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Remote Sensing and Geographic Information System (GIS) Contribution to the Inventory and Investigation of Dikes in Egypt

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ABSTRACT

Dikes are widespread in Egypt and are partly even the prevailing elements in the landscape besides the youngest sedimentary covers, especially in the southern and eastern part of the country. Although dikes are one of the predominant phenomena in Egypt, a systematic, standardized inventory of dikes in the whole country and a dike data base has not been published so far, although several selected areas have been investigated very detailed such as along the Red Sea and in the Sinai. Remote sensing and Geographic Information System (GIS) offer tools for such an inventory. This inventory is of interest for many purposes such as for the mining industry (many dikes are related to mineral occurrence of economic value), and also for hydrogeologic investigations and land use planning. Surface-near dikes, major fault zones, volcanic and structural features were digitized based on Landsat 8 and 9, Sentinel 2, Sentinel 1 and ALOS PALSAR data. High resolution images of World Imagery files/ESRI and Bing Maps Aerial/Microsoft were included into the evaluations. More than 32,000 dikes were digitized and analysed. The evaluations of satellite images allow a geomorphologic differentiation of types of dikes and the description of their characteristics such as dike swarms or ring dikes as well as of their distribution pattern and orientations. Dike density calculations were carried out in ArcGIS to support the detection of areas with dike concentrations. Earthquake data were included into the investigations as dikes might play a role in the development and effects of earthquake swarms in the area of reservoirs.

Keywords: Dikes; Earthquakes; Egypt; Geologic structures; Geographic Information System (GIS); Fault zones; Remote sensing; Reservoir.

1. Introduction

Dikes are widespread in Egypt and are partly even the prevailing elements in the landscape besides the youngest aeolian and fluvial sedimentary covers, such as in the SW, S and of E the country (Fig.1) or along the Red Sea. Although dikes (formed by magma intruding into fractures, faults or bedding planes) are one of the predominant phenomena in Egypt, a systematic, standardized inventory of dikes and data mining of the whole country and a dike data base integrated into a Geographic Information System (GIS) has not been published so far, although several selected areas have been investigated very detailed, especially along Gulf of Suez and the Red Sea and in the southern part of Sinai [1] [2] [3] [4] [5]. Although dikes are of great interest for the mining industry [6] there is not yet a common standardized GIS platform available to integrate dike related data.

1.1. Research Objectives

This study aims to contribute to a dike related data mining and to a dike data information base. Such a data base could be useful for many purposes, for example for mineral prospection [7] [8] [9] or for land use planning such as irrigation management, especially sprinkler irrigation. Remote sensing and GIS tools offer tools for such an inventory of dikes using a standardized data base despite the limits of remote sensing, especially in areas covered by large dune fields, aeolian and fluvial sediment sheets.

Difficulties for mapping dikes based on satellite data appear whenever dikes intruded into bedding planes of host rocks with similar spectral properties. However, as dikes are often more resistant to weathering and erosion than their host rocks or sediments, the contacts between the intruding dikes and their host rocks are in general distinct.

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Nevertheless, it becomes sometimes difficult to separate dikes from ridges in the host strata if there are no tonal differences on the satellite images.

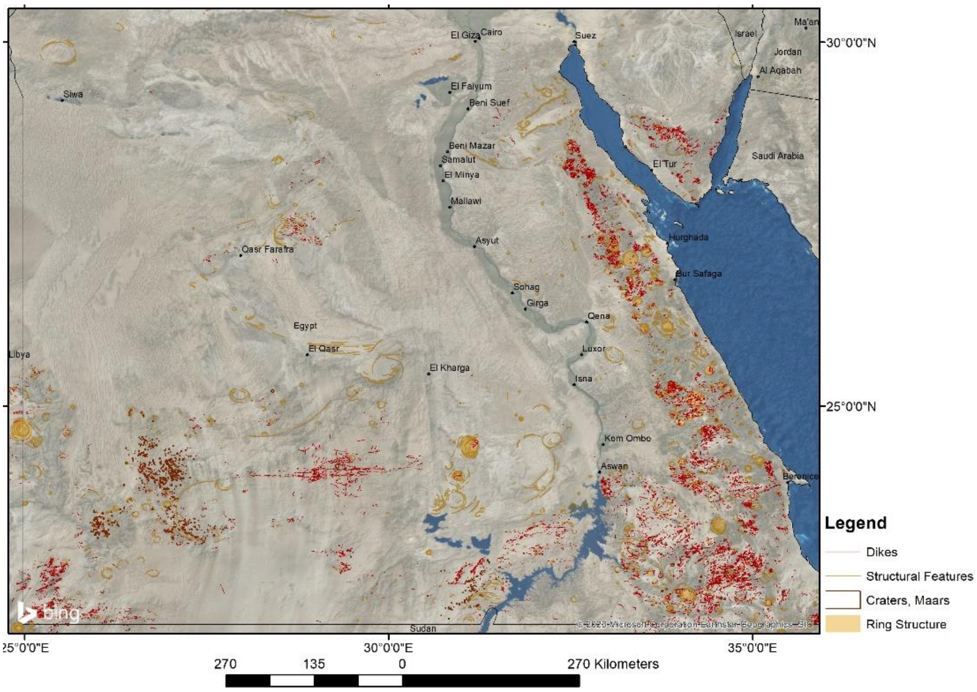

Figure 1. Occurrence of visible dikes on satellite data in Egypt

Linear wind erosion causing narrow linear, parallel ridges and channels hinder the detection of dikes as well. Sealed areas due to the spreading urbanization in the Nile delta play a hindrance role for the detection of dikes, too.

The "human factor" has to be taken into account as well as in case of uncertainty (whether a dike can be identified clearly or not) it was decided not to digitize a linear feature as a dike. Thus, errors cannot be excluded, and field research is required to verify the mapped dikes or to detect dikes not visible on the satellite images. Therefore, this study aims to contribute to the support of focused field research.

Many questions concerning the impact of dikes on their environment, such as on surface water infiltration in case of rare precipitations in the desert environment and on groundwater flow, are still open and need further investigations. This knowledge is important for the irrigation management. This study aims to rise attention to this problem.

Another question deals with complex effects in case of stronger earthquakes considering local site conditions. For example, how do dike swarms interact with seismic waves? Are they forming barriers or are they guiding and focusing seismic waves depending on their strike and dip? It can be expected that they have an influence on macroseismic effects, depending on the earthquake fault plane solution properties such as the orientation of the fault or the earthquake depth. Can a deep-seated stronger earthquake initiate dike development? The possibility of a stronger earthquake triggering the uprise of dikes in areas prone to volcanic activity cannot be excluded.

Further questions arise whether dike swarms have an influence on induced and triggered seismicity around the High Dam reservoirs in the Aswan region [10]. Seismic activity related to reservoir loading was observed worldwide. It influences stressed faults with increased water damming, albeit with a short time lag and/or because the fluid pore pressure causes a shift in the underlying earth, leading to increased seismicity [11] [12] [13]. Along deep-seated, vertical zones of weakness surface water can infiltrate depending on strike and dip into the subsurface allowing movements of fluids downwards up to several kilometers. Dikes can affect this infiltration such as a conductor or tunnel. To raise awareness of these interactions is another goal of this study. Of course, all these questions cannot be answered in the scope of this research, however, some ideas might lead in this direction.

2. Materials and Methods

Satellite data were digitally processed and evaluated such as Sentinel 1 – C-Band, Synthetic Aperture Radar (SAR) and ALOS PALSAR L-Band radar data and optical Sentinel 2 images, and Landsat data (Landsat TM and Landsat 8 and 9 of the Operational Land Imager-OLI) using digital image processing software as the Sentinel Application Platform (SNAP) / ESA and ENVI / L3Harris Geospatial Solutions as well as the geoinformation systems ArcGIS/ ESRI and QGIS (Fig. 2). The data were provided by the USGS EarthExplorer [14], ESA Copernicus Open Access Hub [15], and NASA Earth Data, Alaska Satellite Facility (ASF) [16].

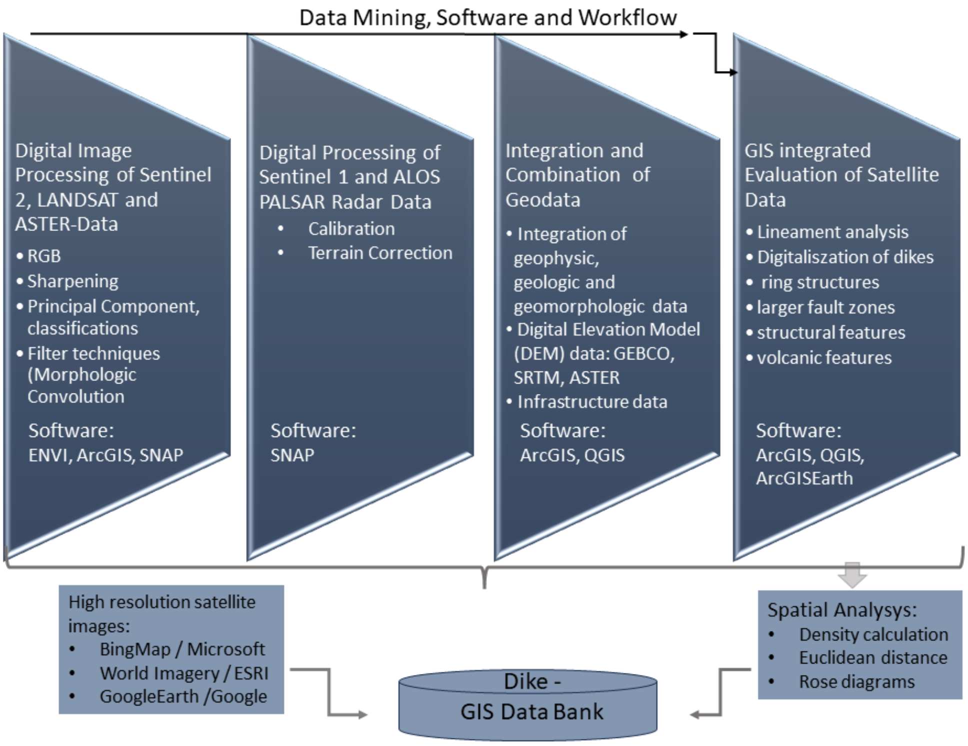

Figure 2. Materials, methods, software and workflow

The use of L-Band radar data is demonstrated in Fig.3 a and b by showing the occurrence of dikes as light lines very clearly. Of course, the illumination geometry of the radar signals plays an important role related to the visibility of dikes.

