Potential Exploitation of the Phanerozoic Glauconites in Egypt

Galal El-Habaak and Mahmoud Abdel-Hakeem

Abstract

Glauconite deposits are considered as one of the most important sources of K commodity. More attention has been paid to these deposits as being an alternative potash fertilizer for the ever-increasing global K demand. Egypt has considerable accumulations of glauconite deposits, with an average 6 wt% K_2O after adequate magnetic separation. These accumulations are reported at many localities in the Western Desert of Egypt: (a) Ghorabi iron mine and on the eastern and western sides of El-Gedida iron mine of El-Bahariya Oasis, (b) through the northern plateau of the Kharga Oasis, (c) the mining sectors of Abu-Tartur Plateau, and (d) at the Fayum Depression and Wadi Al-Hitan, with total thickness varying between 6 and 25 m. Other limited occurrences are distributed through the Upper Nile Valley and the west central Sinai. The Egyptian glauconites are marine Phanerozoic deposits assigned to four different geological ages, including Cenomanian, Lower-Middle Campanian, Upper Campanian, Upper Eocene, and Oligocene. Also, glauconite deposits impart their distinctive green color to some parts of eight rock formations, namely Bahariya, Raha, Quseir variegated shale, Duwi, Hamra, Qasr el Sagha, Ghannam, and Qatrani Formations, and considered useful indications for the sea level changes in Egypt and the world. These Phanerozoic glauconites occur as an overburden above the commercial iron deposits of the El-Bahariya Oasis and the mineable phosphorites of the Abu-Tartur Plateau, a constitutional part of sandstone-dominated formations in the northern Western Desert. This mode of occurrence may be the main reason behind the little attention for the commercial value of such deposits in Egypt. Like the other developing countries, Egypt has limited potash resources and depends mainly on the imported fertilizers to increase the arable areas and crops production for the ever-increasing population. At this point, the present chapter discusses the characterization of the Phanerozoic glauconites in Egypt as a direct K fertilizer and sheds more light on the economic potential of these deposits as one of the key corners of the future potash industry.

Keywords

Phanerozoic glauconites • Fayum depression • Wadi Al-Hitan • Qatrani formation • Abu-Tartur Plateau • Fertilizers

1 Introduction

According to the pioneer works (Burst, 1958a, 1958b; Hower, 1961; McRae, 1972; Odin & Fullagar, 1988; Odin & Matter, 1981; Odom, 1984), glauconite is defined as a green-colored phyllosilicate mineral rich in Fe and K ions, which are trapped within the 2:1 dioctahedral illite-like structure consisting of nonexpandable micaceous layers "10 Å" alternating with expandable smectite layers. Glauconite contains variable Fe content as Fe^{+2} and Fe^{+3} ions, which substitute for Al^{+3} sites in the octahedral sheets. On the other hand, K_2O content is increased from 2 wt% to more than 8 wt% with the progression of glauconite maturation starting from the yellow nascent smectitic glauconite to the deep green micaceous glauconite (Table 1). Apart from the chemical weathering, color variation of glauconite grains is thought to be a function of the Fe^{+2}/Fe^{+3} ratio in the octahedral sheets rather than K content. The deficiency in

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Table 1 Glauconite maturation and structure in relative to potassium content (after Odin & Matter, 1981)

Evolution stages	Maturation stages	Mineralogical structure	Grain color	K_2O wt%
Nascent	Low	Smectitic glauconite ↓	Yellowish green	2–4
Slightly evolved	Moderate		Light green	4–6
Evolved	High		Green	6–8
Highly evolved	Very high	Micaeous glauconite	Dark green	> 8

Fe^{+2}/Fe^{+3} ratio, taking place during glauconitization as a result of the microbial reduction of the octahedral Fe^{+3}, is the main reason behind the gradual absorption of K to compensate the octahedral layer charge (López-Quirós et al., 2020).

Glauconite deposits are mostly recorded in rock successions assigned to the Cambrian-Recent in age and associated with the global sea level changes (Amorosi, 1995, 2012; Baioumy & Boulis, 2012a, 2012b; El-Habaak et al., 2016a; López-Quirós et al., 2019; Van Houten & Purucker, 1984). These deposits are distributed in various geographic zones (e.g., North American continental margin, Palaeo-Tethys, Palaeo-North Sea, and the high southern latitudes) and several countries (e.g., USA, UK, Brazil, Australia, India, and Egypt) (Fig. 1) and exploited for more than 100 years for agricultural purposes due to their K enrichment. However, the exploitation of these deposits as K fertilizers was excluded after the World War I when the manufacturing of K-salt fertilizers (e.g., KCl, K_2SO_4, and KNO_3) was initiated. This can be attributed to the lower water solubility of glauconite compared with the commonly used chemical fertilizers (Dooley, 2006).

K is considered as a critical macronutrient without which plants cannot survive. It is confined to many physiological processes that are necessary for plant growth such as the protein synthesis, enzymes activation, photosynthesis, water relations, and transportations (Lidon & Cebola, 2012; Mengel, 2007; Pettigrew, 2008). The most common K sources applied to plants are mined from brines and salts (e.g., sylvite and carnallite), with about 39 million tons of K_2O mostly come from ten companies in the northern hemisphere, in particular, Russia, Belarus, Germany, UK, and North America, where about 92% of the global potash reserve occurs (Manning, 2017; Sheldrick et al., 2002). On contrast, the developing countries of the southern hemisphere are in a critical need to secure the food supplies and increase the crop production to face the continuously growing population. For example, potash consumption of Africa is expected to be more than 1.6% of the world's potash fertilizers between 2015 and 2050 (Manning, 2015).

In general, the developing countries have limited potash reserves and mainly rely on the imported K fertilizers, which are transported over vast distances, resulting in a high sale price of potash and probable limited access to the conventional markets. This in turn attracted the attention of many researchers to focus and shed more light on the reconsideration and exploitation of the alternative indigenous K sources such as glauconite deposits.

Most literature concerned with evaluation and roast leaching of glauconite as an alternative K fertilizer and soil conditioner. Through this context, glauconite deposits from different regions, including Iran, New Zealand, New Jersey, Southwest Argentina, and India, have been subjected to chemical characterization and lixiviation in water and different acid solutions (e.g., Mazumder et al., 1993; Karimi et al., 2011; Merchant, 2012; Franzosi et al., 2014; Smaill, 2015; Shirale et al., 2019; Shekhar et al., 2020). The results indicated that glauconite grains release lower K^+ levels in water (23 mg K^+/kg) compared to acid solutions (2200 mg K^+/kg). So, glauconite is favored to be used for acidic soils, where K release rate can be accelerated to reach sufficient levels needed by crops.

The agronomic experiments (e.g., McRae, 1972; Bambalov & Sokolov, 1998; Heckman & Tedrow, 2004; Karimi et al., 2011; Franzosi et al., 2014; Rudmin et al., 2020) also proven the efficient contribution of glauconite fertilizers, even those of lower maturity "2.24 wt% K_2O," to enhance the growth rate and production of some crops (e.g., olive plants, wheat, potatoes, and oats) in a similar effect to the application of the commonly used KCl. However, the

