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## Fluid inclusion studies of Bahariya barites (Western Desert, Egypt)

**ABSTRACT:** The role of fluid inclusion studies in genetic discussion is examined on the example of barites from the Bahariya Oasis in Egypt. In the previous works, at least one of the barite generations has been interpreted as a result of crystallization from rising hydrothermal solutions. Detailed studies of fluid inclusions in all barites from the Bahariya Oasis prove that they have crystallized from solutions of meteoric origin. Three generations of fluid inclusions have been distinguished. Two of them are related to the barite crystallization and its progressive coalescence and recrystallization; these are predominantly liquid filled. The third generation is connected with infiltration of ascending solutions of meteoric origin; it includes both liquid and gas/liquid inclusions. On the basis of this study the possible mechanism responsible for the formation of gas/liquid inclusions under low temperature conditions is presented.

### GEOLOGIC SETTING

The Bahariya Oasis in the Western Desert in Egypt is situated 370 km southwest of Cairo, whereas the studied barite occurrences lie within the northern part of the Bahariya depression, about 20 km northeast of the village El-Bawitti (*see* Text-fig. 1). The exposed stratigraphic sequence in the Bahariya Oasis ranges from the Cretaceous to Quaternary (*see* Text-fig. 2). The Cretaceous rocks in this region are differentiated into the Bahariya, the El-Heiz, the El-Hefhuf, the Ain-Giffara and the Khoman/Chalk Formation (SAID 1962, EL-AKKAD & ISSAWI 1963, Kerdany 1968, Khalifa 1977). In the investigated part of the Bahariya Oasis, Early Cenomanian sediments (Bahariya Fm.) are disconformably overlain by Middle Eocene rocks (the Nagb, the Quazzun, and the Hamra Formation) which in turn are overlain by the Oligocene Radwan Formation (EL-AKKAD & ISSAWI 1963, SAID & ISSAWI 1964).

The whole sedimentary sequence in the study area is about 200 m thick (Text-fig. 2). It is composed mostly of: sands and shales with large number of ferruginous intercalations (Bahariya Formation); dolomitic and fossiliferous limestones (Nagb Formation); nummulitic limestones (Qazzun Formation);

limestones with marly intercalations (Hamra Formation); and glauconitic sandstones and sandy clays with silicified wood fragments (Radwan Formation). The whole sedimentary sequence is injected with Tertiary basalts and dolerites that occur in forms of sills and dykes. Quaternary sediments are represented by aeolian sands and lacustrine deposits, with some Recent continental sabkhas.

The Bahariya Oasis is considered to be a range of eroded anticlinal folds formed during the so-called Syrian arc movements (SHUKRI 1954). Synclinal folds within the Bahariya Oasis are separated by anticlinal structures trending the NE-SW direction. Three trends of folds as well as faults are recorded in the Bahariya Oasis; they are the NE-SW, E-W, and NW-SE directed, the latter of which disturbs the younger formations (Middle Eocene) in the northern part of the Bahariya depression (EL-ARKAD & ISSAWI 1963). The hills within the

