The occurrence of primary REE minerals and their paragenesis within S-type granite and quartz vein, South Bangka, Bangka Belitung Islands, Indonesia

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Research Article

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Abstract

Rare earth elements (REE) is categorized as a part of critical mineral resources because of their important uses in modern technology and the limited resources that are dominated by China. The indication of primary REE minerals was identified in some localities in South Bangka, Indonesia. Such minerals were investigated using various methods such as petrography, ore microscopy, XRF, ICP-MS/OES, SEM-EDS/EDX, EPMA, fluid inclusion study, and stable isotope O and S analysis. Two types of REE minerals have been classified, i.e., carbonate and phosphate. The carbonate type consists mainly of parisite, allanite, and bastnasite, while REE phosphate group comprises mainly monazite and xenotime. The presence of such REE types is also accompanied by other REE-bearing minerals such as thorite and zircon in both granite and quartz veins. The granite with the highest REE values has a lesser negative anomaly of Eu. In other words, it is a less perfectly fractionation than the others, it belongs to biotite granite. In contrast, REE-bearing quartz vein is associated with cassiterite, pyrite, chalcopyrite, sphalerite, and tourmaline. Based on homogenization temperatures and incorporated with stable isotope O and S analyses, and fluid inclusion study results, the hydrothermal fluid that plays a role in REE mineral precipitation is subdivided into three stages, i.e., early (> 316°C – 316°C), intermediate (< 316°C – 210°C), and late (< 210°C- 190°C). The isotopic analysis shows that the δ¹⁸O range of 12.7‰ – 13‰ and δ³⁴S range of 3.9‰ – 5.5‰ indicate that the origin of hydrothermal fluid comes from mixing fluids of both meteoric and magmatic sources, and also influenced by metamorphic waters. While the source of sulfur is granitic and sedimentary rocks. REE phosphate is thought to have formed in the early magmatic crystallization stage except for monazite which is formed in the intermediate magmatic-hydrothermal and late hydrothermal stages. Primary REE carbonate may have formed in an intermediate hydrothermal-magmatic stage except for parasite and allanite, they may have formed in late-stage hydrothermal. Sulfide minerals such as chalcopyrite and sphalerite seem to be associated with REE minerals in the intermediate and late hydrothermal stages.

1. Introduction

Rare earth elements (REE) consist of 17 (seventeen) elements from the lanthanide group (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu) plus Y and Sc which have similar chemical and physical properties. REE is categorized as a part of critical mineral resource due to its important uses in modern technology and the limited resources that are only dominated by one country, i.e., China (Phillip, L.V., 2017, Weng et al., 2017). REEs are generally produced from two types of deposits namely primary deposits which are associated with carbonatite, and secondary ones which are associated with weathering products (Wang et al., 2020). The indication of primary REE minerals related to granitic rocks has recently been reported from several countries, among which are in the Southeast Asia Tin Belt such as Myanmar, Thailand, and Laos.

In Indonesia, efforts to discover potential REE deposits at the economic level have been done for the last decade. REEs are mostly observed associated with the tin deposit as REE phosphate minerals such as monazite and xenotime. They are found within alluvial deposits (Soetopo, 2013) and the tailing of tin...
mines (Tampubolon et al., 2015; Zglinicki et al., 2021). However, due to the lack of research on the origin of primary REEs, it is not known where they come from. Monazite and xenotime, in general, form in the initial crystallization stage of magma; although they may form as a result of reacting with apatite crystals and dissolved fluid, hydrothermal process, and metasomatism. In granite, monazite infills pores and fractures in apatite (Harlov, 2015). Sometimes anhedral-subhedral xenotime crystals associate with monazite. Meanwhile, REE mineral grains distributed as monazites are largely found by local people from the tailing of tin mines, which they collect together with cassiterite and other mineral commodities.

The indication for primary REE minerals, in this context, is defined as REE minerals formed during magmatic crystallization and post-magmatic hydrothermal processes were found in some localities overlapping with artisanal tin mining in South Bangka. The primary was observed in veinlets within biotite granite that have been altered to quartz, apatite, zircon, and pyrite (Hamdan et al., 2014). In addition, it was also discovered within quartz veins in weathered granite bodies at Jangkang and Pulau Tinggi, Sungai Liat, North Bangka. From the measurement of fluid inclusions, it shows that tin was formed at low temperatures (210-220°C) with a salinity of 5–6 wt. % NaCl eq. (Shita & Lucas, 2009). In general, the temperature of the hydrothermal fluid in depositing cassiterite ranges from 250 to 450°C (Faiz et al., 2019). This means that the range of temperature formation for cassiterite in the Bangka Belitung is within the interval of 210 °C and 450 °C. Such a slightly wide range indicates an evolving process of the hydrothermal solution system from high to low temperatures. Based on previous investigation results, granite in South Bangka has significant REE values. Granite identified as biotite granite has REE content of 297.53 ppm in Toboali, 302.34-316.59 ppm in Pading (Simpang Rimba), and 274.08 ppm in Permisan (Ng et al., 2017).