Those oriented perpendicular to the radar signals are better detectable than those oriented parallel to the viewing geometry. The black lines on Fig.3 are related to linear valleys filled with loose sediments. Their development was influenced in general by fault and fracture zones.

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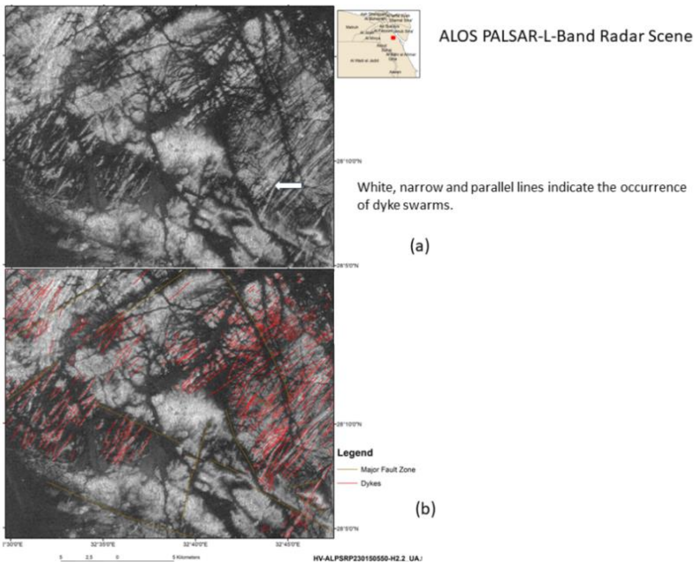

Figure 3 a and b. Visibility of dikes as white lines on a ALOS PALSAR radar scene (a) and its evaluation (b)

Digital image processing of LANDSAT 5 Thematic Mapper and Landsat 8 /9, - the Operational Land Imager (OLI), data was carried out by merging different Red Green Blue (RGB) band combinations, especially including the thermal bands 7 and 10. Thermal inertia controlling surface temperatures support the identification of dikes as their reflection in the thermal band is different from the environment. The combination of Bands 2,7 and 10 provided a useful base for the detection of dikes as demonstrated in Fig.4. Dikes, volcanic features, major lineaments and structural units (synclines, anticlines, ring structures) were digitized visually based on the different satellite data.

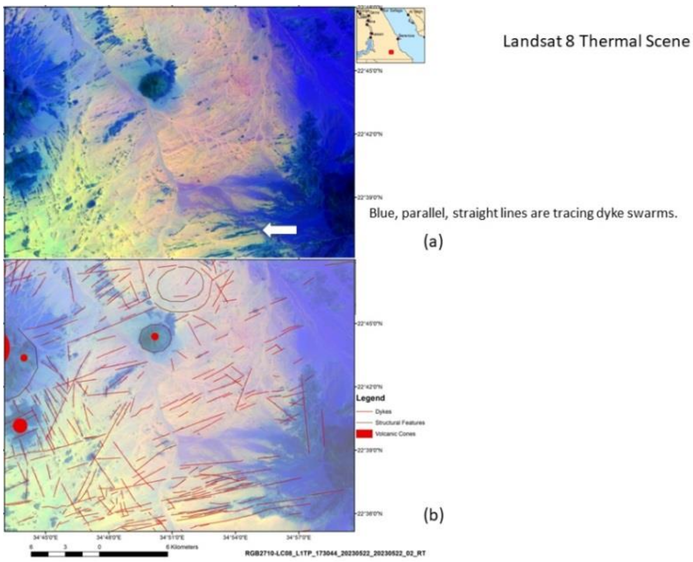

Figure 4 a and b. Landsat 8 RGB (Bands 2,7 and 10) scene (a) showing dike swarms striking in different directions visible as dark-blue lines and the evaluation results (b)

Principal Component Analysis (PCA) was carried out as well. PCA has been utilized on Landsat-8/9, ASTER and Sentinel 2 data to enhance the lithological discrimination. High resolution images of World Imagery files and ArcGIS Earth / ESRI and Bing Maps Aerial / Microsoft were included into the evaluations.

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Shapefiles were created in ArcGIS related to dikes, volcanic features, ring structures, lineaments, and structural features. Especially Sentinel 1 and ALOS PALSAR radar images reveal larger fault zones, for example by dislocations of lithologic units that can be digitized. Because of the used methods dikes were mainly classified according to their characteristic appearance in size and morphology and combination with other volcanic features. More than 32,000 dikes were digitized. The specific regional differences of dikes related to their occurrence, distribution, density, and morphologic properties appear clearly when evaluating high resolution satellite images such as from Google Earth, Bing Map Aerial /Microsoft, and World Imagery / ESRI. Besides the mapping of dikes the focus was directed to the detection of different types of ring structures such as domes, concentric basins, and craters. The term crater is used as neutral description of the morphology, again without relation to its origin. It can be related to maars, explosive monogenetic volcanic eruptive centers, as well as to cosmic impact craters.

3. Geographic and Geologic Overview

The main morphologic regions comprise the Nile Valley, the Nile Delta, the Western Desert, the Eastern Desert and the Sinai Peninsula. Due to the coverage of the lower areas of Egypt with sediments dykes are more visible in higher situated region as demonstrated in Fig.5. Therefore, the height level map shows that below 100 m height level dikes (if there) could not be detected. Most of the digitized dikes were mapped in height levels between 800 to 1000 m.

The general geologic/tectonic framework of Egypt is comprising several units that have controlled the sedimentological history and the structure of the country. Large fault systems represent major transcontinental and regional fracture zones [17]. These originated during different episodes of crustal deformation. Phanerozoic intraplate deformation and related processes of erosion and sedimentation were generally controlled by structural trends which were frequently reactivated along existing fault systems. Magmatic and tectonic activity in Egypt at the end of the Palaeozoic continued into the Triassic.

Nubia Sandstone strata were deposited in southern Egypt from Jurassic to Late Cretaceous or Early Cenozoic. The Arabo-Nubian massif occupies the eastern part of the Eastern Desert of Egypt and extends to the southern part of Sinai Peninsula. It is a surviving aggregate of a mobile belt that developed in the early part of geologic history before the differentiation of preservable faunas. They include widespread acidic igneous intrusions. Large-scale of ultra basic to basic intrusions such as lava flow or dikes intruded into the sediments before their metamorphism [18]. Tectonic and magmatic activity increased again towards the end of the Cretaceous Period [19] [20].

ENE to E-W wrench faults control the Cretaceous-related structures all over the country. In the central and southern parts of Egypt the sedimentary units of the Jurassic-Nubian interval are capped by younger formations. The base of the Nubia Sandstone forms swell-like uplifts separated by troughs. Restricted tectonic basins are characterized by a thick accumulation of Mesozoic-Cenozoic sediments. Old fractures inherited from the basement were used after vertical propagation as shear zones along which the whole sedimentary cover would deform. Geological observations made in southern Egypt support the tectonic origin of the Nile Valley [21]. A geologic overview is shown in Fig.6.

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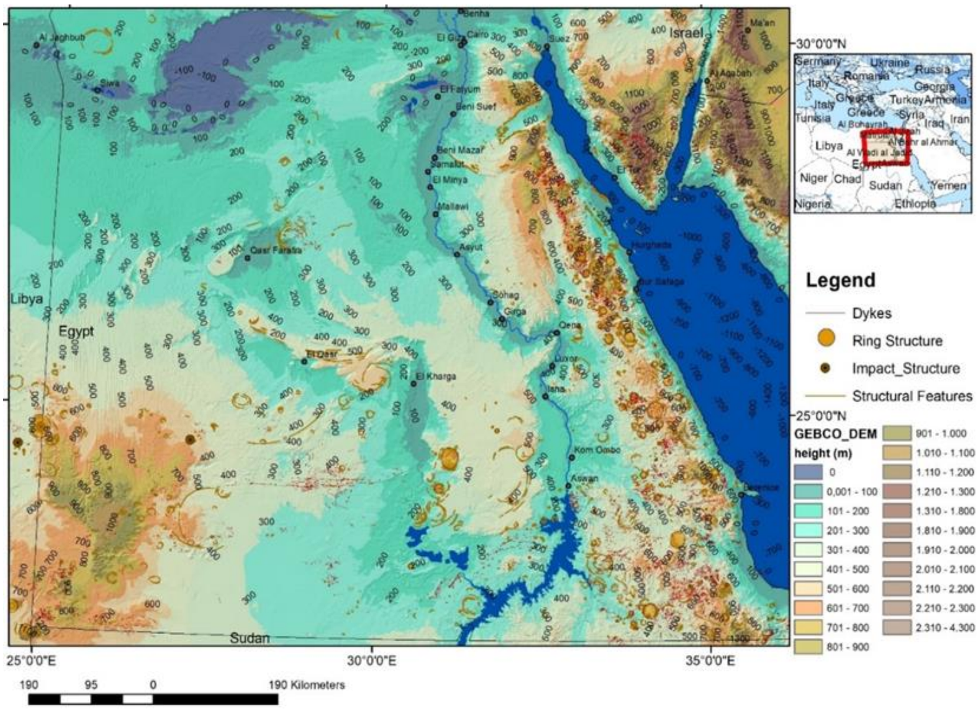