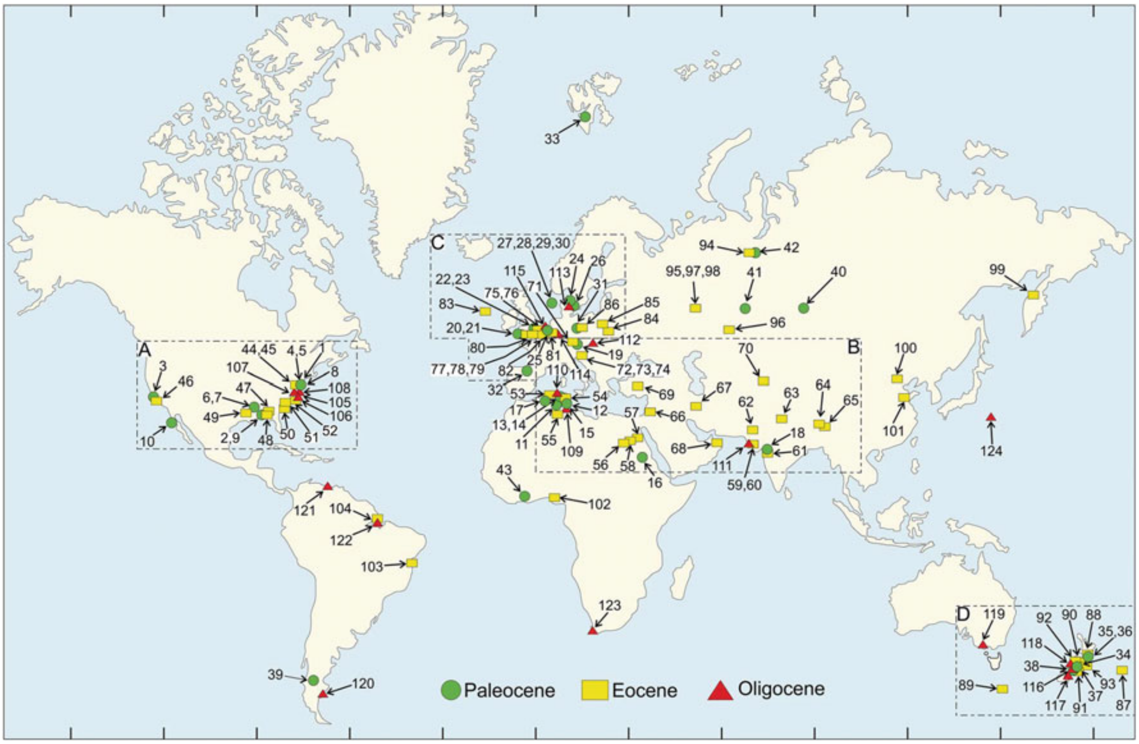

Fig. 1 Palaeogeographic distribution of the Paleogene glauconite deposits mainly at four zones: **a** North American continental margin (1–9, 44–48, and 105–108), **b** Palaeo-Tethys (11–19, 54–74, and 109–111), **c** Palaeo-North Sea deposits (21–32, 76–86, and 113), and **d** High southern latitudes (34–36, 88–93, and 119) (after, Banerjee et al., 2020)

chemical K fertilizers still attracted more farmer attention due to their high water solubility, resulting in immediate nutrient supply for plants. This pushed many researchers to find out a suitable technique to accelerate the K release rate from glauconite grains. Some studies dealt with increasing the water solubility of glauconite via adequate roasting with a fluxing agent (e.g., $CaCl_2.H_2O$ and LiCl) followed by water leaching. About 96–100 wt% K_2O can be obtained from this route (Mazumder et al., 1993; Santos et al., 2017). The other trend highlighted the production amenability of liquid K fertilizers (e.g., KCl and K_2SO_4) from glauconite through acid roasting followed by water leaching (e.g., Shekhar et al., 2017, 2020).

As aforementioned, glauconite deposits have been and still a matter of several discussions in the field of agriculture and soil fertility. The cultivation activities in Egypt are highly limited to fertile soils distributed along the Nile Valley provenance, with little attention paid to the other sandy soils that occupy vast areas through the Western and Eastern Deserts. Reclamation and mediation strategies of such sandy soils are indispensable demand to secure sufficient food supplies for the ever-increasing populations. Generally, systematic plans are required to exploit the indigenous Egyptian mineral resources for agricultural purposes, leading to sufficient crops production and great progression in the sustainable agricultural development. Egypt has considerable quantities of glauconite deposits and limited potash resources, which makes a continuous demand for the imported potash fertilizers. From this perspective, the current review will discuss all the previous studies conducted on the Egyptian glauconite in terms of the occurrence, characterization, and beneficiation along with the agronomic experiments to highlight the economic potential of the Phanerozoic glauconites in Egypt as an alternative potash fertilizer and soil conditioner.

2 Glauconite Occurrence and Stratigraphy in Egypt

Occurrences and stratigraphy of the Egyptian glauconite deposits are discussed by many works (Said, 1971; El-Sharkawi & Khalil, 1977; Khalifa, 1983; Soliman & Khalifa, 1993; El Aref et al., 1999; Masaed and Suror, 1999; Hassan & El-Shall, 2004; Mesaed, 2006; El Aref et al., 2006; Pestitschek et al., 2012; Baioumy et al., 2011; Baioumy & Boulis, 2012a, 2012b; El-Habaak et al., 2016a, 2016b; Hegab & Abd El-Wahed, 2016; Ibrahim et al., 2017; Banerjee et al., 2019; El-Habaak et al., 2019). Glauconite deposits, as a pelletal type, are mainly recorded in detail

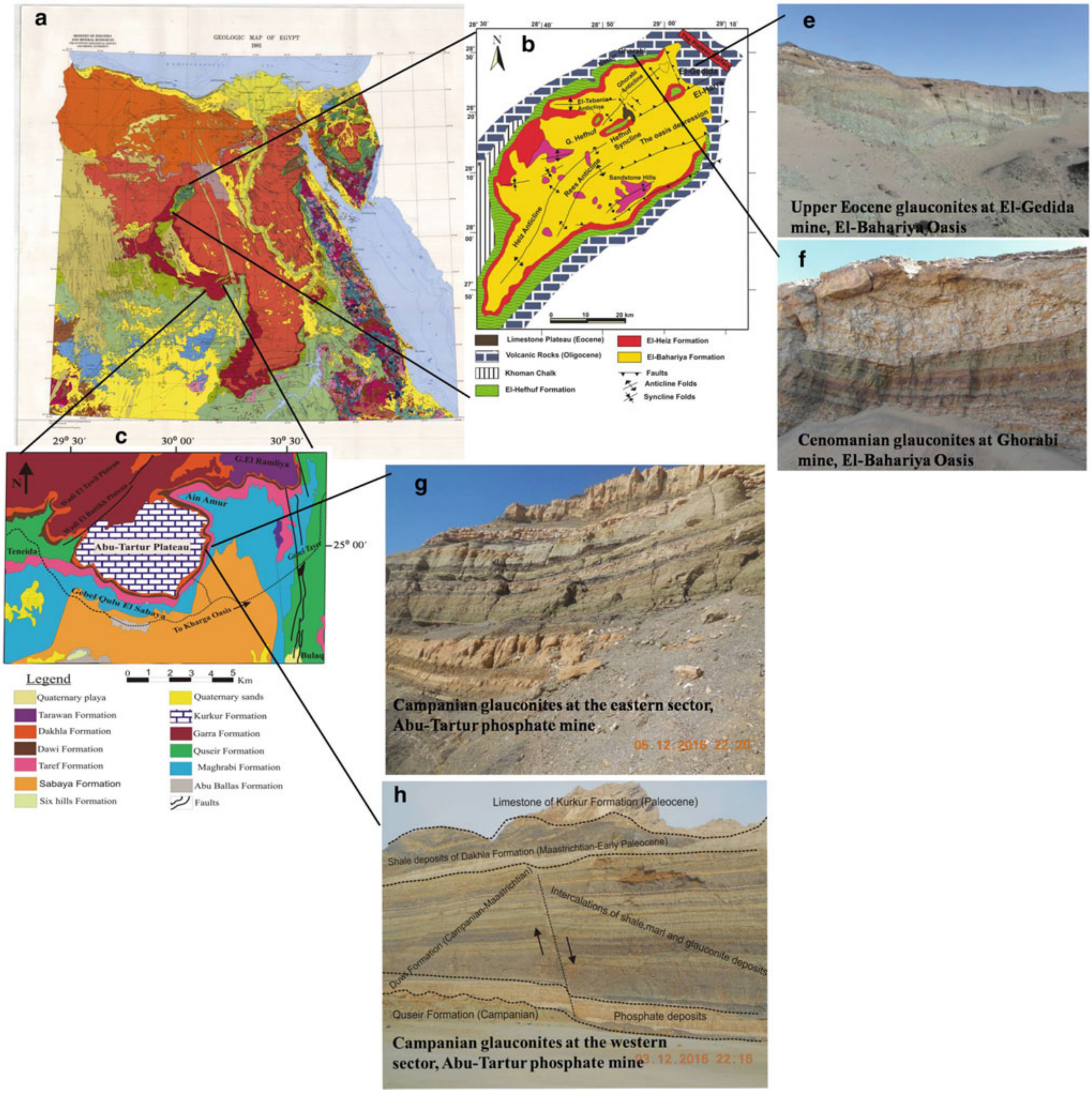

Fig. 2 Geological map of Egypt **a** with a close-up showing the different rock units at El-Bahariya Oasis **b** and Abu-Tartur Plateau **c** as well as field views of the Cenomanian and Upper Eocene glauconites at El-Bahariya Oasis (**e** and **f**, respectively) and the Campanian counterparts at Abu-Tartur Plateau (**g** and **h**)