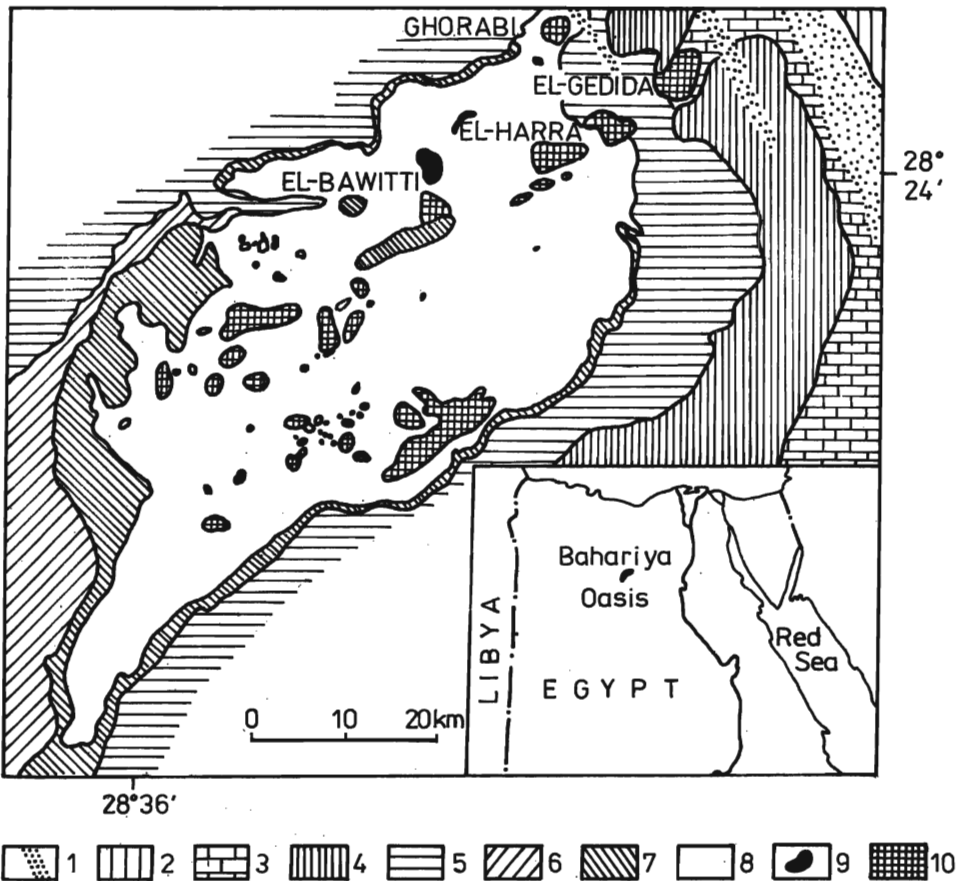
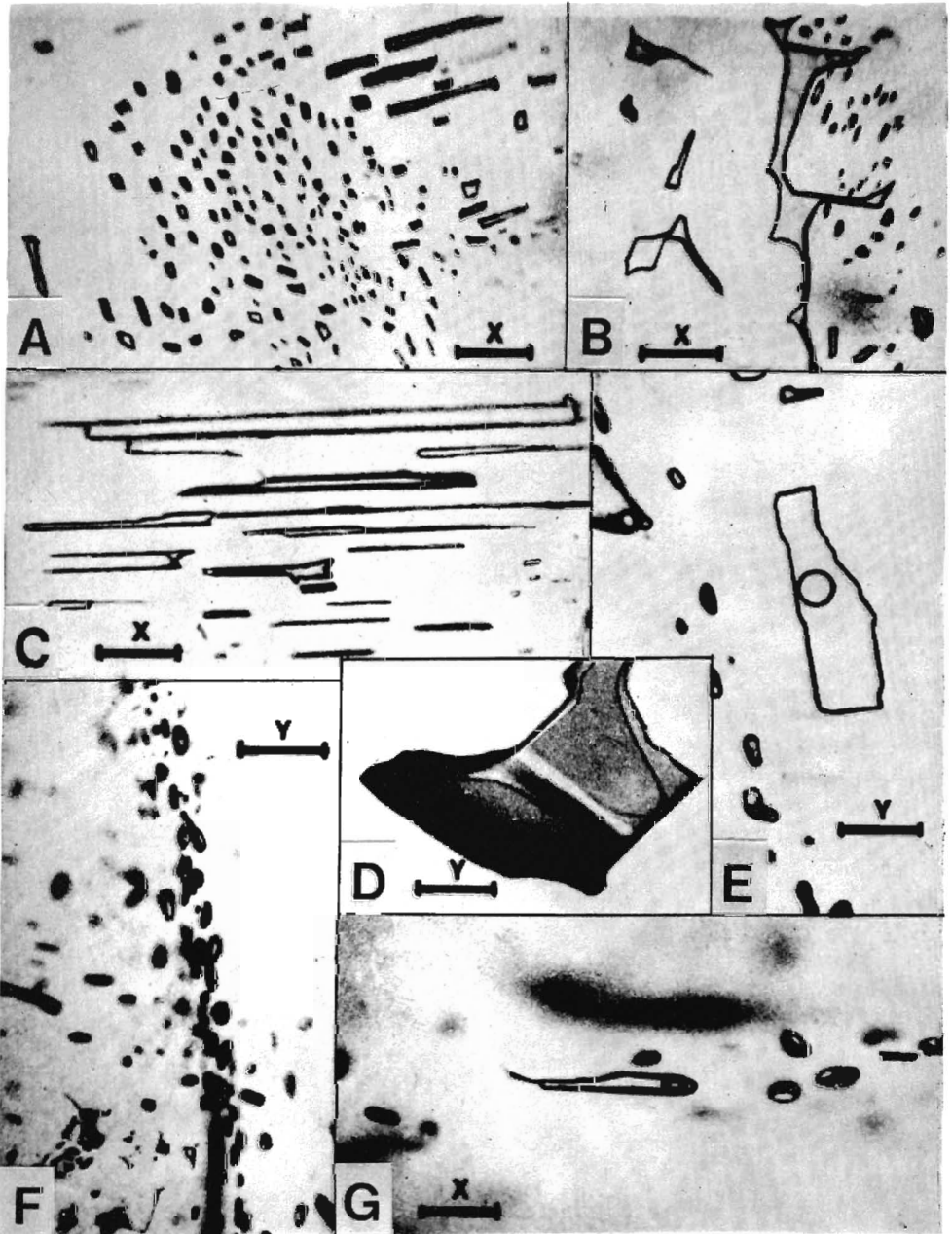