This paper attempts to expose and discuss the origin of primary REE minerals within both granite and quartz vein in South Bangka, Bangka Belitung, Indonesia. The focused areas are located in Toboali and Air Gegas. Selected laboratory methodologies were performed to obtain the content of REE primary minerals and their paragenesis.

2. Geology

The research area is part of the Southeast Asian tin belt in Bangka Island, one of the world-class tin-producing areas. It is largely covered by granite rock known as Triassic-Jurassic Kelabat Granite. This rock consisting of I-Type and S-Type-S granites intruded the Permo-Carbon Pemali Complex in the form of phyllites, schists, and gneiss of Permo-Carbon age and the Triassic Tanjung Genting Formation which is composed of alternating metasedimentary claystone, siltstones, and sandstones of Triassic age (Mangga & Djamal, 1994).; Margono et al., 1995). The Kelabat granite from the Late Permian to Late Triassic occupies West, South, Central, and East Bangka. The lithology of this granite consists of granite, granodiorite, adamellite, diorite, and S-type and I-type quartz diorite (Kurnia & Priadi, 2013; Kurniawan, 2014; Ng et al., 2017).
The Southeast Asian tin belt itself consists of three granite provinces, namely: the East Belt with a north-south trend is dominated by I-type granite, the Main Belt across Thailand, Malaysia, and Indonesia are occupied by S-type granite while the West Belt across Thailand and Burma represented by S-type granite and I-type granite (Ng et al., 2017). The N–S Palaeo-Tethys Bentong-Raub suture line that divides peninsular Malaysia into the Sibumasu Block in the west and the Indochina Block in the east, also crosses the eastern part of Bangka Island in the Bangka-Belitung sea but is not exposed on land (Hutchison, 2014).

Tin mineralization is grouped according to the location of the granite pluton. These plutons are divided into two types: Main Range including S-type Kelabat Granite and I-type Eastern Belt granite. Sn-W ores come from the Main Pluton (Fig. 1) (Schwartz et al., 1995; Crow & Van Leeuwen, 2005). In placer tin deposits, REE occurs as monazite, xenotime, and zircon minerals. It is interpreted that REEs are derived from Kelabat Granite rocks as found in South Bangka (Hamdan et al., 1999; Soetopo, 2013).

3. Granite Observation And Sampling

Granite samples were collected by chip sampling from the base of the weathering profile, exposed by tin mining excavation. From a number of mining pits, no fresh granite bedrock was found as it had been destroyed by mining excavation, most granites have been completely weathered. Seven samples have been collected: four from Toboali (TBL-21MN/02B/R, TBL21KP16/R, TBL21KP-7/F), and two from Air Gegas (TBL-21MN/05E/R, TBL-21MN14/R), and one from Simpang Rimba (TBL-21MN/11/R) (Figure 1).

The indication of strong deformation is found in Toboali granite marked with a lateral fault in the north along with NW-SE foliation. The granitic plutons identified at Toboali and Simpang Rimba are composed of hornblende and biotite as mafic minerals. The Toboali and Simpang Rimba Plutons are classified into young magmatic episodes. The plutons have an average magmatic age of 220 million years (Ng et al., 2017).

In general, the granite observed in Toboali and Air Gegas has a medium texture, composed of quartz, feldspar, biotite, ± hornblende. Quartz veins are discovered within granite in the bottom of the weathering profile at the Air Gegas mine (TBL-21MN/5E/R). So far, no fresh granite has been observed at the bottom of the Air Gegas tin mine as it was submerged in the water.

Toboali Area

All sample localities are within the Kelabat Granite, two main locations were focussed to observe:

1. TBL-21MN/02B/R

Sampling was carried out in a large granite boulder of 2 x 3 meters in diameter. It is found on the bottom of the lateritic profile. The distribution of laterite is widespread where many abandoned and active small tin mine pits were found. Granite is gray in color, faneric texture, relatively fresh, and composed of quartz, K-feldspar, biotite, and hornblende (Figure 2).
2. TBL 21 KP/07/F dan TBL-21KP/16/F

Two samples (TBL 21 KP/07/F dan TBL-21KP/16/F) are a relatively fresh granite rock, they are gray in color, aphanitic texture and contain quartz, feldspar, and iron oxide, presumably the bottom part of the alluvial weathering profile.

