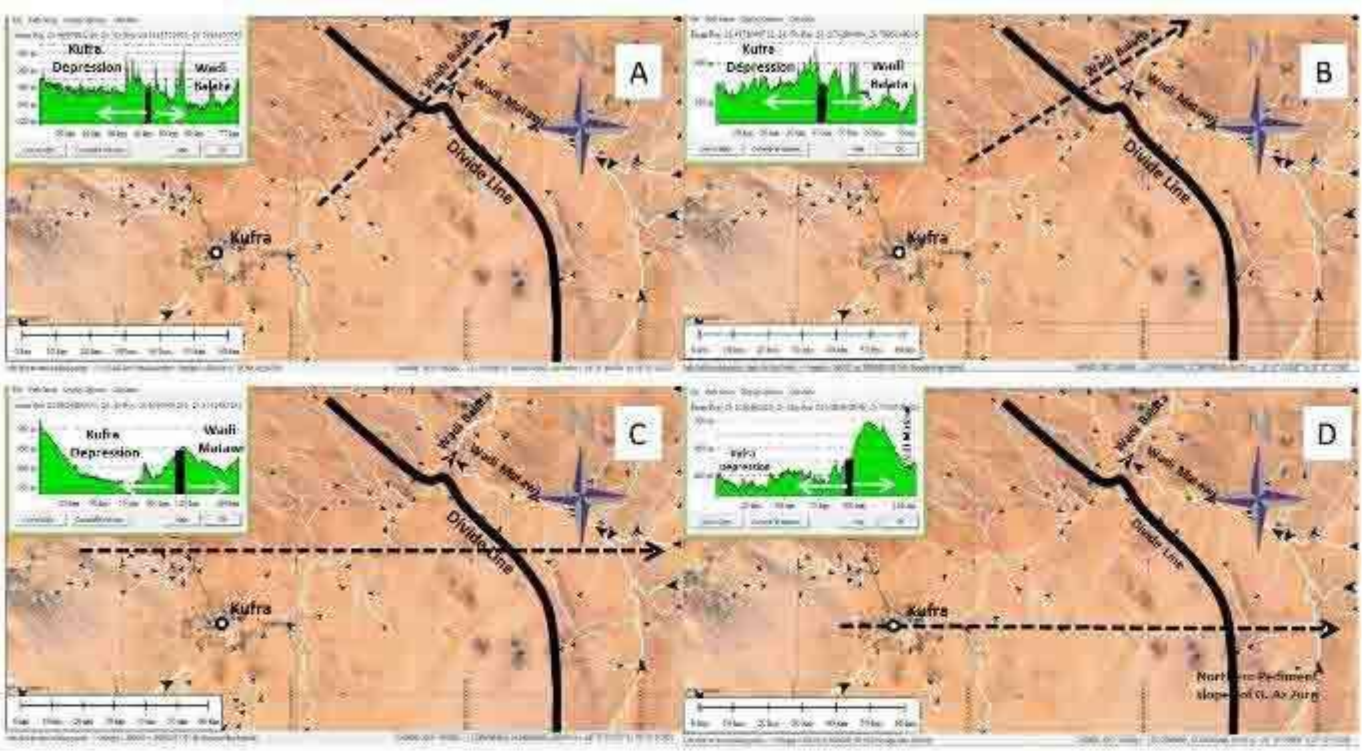


Fig. 43. A-E: Satellite image based on SRTM data showing the Nahda plain in the north western part of the Great Sand Sea Egypt. The plain represents the easternmost extension of a vast delta plain of the paleoriver system of the Balatah Valley in northeastern Libya (A-B). The main paleoriver channel was distributed into 22 second order distributaries, 19 of which range in length from 100 km to 250 km two of which flowed northeastward into Egypt, while 3 of which range from 75 to 99 km, beside hundreds of small third order streams which are less than 74 km in length running north, northwest and northeast (A-B). 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 (C-D) and dissected by rows of radiating draining lines running northeastward (E). The flatness of this sandy plain indicates that it has a long history with periodic phases of flooding of the paleoriver of the Balatah valley in northeastern Libya during the Pleistocene leading to complete destruction of the Nubia Sandstone ridges.