through two localities in the Western Desert of Egypt, namely El-Bahariya Oasis and the Abu-Tartur Plateau (Fig. 2).

El-Bahariya Oasis is an oval-shaped depression that can be encountered toward the northern part of the Western Desert between coordinates of 27° 48′–28° 30′ N and 28° 35′–29° 10′ E. It is built up of the Upper Cretaceous succession, including the Bahariya, El-Heiz, El-Hefuf, and Khoman Formations, unconformably covered by the Upper-Middle Eocene Naqb, Qazzun, and Hamra Formations. El-Bahariya Oasis is well-known for its considerable reserves of iron deposits located in the northeastern part of the depression at four sites: El-Gedida, Ghorabi, Nasser, and El Harra. Glauconite deposits are mainly reported in El-Gedida and Ghorabi mining areas and confined to the Cenomanian Bahariya Formation and the Upper Eocene

Hamra Formation. The Cenomanian glauconites represent the upper part of the Bahariya Formation and are exposed as 4 m thick brownish-green to yellowish-green, moderately hard-friable, fine-medium-grained deposits with 50 cm thick concretions of glauconitic ironstone. These deposits are overlain by the Middle Eocene iron deposits of the Naqb-Qazzun sequence and considered as an indication for the Cenomanian sea level rise in Egypt. Moreover, some restricted occurrences of the Cenomanian glauconites are reported from the lower beds of the Raha Formation located at Wadi Feiran and Wadi El Gheib, west central Sinai (Gertsch et al., 2010; Kora et al., 1994). The Upper Eocene glauconites occur at the eastern wadi of El-Gedida mine as an overburden above the Middle Eocene iron deposits and appear as 6–25 m thick green, moderately hard, moderately sorted deposits with spots of iron oxyhydroxides and veinlets of calcite and alunite. On the western wadi of El-Gedida mine, glauconites are affected by minor postdepositional folding and faulting. Likewise the Cenomanian counterpart, the Upper Eocene glauconites are related to the Upper Eocene marine regression in Egypt.

On the other side, another accumulation of glauconite is outcropped at the Abu-Tartur Plateau in the central part of the Western Desert between latitude 25° 25′ 23.78″ N and longitude 30° 05′ 15.6″ E. Abu-Tartur Plateau is a limestone plateau that contains one of the most important phosphorite deposits in North Africa. Lithologically, the plateau escarpment is started, from base to top, by the Upper Cretaceous Nubia plains covered by the Campanian Quseir and Duwi Formations, Maastrichtian Dakhla Formation, and Early Paleocene Kurkur Formation. Abu-Tartur glauconite is enclosed within the Campanian Duwi Formation-hosted phosphorites. At the western mining sector, it is restricted to the middle part of the Duwi Formation as 5 m thick green to yellowish-green, moderately hard, sandy deposits with gray clay intercalations. Occasionally, these glauconite deposits undergone postdepositional faulting and enclosed ferruginous concretions of glauconitic ironstone along with evaporites interlayers: Veinlets are perceived within the upper part of glauconite deposits. Glauconite deposits cover 3.5 m intercalations of black shale and marl. Toward the uppermost part of the succession, 2 m thick greenish to brownish shale deposits belonging to the Dakhla Formation overlay glauconite deposits. At the eastern mining sector, glauconite deposits are reported in a greater thickness compared to the western sector succession. They attain about 8 m thick beds alternating with 10.5 m thick gray to brown shale to form a total of 18.5 m thick section that covers the mineable phosphate bed and underlain by the Maastrichtian Dakhla Formation and the Early Paleocene Kurkur Formation. Moreover, restricted occurrences are perceived from the Beris member of the Maastrichtian Dakhla Formation at Gabal Um El-Ghanayem, 19 km to the northeastern part of El Kharga Oasis (Orabi & Khalil, 2014).

The northern part of the Western Desert, in particular the northern escarpment of the Fayum Depression, is also endowed with considerable accumulations of pelletal glauconite deposits that are assigned to the Upper Eocene Qasr el Sagha Formation (Dir Abu-Lifa Member) and the overlying Oligocene Qatrani Formation. Glauconite deposits of Dir Abu-Lifa Member are made up of 7.5 m fine-medium-grained glauconitic sandstone characterized by bioturbation and nodules of barite and siderite. These deposits are considered as a part of 77 m thick accumulation of gypsiferous, muddy, and cross-bedded sandstone whose uppermost part is marked by unconformity surface separating between the Dir Abu-Lifa Member and the Oligocene Qatrani Formation. The latter contains about 10–13 m thick glauconitic sandstone that represents the lower part of the Qatrani Formation and contains mud clasts, reworked nodules of limonite, interbeds of gypsiferous sandstone, and sometimes rhizolith masses cemented by calcite. It is worthy to mention that the two glauconite types here are confined to the gradual Late Eocene marine regression in Egypt, which results in the deposition of nearshore marine and alluvial deposits dominated by variegated, cross-bedded sandstone (Bown & Kraus, 1988; Gingerich, 1992). Furthermore, minor occurrences of glauconitic clays intercalated with sandy mudstone, marls, and calcareous sandstone were documented from the Upper Eocene Gehannam Formation in the Wadi Al-Hitan area, about 80 km west of the Fayum Depression (Gingerich et al., 2019) (Fig. 3).

By comparing with the Western Desert, occurrences of glauconite through the Nile Valley provenance are only

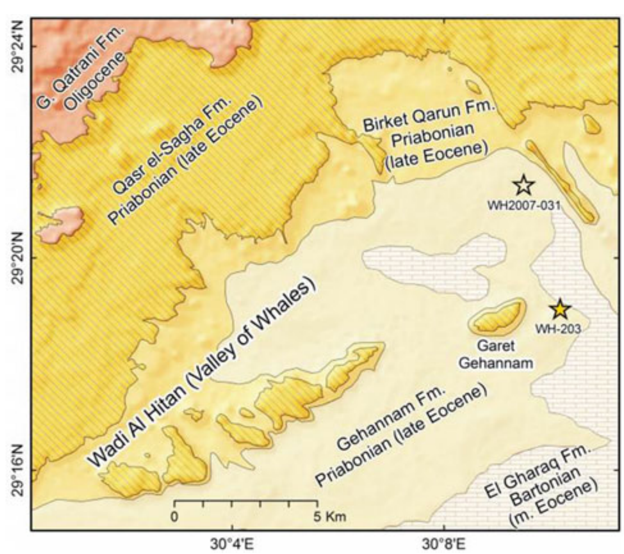

Fig. 3 Location map of the Wadi Al-Hitan in the northern Western Desert showing the distribution of the glauconite-bearing rock units (Qatrani Fm., Qasr el Sagha Fm., and Gehannam Fm.) (after Gingerich et al., 2019)