Fig. 1. Geological map of the Bahariya Oasis depression in Egypt

- 1 — Quaternary sand dunes, 2 — Oligocene Radwan Fm., 3 — Middle Eocene Hamra Fm.,  
 4 — Middle Eocene Qazzun Fm., 5 — Middle Eocene Nagb Fm., 6 — Maastrichtian Chalk Fm.,  
 7 — Santonian El-Hefhuf Fm., 8 — Lower Cenomanian Bahariya Fm., 9 — Tertiary volcanics,  
 10 — Iron ore deposits



### Inclusions in barite from the Bahariya Oasis

A — Cluster of small *P1* liquid inclusions; B — Irregular larger *S2* liquid inclusions; in other plane visible are vanishing *P1* inclusions; C — needle-like liquid *S2* inclusions; D — large *S2* inclusion, partly filled with liquid; E — gas/liquid *S2* inclusion, near by a row of *S3* gas/liquid and liquid inclusions; F — *S3* inclusions in a zone of healed fracture; G — *S3* gas/liquid inclusions  
 Scale bars:  $x = 10 \mu\text{m}$ ,  $y = 100 \mu\text{m}$

Bahariya Oasis represent the cores of synclinal structures, whereas depressions and other topographic lows correspond to eroded anticlines.

The samples were collected in three locations (El-Gedida, El-Harra, and Ghorabi; see Text-fig. 1) and embrace all available varieties of barite.