Figure 5. Height level map of Egypt based on GEBCO data and dike occurrence

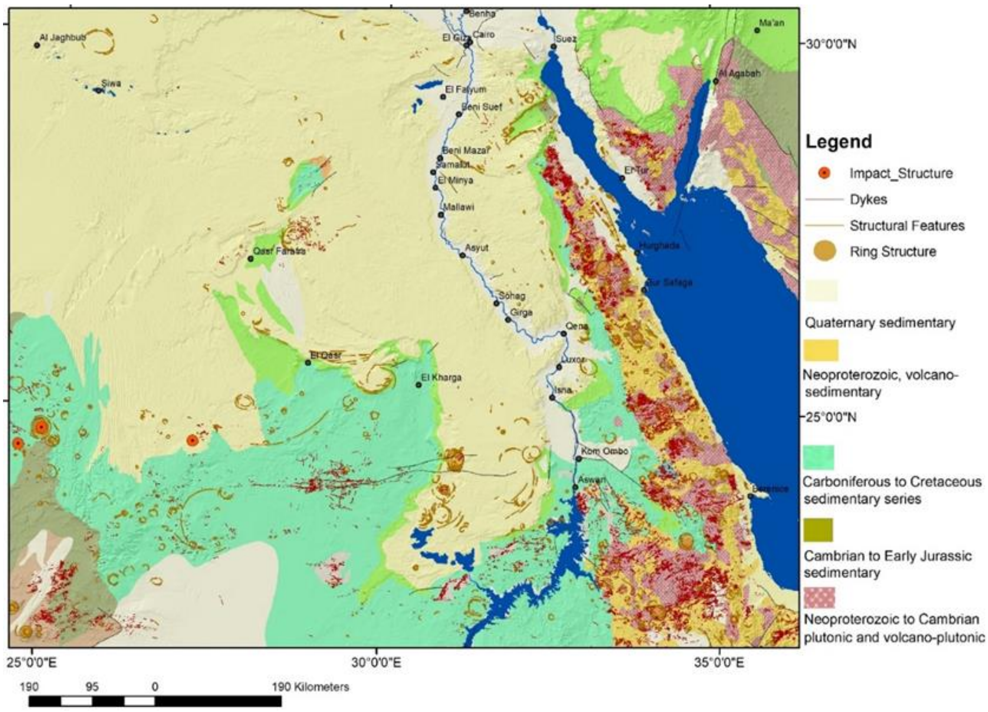

Figure 6. Geologic overview according to BRGM SIGAfrique Bedrock and Structural Geology (1: 10 Mio) and about 32,000 digitized dikes

3.1. Dikes

Dikes vary in their mineralogical composition, age, morphological appearance, and structural environment. In the volcano-tectonic regions of Egypt dike propagation from shallow magmatic chambers is often controlled by the interaction of the local and regional stress fields. The variations of the stress fields result from a combination of factors including the regional tectonic strain, the geometry of pressurized magma chambers, the layering and the pre-existing discontinuities [22] [23] [24]. Reactivations of pre-existing normal fault structures play an important role for the development dike swarms. However, dikes themselves can influence and modify the fault pattern during the uprising and intrusion of magma as well by inducing stress changes in the surrounding rocks, leading to deformation and movement on faults [25].

Some examples of the variety of dikes are presented: In the Eastern Desert and Sinai Peninsula dikes are basaltic to rhyolitic in composition, closely associated with granitoids, and intruded under extensional conditions. The Eastern Desert of Egypt includes numerous undeformed to slightly deformed mafic dyke swarms. The dike swarms provide a window into the composition and evolution of the sub-continental mantle and the tectonic evolution of the overlying continental crust. Their orientation can provide information on the regional stress field at the time of emplacement [26] [27]. The mafic dikes were fed by deep-seated basaltic magma reservoirs or chambers located at the crust-mantle boundary or in the lower crust, close to the Moho (20–25 km) and the Conrad (15–18 km) discontinuity in the area. The dikes occur in sub-parallel sets of a variety of trends which are inferred to represent separate swarms of distinct ages. The largest swarms are up to 60 km long and 20 km wide. The thickness of individual dikes ranges from 3 to 70 m, but there is tendency for each swarm to have a characteristic thickness. Age constraints on some swarms are available from crosscutting relationship with host rocks of known ages. Many of them are related to deep seated, nearly vertical dipping planes. Isotope geochronology of the Eastern Desert swarms is scarce, but from crosscutting relationships and field observations the following swarm ages are inferred: N-trending swarm (assumed to be younger than 660 Ma), NE- trending dikes (Rb—Sr age of ~590 Ma), E- trending dikes, and NNW- dikes (c. 25 Ma). The latter is assumed to coincide with the Red Sea opening (~25 Ma), which was originated as an Oligocene continental rift impacted by left-lateral wrenching [28]. Limited geochemistry is available for the swarms, and broadly indicates tholeiitic to calc alkaline compositions [3] [29] [30].

A large late Cenozoic basalt field exists in northern Egypt centered on the city of Cairo. Large-scale basaltic dikes, monogenetic volcanoes, and coeval extensional faults and grabens are associated with these alkali basalts and physiographically and structurally link this province to the Gulf of Suez [2] [31]. New 40Ar/39Ar dating indicates that this widespread and voluminous Egyptian volcanism occurred over a short time interval of less than 2 Ma at the Oligocene–Miocene boundary (23 Ma). Some outliers of basalt flows were erupted at the cores of Late Cretaceous Syrian arc anticlines as at Bahariya oasis [31].

Dikes predominate within the Neoproterozoic rocks such as in the southern Eastern Desert of Egypt. The dike swarms form three major suites: from the oldest to the youngest, they are basaltic andesite—Suite 1 (E-W and ENE-WSW), rhyolite—Suite 2 (NE-SW), and andesite—Suite 3 (NNE-SSW, NNW-SSE, and NW-SE). It is supposed that the Suite 1 and 2 dikes are a conjugate set emplaced due to the NW-SE crustal extension in the Arabian-Nubian shield, whereas the Suite 3 dikes generated due to the rifting along the Red Sea [32]. Field and geochemical characteristics of the Egyptian Tertiary volcanism proved that it is spatially and temporally related to extension that has occurred during Red Sea rifting. Extension most likely due to the NE–SW tensional stresses

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which reactivated the old fractures and triggered mafic magma generation through passive upwelling of the asthenospheric mantle [33].

Compared with widespread Egyptian Tertiary basaltic rocks, Mir Tertiary basaltic dikes from the Southwestern Desert of Egypt show distinct mineralogical and geochemical characteristics that provide insights into the nature of their mantle source and geotectonic evolution as well as melting and crystallization conditions. [2] [34]. Their mineralogical features distinguish them from the other Egyptian Tertiary basalts. They have basaltic andesite compositions with tholeiitic character.

Variable single and/or swarms of post-granitic dikes are widespread at Gabal Serbal, Southwestern Sinai [9]. These dikes are classified into two subphases: (1) acidic dikes (porphyritic dacite, microgranite, granophyre, and alkaline granophyre dikes); and (2) basic dikes (basalt and dolerite dikes). They range from vertical or steeply inclined bodies, 0.5–15 m wide, and striking in NE–SW to N–S directions.

4. Evaluation Results

The development of dikes was marked by extension and emplacement of many generations of dikes, during earth's history affected strongly by tectonic movements. The presence of dikes indicates that Egypt was affected by great tensional stresses, and the fractures and faults created by these stresses where subsequently filled by dikes and veins. Age constraints on some swarms are available from crosscutting relationship with host rocks of known ages. Isotope geochronology of dikes is scarce, but from crosscutting relationships and field observations the following swarm ages are inferred. This is demonstrated by examples from the Sinai and the Eastern Desert.

The evaluations of satellite data reveal the existence of the different suites of dikes related to differences in melting or crystallization regimes and ages (Fig.7 a and b). The light-brown dikes are overlaying the previous dike systems (Fig.7 b). Different types and patterns of dykes are revealed as well (Fig.8).

4.1. Types and Patterns

The main striking direction, the pattern and types of dikes show variations from area to area. The directional trend analysis indicates that the dikes exhibit several main trends accordingly (Fig.9). The different patterns and spatial arrangements of the dikes reflect the varying specific stress situations, the properties of the host rocks, pre-existing faults and fractures, as well as the influence of the type of magmatism. In the Gilf Kebir Paleogene volcanic province in SW-Egypt with extent of scattered surface flows, cones, and explosive craters, partly with central plugs [2], the associated dikes are often more an alignment of plugs and smaller cones, like geomorphologic type c) of Fig.8. Radial and concentric dikes are here related to craters.

In comparison with other volcanic provinces in Egypt the number and density of dikes in the Gilf Kebir region is relatively low and the distribution pattern more irregular. The maars in this area are low-relief, broad volcanic craters formed by shallow explosive eruptions. The explosions were probably caused by the heating and boiling of groundwater when magma invaded the groundwater table.