Air Gegas

1. On the basis of the geological map of a 1:250,000 scale, the sample numbers TBL-21MN/05E/R and TBL-21MN/14/R are within the contact between the Pemali Complex and the Kelabat Granite (Figure 1). It is an active mining pit (Figure 3) with a depth of about 20 meters. Samples were collected from the bottom of the pit.

2. TBL-21MN/05E/R

This sample is of mineralized quartz vein hosted in granite, Air Gegas (Figure 4.16). It is brownish-yellow color, vuggy, and partly filled with cassiterite ores and clay minerals. Quartz veins appear to be destroyed, presumably due to the structure in the form of a lateral fault trending northeast-southwest as the main structural control of this region. Granite is greenish-white, medium-grained, and strongly altered. Quartz minerals are still clearly visible. However, feldspar and other minerals have been strongly altered to kaolinite and chlorite minerals.

3. TBL-21MN/14/R

This sample is also located in the operating tin-mining area, Air Gegas, covered by a widely large area of laterite (Figure 4a). The excavation of about 10 meters in depth is a weathered granite characterized by the presence of feldspar relics, kaolinite, biotite, and iron oxide (altered hornblende). The sample was taken from the bottom of the mine pit, with a medium-coarse grained granite containing tourmaline alterations (Figure 4b).

3. Analytical Methods

X-Ray Fluorescence analyzer (XRF) and Inductively Coupled Plasma Mass Spectrometry and Optical Emission (ICP-MS) analyses were conducted at Intertek Laboratory Jakarta, Indonesia. They applied ICP-MS and OES Determination 4 acid digest in Teflon tube for REE and trace elements besides ICP-OES Determination 4 acid digest in Teflon tube. Samples were dried and crushed by a jaw crusher or iron mortar and were ground by a mill. Major and trace elements including REE were determined using XRF and ICP-MS Agilent type 7700 and ICP-OES Agilent type 725. Solution of rock samples for ICP-MS analyses was made by acid digestion of fused glass bead using lithium metaborate and tetraborate as flux.

Petrographic descriptions and ore microscopy were carried out at the Laboratory of the Centre for Mineral Coal and Geothermal Resources, Geological Agency of Indonesia. X-Ray Diffraction (XRD) was performed
at the Laboratory of Centre for Geological Survey, Geological Agency of Indonesia, and Laboratory Wuhan Centre, China Geological Survey (CGS). The main XRD instrument used is PANalytical X’Pert PRO with type series of PW3040/x0 X’Pert PRO, made in Nederland. For the test of sample materials totally, they used Cu-tube with a spinning sample holder or flat sample holder. The measurement angle (2-theta) that is used to perform was around 30 – 600. Grinding tools used were agate grinders with grain sizes ranging 5 – 10 um or approximately 200 mesh.

SEM-EDX/EDS instruments applied for analysis were of type JEOL JED-2200 Series (SEM JEOL-JSM6360LA). This work was performed at the Laboratory of the Centre for Geological Survey, Geological Agency of Indonesia in Bandung. The chemical compositions of minerals were measured using a Shimadzu EPMA 1600 at the laboratory of Wuhan Center, CGS, China. At the same time, backscattered electron (BSE) images were also taken. During quantitative analysis, the operating conditions were set as follows: 15 kV accelerating voltage, 10 nA beam current, and 1 µm beam diameter. Minerals from SPI company of America were used as standards, and a program based on the ZAF procedure was used for data correction.

To obtain the secondary image of BSE and their REE composition, further methods were performed. The element composition of REE-bearing minerals was analyzed by a JEOL JSM_7500F- SEM coupled with Oxford Aztec X-MaxN Energy Dispersive Spectroscopy (EDS). These minerals were tested in the setting of 15kV accelerating voltage, 10µA beam current, and 6.5-8mm work distance. Scanning electron microscopes equipped with an X-ray energy spectrometer achieve the mapping of the high-resolution elements to obtain the chemical compositions of small areas of samples.