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. (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 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 Balatah paleoriver basin and its distributaries in Egypt.

The 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 Balatah for a distant of about 245 km (Bearing 7º 10′ 55.2″) before the entrance of the huge lake (Fig. 44). The ground of the area occupied by the Balatah paleoriver is gradually sloping to the north, from elevation of 345 m a.s.l. northeast of Kufra 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 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. In addition there are hundreds of small third order streams which are less than 74 km in length running in the same directions.

The source of the Balata paleoriver is independent from the Kufra paleoriver system. 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 (Fig. 44A-D). 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 Balatah. 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. The western streams are short but dense and flowing southeastward. Both systems were met to discharge into the Balatah Valley at the point of its intersection with Wadi Matawi.



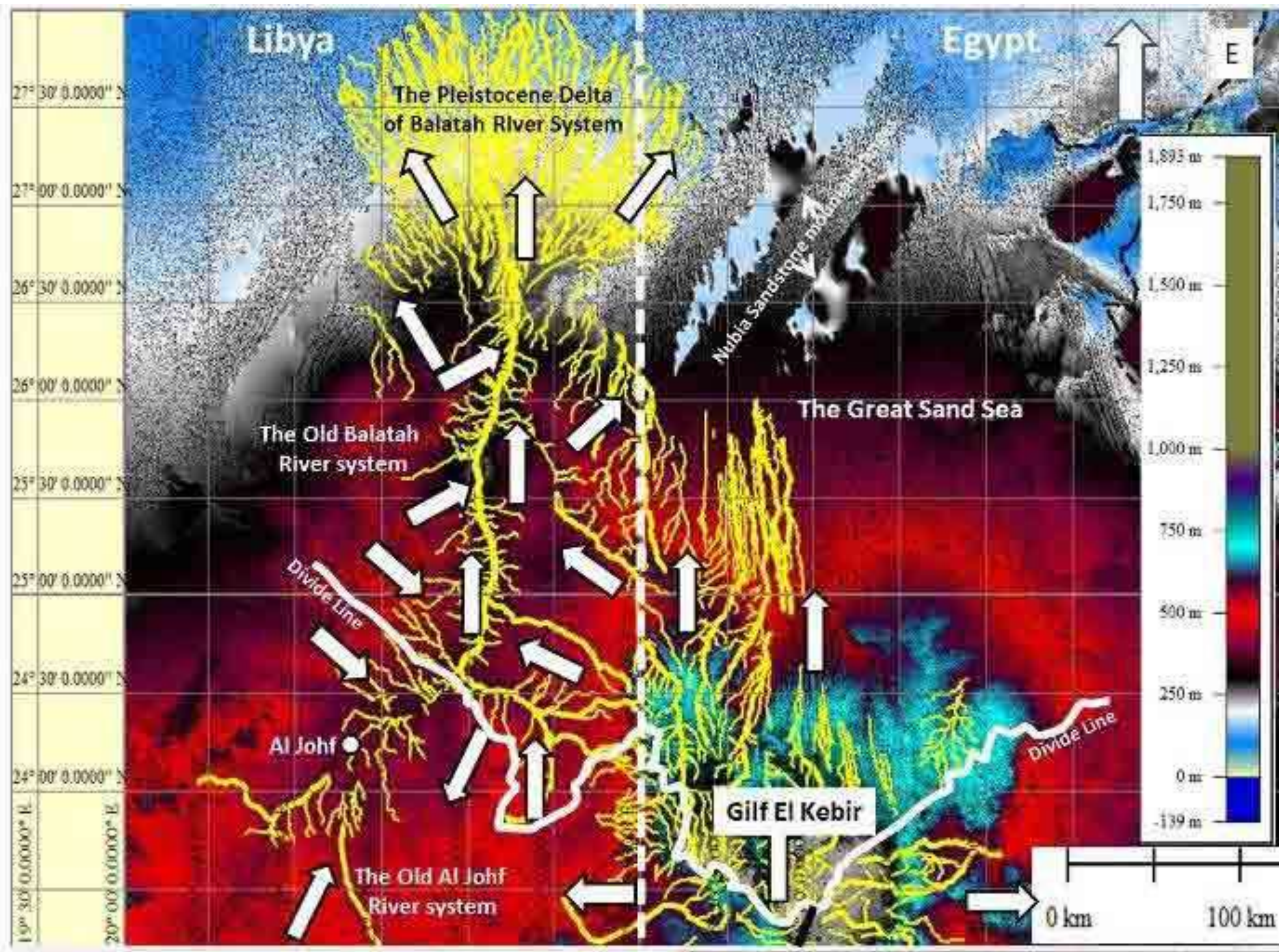


Fig. 44. A-E: Satellite images based on SRTM data showing that the source of the Balata paleoriver system in northeastern Libya is independent from the Kufra paleoriver system. It started at Lat. 24º 37′ 2″ N and Long. 23º 56′ 46″ E, ~78 km NE of Al Johf (Kufrah), and ~108 km west of the Libyan/Egyptian 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 Balatah (figs. A-D). The divide (topographically high