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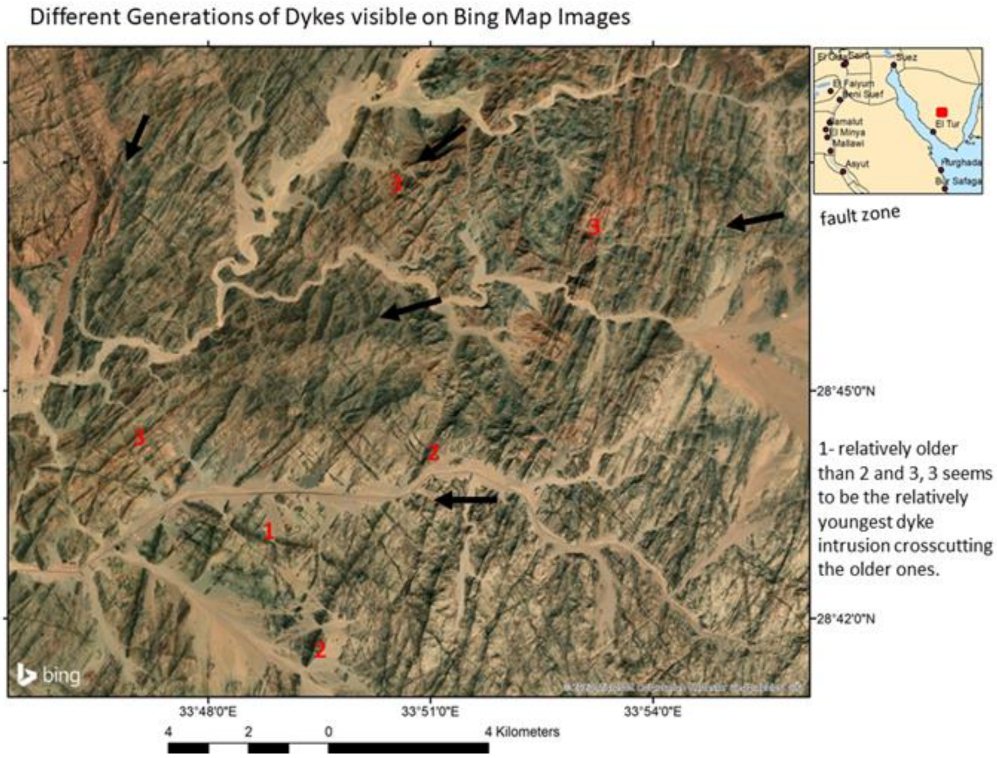
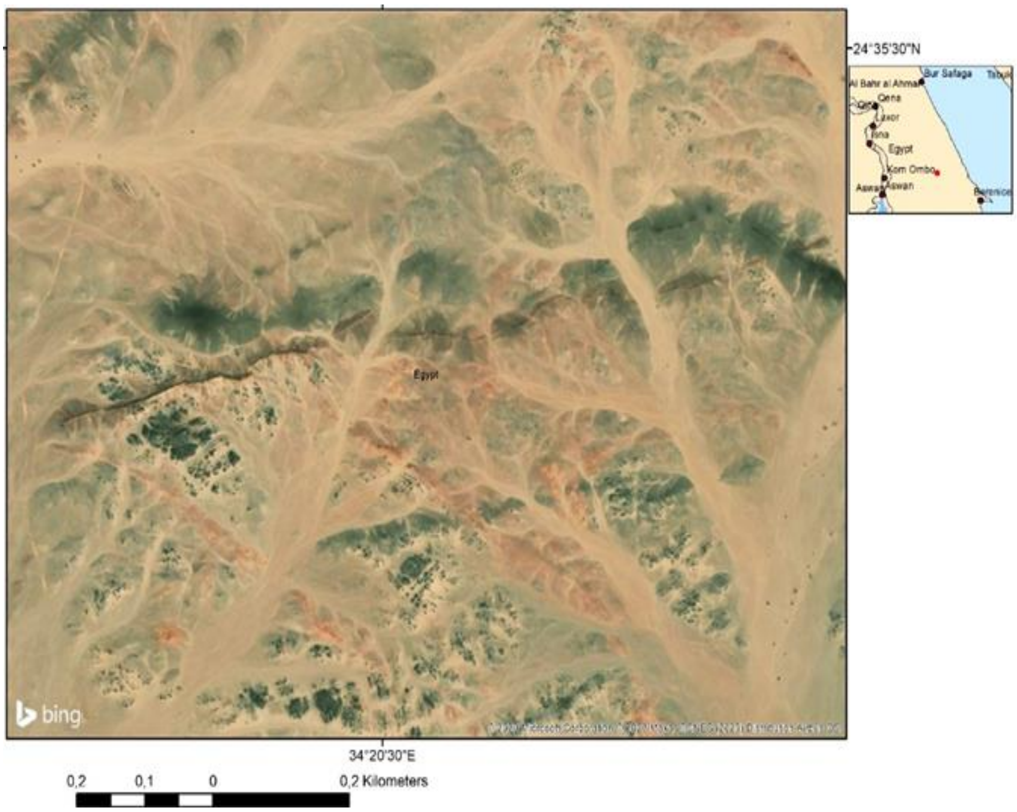


(a)



(b)

Figure 7 a and b. Deriving relatively generations of dykes and veins from Bing map images (the light-brown dykes seem to be the youngest generation as 3 in a), b)

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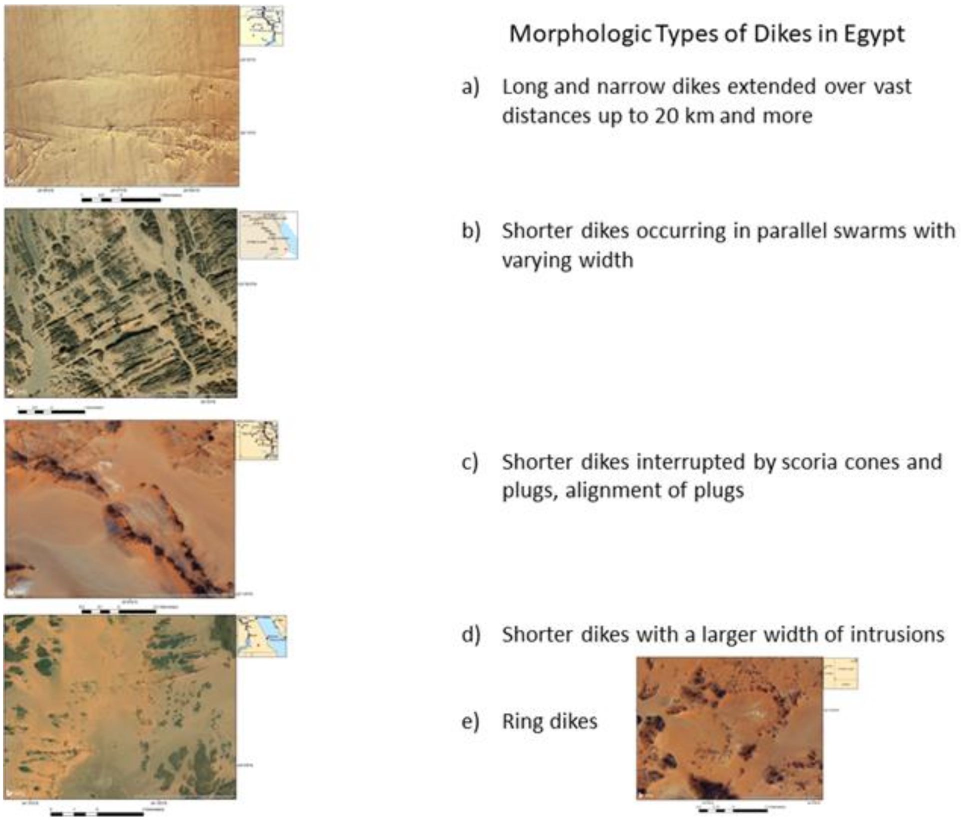

Figure 8. Morphologic types of dikes

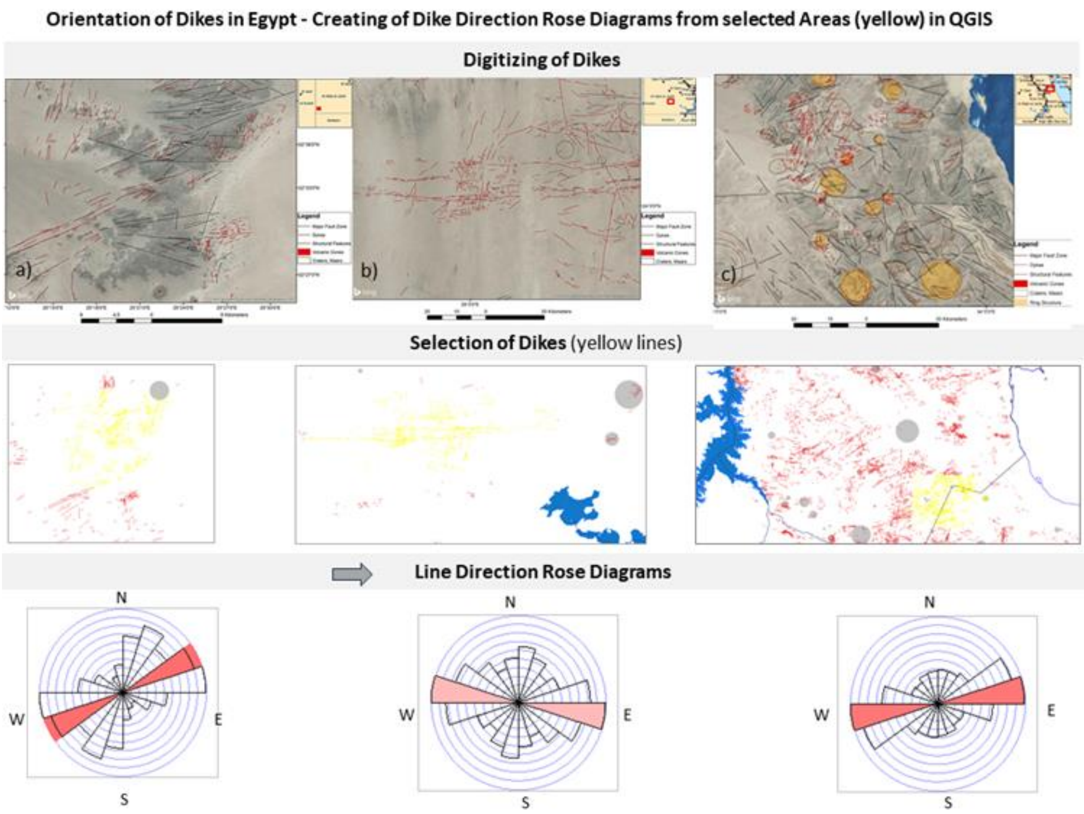

Figure 9. Varying types of dikes, dike pattern and main orientation of from area to area (main orientation trends are shown in red)

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The Western Desert and central southern part of Egypt is dominated by extended, parallel, mainly W-E oriented dike intrusions (Figs.9 b, and 10) along distinct fault zones such as the Kalabsha fault. The height level map based on ALOS PALSAR DEM data (12.5 m spatial resolution) of that area (Fig.10 a) the dike segments appear as long, linear ridges, on the ALOS PALSAR, L-Band radar scene (Fig.10 c) as white lines due to the stronger radar backscatter, and on the Landsat 8 scene as linear features (Fig.10 d).