Fluid inclusion studies were conducted at the Wuhan Center Laboratory, China Geological Survey, China. Two samples were selected, namely: TBL-21MN/05E/R, and TBL-21MN/14/R, both samples are of the transparent quartz veins. Such samples were first checked to see if they were rich in fluid inclusions, afterward a 0.3 mm thin section thick was made. Measurements were performed using the AXiolab polarizing microscope and the LINKAM THMS heating–freezing stage according to the EJ/T 1105-1999 standard. Parameters measured were homogenization temperature (Th), final ice melting temperature (Tm), and determination of salinity (w% NaCl eq). Individual fluid inclusion composition was measured using the RENISHAEW Raman Spectrometer and Leica Deflected Microscope.

Stable isotopes O and S were carried out at the Wuhan Center Laboratory, China Geological Survey, China. The analytical method of quartz grains is separated using a binocular microscope to ensure 99% purity. Quartz is reacted with BrF$_5$ to release oxygen at 550°C, impurities are removed by freezing, purified O$_2$ is converted to CO$_2$ by reacting with graphite at 700°C, and collected by freezing. The oxygen isotope composition was determined using the MAT-253 mass spectrometer. The results are reported in conventional notation relative to the Vienna standard mean ocean water (V-SMOW). Analytical accuracy ± 0.2‰. The stable isotope S analysis was also carried out at the Wuhan Center Laboratory, China Geological Survey, China. Fresh ore samples are ground to a size of 40-80 mesh. Single sulfide granules were taken from samples ground under a binocular microscope, with a purity of more than 99%. Sulfur
isotope analysis was performed using MAT-251. The 34S/32S ratio is expressed as 34S per mil value relative to the standard Vienna Cannon Diablo Troilite (V-CDT) to an accuracy of 0.2‰.

4. Results

4.1. Petrography description of granitic rocks

Four samples were observed under petrography, namely samples TBL-21MN/2B/R, TBL21 KP-14/R from Toboali, TBL-21MN/5E/R, and TBL 21MN/14/R from Air Gegas. Sample TBL-21MN/2B/R shows colorless, holocrystalline, hypidiomorphic granular, fine grain size up to 8.0 mm, euhedral to anhedral crystals, consisting of quartz (35%), orthoclase (30%), plagioclase (5%), microcline (12%), hornblende (6%), biotite (4%), clay (3%), monazite (1%), zircon (1%), chlorite (1%) and opaque minerals (2%) (Figs. 5A and B). Sample TBL-21MN/5E/R shows colorless, holocrystalline, hypidiomorphic granular, fine grain size up to 6.0 mm, subhedral-euhedral crystals, composed of quartz (50%), orthoclase (17%), monazite (20%), cassiterite (12%), opaque minerals (1%) (Figs. 5C and 5D). Sample TBL21 KP-14/R shows holocrystalline, hypidiomorphic granular, size up to 3 mm, euhedral-anhedral crystals, composed of quartz (60%), orthoclase (26%), muscovite (5%), plagioclase (4%), chlorite (3%), and opaque minerals (2%) (Figs. 5E and F). Sample TBL 21MN/14/R has textures: holocrystalline, hypidiomorphic granular, grain size up to 4 mm, composed of quartz (> 90%), cassiterite (5%), pyroxene (1%), and opaque (1%) (Figs. 5G and H).

4.2. Ore microscopy

There are three samples observed on the polish section using reflected polarization microscopy: samples TBL-21MN/02B/R Toboali, TBL-21MN/05E/R, and TBL-21MN/14/R Air Gegas. Under the microscope, sample TBL-21MN/02B/R that was taken from the bottom of the lateritic profile, are observed to contain pyrite, chalcopyrite < 0.5%, stannite (Cu$_2$FeSnS$_4$) < 0.5%, magnetite (trace), and sphalerite (trace) (Fig. 6). It is shown that stannite and chalcopyrite are in intergrowth with each other. Cassiterite (SnO$_2$) was clearly observed on a polished section of sample TBL-21MN/05E/R (quartz vein), Air Gegas (Fig. 7). Ore minerals such as cassiterite (SnO$_2$), hematite (Fe$_2$O$_3$), and hydrous iron oxide were also observed on a polished section of sample TBL-21M/14/R, Air Gegas (Fig. 8).