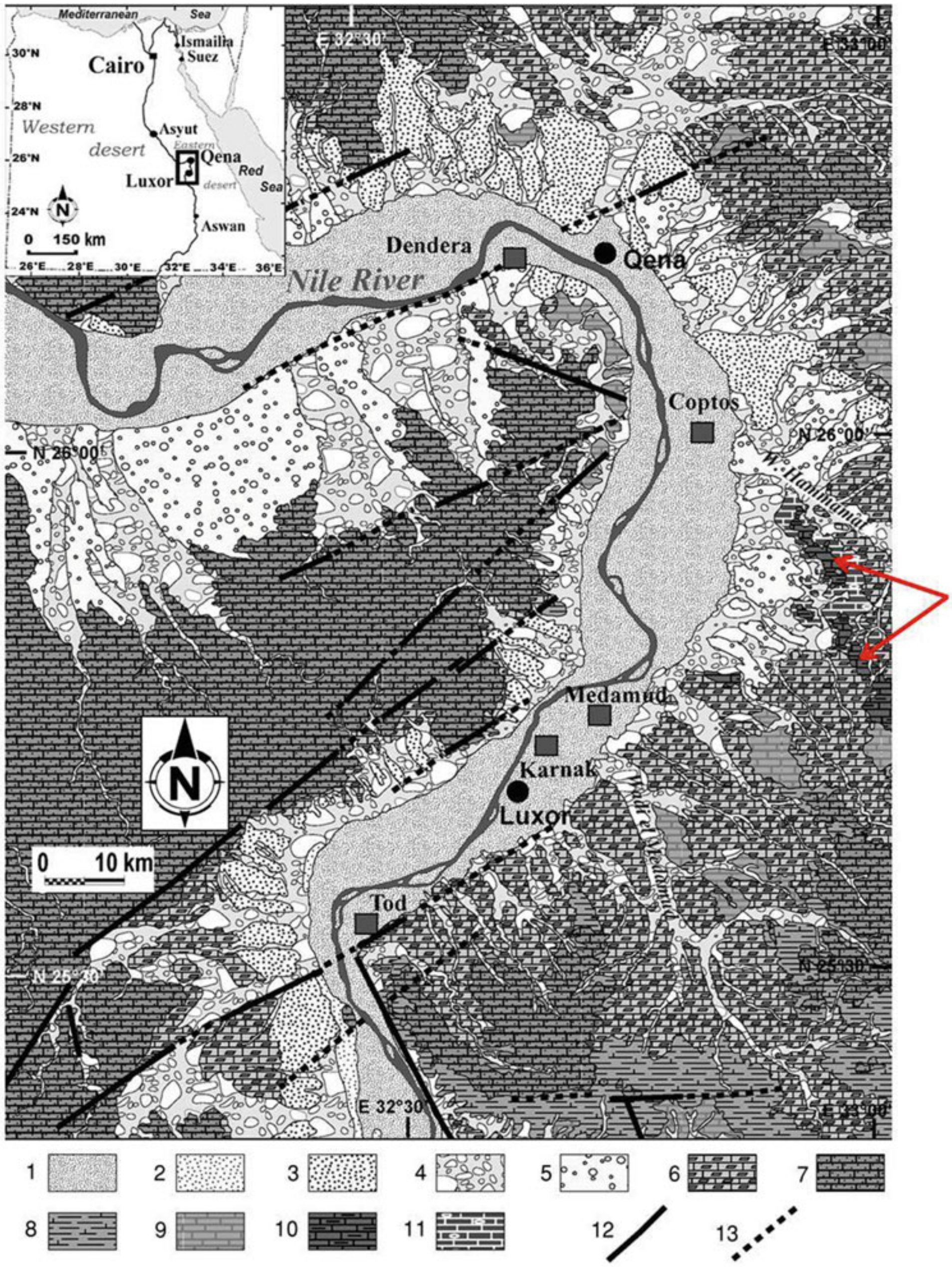

Fig. 4 Geological map of the Theban Plateau, Upper Egypt, showing the Upper Cretaceous-Lower Tertiary succession among which the glauconite-bearing Duwi Formation exists (look at red arrow) (after Ghilardi et al., 2012). The illustrated rock units include: (1 and 2) Holocene Nile alluvial sediments; (3) Pleistocene Prenile sediments; (4) Wadi deposits; (5) Fanglomerate; (6) Pliocene intercalations of sandstone, siltstone, and claystone; (7) Thebes formation (Eocene); (8) Esna formation (Paleocene-Eocene); (9) Dakhla formation (Campanian–Maastrichtian); (10) Duwi formation (Upper Campanian), consisting of phosphorites overlain by intercalations of glauconitic sandstone, gray shale, and oyster limestone; (11) Quseir variegated shale (Lower-Middle Campanian); (12) Main fault line; (13) Hidden fault lines

documented in the geological map of Qena (Fig. 4). It is confined to the Campanian Duwi Formation intercalated with gray shale and oyster limestone (Ghilardi et al., 2012). These lithological associations are laterally changed toward the Eastern Desert, where the Duwi Formation is expressed as a considerable thick succession of phosphorites overlain by gray shale, marl, and oyster limestone (Baioumy & Tada, 2005). Until the present day, there is no published information about any accumulation of mineable pelletal glauconite deposits through the Upper Cretaceous-Lower Tertiary succession in the Eastern Desert of Egypt. On contrast, the nonpelletal glauconite, occurring as clayey layers and as argillaceous matrix under the optical microscope, is widely distributed through the Western Desert, Nile

Valley, and Eastern Desert. It is reported from the Lower-Middle Campanian Quseir variegated shale whose greenish color is imparted from glauconite (Baioumy & Boulis, 2012a, 2012b). Moreover, some restricted occurrences of the Cenomanian glauconites are reported from the lower beds of the Raha Formation located at Wadi Feiran and Wadi El Gheib, west central Sinai (Gertsch et al., 2010; Kora et al., 1994).

3 Glauconite Genesis

Glauconite deposits are mainly deposited under marine conditions from a wide variety of substrates, including Fe-smectite, mica, Al-illite, bioclasts, fecal pellets, and feldspar. Two main hypotheses were suggested for glauconite formation (Burst, 1958a, 1958b; Hower, 1961; Odin & Matter, 1981). They are degraded lattice theory and