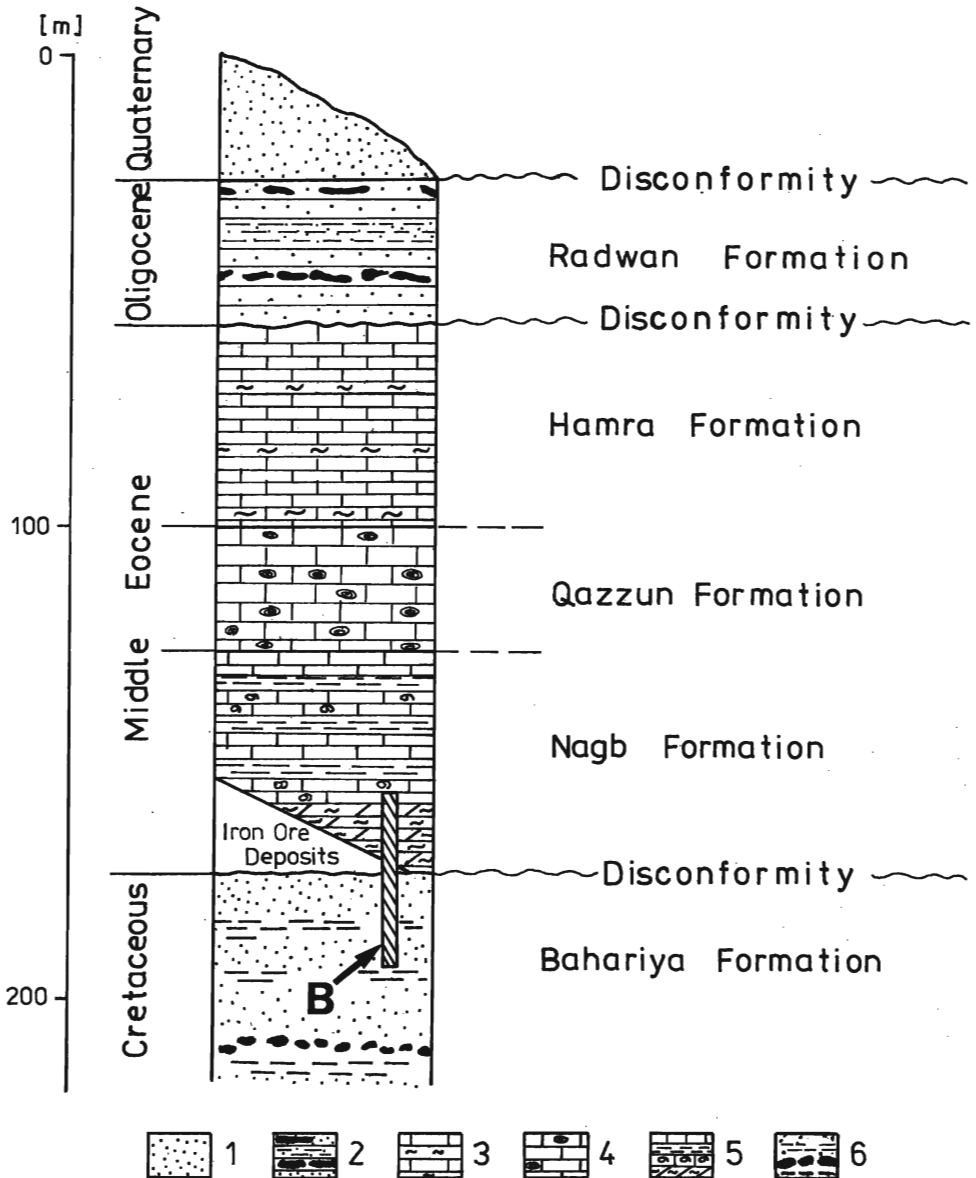


Fig. 2 Generalized lithostratigraphic column of the deposits exposed in the Bahariya Oasis, with marked position (B) of the investigated barite occurrences

- 1 — sands, 2 — glauconitic sandstones with sandy clays, and containing silicified wood fragments,  
 3 — limestones and marls, 4 — nummulitic limestones, 5 — fossiliferous dolomitic limestones,  
 6 — sands and shales with ironstones

## BARITES OF THE BAHARIYA OASIS

There are three principal modes of the barite occurrence in the investigated part of the Bahariya Oasis: (i) Barite cement and fracture filling in the Bahariya Formation, at El-Harra location; (ii) Reworked barite fragments on the disconformity surface between the Bahariya and the Nagb Formation as well as on the surface of the iron ore, in the El-Gedida and Ghorabi areas; (iii) Barite aggregates and barite infillings in fractures and cavities in the iron ore, in the locations El-Gedida and Ghorabi. All the investigated barite occurrences represent commercial type reserves.

Two generations of barite have been distinguished in the Bahariya Oasis (SHAALAN 1980), one being older and the other younger than formation of the iron ores. Detrital barite was derived most probably from pre-existing rocks by physical weathering, therefore it is older than the overlying iron ore. The second generation of barite is connected with crystallization from rising solutions. Both, BASTA & AMER (1969) and SHAALAN & *al.* (1988) came to conclusion that these barites are connected with migration of hydrothermal solutions generated by adjacent Tertiary volcanics. The amount of barite in investigated samples varies from 2 to 50% in barite-bearing rocks, and up to 95% in veinlets and barite infillings. The main impurities associated with barite are iron oxides (mostly hydrated) that impregnate barite crystals along cleavages and fractures together with minor amount of calcite and sulphides.

## FLUID INCLUSION STUDIES

Three types of fluid inclusions (one primary and two secondary) have been distinguished in the investigated barites of the Bahariya Oasis.

The primary inclusions of the first type (*PI*) are connected with nucleation and early crystallization of the elaborated barites. The *PI* inclusions are mostly liquid with very small number of those aqueous gas/liquid (Text-fig. 3A, 3B). All of them are generally very small, less than 5  $\mu\text{m}$ . The forms of *PI* inclusions are predominantly oval, conical, lenticular and rounded, less commonly rectangular and elongated. These inclusions are unevenly disseminated throughout the barite crystals and they also form some kind of dense sieve-type textures in different crystal planes. The *PI* inclusions are not visibly related to any barite structural and textural features, *i.e.* microcracks, cleavages, fissures, etc. It has been observed that near the microcracks and growth zones these inclusions are vanishing.

The *PI* inclusions in plain light are mostly transparent and colorless. When present, the gas bubbles are very small and are often moving, changing their position in the inclusion and disappearing. It was difficult to make exact measurements of their homogenization temperature, as they homogenize due to prolonged heating by the beam of microscope light. The  $T_h$  temperature of about 20 individual measurements scatters in a wide range from 30 to 50°C. The *PI* inclusions are

especially abundant in smaller and subhedral barite crystals (the Bahariya Formation). In more recrystallized barites they are not so common and when present they have patchy distribution forming clusters composed of several to hundreds inclusions. This type of inclusions has been noted in all investigated occurrences and it comprises the whole examined barite-bearing sequence. Therefore, these inclusions are not necessarily contemporaneous in every particular occurrence, and they cannot be recognized as one, well-defined generation.