4.3. Major/trace elements, and REE

Nine samples of granites were analyzed for major and trace elements using the XRF method, the analysis results are shown in Table 1. The silica content of granite samples ranges from 72.4–76.17%, and the highest quartz content which is more than 84% is shown in the granite that hosts quartz veins (TBL-21MN/5E/R). Using Middlemost diagram plots (1994), most rock samples are classified into granite (Fig. 9a) where their magmatic sources are grouped into high K-alkaline or calc-alkaline series (Fig. 9b), and the chemical composition of magma fluid is peraluminous (Fig. 9c). Using the Rb versus (Y + Nb) diagram can be shown that the granite is emplaced in syncollisional and within-plate tectonic settings (Fig. 9d).
The REE pattern of the granite tends to be enriched from heavy rare earth elements (HREE) toward light rare earth elements (LREE) with a sharply negative anomaly for Eu (Fig. 10a). Total REE content ranges from 180.80 ppm to 1126.6 ppm, where the highest value belongs to sample TBL-21MN/02B/R from Toboali. Sample TBL-21KP/07/R has the second-highest REE value which is 1014.69 ppm. The LREE values are much higher than the HREE values indicating that the magma underwent strong differentiation and perfect fractionation. A primitive mantle-normalized spider diagram (McDonough & Sun, 1995) shows the enrichment of large-ion lithophile elements (LILEs) in granite, such as Pb, Rb, Cs, and K, exhibiting negative anomalies for high-field-strength elements (HFSEs), such as Nb, P, Zr, Ti, and negative anomalies of Ba and Sr relative to Rb (Fig. 10b).

4.4. EPMA analysis dan BSE images

Based on the results of the EPMA analysis of two samples, namely TBL-21MN/02B/R (granite rock) from Toboali and TBL-21MN/05E/R (quartz vein) from Air Gegas, several types of REE minerals and those containing REE have been identified, consisting of parisite, allanite, monazite, and thorite along with cassiterite (Table 2). From the BSE images, some other REE minerals were also confirmed such as bastnasite, xenotime, and zircon that proved to contain REE as analyzed using EPMA (Tables 3 and 4).

4.4.1. Allanite

Allanite with chemical formula $A_2M_3Si_3O_{12}(OH)$, where $A_2 = \text{Ca, Sr, and REE (Ce, La, Nd or Y)}$ are depicted in the biotite that makes up the granite sample TBL 21 KP-07/F, Toboali. The presence of longitudinal allanite filling in the biotite cleavage and in the form of granules growing and crystallizing together with the biotite indicates primary formation (Fig. 12a). Such allanite grain is more clearly seen in the secondary BSE image (Fig. 12b) and contains Y, La, Ce, and Nd (Fig. 12c). The content of REE oxide compounds based on confirmation of EPMA analysis shows significant values of REE (Table 3). From another view, allanite with zircon appears as inclusions in biotite (Fig. 13).

4.4.2. Parisite

REE mineral of parisite ((Ca (Ce, La)$_2$(CO$_3$)$_2$F$_2$)) in the plagioclase and biotite are detected within the granite sample TBL-21MN/02B/R, Toboali. The elongated form of the parasite fills in the plagioclase fractures (Fig. 11b) and biotite (Figures. 11e and 11f) along with inclusions of monazite, thorite, and zircon indicating the primary origin of the post-mineralized formation of monazite, thorite, zircon, and chalcopyrite in biotite (Fig. 11f). The granite sample hosting mineralized quartz veins (TBL-21MN/05E)/R) is seen to have parasite that fills the biotite cleavage (Figs. 15a and 15b), while the quartz vein itself is observed to contain cassiterite (Fig. 15c). Secondary BSE images of parasite are depicted to contain Y, Nd, Ce, and La (Fig. 14b).

4.4.3. Monazite

The presence of the primary REE mineral in the form of monazite is shown from the results of EPMA, EDS, and BSE images analysis on a number of granite samples, especially from the Toboali. Monazites
ranging in size from less than 10 µm to several tens µm are shown in the photomicrograph of the sample TBL-21MN/02B/R (Figs. 9c, 9f, 13A, and 13B) as inclusions in biotite.

BSE image of granite sample hosting mineralized quartz veins TBL-21MN/14/R, Air Gegas (Fig. 17) contains monazite inclusions filling cavities in rock-forming quartz. The results of the analysis of the chemical composition of the EPMA method confirmed the presence of a significant amount of REE oxide compounds (Table 4). This REE compound is thought to have come from monazite.

**4.4.4. Bastnasite**

Based on the BSE images in Fig. 11b, bastnasite ((CeF)CO$_3$) is present to fill cavities in plagioclase measuring 40 µm, indicating its formation after crystallization of granite sample TBL-21MN/02B/R, Toboali Region. Its formation was followed by parsite filling fractures in plagioclase. Bastnäsite, REECO$_3$F, and synchysite, CaREE(CO$_3$)$_2$F, represent end members of a polysomatic mineral series including parsite, CaREE$_2$(CO$_3$)$_3$F$_2$, and röntgenite, Ca$_2$REE$_3$(CO$_3$)$_5$F$_3$, as intermediate members (Zeug et al., 2021).