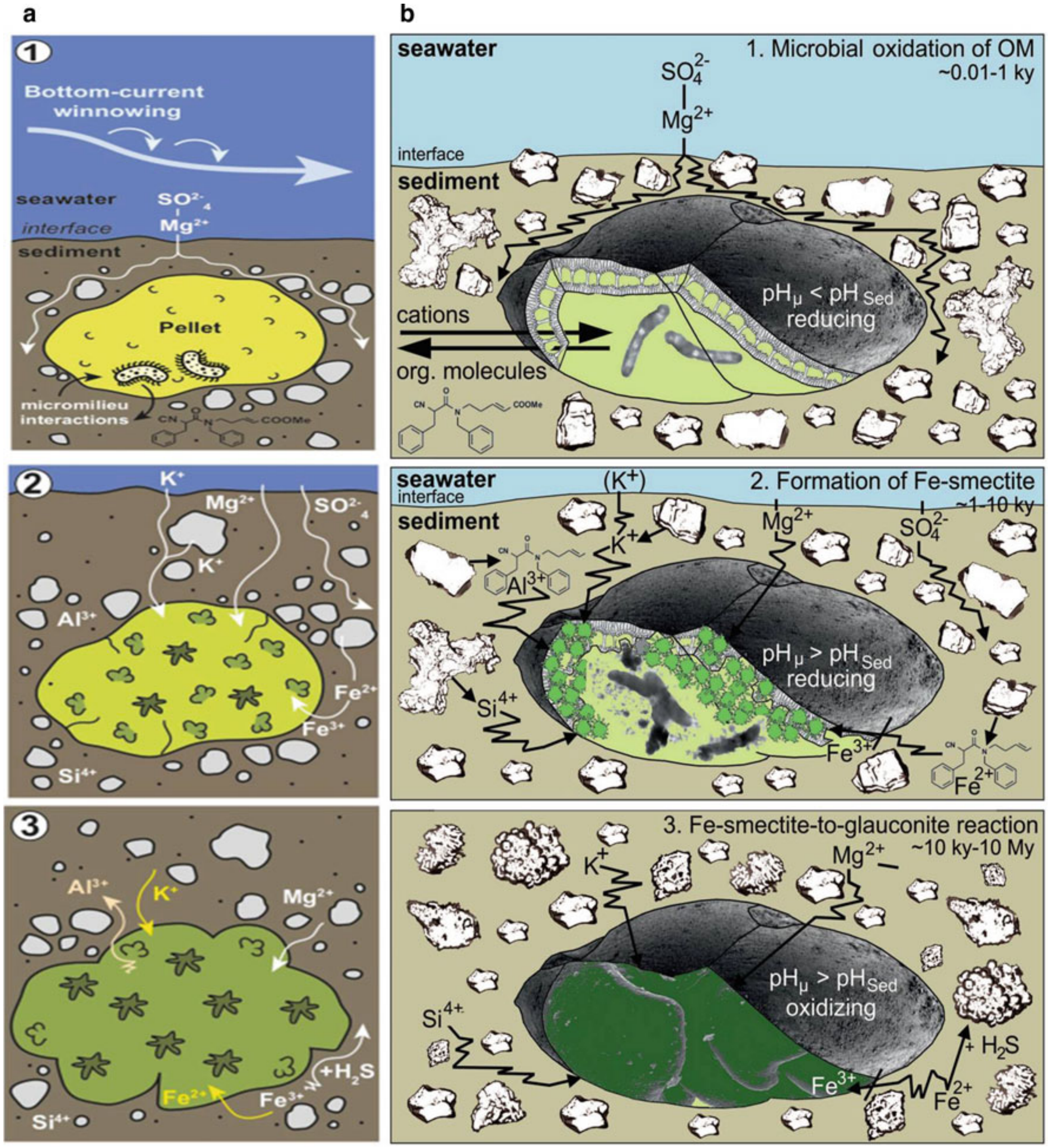

Fig. 5 Glauconitization mechanisms of argillaceous pellet (**a**) and foraminifera test precursors (**b**) by the degraded lattice and neoformation theories, respectively (after Baldermann et al., 2013; López-Quirós et al., 2020)

neoformation theory (Fig. 5). The first hypothesis involves simultaneous absorption of K^{+} and Fe^{+2} ions from the ambient seawater into degraded crystal lattice of clay particles. For more explanation, clay particles may be enclosed within fecal pellets, which undergo microbial oxidation at the sediment–water interface, resulting in partial/complete degradation of the contained clay minerals and also the surrounding sediment particles due to the surrounding metabolic activities. The degraded clay lattice gradually uptakes K^{+} and Fe^{+2} from the surrounding microenvironment and is converted from nascent glauconitic smectite into evolved/highly evolved glauconite. The latter theory proposes that glauconite starts as a glauconitic smectite directly precipitated from seawater within the micropores of substrate (e.g., foraminifera tests) and its micaceous nonexpandable layers are then increased by the gradual incorporation of K^{+} from the surrounding pore water. Banerjee et al. (2012) added that the co-incorporation of K^{+} and Fe^{+2} into the interlayer sites and octahedral sites, respectively, is associated with the release of Al^{3+} from glauconite crystal structure. This can be undertaken as the main difference between glauconite and its analogue high Al-illite. According to these theories, the Phanerozoic glauconites in Egypt were interpreted as a result of the successive formation of nonexpandable, K^{+} and Fe^{+2}-enriched layers at the expense of degraded smectite lattice (e.g., the Cenomanian glauconite deposits) (Baioumy & Boulis, 2012a, 2012b), the direct precipitation from seawater, starting as Fe-smectite from gel precursor rich in K, Fe, Mg, Al, and Si, within the micropores of argillaceous pellets (e.g., the Upper Eocene glauconite deposits) (Masaed & Suror 2000; El-Habaak et al., 2016a), and the degraded layer and neoformation mechanisms together (e.g., the Campanian glauconite deposits) (Banerjee et al., 2019).

4 Glauconite Alteration Products

Numerous white-pinkish pockets of alunite, halloysite, and kaolinite are randomly distributed through glauconite successions at El-Gedida mine and recorded by Hassan and Baioumy (2007). They interpreted the formation of these pockets as alteration products of glauconite under oxidizing, acid sulfate environment, where glauconite is gradually dissociated into mobilized Fe, K, Al, and Si. Fe species may form amorphous grains of iron oxyhydroxides associated with glauconite grains or may percolate downward forming at least part of El-Gedida iron ores. K may combine with Al, Si, and sulfate ions, resulting in alunite, halloysite, and kaolinite. These alteration products are absent in the case of Abu-Tartur counterpart, but instead evidences on the destabilization of glauconite into Fe-rich smectite along with color zonation of glauconite grains are documented by Pestitschek et al. (2012). They suggested that glauconite grains release differential amounts of K and Fe under acidic oxidizing conditions, causing fuzzy grain boundaries and gradual transformation into argillaceous matrix of reddish-brown Fe-rich smectite. The acidic environment may be driven by the chemical oxidation of pyrite, resulting in free sulfate ions. The latter reacted with Ca ions in the percolating surface water to form gypsum and anhydrite, while the interaction with K ions enabled jarosite to precipitate.

5 Glauconite Characterization as K Fertilizers

In order to directly exploit glauconites as K fertilizer and soil conditioner, some physical and chemical requirements have to be assessed such as grain-size range "−250 μm + 88 μm," the proportions of clay matrix "2–3%" and glauconite pellets "90%," and the contained K level "at least 6%" (Dooley, 2006). Accordingly, the following lines highlight the physical and chemical properties of the glauconite in Egypt and the optimum conditions by which we can achieve the ideal exploitation of such deposits.

5.1 Physical Characterization

Glauconite appears in different shades of green color as oval, suboval, rounded, moderately sorted grains set in glauconitic argillaceous and iron oxides-rich cement (Fig. 6). Three main size fractions, including 100–200 μm, 125–400 μm, and 100–500 μm, were reported for the Cenomanian, Campanian, and Upper Eocene glauconites, respectively (Baioumy & Boulis, 2012a, 2012b; Baioumy et al., 2011; Banerjee et al., 2019; El-Habaak et al., 2016b; Ibrahim et al., 2017). They all fall within the sand size and can be reached the optimum size fraction of glauconite fertilizers (−250 μm + 88 μm) by means of crushing and grinding. As such example, El-Habaak et al. (2016b) found that about 73.94–81.74 wt% of the Upper Eocene glauconite grains are concentrated at grain fraction −250 μm + 125 μm after adequate crushing and grinding up to −1 mm using jaw crusher and rod mill in a closed circuit (Fig. 7). This uniform size of glauconite causes a great enhancement in soil texture, porosity, and permeability, and considered valuable character stands behind the application of glauconite as a soil conditioner (Heckman & Tedrow 2004; Indian Minerals Yearbook, 2011, 2012). Further, the dry sieve analysis of the Egyptian glauconite revealed that the finer size fraction −75 μm, where clay matrix is concentrated, does not exceed the range 2.2–2.5 wt% (El-Habaak et al., 2016b; Ibrahim et al., 2017). The increased proportion of clay matrix can be