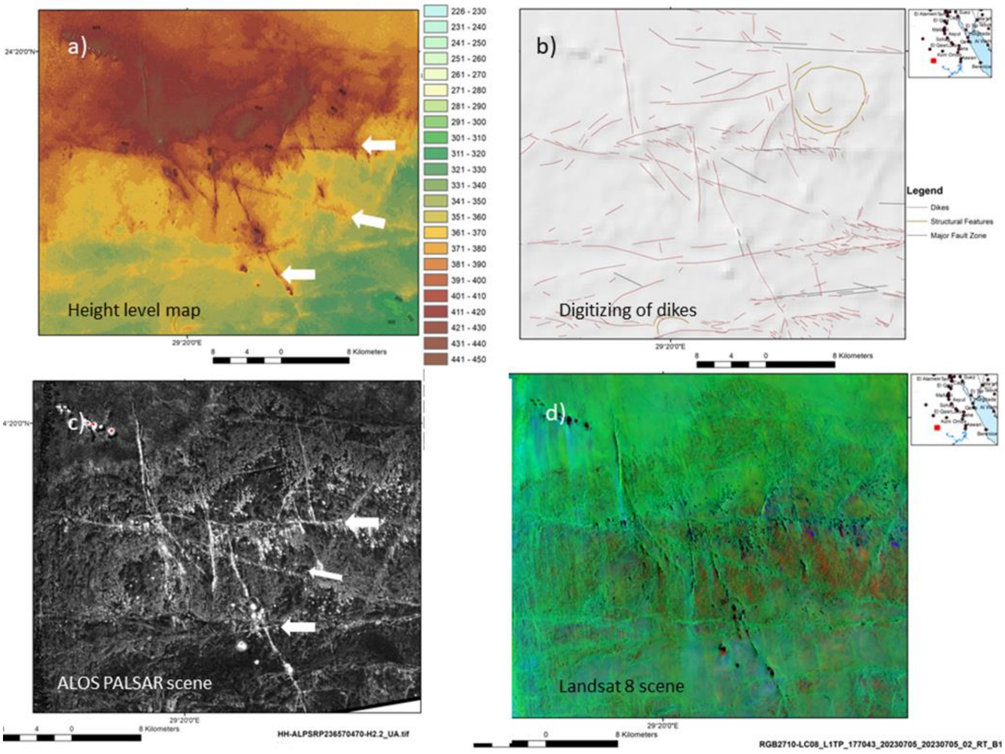

Figure 10. Dikes forming long, narrow ridges in the Western Desert visible on different remote sensing data. (a) Height level map based on ALOS PALSAR DEM data, (b) ALOS PALSAR radar scene, (d) Landsat scene (RGB 2,7,10)

The dike pattern along the Red Sea Hills is characterized by the occurrence of dike swarms with different ages and varying orientations (Figs.9 c and 11 a and b). The main strike direction of dikes in the Red Hills changes from north to south from SSW-NNE to SW-NE about nearly 20° (Fig.11 a and b). The first principal strains of all epochs are compression force in the SW- NE direction and the second principal strains are extension in the SE–NW direction. The direction of the compression force is from NE to SW [18].

4.2. Influence of Ring Structures on Dike Occurrence

The role of ring structures and larger fault zones has to be considered when analyzing the occurrence and distribution pattern of dikes. The different types of ring structures such as granitic domes, deeply eroded traces of magmatic bodies forming circular basins, or larger [maars have an influence on the development of ring and radial dikes and dike swarms (Figs.11,12 &13).

The crystalline basement of the Egyptian Red Sea rifted margin and the Eastern Desert formed during the Neoproterozoic and resulted from several magmatic and metamorphic phases developed during the Pan-African

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orogeny [4] [35]. The Pan-African orogeny was terminated by intrusion of granites (595 Ma) and its volcanic equivalents.

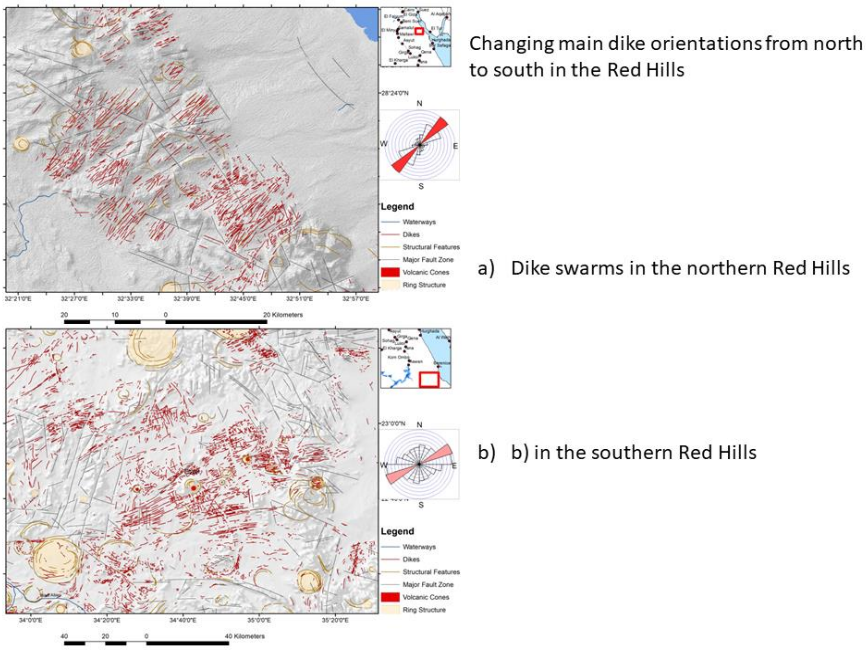

Figure 11 a and b. Dike pattern variations depending on factors such as the lithologic conditions of the host rocks, tectonic stress, larger fault zones, ring structures and geodynamic movements

Whereas within granitic domes forming outstanding hills relatively fewer dikes to be detected, the circular structures forming basins often contain dike swarms of different ages. Some granitic domes seem to form a barrier to dikes. However, the more weathered and eroded domes become along the Red Sea area, the more they are intersected by dike swarms (Figs.11,12 & 13).

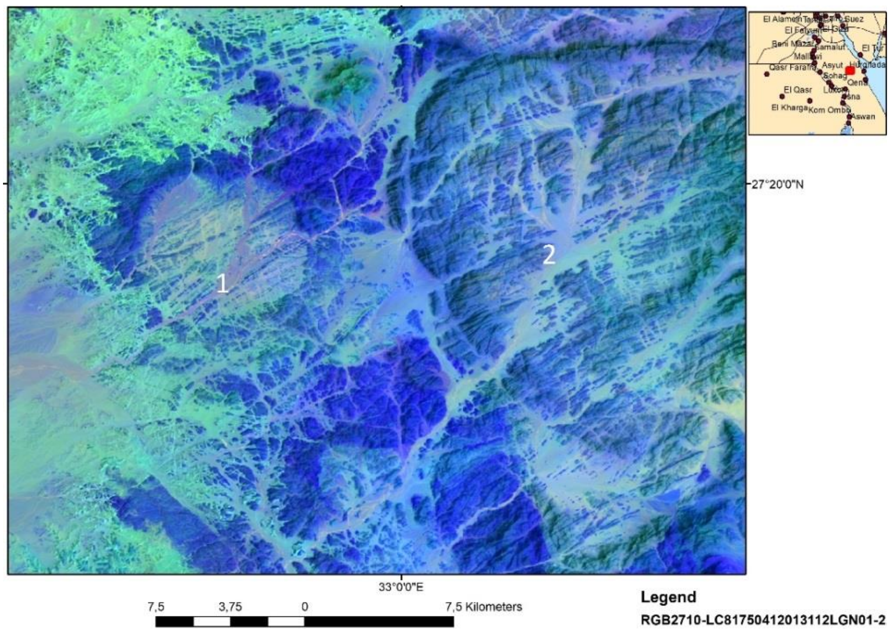

Figure 12. Larger ring basin (1) and eroded and fractured domes (2) intersected by dike swarms visible on a Landsat 8 RGB scene composed of Bands 2,7 and 10

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The larger ring depressions are often “filled” with dike swarms striking in different directions. Thus, the lithological and geomechanically properties and strain conditions of the host rocks are clearly a decisive factor related to the density of dike swarms. Younger volcanic craters, often with central plugs, generally are rarely crossed by linear dikes, but sometimes surrounded by ring dikes (Fig.13 (1)).

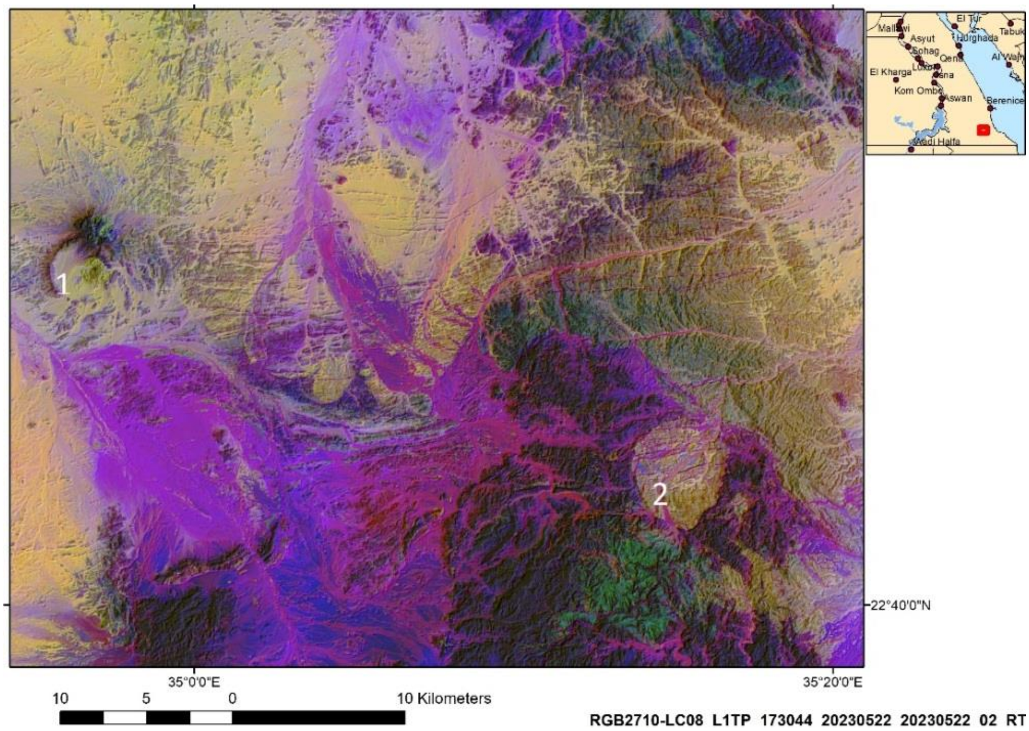

Figure 13. Different lithologic types of ring structures visible on a Landsat 8 RGB scene (Bands 2,7 and 10), 1) a volcanic structure with a central plug seems to be the youngest ring structure with few dikes cutting through, 2) ring basins are intersected by dike swarms

4.3. Potential Influence of Dikes on Seismicity during the last Decades?

The question arises whether dike occurrence has an influence on earthquakes, especially whether magmatic bodies have an influence on fault plane solution processes (asperities?) with interactions? Is there a possibility that stronger earthquakes might trigger the development of dikes, especially along the Red Sea? Dike intrusions induce stress changes in the surrounding rock, leading to seismicity and deformation as well as to movement on faults [25]. Furthermore, this interplay affects volcanic and seismic hazards, as large earthquakes are sometimes triggered or entirely induced by dikes [36]. Moreover, faulting can alter the dynamics of dike intrusions. To find potential relationships and patterns or complex interactions between dike and earthquake occurrence and effects, earthquake data of Egypt (sources: [37] International Seismological Centre - ISC, [38] Euro-Mediterranean Seismological Centre - EMSC, [39] US Geological Survey – USGS, and references [40] were included into these investigations. Fig.14 shows earthquake epicenters of the last decades in Egypt with magnitudes > M 3.

