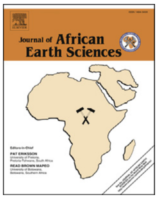
Journal of African Earth Sciences 112 (2015) 276–286

Contents lists available at ScienceDirect

Journal of African Earth Sciences

journal homepage: www.elsevier.com/locate/jafrearsci



Origin of fluorite mineralizations in the Nuba Mountains, Sudan and their rare earth element geochemistry

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ARTICLE INFO

Article history:
Received 25 June 2015
Received in revised form
21 September 2015
Accepted 21 September 2015
Available online 28 September 2015

Keywords:
Fluorite
Nuba Mountains
Sudan
REE
Fluid inclusion
Origin

ABSTRACT

Among other mineralizations in the basement complex of the Nuba Mountains, fluorite occurs as lenses and veins in a number of localities. The rare earth elements (REE) geochemistry in these fluorites along with their petrography and fluid inclusion was investigated in this study to discuss the origin the fluorites and shed the light on the economic importance of the REE.

Fluorites in the Nuba Mountains are classified into four categories based on their petrography. Category I (F1) is characterized by pink color and free of inclusions. Category II (F2) is zoned of alternating pink and colorless zones with euhedral outline or anhedral patchy pink and colorless fluorite enclosing category I fluorite and is usually sieved with submicroscopic silicate minerals. Category III (F3) is colorless, euhedral to anhedral fluorite and associated with quartz and/or orthoclase. Category IV (F4) is colorless, either massive or dispersed, corroded grains associated with calcite and pertain to the late introduced carbonatites in Dumbeir area. Gangue minerals in the studied fluorites include quartz, calcite, orthoclase and muscovite.

The ΣREE ranges between 541 and 10,430 ppm with an average of 3234 ppm. Chondrite-normalized REE patterns for fluorite from different localities exhibit LREE enrichment relative to HREE as shown by $(La/Yb)_N$ ratios that vary from 16 to 194 and significant positive Eu anomalies that are pronounced with Eu/Eu* from 1.1 to 2.5.

The Tb/La and Tb/Ca ratios of fluorites in the present study indicate that they plot mainly in the pegmatitic or high-hydrothermal field with the characteristics of primary crystallization and remobilization trend. The clear heterogeneity of fluorite, abundance of growth zones, irregular shapes of grains, presence of fluorite inclusions in other minerals as well as the relatively high concentration of REE in the studied fluorites are supportive for this interpretation. The relatively high Tb/La (0.002–0.013) and low Tb/Ca (0.0000007–0.0000086) ratios of the studied fluorites suggest that they precipitated from fractionated ore-bearing fluids at a late stage of deposition.

The microtherometric measurements of the primary inclusions show that the Nuba Mountains fluorites were formed at temperatures greater than 600 °C. These values along with the low salinity of the fluid inclusions indicates homogenize at moderate temperatures. Thus the studied fluorite probably formed during the late stages of pegmatite consolidation under magmatic–hydrothermal transition conditions supporting the previous conclusions from REE geochemistry.

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1. Introduction

Fluorite of varied color and habit occurs in a wide range of ore deposits from low-temperature and moderate salinity epithermal veins and replacements to high-temperature and high-salinity

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http://dx.doi.org/10.1016/j.jafrearsci.2015.09.016
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magmatic deposits such as greisens, skarns, porphyries, and pegmatite systems (e.g. Coniglio et al., 2000; Bühn et al., 2002). Because of its distinct geochemical pattern, fluorite rare earth element (REE) geochemistry has been widely used as an aid to investigating its genesis (e.g. Hill et al., 2000; Williams-Jones et al., 2000; Bosze and Rakovan, 2002; Monecke et al., 2002; Ehya, 2012). Fluid inclusion petrography and microthermometry were also extensively applied to eamine the origin of mineral deposits in general (e.g. Gagnon et al., 2003; Ouyang et al., 2014) and in particular to distinguish between fluorite of pegmatite origin from that of hydrothermal source (e.g. Hein et al., 1990; Ackerman, 2005; Sasmaz et al., 2005a,b; Sasmaz and Yavuz, 2007; Ehya, 2012).

Nuba Mountains represent a major geological feature in the center of Sudan. The basement rocks of these Mountains host a number of mineral deposits such as fluorite, gold, copper, iron, talk, zinc, graphite, manganese, uranium and chromite (e.g. El Sharkawi and El Rabaa, 1973; Shaddad et al., 1979; Khalil, 1980; Abdel Galil, 2008). Fluorite deposits occur as lenses and veins in many localities in the Nuba Mountains. Based on the structural feature and occurrence, it was suggested that fluorite mineralization has a hydrothermal origin (e.g. El Sharkawi and El Rabaa, 1973; Shaddad et al., 1979; Khalil, 1980; Abdel Galil, 2008). No geochemical and fluid inclusion data have been published about this mineralization. This study reports for the first time, the REE distribution and patterns, as well as fluid inclusion analysis of fluorite in the Nuba Mountains to discuss its origin. The study also sheds light on the economic significance of REE, since they occur in relatively high concentrations in the fluorite deposits.