**4.4.5. Xenotime**

Based on the BSE photomicrograph in Fig. 11d, xenotime is present in the form of fine inclusions (< 2 µm) in biotite, indicating its formation as an REE mineral, especially Y along with magmatic crystallization of granite rock sample TBL-21MN/02B/R, Toboali. Its formation coincides with the deposition of other minerals such as zircon, sphalerite, and ilmenite in biotite.

**4.4.6. Thorite**

BSE images of sample TBL-21KP/07/F represent the radioactive mineral of thorite (Th,U SiO$_4$) grains with 25 µm size, filling the cavity that cuts the biotite cleavage (Fig. 13). This structure indicates that thorite was formed post-crystallization of granite. Thorite also appears as fine inclusions in the biotite granite sample TBL-21MN/02B/R (Figs. 11c and 11f), indicating that its formation took place concurrently with biotite crystallization. Based on the EPMA analysis of samples TBL-21MN/02B/R and TBL-21MN/05E/R confirmed that thorite also contains REE (Table 4).

**4.4.7. Zircon**

Under BSE images, zircon is the most common granite accessory found in rock samples. It is present in the form of inclusion grains (< 2µm to 50µm) in biotite (Figs. 11 and 18). Zircon is thought to form during the crystallization of rock-forming minerals such as biotite. In another site of this sample, zircon is present as fine inclusions in quartz along with fluorite and parsite (Fig. 14c). In addition, zircon is also present together with other REE minerals in the BSE image of sample TBL 21KP-16/F (Fig. 18).

REE content of zircon (Table 5) is represented by Y oxide compound with the range of 0.04–0.38% determined using the EPMA analysis at the spot of the zircon surface. This zircon also contains Th ranging from 0.02–0.33% analyzed on the same spot.
4.5. Fluid inclusion

Based on observation of a sample quartz vein hosted in granitic rocks from Air Gegas (TBL-21MN/05E), quartz contains significant fluid inclusions that are well developed but small (Fig. 19).

1. L+V type fluid inclusions (FIs)

The L+V type FIs are widespread in quartz and are about 40% of the total FIs. The FIs exhibit long stripy, polygon, or irregular shapes, and their diameters range from 3 to 10 μm, individually 20 μm. The FIs have $V_{H2O}/(V_{H2O}+L_{H2O}) = 20-30$ vol%. The FIs are gathered in a small group. The final ice-melting temperature Tm is range from -1.3 to -7.4°C, corresponding to Salinity from 2.23 to 10.99 wt.% NaCl and final homogenization temperature from 210 to 316°C (Table 6). Histogram of homogenization temperature and salinity are shown in Figure 20.

2. L type fluid inclusions (FIs): widespread and found in quartz, about 40% of the total FIs, exhibit ellipse, quadrilateral or irregular shapes, and their diameters range from 4 to 10 μm. The FIs are gathered by a small group.

3. V type fluid inclusions (FIs): 20% of the total FIs, exhibit ellipse and nearly close circular, and their diameters range from 3 to 6 μm, gathered by a small group.

4. L+V+S type fluid inclusions (FIs): the V type FIs are much less than other types. The FIs exhibit ellipse and polygon, and their diameters range from 3 to 8 μm. The FIs are gathered by a small group.

5. $L_{H2O}+L_{CO2}+V_{CO2}$ type fluid inclusions (FIs): the type FIs are much less than other types. The FIs exhibit ellipse and long stripy, and their diameters range from 8 to 12 μm. The FIs are gathered by a small group. The FIs have $V_{CO2}/(L_{H2O}+L_{CO2}+V_{CO2})=10-20$ vol%, $L_{CO2}/(L_{H2O}+L_{CO2}+V_{CO2})=10-20$ vol% and $L_{H2O}/(L_{H2O}+L_{CO2}+V_{CO2})=60-70$ vol%. Its eutectic temperature is -76°C, disappeared clathrate temperature +8.0°C, partial homogenization temperature +26.8°C, and final homogenization temperature 317°C. Using equation wt.% NaCl = 15.52022 – 1.02342T – 0.95286T², T : final clathrate melting temperature (Htun et al., 2019), salinity were calculated to be 3.96 wt.%NaCl (Table 7)

4.6 Stable isotopes O and S

The results of stable isotope analysis of O and S for samples of mineralized quartz veins (TBL-21MN/05E and TBL-21MN/14/R) from Air Gegas are shown in Table 8. The analyzed value of δ$^{34}$S from pyrite for the both samples is almost the same, namely 5.3 ‰ and 5.5 ‰, while the analysis results from sphalerite are only obtained from samples TBL-21MN/05E/R which is 3.9 ‰.