areas) which separates the drainage basin of the Balatah paleoriver system from the adjoining Kufrah paleoriver one is running NW-SE ~8 km before the entrance of Wadi Balatah at Lat. 24º 33′ 45.17″ N and Long 23º 53′ 43.6″ E. This divide (black lines in figs. A-D and white line in fig. E) separates drainage in opposite directions of the 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 divide eventually goes to the Wadi Balatah basin and then to the Balatah delta plain. Note in Fig. E the direction of drainage (white arrows) relative to the divide in both the Gilf El Kebir Plateau and the Balatah paleoriver. Note also that the 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 Balatah for a distant of about 245 km (Bearing 7º 10′ 55.2″) before the entrance of the huge Pleistocene lake.

The divide (topographically high areas) which separates the drainage basin of the Balatah Paleoriver system from the adjoining Kufrah Paleoriver one is running NW-SE ~8 km before the entrance of Wadi Balatah at 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 (Fig. 44E).

This divide (topographically high areas) separates drainage in opposite directions of the 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 divide eventually goes to the Wadi Balatah basin and then to the Balatah delta plain (Fig. 44E). The drainage of the eastern and southeastern piedmont slopes of the Az Zalamah (Delma) mountain (west of the Balatah Valley) goes directly to the Balatah paleoriver basin. However the drainage of the northeastern piedmont slopes of Gebel Zurg goes indirectly to the Balatah Valley via a long sinuous channel stream (150 km long) extending northwestward