A dike density calculation was carried out (Fig.15) and compared with the earthquake depth data (Figs.16 and 17). In Fig.16 are presented the Inverse Distance Weighted (IDW) interpolated depths of the earthquakes based on ISC data. The deep-seated earthquakes > 20 km depth along the Red Sea indicate the tectonic rifting processes combined with magmatic activity [41] [31]. Recent magmatic eruptions were documented in Saudi Arabia in 2009 and 2011 [42] [43]. The dike density calculation was compared with the earthquake depth data (Figs.16 and 17).

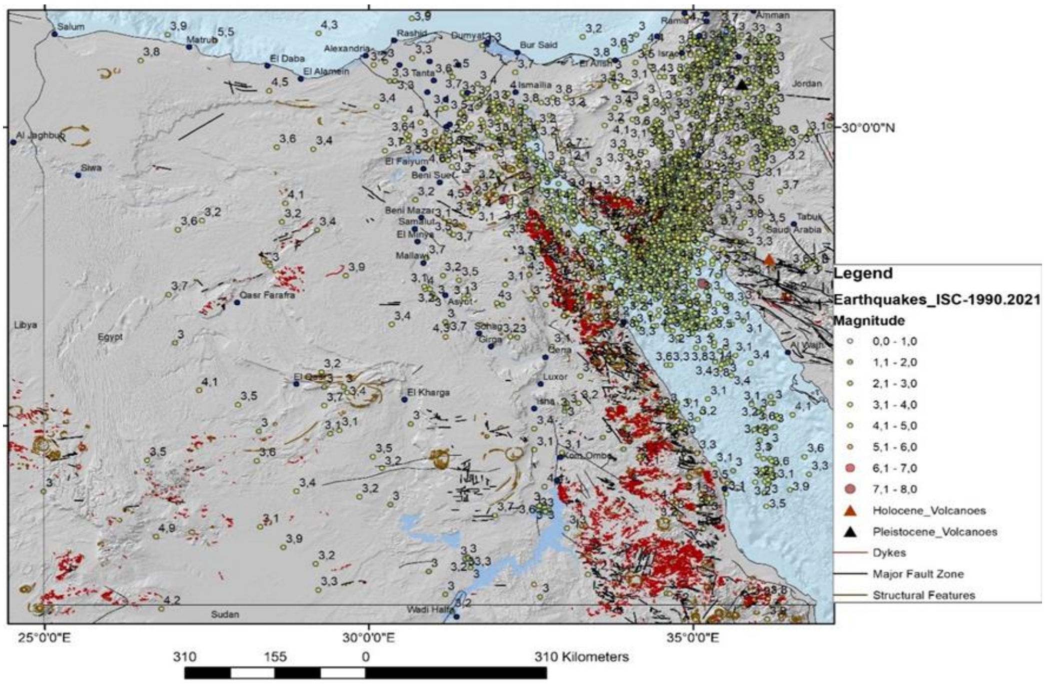

Figure 14. Earthquakes in Egypt with magnitudes M > 3 from 1990 to 2023 (data source, ISC, EMSC, USGS)

Although there are no earthquake events with higher magnitudes known in Egypt that can be linked to recent dike development, it can be assumed that past and more recent magmatic activity and so far documented earthquake distribution and depth provide hints about areas exposed to higher tectonic stress and geodynamic activity.

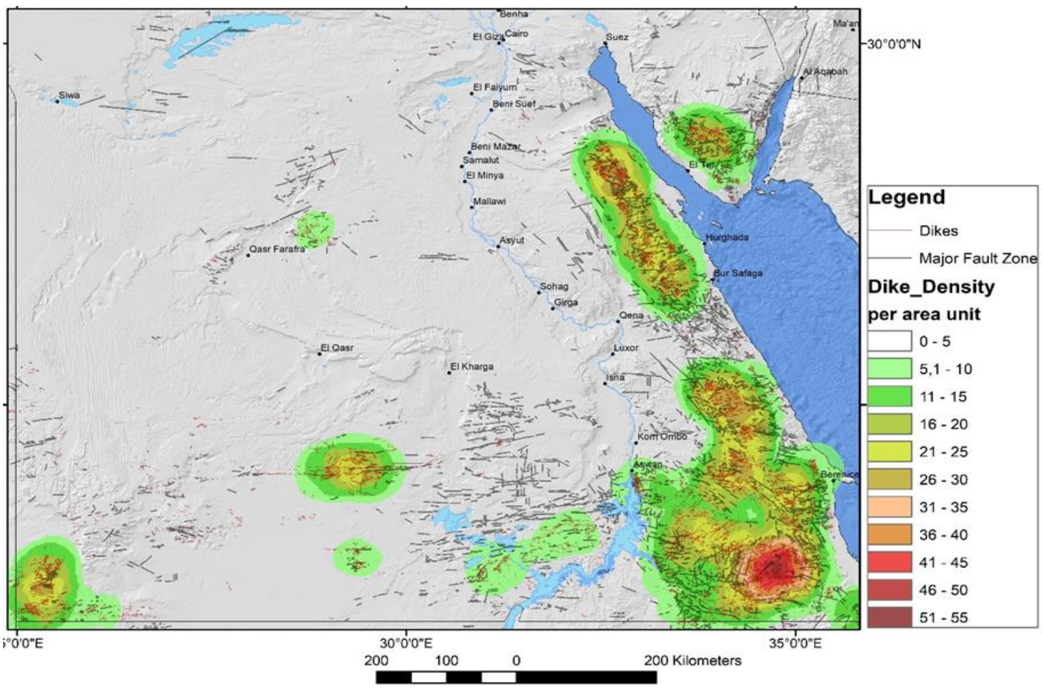

Figure 15. Density calculation (per area unit) of visible dikes in ArcMap visualizing the areas with the highest dike density

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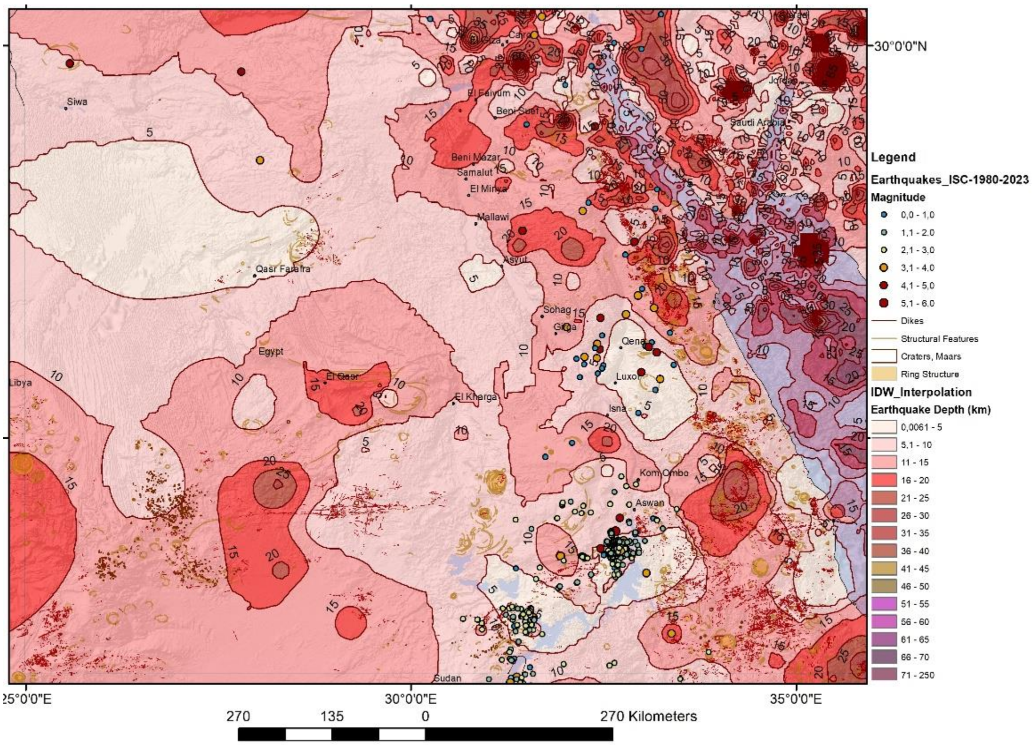

Figure 16. Inverse Distance Weighted (IDW)- interpolation of the depth of earthquakes (data source: ISC, data range:1990-2023)

The highest dike density of different types and ages coincides along the Rad Sea with areas of higher earthquake concentration during the last decades and higher earthquake depth.

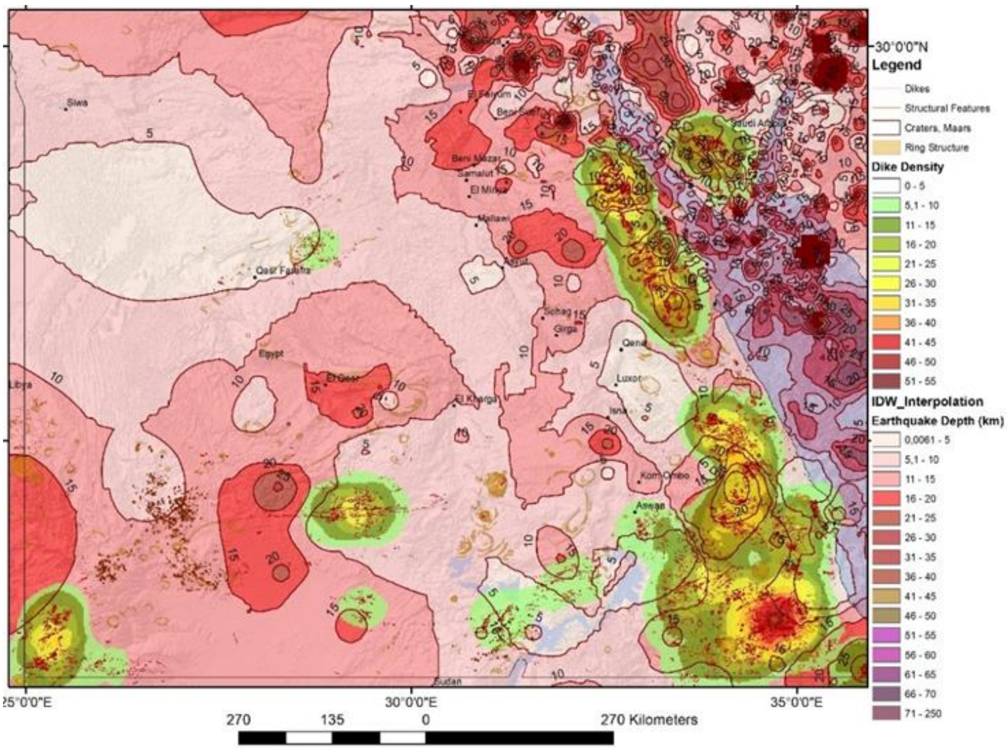

Figure 17. Inverse Distance Weighted (IDW)- interpolation of the depth of earthquakes (data source: ISC, data range:1990-2023) combined with the dike density calculation

The question arises whether stronger earthquakes in depth > 15 km might have the potential to initiate magmatic activity like the recent dike eruptions in Saudi Arabia occurred in 2009 and 2011 along the eastern part of the rift shoulder [25] [42] [43]? GPS measurements indicate that the magnitude of horizontal, geodynamic movements may reach up to 25 mm in some points close to the Red Sea [44] [45] leading regionally to extensions and to compressions.