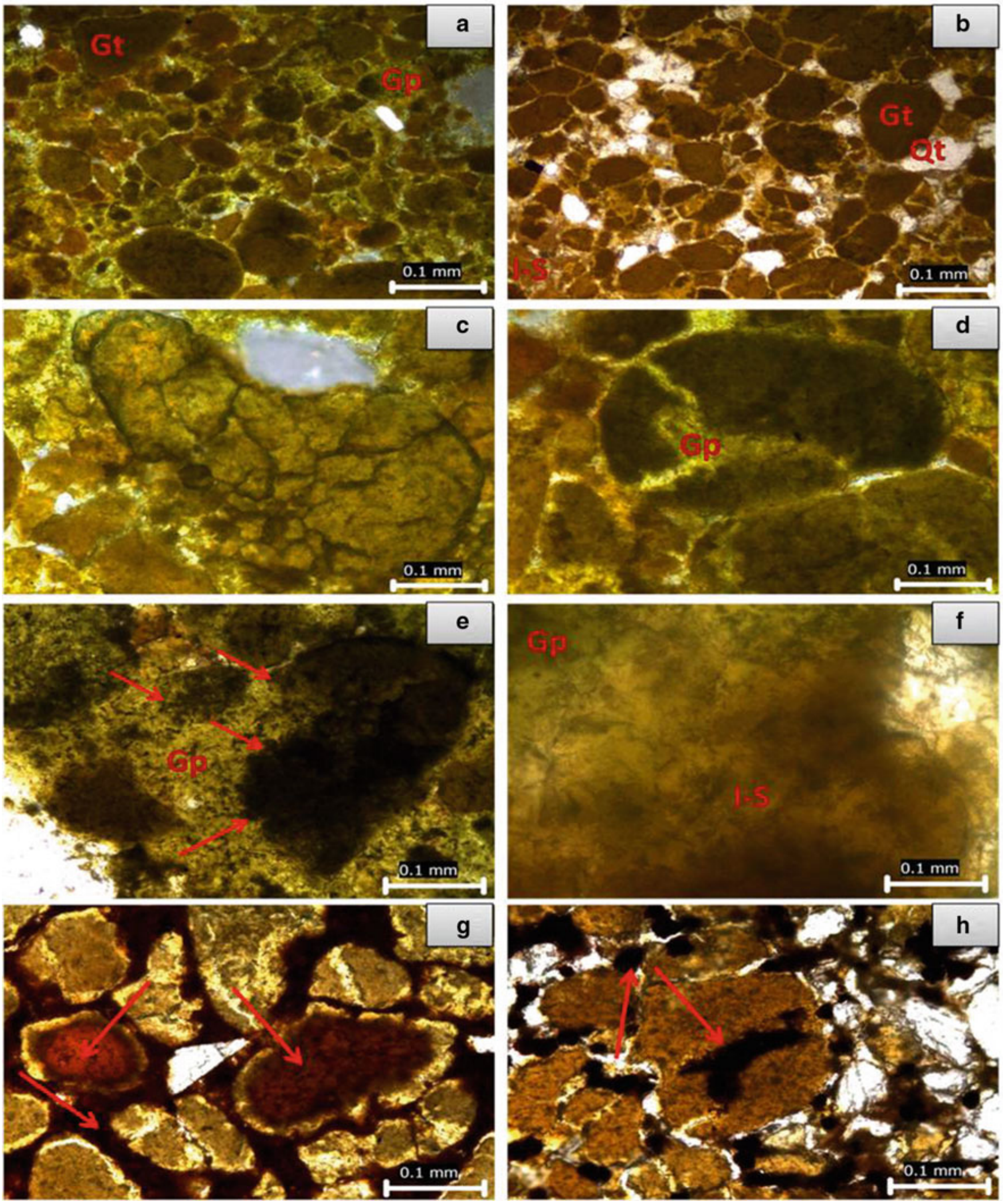

Fig. 6 Photomicrographs showing green-yellowish green, oval, suboval, rounded, fine to medium-grained glauconite pellets (Gt) along with quartz grains (Qt) set in argillaceous matrix of greenish glauconitic plasma (Gp) and reddish-brown illite–smectite mixed layer (I–S) (**a** and **b**); glauconite pellets with deeply invading fractures within the entire grain (**c**) and interior as triangular cracks (**d**) filled by the glauconitic plasma; alteration of glauconite pellets manifested by the fuzzy grain peripheries and formation of the glauconitic plasma (**e**) that gradually converted to the reddish-brown illite–smectite mixed layer (**f**); the liberation of Fe from altered glauconite grains cementing the pellets (**g**) or as individual grains (**h**) (look at arrows)

an indication for the imposed chemical weathering conditions, which lead the external boundaries of glauconite pellets to be fuzzy as well as a greenish alteroplasma forms. The latter becomes reddish brown (iron-rich illite/smectite-mixed layer) due to the gradual decrease in Fe and K-contents (Meunier, 2004). As a result, the economic value of glauconite is expected to dropdown.

Regarding glauconite grains' percentage, the Upper Eocene glauconite contains about 75%, while the Campanian counterpart comprises about 65–75% compared to the

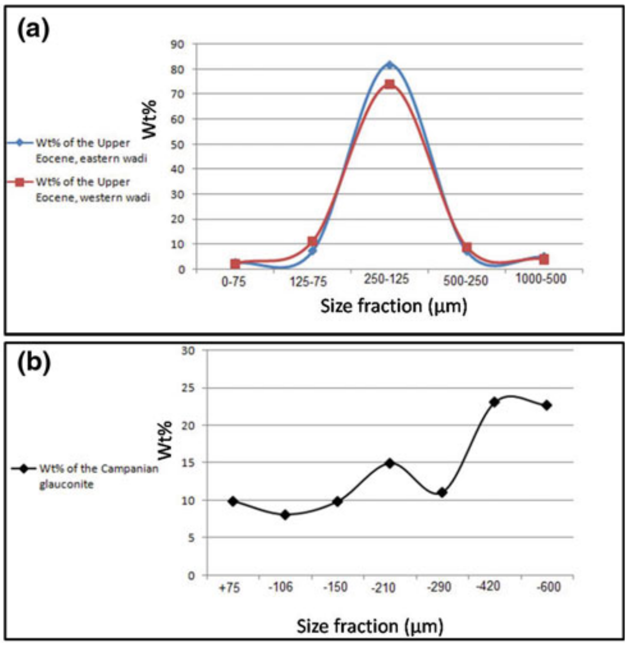

Fig. 7 Distributions of wt% of the Egyptian glauconite showing that the majority of the Upper Eocene glauconite is concentrated at + 250 −125 µm fraction (**a**), while that of the Campanian counterpart is met at the coarser fractions (**b**)

associated impurities including quartz, calcite, gypsum, and goethite. These percentages were upgraded to about 94–97% using Frantz isodynamic magnetic separator, and the results were supported by conducting XRD analysis on the head samples along with the magnetic and nonmagnetic fractions (El-Habaak et al., 2016b; Ibrahim et al., 2017). The magnetic susceptibility of glauconite is ascribed to the contained Fe^{+2} in the octahedral sheets. Glauconite with high Fe^{+2}/Fe^{+3} ratio is characterized by highly magnetic, dark green grains (Baldermann et al., 2015, 2017; Bentor & Kastner, 1965). The high recovery of glauconite grains can be interpreted here depending on the discussions of Amstutz and Giger (1972) and Petruk (2000) regarding the critical influence of the interlocking nature between valuables and gangues. For example, the straight, rectilinear, curved grain boundaries are regarded as indications for the high liberation degree during comminution and concentration processes due to the simple locking between the mineral grains. This example was manifested by El-Habaak et al. (2016b) who expected high glauconite recovery from the Upper Eocene deposits as a result of the simple locking between glauconite grains and quartz, the main gangue mineral. According to the previously mentioned physical characters, the Egyptian glauconite deposits are suitable to be exploited as a direct K fertilizer and soil conditioner. Also, the Cenomanian glauconite needs further studies and investigations through the northern and central parts of the Western Desert, where the host Bahariya Formation is 90–100 m thick (Said, 1971).