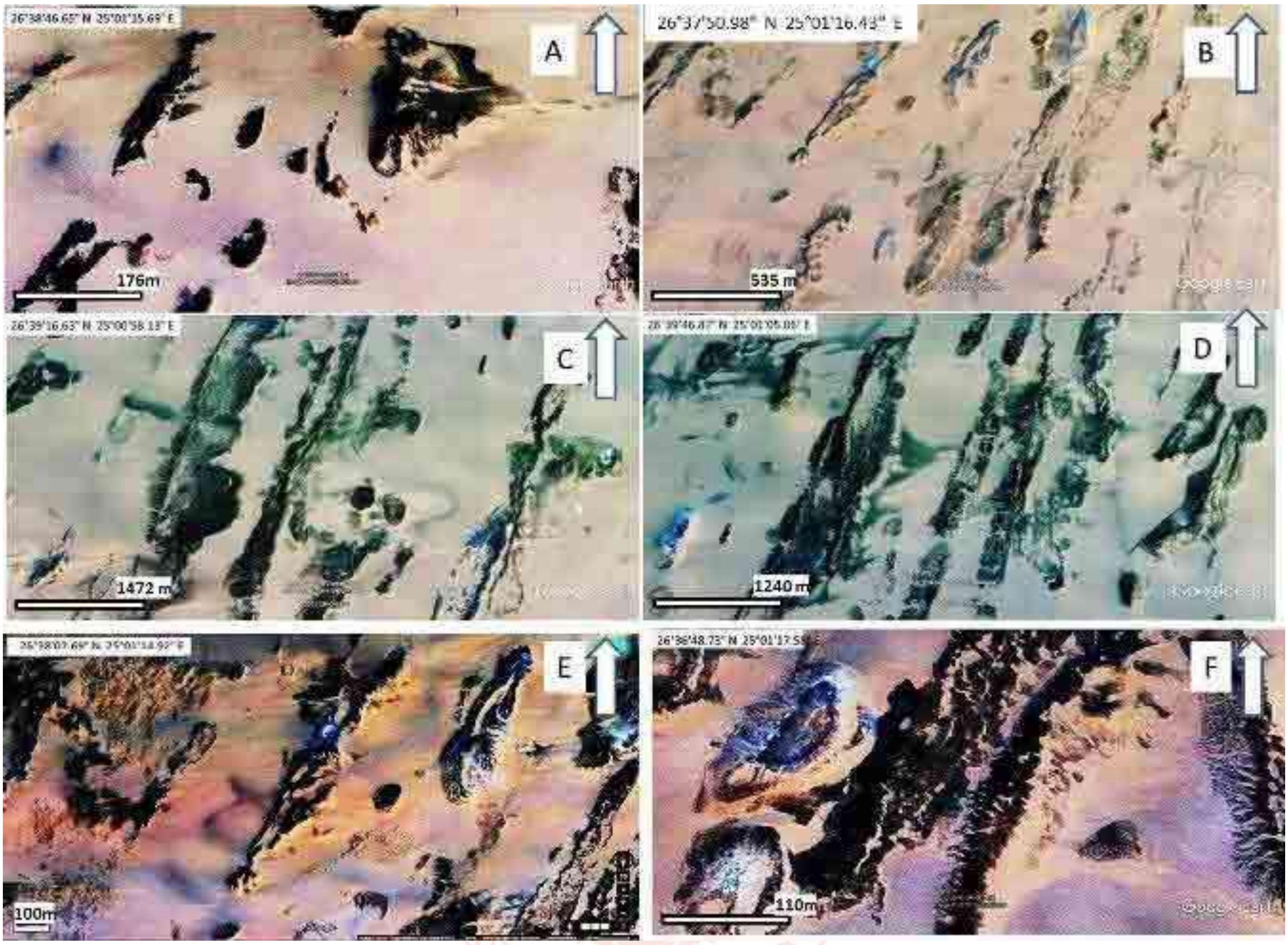


Fig. 45. A-F: Satellite images of Google Earth (A-D and F) and Google Map imagery (E) showing that the drainage pattern in the Nahda Plain is mainly oriented ENE/WSW and originated as a result of the flowing of the distributaries of the Balatah paleoriver of eastern Libya northeastward into Egypt. Two major distributaries of this old river system flowed northeastward into Egypt where they contributed a trellis pattern of parallel draining lines running down slopes of the delta towards northeast in the Egyptian flat sandy plain of El-Nahda. Indications of near-surface groundwater table are evident in this sandy plain where patches and shallow depressions are filled with groundwater seepage coming to the surface. The entire absence of sandstone ridges or sand dunes in the Nahada Plain would indicate that the older periodic or seasonal flooding of the Balatah paleoriver 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.

through Wadi Matawi where it meets with those coming from the southeastern piedmont slopes of Gebel Az Zalmah at the entrance of Wadi Balatah, thus contributing to form the main stream of the old Balatah river at Lat. 24º 37′ 2.31″ N and Long. 23º 56′ 45.91″ E. The drainage pattern in the Nahda Plain is mainly oriented ENE/WSW. It is originated as a result of the flowing of the distributaries of the Balatah paleoriver of eastern Libya northeastward into Egypt.