In the SW and central South of Egypt such a coincidence between earthquake depth and dike occurrence cannot be observed with the available data. As there are obviously traces of Holocene volcanic activity, a combined analysis of magmatic and earthquake activity should be carried out as earthquake swarms are often observed combined with magmatic activity. For example: Volcanic cones and dikes are intersecting Quaternary longitudinal dunes, in SW-Egypt, thus, being younger than the dunes (Fig.18).

4.4. Seismicity within and around Reservoirs

Earthquake clusters have been documented during the last decades around the High Dam Lake (Lake Nasser) in the Aswan region. Whether recent seismicity is induced or triggered by the lake reservoir or is of natural origin, is still under investigation. Nevertheless, the role of dikes in the reservoir lake of the Awan Dam has to be monitored. Will there be interactions of dike swarms with the reservoir lake of the Aswan Dam? The focal depths of most Aswan seismic events are significantly shallower than the estimated focal depths for inter-plate and intraplate earthquakes in and around the area under investigation.

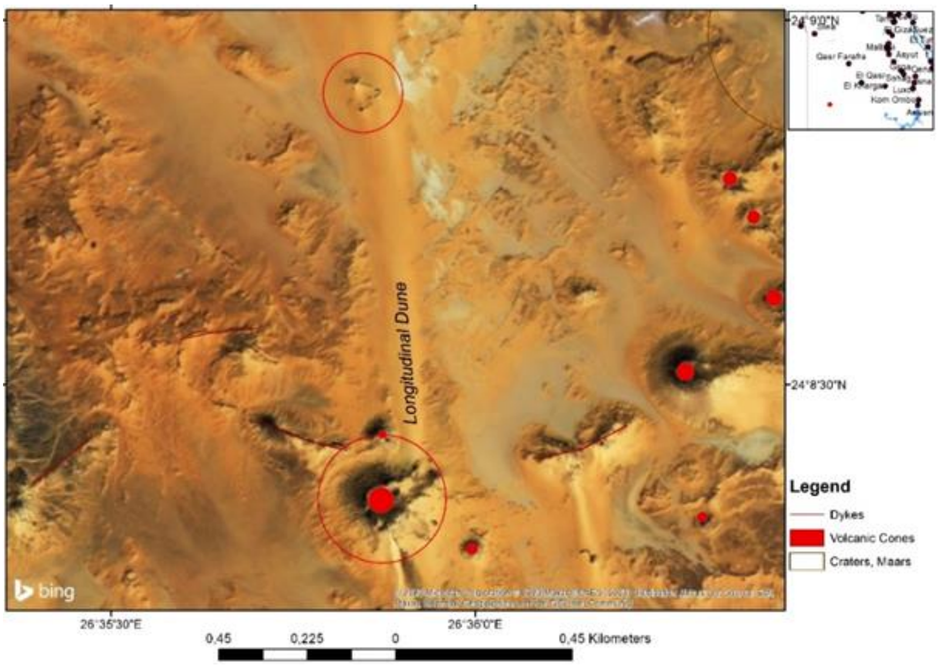

Figure 18. Traces of volcanic activity intersecting Quaternary longitudinal dunes oriented in N-S-direction in SW-Egypt

The focal depths of 80% of the triggered events are shallower than 10 km, while 80% of the tectonic earthquakes are deeper than 15 km. In many areas of worldwide dam sites increasing earthquake activity has been observed, up to earthquake swarms[12] [13] [46].

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Satellite data document the flooding situation in the High Dam Lake (Lake Nasser) in the Aswan region over the decades. The following figures show the situation in 1984 and, then in comparison with the situation in 2023 (Fig.19). Two major faults system can be defined in this area: The east–west fault trend as Seiyal and Kalabsha faults and the north–south fault system such as Gabel el-Barqa fault, Kurkur fault, Khor el-Ramla fault, Abu Dirwa fault and Gazelle fault. The Kalabsha fault, one of the east–west faults, is approximately 300 km long and is the most active fault in the study area where the 14 November 1981 earthquake occurred. The Seiyal fault, one of the east–west faults, is approximately 100 km long [47]. Older Landsat images allow the detection of subsurface structures before the flooding (Fig.19 a). The increasing volume and water extension of the reservoir become clearly visible on the Landsat scene of 2023 (Fig.19 b).

The position of the earthquake swarms and clusters occurring during the last decades after the rise of the water level and the extent of flooded areas confirms that Aswan seismicity is controlled by three main factors: pre-existing complex faults system, water load, and the pressure of pore fluid. The clusters in the northern part of the reservoir lake are situated in those areas where N-S, WSW-ENE and NW-SE striking lineaments are intersecting each other [40]. In the NE part of the lake in the Aswan Hills numerous dikes become visible on a Landsat 8 RGB-scene of Bands 2,7 and 10 (Fig.20), some of them now flooded by the reservoir. So far, an impact of dike occurrence on earthquakes cannot be detected. As larger dikes might serve as conduits for surface water infiltration the earthquake development should be monitored. Along the mostly vertical dikes water can infiltrate into larger depth and, thus, fluids can trigger earthquakes along fault zones under strain by the effects of pore-fluid pressure. Future research might consider this aspect.

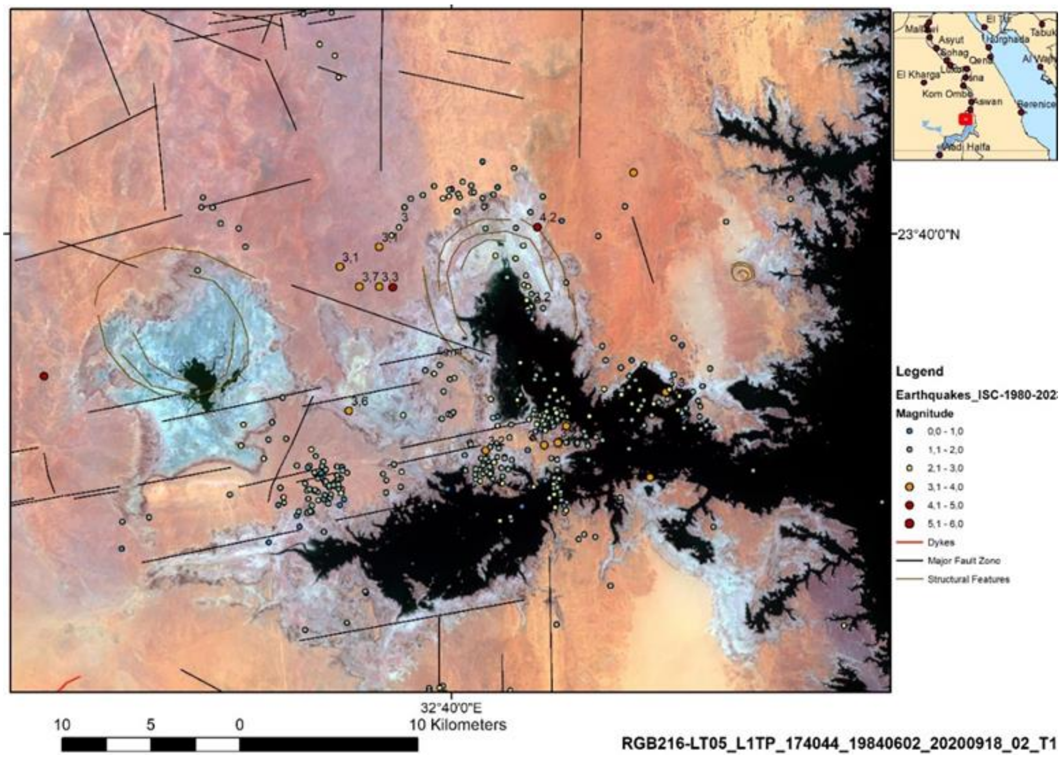

Figure 19 a. Landsat 5 scene far,.06.1984) of the NW-reservoir revealing subsurface structures combined with earthquake data of the last decades