The range of δ$^{18}$O values in quartz veins originating from magmatic fluids is generally 9.1 ‰ - 9.7 ‰ (Nascimento & Souza, 2017). The value of oxygen stable isotopes in the study area is greater than this value range. In a large number of hydrothermal deposits, the value of δ$^{18}$O ranging from 0‰ to 10‰ is interpreted as a result of mixing meteoric fluid with magmatic fluid (Nascimento & Souza, 2017).
The stable isotope value of O in the study area is more positive, exceeding the range of magmatic fluids, possibly due to the effect of mixing water rather than the magmatic fluid.

The range of $\delta^{34}$S values of sulfide from mineralized quartz veins of sample TBL-21MN/05E/R and TBL-21MN/14/R, Air Gegas is from 3.9‰ to 5.5‰. This range lies in the typically range of granite rocks (-10‰ – 14‰), hydrothermal deposits (-30‰ - 22‰), hydrothermal vents (0‰ – 5‰), and magnetite series granite (2‰ – 9‰) (Seal, 2006). In particular, the average sulfur isotope composition of pyrite (5.4‰) and sphalerite (3.9‰) for the quartz veins of TBL-21MN/05E/R and TBL-21MN/14/R were interpreted as originating from sedimentary rocks, metamorphic rocks and granitic rocks (Figure 22).

5. Discussion

5.1. REE-bearing granite characteristics

In general, the granites in the study area formed in a syn-collision tectonic environment, peraluminous in nature, with magma affinity of high K-calc alkaline series, and contain REE which range from 180.8 ppm to 1124.6 ppm. REE patterns of these samples show LREE enrichment as an indication of perfect fractionation. Two granite samples (TBL-21MN/02B/R and TBL-21KP/07/F) contain the highest REE up to 1124.6 ppm and 1014.69 ppm respectively with an LREE/HREE ratio of 7. The characteristics of the two granite samples, in general, are not much different from the other granitic samples. However, they show a positive anomaly in high field strength elements (HFSE) such as REE and radioactive elements while Zr, Nb, and P are depleted. The large ion lithophile elements (LILE) have negative anomalies, especially for Cs, Rb, K, and Ba (Fig. 10b).

The highest REE content of two granitic rocks is thought to have resulted from the presence of primary REE minerals such as REE phosphate (monazite, xenotime, and apatite) and REE carbonate (parisite, allanite, and bastnasite) as confirmed by BSE images. REE phosphate minerals are more dominant than carbonate ones. The distinguishing features of these two rocks included are a lesser negative anomaly of Eu compared to the other granite samples (Fig. 10). It means that the two samples are fractionated less perfectly than the others. (Fig. 14). The presence of fine inclusions of fluorite along with parisite, and zircon in quartz of sample TBL-21MN/02B/R, Toboali, indicates that fluorite precipitated as a result of the changes in temperature and pressure along with the channel way of the hydrothermal solutions or due to fluid mixing or interactions with the wall rock (Richardson and Holland 1979). It may be the result of the late crystallization of granite or magmatic fluid (Deer, 2013). Since fluorite is spatially present together with inclusions of REE minerals such as parisite, and the considerable higher of LREE value than HREE, this may have resulted from precipitation in the early precipitated of fluorites, whereas HREE is enriched in late precipitated of fluorites (Möller et al. 1976). It is suspected that this led to the enrichment of HREE especially $\text{Pr}_2\text{O}_3$ and $\text{Gd}_2\text{O}_3$ in the quartz vein in Air Gegas (TBL-21MN/05E/R) but depleted in the granite of Toboali (TBL-21MN/2B/R) as confirmed by EPMA analysis in Table 4. The presence of sulfide mineralization such as chalcopyrite and sphalerite in granite samples of TBL-21MN/02B/R (Figs. 6 and 11) indicates that mineralizing fluid of post-magmatic crystallization may have affected this granite rock.
5.2. Characteristics and composition of hydrothermal fluid

The significant REE content of up to 363.34 ppm (Table 1) in the sample TBL-21MN/05E/R, which is dominated by LREE with an LREE/HREE ratio of 10, is interpreted as originating from fracture-filling of pararites and fine inclusions of monazite in the quartz veins as confirmed by BSE images (Fig. 12). Besides REE, this quartz vein sample also contains significant Sn, Cu, W, Pb, Zn, and Li values (Table 1), which is typically indicating a polymetallic tin deposit.