Two major distributaries of this old river system flowed northeastward into Egypt where they contributed a trellis pattern of parallel draining lines running down slopes of the delta towards northeast in the Egyptian flat sandy plain of the Nahda and separating the main delta plain from the eastern sandstone ridges (Fig. 45). The flatness of this sandy plain indicates that it has a long history with periodic phases of flooding of the paleoriver of the Balatah valley in northeastern Libya during the Pleistocene leeding to complete destruction and disintegration of the Nubia Sandstone high ridges. The total area is covered with a thin veneer (from 5cm to 15 cm thick) of free sands overlying directly the Nubia Sandstone bedrock. The sand cover often shows well developed current ripple marks expressing periodic flooding and overland flow from west to east. Indications of near-surface groundwater table are evident in this sandy plain where patches and shallow depressions are filled with groundwater seepage coming to the surface. The entire absence of sandstone ridges or sand dunes in the Nahada 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.

5. Conclusions

1- The groundwater flowed through and emerged from the highly permeable steeper walls of the Nubia Sandstone (Six Hills and Sabaya formations) ridges, scarps and hillslopes at the free slope surface. The same process has also led to the formation of discontinuous draining channels that migrate headward in ridges and plateaus of steep sides, and theater-like heads that lack well-developed tributaries. The areas of concentrated moisture often induce weathering of the sandstone at and along the seep area. The retreat of the scarp face would cause undermining and, thus, mass wasting of the overlying sandstone which falls into the valley floor below.

2- The widespread distribution of arches, alcoves and eyes in the Gilf El Kebir, the Dakhla Basin and the Great Sand Sea are good indicators of groundwater sapping process where they represent theater-shaped depressions of variable dimensions within the wall or slope on which they have formed. It is worth of mention that the eroded quartz sandstone bed rock below the draining channels is not covered in the flat low-lying tracks by drifted loose sands which come daily from the surrounding slopes, thus suggesting recent groundwater seepage. The general slope of the flat tracks towards north as well as the permeable characters of the surface sandstone bed rock would greatly support the groundwater seepage. Thus, the distribution and morphology of the eroded quartz sandstone bed rock in the flat-floored linear tracks that lack well developed connection to possible surface water sources at the up-dip end of the tracks, leads us to propose that they were eroded by groundwater seeps.

3- The main conditions controlling the groundwater sapping process include a seasonal recharge, a highly permeable trans-missive bedrock (Six Hills and Sabaya Formations which cover an extensive area in the Western Desert), a common development of scarps with free faces at which water can emerge, a frequent development of alcoves and headwall seepage zone almost extended along bedding planes, the undermining of sediments overlying the seepage zone and the low drainage density with short first order headwall streams that are almost running in parallelism.

4- The drainage pattern formed by runoff at the top surface of the western part of the Gilf El Kebir Plateau (Abdel Malik Plateau) is represented by a high complex network of dendritic streams flowing northwards toward the Great Sand Sea. Some of these streams are running down slopes in opposite direction drainage to the west toward Libya whereas to the north and northeast eventually reached to the Great Sand Sea. These streams are parts of larger paleoriver systems consisting of four main parallel channels flowed northward between the passage of Um Ras at west and the Aqaba Passage at east.

5- On the top surface of the eastern part of the Gilf El Kebir Plateau (Kemal El-Din Plateau), east of the Aqaba Passage an independent drainage pattern started at elevation 1050 m a.s.l and the overall streams show a well-marked radial distribution characterized by flow of water outward in all directions from a more or less central point, thus indicating that this part of the plateau is merely an dome

6- All channels and streams of the paleodrainage systems formed by runoff are ephemeral (only carry water during storms). The surface flows suffer rapidly a north- and eastward decreasing discharge downstream due to increased rate of transmission losses. The runoff on slopes of the scarps and cliffs in the Gilf El Kebir Plateau can also be considered to be characteristically Hortonian flow.