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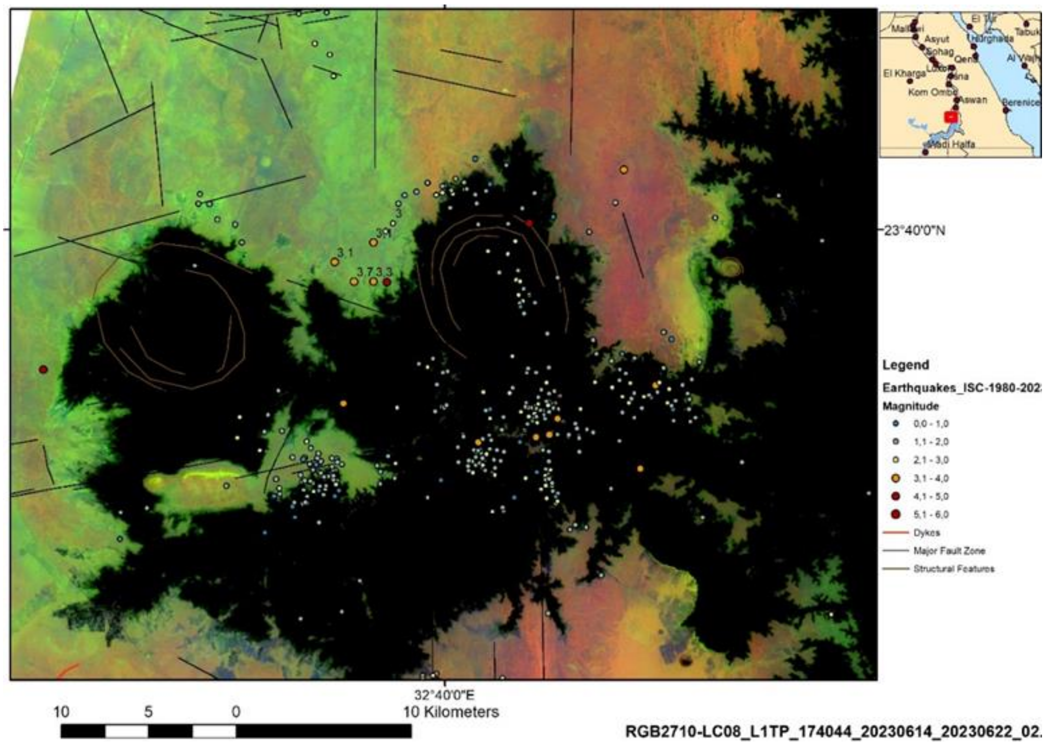

Figure 19 b. Landsat 8 scene (14.06.2023) of the same area about 40 years later

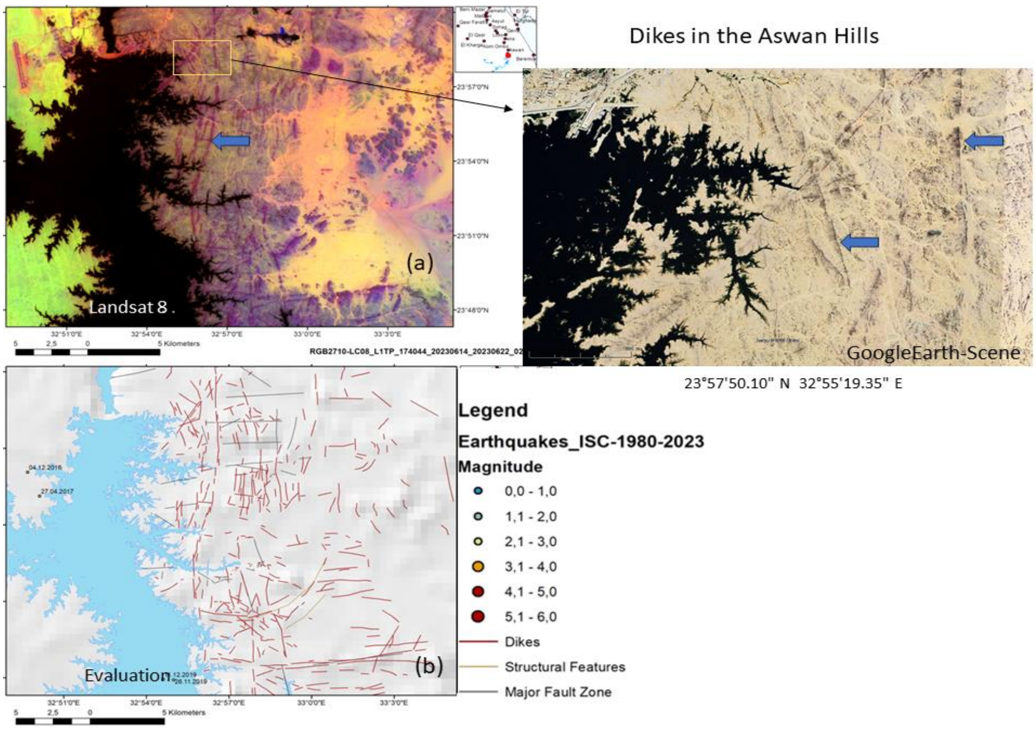

Figure 20. Dikes visible on a Landsat 8 scene (a) along northeast side of the reservoir lake in the Aswan Hills consisting of Neoproterozoic metamorphic rocks and evaluation result combined with recent earthquakes

4.5. Impact of Dikes on Land Use

The inventory of dikes is important for the land use planning as well, especially of the agriculture. Faults, fractures and dikes may play a very important role in groundwater recharge and flow in bedrock terrains. In detail, however,

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the effects of these structures on the bedrock permeability depend on their distribution, orientation, and density [48].

Sprinkler irrigation system is one of the important irrigation systems in Egypt, and especially used in sandy soils [49]. The influence of dikes on surface water and groundwater flow within irrigated areas has to be analyzed when dealing with irrigation management, especially whenever dikes form morphological and lithological barriers for the use of sprinkler or drip irrigation, and to the infiltration of surface water and a continuously water flow. Dikes can act as barriers to groundwater flow but can also be conduits for flow through otherwise impermeable layers. Strike and dip of the dikes and their lithologic conditions (mineralogic composition and degree of weathering) should be investigated in detail to learn more about their specific influence on irrigation measurements, especially on the managements of the irrigation water volume.

Fig.21 shows an example of visible dikes on a Sentinel 2-scene in an irrigation area, mainly striking SW-NE. In around the outcropping dikes, the irrigated fields show less reflectance intensity of the crops (green color in Fig.21). Provided, that these irrigated fields got the same amount of water as the others and the same crop type, it seems that the dikes have a negative influence on crop growth.

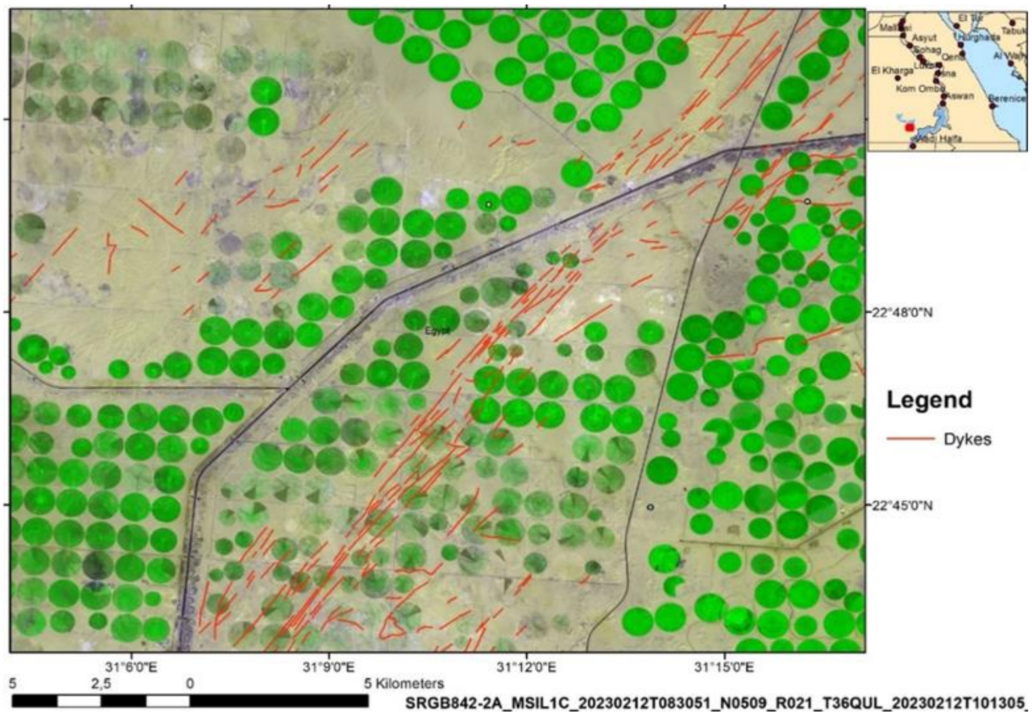

Figure 21. Dikes visible on a Sentinel 2-scene forming a morphological and lithological hindrance for sprinkler irrigation

5. Conclusion

Many traces of magmatic activity can be found in Egypt distributed over the whole country, even crosscutting youngest sediments. There is an urgent need to monitor and map carefully the volcanic features of the geologic past, not only for the economic development of Egypt [50] (mineral resources, or energy resources by geothermal energy), but also land for use planning and geologic hazard preparedness. This study was focused especially on dikes as they have an impact on many fields, while the complex interactions are still under investigations. Prerequisite for this task is the knowledge about the occurrence of dikes, their types, patterns, ages and mineralogic composition as well as their structural setting. However, this complex task could not be accomplished in the scope of this study. According to their morphologic appearance several types of dikes could be distinguished as indicated in Figs.8 and 9. The distribution pattern of dikes varies regionally with a more irregular pattern in the volcanic areas in the SW to long distance, straight, parallel dikes in the southern central part of Egypt. The more volcanic activity has taken place, the more irregular is the distribution pattern of dikes.

The pattern of the dike swarms in the Red Hills is strongly controlled by lithologic and structural / tectonic conditions, especially by larger fault zones and plutons. The influence of geodynamic movements (uplift, subsidence or horizontal displacements) has still to be investigated. Due to the differences of dikes and their lithologic and structural setting the impact of dikes on their environment (such as on the hydrogeologic situation) varies from region to region. The evaluation results could support the focused planning of necessary field work.

Suggestions for future work: The hereby presented, standardized approach of the inventory of dikes is one of the steps in the direction of data mining by using the same data sets all over the area of Egypt. The GIS integrated inventory of dikes could be part of a systematic WEB-dike information system. Such a dike data base related to the impact of dikes on the environment is important as background information for the before mentioned purposes. It is suggested that the WEB- dike GIS includes the following data:

- Type, mineralogic composition and age of dikes (straight aligned dikes over long distances, dike swarms, ring dikes, etc.),
- type and age of surrounding magmatic activity,
- type of host rocks,
- type of tectonic environment (inventory of fault and fracture zones, bedding planes, horst, graben, etc.),
- geodynamic movements (GPS data base),
- impact of dikes on the hydrogeologic situation (groundwater flow), on reservoirs,
- earthquake data base,
- infrastructural data.

Such a dike GIS would require the joint interdisciplinary efforts of many geoscientific institutions and scientists.

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Competing Interests Statement

The author has declared that no competing financial, professional or personal interests exist.

Consent for publication

The author contributed to the manuscript and consented to the publication of this research work.

Availability of data and material

Supplementary information such are available from the author upon reasonable request.

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