5.2 Chemical Characterization

For considering a given deposit as a potential fertilizer, there are specific chemical aspects that have to be considered including the valuable nutrient concentration, the contained levels of heavy metals to avoid the toxicity of plants and animals, the values of pH and salinity to protect the cultivated soil from long-term acidification and salinization, and the solubility in water. At this point, the current review discusses the economic value of the Egyptian glauconites as a potential potash resource.

5.2.1 Macronutrients Content

K is one of the most important macronutrients needed by plants, for which glauconite deposits are considered the future potash resource. As listed in Table 2, there is a similarity in the content of most nutrients between the Upper Eocene glauconite of Egypt and the exploited deposits of New Jersey, USA. It can be also classified as evolved glauconites with higher K-contents (6.75–7.3 wt% K_2O) than the other nascent-moderately evolved Campanian (3.12–5.3 wt% K_2O) and Cenomanian glauconite types (4.84–6.11 wt% K_2O). According to Dooley (2006), the Upper Eocene glauconites can be undertaken for direct fertilizing applications, while the other types need to be beneficiated by a suitable procedure. This was done by Ibrahim et al. (2017), as mentioned before, depending on the magnetic susceptibility of glauconite. They obtained magnetic fraction assaying 6.14 wt% K_2O from head glauconite sample containing 4.41 wt% K_2O. Besides K commodity, the present glauconites contain 50.89–59.12 wt% SiO_2. Silicon is considered to be another commodity and a beneficial element for different crops due to its ability to enhance the maintenance of nutrients for plants in available forms and increases the tolerance level of plants to diseases and insect attacks (Meena et al., 2013). Al_2O_3 content varies between 5.88 and 13.84 wt%. The increased alumina content is related to glauconite maturity. The gradual absorption of K^+ and Fe^{+2} from the surrounding seawater is associated with the liberation of Al^{+3} from the octahedral sites during the glauconitization process (Banerjee et al., 2012). So, it is expected that the high Al-glauconite is enriched in smectite as a product of the deglauconitization process, as revealed during the mineralogical studies performed by Pestitschek et al. (2012), Baioumy and Boulis (2012a, 2012b), El-Habaak et al. (2016b), Banerjee et al. (2019). In all cases, high alumina concentration is not favorable for most crops due to the toxic effects of aluminum on plant growth represented by the disturbance of the uptake and transport of water and essential nutrients (Ca, K, and P) by plant roots, leading to increase the sensitivity to drought stress. However, the toxic effects of aluminum can be mitigated by

Table 2 Comparison between the chemical composition of glauconites in Egypt and the exploited New Jersey glauconite (USA) (after Baioumy & Boulis, 2012a, 2012b; Banerjee et al., 2019; El-Habaak et al., 2016b)

Oxides (100%)	Upper Eocene glauconite		Cenomanian glauconite	Campanian glauconite	New Jersey glauconite
	El-Bahariya Oasis				
	El-Gedida mine		Ghorabi mine	Abu-Tartur Plateau	
	Eastern wadi	Western wadi			
SiO_2	52.10	50.89	58.19	54.74	51.83
TiO_2	0.13	0.04	0.40	0.02	nd
Al_2O_3	5.99	5.88	7.74	13.84	6.23
Fe_2O_3	22.23	22.99	17.64	25.56	20.08
MgO	3.75	4.34	2.49	4.01	3.66
CaO	0.31	0.20	0.58	0.18	0.52
Na_2O	0.10	0.05	0.30	0.02	0.76
K2O	6.75	7.30	5.41	3.12–5.30	6.60
MnO	0.02	0.08	0.02	0.04	nd
P_2O_5	0.14	0.07	0.29	0.45	0.31
SO_3	0.21	nd	nd	nd	nd

nd not determined

silicon, which promotes higher accumulation of biomass by increasing the supplement of nitrate and iron and stimulating the photosynthesis process (Ma, 2005). The soluble forms of iron (Fe^{+2}) have a vital role in the building up of chlorophyll and facilitating the transport of oxygen through the roots and leaves of plants. Under acidic soil conditions, the iron concentration will increase in the soil solution. This can cause harmful effects for plants such as the root flaccidity and leaves mottling (Rout et al., 2014). The present glauconites have noticeable iron content varying between 19.54 and 25.56 wt% as Fe_2O_3, which must be considered for the cultivation-based glauconite in acidic soils.

5.2.2 Heavy Metals Content

The high levels of heavy metals have toxic effects on soils, plants, animals, and human health. For instance, heavy metal contamination of the soil is caused by various metals among which Cr, Mo, Pb, and Cd, leading to decrease the diversity and activity of soil microorganisms responsible for the supplement of plant nutrients through degradation of organic matter. Also, accumulation of plentiful amounts of heavy metals in plants can prevent them from absorbing water and photosynthesis, resulting in reducing the growth rates of roots and seedlings (Hinojosa et al., 2004). Human health can also be subjected to the heavy metal toxicity through the food chain, which starts with plants and animals. As, Cd, Hg, Cr, and Pb are considered as the most toxic metals and classified as human carcinogens (Tchounwou et al., 2012). Accordingly, the heavy metal content of the present glauconite was compared with the tolerant levels issued by the Canadian Inspection Food Agency "CIFA" (2020) and Kenya Bureau of Standards for fertilizers (2018), as listed in Table 3. It is clear that glauconite deposits in Egypt have allowable content of the harmful heavy metals, and their exploitation as natural fertilizers does not pose critical environmental thrives.

Table 3 Comparison between heavy metal contents of the Upper Eocene glauconite in Egypt and that reported by the Canadian Food Inspection Agency (CFIA, 2020) and Kenya Standards (2018)

Heavy metal content (ppm)		Mo	Cu	Pb	Zn	Ni	As	Cd	Co	Cr
Upper Eocene glauconite	Eastern wadi glauconite, El-Gedida mine	< 0.1	3.7	2.0	86	15.4	2.4	< 0.1	25.8	110
	Western wadi glauconite, El-Gedida mine	< 0.1	2.4	0.3	208	30.7	2.2	< 0.1	28.0	130
CFIA		5	400	150	700	62	13	3	34	210
Kenya Standards		–	–	30	–	–	20	15	–	500

5.2.3 PH and Salinity

Measurement of pH values and salinity levels for a given rock-based fertilizer is an important procedure for two reasons. The first one is that the continuous and intensive application of fertilizers contributes mainly to change the soil pH value to become more acidic or highly basic state. For most plants, the appropriate pH values range between 5.5 and 7 (Kidd & Proctor, 2001). Under highly acidic conditions (pH $\leq$ 4.5), some harmful elements (e.g., Al) can be released into the soil solution and affect the availability of macronutrients such as phosphorous, which easily reacts with aluminum to form insoluble aluminum phosphate (Matsumoto, 2000). Further, pH values > 8 lead to increase the adsorption of nutrients on the particles of clay minerals and organic matter, which makes them unavailable for plants (Neina, 2019). The second reason is owing to the detrimental effects stem from the annual consumption of the fertilizers. For example, the salt stress can lead to several disorders for plants including osmotic imbalance, nutrient imbalance, reduction in leaves number and roots length as well as low photosynthesis activity due to the competitive process between nutrients and salt ion species, in particular Na^+ and Cl^- (Munns & Tester, 2008). Literature (El-Habaak et al., 2016b; Morsy et al., 2016) has showed that the glauconite deposits in Egypt are characterized by mild pH values (19.10–7.59) and lower salinity levels (0.1–2.83 dS/m), which are consistent with the other studies carried out in other countries, e.g., Argentina and India, on the low pH and salinity effects of glauconite on arable soils (Franzosi et al., 2014; Rudmin et al., 2020).