The inclusions of the second type (*S2*) are intimately associated with the *P1* inclusions. They are apparently growing at the expense of primary inclusions due to processes of coalescence and recrystallization (Text-fig. 3*B*). These inclusions are located in other planes than those of *P1* or are superimposed on earlier primary inclusions. The *S2* inclusions are larger than the primary inclusions, with size varying within a width range from 20  $\mu\text{m}$  to 1 mm (Text-fig. 3*D*). The forms of *S2* inclusions are predominantly very irregular with complicated line of crystal / inclusion interface. Elongated, rectangular, acicular inclusions are also common (Text-fig. 3*C*). The inclusions of this shape are organized parallelly to each other and they additionally show correlations to distinct crystal planes. Minor gas bubbles in *S2* inclusions are larger than those of *P1* inclusions, but are not exceeding 10% by volume (Text-fig. 3*E*). The iron oxide microcrystals in the liquid *S2* inclusions are very rare. The spatial distribution of *S2* inclusion may indicate that larger euhedral crystals of barite resulted from development and coalescence of smaller barite grains.

The secondary inclusions of the third type (*S3*) are especially abundant in barites associated with iron ores and those that fill veinlets and heal tectonic fissures (Text-fig. 3*E*, 3*F*). Fluids occur through dense set of microcracks and microfissures in all scales. The migration directions of the fluids were mostly dependent on local direction of microfracturing and different direction of microcracks openings. Considering only the orientation of the trails of fluid inclusions, several generations of *S3* inclusions could be recognized. But this is an unjustified complication, it seems rather that the *S3* inclusions were related to one geological process with some spatial and temporal discrepancies in different barite occurrences.

The *S3* inclusions have very different size from several micrometers up to 0.5 mm. The liquid inclusions are still dominating (about 98%), but in some preparations the amount of the gas/liquid inclusions increases up to 10%. It is characteristic of gas/liquid inclusions that even in the same preparation they contain highly variable amount of vapor, from 5 to 40% by volume (Text-fig. 3*G*). Stable iron oxides and minor translucent unrecognized intergrowths occur very often in the *S3* inclusions, which in plain light are transparent to translucent and often have pale yellow to light brown color. Colorless equilibrium solution exposed to atmosphere becomes yellowish during a couple of days, that may suggest the presence of  $\text{FeCl}_2$ .

As more than 99% of *P1* and *S2* inclusions are liquid and the volume of gas in gas/liquid inclusions is very small, it is suggested that these inclusions have been formed at very low temperatures characteristic of meteoric conditions. This inference is confirmed by solid phases dissolution measurements in solid/liquid

*S2* inclusions. The dissolution temperature of 45 to 55°C was credibly a minimum trapping temperature.

It is believed that also the *S3* inclusions are of meteoric - infiltrational origin. The particular distribution of the *S3* inclusion trails suggests ascending character of solutions, what agrees with the earlier interpretations of SHAALAN & *al.* (1988). This view is suggested by the dominance of liquid inclusions and by microchemical analysis of the gas phase. Because of small amount of the gas phase only three successful determinations of gas composition in *S3* gas/liquid inclusions have been made. The average composition of the gas phase, viz.: N<sub>2</sub> — 70 to 76%, O<sub>2</sub> — 19 to 22%, CO<sub>2</sub> — 3 to 8%, and a lack of CO, H<sub>2</sub>, hydrocarbons and acid gases clearly suggest a meteoric origin. Additionally, it would be very hard to explain the presence of the so variable amount of vapor in the same *S3* inclusions trail, if assuming a hydrothermal concept of their origin. Therefore, in this particular case, measurements of homogenization temperature into the fluid phase would have been meaningless and misleading.

#### DISCUSSION OF THE RESULTS

The results of the presented investigation support the view of SHAALAN & *al.* (1988), about two barite generations varying in age relative to the iron mineralization. The primary *P1* and the secondary *S2* inclusions are connected with crystallization, coalescence and recrystallization of the first barite generation. This process occurred at low temperatures, and the pressure on this stage of barite evolution is considered to be nearly hydrostatic. The exact time and the sequence of these processes in particular barite occurrences were probably slightly different.