2. Geological settings of the studied localities

Nuba Mountains (also referred to as the Nuba Hills) is an area located about 550 km south west of Khartoum (Fig. 1A) in South Kordofan State, and occupies about 140.000 km^2. It is an uplifted crystalline basement entirely surrounded by Mesozoic to Cenozoic rocks filling several graben (Browne and Fairhead, 1983). Studies by Vail (1973), Shaddad et al. (1979) and Sadig and Vail (1986) have established two subdivisions of the basement in the Nuba Mountains: 1) the high-grade gneisses in the west; and 2) the low-grade volcano-sedimentary sequence to the east (Fig. 1B). The high-grade gneisses, exposing as low outcrops, are overlain in places by thick Quaternary sediments (Abdelsalam and Dawoud, 1991). Two structural cycles are recognized within the Basement Complex of the Nuba Mountains. The older, represented by migmatite gneisses and subordinate crystalline schists of high-grade metamorphism (amphibolite facies) predominate in the central part of the Dome. The younger structural cycle is composed of metavolcanics and metasediments of low-grade metamorphism (green schist facies). These units cover those of older structural stage unconformably and are confined mainly to the western and eastern parts of the Dome. In some localities, these younger units are preserved by block and graben faulting within the older units of the Dome. Both older and younger unites are intruded by post-tectonic intrusive bodies of various compositions, ranging from gabbroids to granitoids. These intrusive rocks, together with their associated extrusive equivalents are specially concentrated along three belts: southwestern, central and northeastern belts. The third belt consists of scattered syenitic and granitic intrusions (Jebel Ed Dair, Kadero, Dumbier, El Semieh and Tibna). In Dumbier, carbonatite has been reported (El Sharkawi and El Rabaa, 1973; Shaddad et al., 1979; Khalil, 1980; Abdel Galil, 2008).

In this study, fluorite deposits from four localities in the Nuba Mountains, including Jebel Dumbier, Jebel Gidian, Gebel Ahmar and Jugob Al Kharasana areas are investigated (Figs. 1B and 2).

2.1. Jebel Dumbier

Jebel Dumbier represents the northern limit of the uplifted basement complex of the Nuba Mountains (Fig. 1B). It is located 15 km south west of El Semieh village and 10 km north of the Jebel El Dair, approximately 512 m above the sea level. It represents the largest young intrusion in the northern part of the Nuba Mountains (Khalil, 1980; Abdel Galil, 2008). The dominant lithological units in the Jebel Dumbier area are represented by orthoclasite, nepheline syenite and carbonatite (Fig. 2A). Fluorite mineralizations occur as veins especially in the north and northeastern parts of the area with length up to 1 km and thickness of approximately 1 m, cutting the host rock.

2.2. Jebel Gidian

Jebel Gidian complex is an isolated lensoid body with a length of 125 m, width varying from 1 to 45 m, and height up to 2 m above the surrounding clayey plains. The hillock consists mainly of brecciated fluorite and quartz veins cutting through the nepheline syenite country rocks. Two brecciated massive fluorite veins cut along the general trend of the hillock engulfing both nepheline and orthocalse syenites (Fig. 2B). In the eastern branch, fluorite vein is about 100 m in length and up to 3 m in width. The western branch constitutes the main body of the fluorite ore with a length of 125 m and average width of 7 m cutting the orthoclasite. The two branches meet at both the northwestern and southeastern limits of the hillock. Quartz as veins and veinlets cut both the syenitic country rocks and fluorite bodies. Brecciation and silicification are believed to be due to rejuvenation of the famous NW–SE Dumbier fault. The reserve of fluorite deposits at Gidean area is approximately 38,038 metric tons (e.g. El Sharkawi and El Rabaa, 1973; Shaddad et al., 1979; Khalil, 1980; Abdel Galil, 2008).

2.3. Jebel Ahmar

Jebel Ahmar is one of twinned hillocks on the Western border of Dumbier igneous complex. The hillock is about 549 m above sea level and about 35 m above the surrounding plains. The dominant lithological units building the hillock in decreasing order are: orthoclasite, nepheline syenite and calc-silicate. The last two are found only at the foot of the hill rafted by the igneous intrusions. Older gneiss, meta-sediments and meta-volcanics are found as digested xenolithes in the nepheline syenite member of igneous complex, which is dissected by a number of faults (Fig. 2C). Mineralization was controlled by these fracture zones. Swelling and pinching fluorite veins of 94 m length and average 3 m width filled one of these faults. Carbonatite mineralization has also been reported in this hillock (Khalil, 1980; Abdel Galil, 2008). The reserve of fluorite deposits at J. Ahmar area is approximately 11,903 metric tons.

2.4. Jugob Al Kharasana

Jugob Al Kharasana is located along a fault zone affecting massive orthoclasite country rocks. Reverse faulting resulted in uplift of older Precambrian gneisses and schists, and cal-silicate rocks. Fluorite occurs as vein of about 150 m in length and 1.5 m in width at the foot of the hill (Fig. 2D). The reserve of fluorite deposits at Jugob Al Kharasana area is approximately 119,106 metric tons (Khalil, 1980; Abdel Galil, 2008).

3. Materials and analytical methods

Nine fluorite samples were collected from a number of localities

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