7- The widespread distribution of a network of drainage pattern on the top surface of the Gilf El Kebir Plateau indicates that the well exposed joints, pits and cavities on the plateau surface acted to concentrate surface run-off and thus enlarged to form channels. However, much of this surface water is lost due to infiltration in the Nubia bedrock while the remainder flows through narrow notches and falls as a small cascade to the canyon floor. Gullies which develop from the runoff along the edge of the escarpments act together with alcoves to form unsupported roof and the side materials collapse. Continued groundwater sapping processes remove the collapse debris.

8- An Additional but less complex network of dendritic streams of runoff started north of the Abdel-

Malik Plateau at or near Lat. 25º (at elevation of 600 m a.s.l.) and flowed northward in the Great Sand Sea. The network is made up of three main channels varying in length from 120-137 km. One of these channels were flowed northwards and drained out in the North Gilf sandy plain which is situated along the Egyptian-Libyan borders whereas the other two channels ran down slopes towards northeast where they attacked the older Nubia Sandstone ridges in the Great Sand Sea and drained out in closed basins within the tracks between the sandstone ridges. One of the most characteristic features of the Great Sand Sea is the flood breakouts through the cordon of the Nubia Sandstone ridges along the Egyptian-Libyan borders, sometimes as catastrophically large flows termed floodout, thus leading d to the distortion, deterioration and collapse of the Nubia Sandstone ridges due to infiltration of the surface flow through the sandstone beds along joints and faults.

9- There are two main flat sandy plains in the western part of the Great Sand Sea, (the North Gilf Plain in the South and the Nahada Plain in the North) situated along the Egyptian/Libyan borders. These sandy plains seem to have a long history with periodic phases of flooding of the paleoriver systems coming from the northern slopes of the Abdel-Malik plateau and from the Balatah Valley in northeast Libya during the Pleistocene, leading to the complete destruction and disintegration of the pre-existing Nubia Sandstone ridges, thus contributing to the flatness of the plains. The bedrock of the plains is made up of Sabaya Formation covered by a thin veneer of loose sands.

10- The North Gilf Plain extends for a length ranging between 68 km along the Egyptian-Libyan borders to 87 km eastwards, and a width decreasing from 35.6 km at the south to 10.2 km at the north, assuming a total area of 1678 km². It has a flat surface sloping gradually from an elevation of 435 m in the south to 290 m above sea level in the north. The plain is dissected by a dendritic drainage pattern running north and northeastward representing northward streams (75-135 Km long) flowed from the northwestern slopes of the Abdel-Malik Plateau near the Egyptian-Libyan borders. Some of these streams drained out within the Northern Gilf Plain, whereas others are twisted towards northeast where they attacked the older Nubia Sandstone ridges in the southern part of the Great Sand Sea and drained in closed basins in wide valleys and among flat tracks between the sandstone ridges.

11- The Nahda Plain is a large triangular flat plain extending ~120 km along the Egyptian/Libyan border 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. This plain represents the eastern extension of a vast delta plain in northeastern Libya which belongs to the paleoriver system of the Balatah Valley and not belonging to the Kufrah paleoriver as previously proposed. The delta was formed when the old River system of Wadi Balatah in northeastern Libya discharged northward into a huge, freshwater Pleistocene lake occupying ~ 24218 Km², between latitudes 26º 30' and 28° N, and longitudes 23º 22' and 25º 22' E. It 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 most lowest lands in northeastern Libya.

12- The source of the Balata paleoriver is independent from the Kufra paleoriver system. 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 Balatah. The divide (topographically high areas) which separates the drainage basin of the Balatah paleoriver system from the adjoining Kufrah paleoriver one is running NW-SE ~8 km before the entrance of Wadi Balatah at Lat. 24º 33′ 45.17″ N and Long 23º 53′ 43.6″ E. This divide separates drainage in opposite directions of the 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 divide eventually goes to the Wadi Balatah basin and then to the Balatah delta plain.

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