Oriented fluid inclusion trails of the secondary *S3* inclusions occur both in barite of the first and second generations and have ascending, infiltrational character. It is generally thought that the chemical (ore) profile of a parent fluid is in direct relation with the daughter minerals in the fluid inclusions. Thus, it could be assumed that a certain amount of iron ore has been distributed or leached and redistributed by ascending barite-bearing solutions. The crystallization of the second barite generation occurred also at low temperatures, but with a credibly variable pressure. It seems, that the formation of the *S3* inclusions at the investigated barite occurrences has been governed by the same mineral solutions.

It is envisaged, that composition of the *S3* fluids that resulted in unexpected, increased amount of the gas/liquid inclusions has been in a great part due to pressure release. It is suggested that water of meteoric origin percolated through the sedimentary sequence deeply beneath the investigated section and later, under elevated pressure in some kind of phreatic system, it ascended upwards. The major tectonic structures may acted as conduits for rapidly ascending solutions. It is also credible that a part of the *S3* gas/liquid inclusions resulted from mixing of different concentration and origin solutions.

Various crystallization mechanisms could be responsible for formation of the *P1* and *S2* gas/liquid inclusions. Some part of the *P1* inclusions has primary content of vapor, that reflects gas oversaturation of parent fluids in an open meteoric system. The other explanation for the *P1* inclusions could be also assumed with gas bubble stucked to a growth plane and trapped within a rapidly growing crystal. The secondary *S2* inclusions correspond to a multistage fluid migration and trapping due to the coalescence and recrystallization. Therefore, several different mechanisms may be responsible for their formation at very low temperatures. The most important ones could be: mixing of fluids of different concentration and chemical composition, enlargement of inclusions, entrapment of gas phase contained in open spaces, loss of previous content by diffusion or leakage.

### CONCLUSIONS

The early fluid phase responsible for the *P1* and *S2* inclusions is genetically linked to the process of barite crystallization, and the progressive coalescence, whilst the later fluids are connected with infiltration of subsurface waters of mostly meteoric origin. The *P1* and *S2* inclusions indicate low (meteoric) temperatures and hydrostatic pressure of barite crystallization. In the light of the performed analysis the formation of the second barite generation due to a hydrothermal activity related to the Tertiary volcanism seems to be highly improbable. The diagenetic-infiltrational origin of the barite second generation is preferably assumed.

Any geologic interpretation based on the presence of the gas/liquid inclusions or the volumetric relation between the coexisting phases as viewed by these results could, however, be a misleading oversimplification.

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## INKLUZJE FLUIDALNE BARYTÓW Z OAZY BAHARIYA W EGIPCIE

### (Streszczenie)

Oaza Bahariya położona jest około 370 km na SW od Kairu i leży w północnej części struktury geologicznej zwanej depresją Bahariya (fig. 1 i 2). W pobliżu oazy znane są z szeregu lokalizacji złoża hematytowych rud żelaza i współwystępujących z nimi barytów. Próbkę barytów pobrano z trzech odsłoneń: El-Gedida, El-Harra i Ghorabi. Dotychczas pochodzenie tych barytów wiązano z ascensyjnymi roztworami generowanymi przez pobliskie trzeciorzędowe wulkanity. Jako jeden z argumentów za tą koncepcją przytaczana była powszechna obecność w barytach inkluzji, w tym gazowo-ciekłych.

Przeprowadzone badania pozwoliły wyróżnić trzy generacje inkluzji. Inkluzje pierwotne (P1), głównie ciekłe (99%), powstały na etapie nukleacji i krystalizacji barytu (fig. 3A i 3B). Inkluzje wtórne obejmują inkluzje wcześniejsze (S2) związane z rekrystalizacją barytu (fig. 3B-3E) oraz inkluzje najmłodsze (S3) utworzone w trakcie zablizniania spękań w kryształach (fig. 3E-3G). Jedynie w inkluzjach S3 występuje większa ilość fazy gazowej, od 2 do 10%, o składzie odpowiadającym powietrzu atmosferycznemu. Wykonane oznaczenia temperatur homogenizacji dla inkluzji P1 oraz S2 są bardzo niskie, rzędu 30 do 50°C. Obecność zmiennej ilości fazy gazowej w części inkluzji S3 zinterpretowano jako wynik zmniejszenia ciśnienia w ascensyjnym systemie freatycznym. Genezę wszystkich złóż barytów z rejonu Oazy Bahariya powiązano ze środowiskiem hipergenicznym.