5.2.4 Glauconite Solubility

Glauconite is well-known for its low water solubility along with its behavior as a slow-acting K source. This character can be attributed to the low hydration energy of K^+ ions occurring in the crystal structure of glauconite as nonexchangeable interlayer cations tightly bonded to the negatively charged tetrahedral layers (McRae, 1972, 1975). Water solubility rate of K from glauconite crystal lattice is measured between 6.94 and 23 mg K^+/kg of glauconite (Rao & Rao, 2008; Karimi et al., 2012; Smaill, 2015). From an environmental perspective, the slow-release nature of glauconite is favored to make a sustainable supplement of nutrients needed by plants and to avoid the detrimental accumulation of heavy metals in soil resulted from the continuous application of the fast-release salt fertilizers (Rudmin et al., 2019). Also, glauconite can remediate the soil deficiency in K, which results from the downward percolation of K-bearing soil solution, crop harvest, and K-fixation in the interlayer sites of the weathered clay minerals (e.g., vermiculite and smectite) (Meena et al., 2016). However, the direct application of glauconite is not preferred for the short-season crops, which need an immediate supplement of K. At this point, the chemical K fertilizers outperform glauconite due to their high water solubility and the quick nutrient supplement for plants. Consequently, the research work was directed to investigate all possible methods by which the water solubility of glauconite can be accelerated. It was found that about 96–100% of the interlayer K can be lixiviated either after adequate roasting at 900 °C in the presence of the chloridizing agent, in particular $CaCl_2.H_2O$ and LiCl, followed by water leaching or through acid roasting to obtain liquor rich in KCl or K_2SO_4 (Mazumder et al., 1993; Santos et al., 2017; Shekhar et al., 2017, 2020). Also, the liberation of K can be promoted by mixing glauconite with composts or inoculation with K-solubilizing bacteria (e.g., *Thiobacillus, Bacillus, and Clostridium*), resulting in a gradual destruction and collapse of glauconite crystal lattice due to the metabolic microbial products (e.g., organic and inorganic acids, extracellular polysaccharides, enzymes, and hydroxyl anions) (Ullman et al., 1996). In Egypt, the only published work on K extraction from glauconite is that of Amer and Sediek (2003). They recovered about 90% of the interlayer K from the Campanian Abu-Tartur glauconite by the direct acid leaching for 2 h at 20 wt% HCl and 225 °C. So, this point needs more consideration to perform a detailed study on the possible response of the Cenomanian, Campanian, and Upper Eocene glauconites to the thermal, chemical, and biological treatments. This is considered the second important step after glauconite evaluation for building up the future potash industry in Egypt.

6 Glauconite as a Soil Conditioner

Glauconite grains are characterized by high cation exchange capacity, up to 30 cmol/kg, and numerous micropores. Consequently, the application of glauconite to agricultural soils can contribute to enhance the ability of soil to hold water and store substantial amounts of plant nutrients (e.g., K, Ca, and Mg) (Heckman & Tedrow, 2004). Also, the uniform sand size of glauconite grains makes a noticeable improvement in soil porosity, permeability, and texture (Indian Minerals Yearbook, 2011, 2012). Accordingly, glauconite deposits are considered as a good soil conditioner. Moreover, glauconite is commonly found in association with gypsum, anhydrite, and calcite minerals, which behave as amendments to strength the erosion resistivity of soil and increase the pH value of soil solution. The latter reduces the movement of toxic metals (e.g., Al) and inhibits their reaction with the essential macronutrients (Roy et al., 2006).

Table 4 Comparison between the efficiency of glauconite application on some vegetation parameters in Egypt and the Western Siberia (after, Morsy et al., 2016; Rudmin et al., 2019)

Fertilizing rate (ton/feddan)	Upper Eocene glauconites of Egypt						Meso-Cenozoic glauconites of Western Siberia			
	Plant height		Fresh weight		Dry weight		Plant height		Grain yield	
	cm	R. C.	g/pot	R. C.	g/pot	R. C.	cm	R. C.	Kg/ha	R. C.
0	66.6	100	24.6	100	2.32	100	69.6	132	1613	118
2	74.0	111	26.3	106	2.78	119				
4	75.8	113	29.0	117	2.92	125				
6	77.8	116	30.2	122	2.94	126				
8	77.6	116	30.5	123	3.03	130				
10	78.6	118	32.5	132	3.12	134				

Note R.C.— Relative to control

7 Cultivation with Glauconite

Glauconite deposits were investigated in different regions as a direct K fertilizer applied to various crop types such as olive trees, coffee, oats, and sunflowers. The field experiments were monitored during the first and second cultivation seasons, and all results indicated the effective role of glauconite-based fertilizers in enhancing the plant height and the total yield of crops (Karimi et al., 2012; Franzosi et al., 2014; Rudmin et al., 2019, 2020). In addition, the glauconite-amended soils are characterized by increasing the concentrations of organic carbon, exchangeable ammonium, K, P, Ca, and Mg as well as a noticeable improvement of the soil physical characters (e.g., moisture retention capacity, porosity, and permeability) due to the uniform size of glauconite grains and their surface micropores. Field experiments were also conducted on the sandy soils of El-Minia Governorate, Egypt, using the Campanian and Upper Eocene glauconites collected from El-Bahariya Oasis and the Abu-Tartur Plateau (Morsy et al., 2016). Six treatment rates of glauconite deposits (0, 2, 4, 6, 8, and 10 ton/feddan) were applied to the sandy soil cultivated with peas plants. The obtained results indicate the efficiency of glauconite in enhancing some vegetation parameters (e.g., plant height and fresh and dry weight of plant shoots) as well as increasing the water efficiency use by plants at application rate of 10 ton/feddan (Table 4).

8 Conclusions and Recommendations

Egypt has considerable accumulations of the Phanerozoic glauconites reported mainly in El-Bahariya Oasis, the Abu-Tartur Plateau, west central Sinai, and Fayum Depression. They are assigned to the Cenomanian, Campanian, Upper Eocene, and Oligocene ages. The Egyptian glauconites are associated with the Tethys sea level changes in terms of transgression (Cenomanian) and regression (Upper Eocene and Oligocene). The reported glauconites are condensed sections of variable thickness between 7.5 and 25 m. The present glauconite deposits were subjected to more detailed geochemical, mineralogical, and beneficiation studies to reveal their economic potential as alternative potassium fertilizers. At El-Bahariya Oasis and the Abu-Tartur Plateau, glauconites form green-yellowish green, friable-moderately hard, moderately sorted deposits and can be classified as low–high mature deposits, with K-content varying between 3.12 and 7.3 wt% K_2O. Mineralogically, glauconite deposits comprise 65–75% glauconite pellets together with quartz, calcite, goethite, gypsum as the main gangues. Although the Egyptian glauconite deposits are in accordance with the physical and chemical specifications as an alternative potash fertilizer, they attract little attention. This is ascribed to the occurrence of such deposits as overburden covering the commercial iron deposits in El-Bahariya Oasis and the mineable phosphorites in the Abu-Tartur Plateau. Egypt has limited potash resources and depends mainly on the imported fertilizers to increase the arable areas and secure the food supplies for the ever-increasing population. Any probable future control on the imported potash (e.g., the German control on potash exports in the early twentieth century) will negatively affect the agricultural activities and crops production in Egypt. So, it is the time to investigate and exploit the alternative K resource for the future potash industry in Egypt. Glauconites are one of these resources and greatly eligible for the production of potash fertilizer after the following recommendations:

- First of all, the present glauconite deposits need a systematic plan to explore and estimate the possible occurrences and reserves in other areas of the Western Desert, Nile Valley, and Eastern Desert.
- Microscopical, mineralogical, and chemical characterizations have to be carefully performed for the discovered deposits to evaluate the interlocking nature between

glauconite grains and the associated gangues as well as to determine the extent to which such deposits are suitable for potash production.

- A combination of size reduction (−1 mm in diameter) and high-intensity dry magnetic separation is recommended for upgrading K-content. Hence, the obtained glauconite concentrate can be used as a slow-release K fertilizer.
- From another perspective, the concentrated glauconite can undergo procedures of roast leaching or direct acid leaching to produce potash fertilizers in the form of water-soluble K salts (e.g., KCl and K_2SO_4).

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