A quite large range of homogenization temperatures (210–316°C) and a wide range of salinity values (2.23 wt% NaCl – 10.99 wt% NaCl) indicate that there is more than one fluid phase in the sulphide-REE mineralization. The estimated depth of mineralization, based on the Hass (1971) curve plot, range from 1150 m to 1350 m from the present surface (Fig. 21a). In accordance with homogenization temperatures, there are three different inclusion groups which represent the homogenization temperature interval between 212 °C and 261°C for the first group, 223 to 253°C for the second group, and 277 to 316°C for the third group (Fig. 21b). In general, the temperature of the hydrothermal fluid in depositing cassiterite ranges from 250-450°C (Faiz et al., 2019). This shows that the temperature range for cassiterite formation in the Bangka Belitung Tin Belt is 210–450°C.

Compared to the South Bangka which has a fairly wide range of homogenization temperatures (210–316°C) indicates an evolving process of the hydrothermal solution system from high to low temperatures. On the other hand, there are no substantial differences in terms of the salinity of these two groups, ranging from 2.6 to 5.7 wt.% for the first group and 3.7 to 7.3 wt.% for the second group. These differences in homogenization temperatures may be caused by cooling towards the outer zones of quartz. Therefore, the first group is considered to be the early stage of mineralization according to the highest homogenization temperatures obtained from quartz (max 386.8°C). Also, these differences may have resulted from a mixing of two different ore-forming fluids.

The inclusion type of fluid V (vapor) with the main components of H2O, CO2, CH4, and N2, and L (liquid) with the dominant component of H2O indicates that there is a separation process between fluid and vapor during hydrothermal activity or boiling at high homogenization temperatures, then decreases and releases CO2 (decarbonization). The decrease in temperature is thought to be affected by an increase in the composition of the meteoric water upon mixing with the hydrothermal solution (Fig. 21b). CO2 plays an important role in various types of ore deposits including REE, in relation to hydrothermal transport containing REE, therefore CO2 is an integral part of the ore mineralization system and has a partition level of REE (Shua et al., 2020). From the spectrum of the Raman curve, it is reflected that the inclusions are dominated by CO2 gas components, while relatively few CH4 and N2 gases.

The results of the analysis of mineralized quartz veins hosted in granite (samples TBL-21MN/05E/R and TBL-21MN/14/R) Air Gegas show a range of 12.7‰ – 13‰ for δ18O, and 3.9‰ – 5.5‰ for δ34S. The value of the stable isotope of oxygen shows a small range, while the range of values of δ34S has a quite
wide range. Referring to the relationship of salinity to homogenization temperature (Fig. 22a and Fig. 22b) it is interpreted that metamorphic water mixing is thought to affect the composition of $\delta^{18}$O hydrothermal fluid resulting in mineralization in the study area. This condition is supported by the local geology condition that the mineralized quartz veins (TBL-21MN/05E/R and TBL-21MN/14/R Air Gegas) analyzed for fluid inclusions and stable isotopes are in contact with metamorphic rocks of the Pemali Complex (Fig. 1).

The range of $\delta^{34}$S values is close to that of magmatic fluids, namely 0‰ – 5‰, similar with tin deposits in Brazilian Rondonia (Nascimento & Souza, 2017). However, in the context of the study area, the value of $\delta^{34}$S is slightly more enriched, possibly influenced by an igneous sulfide reservoir that has a value range of -2‰ to +35‰ (Ohmoto & Rye, 1970). Kelabat granite is the closest surrounding rock, it may be a stable isotope source of S for the sulfide mineralizing-hydrothermal fluid.

The presence of apatite in the quartz vein of sample TBL-21MN/05E/R (BSE images of Fig. 15a and 15d) may have enriched REE. Apatite may substitute REEs during either formation or a later hydrothermal alteration, so that it is an indication of the role of late-stage hydrothermal (Camilla et al., 2019) and an indication of primary REE as a result of the heavy REE enrichment process (Ng et al., 2017).

### 5.3. Paragenetic sequence of primary REE minerals

Some indicators in estimating the stages of REE formation relative to other minerals are the presence of subhedral-euhedral crystals of REE minerals, the inclusion structure of REE minerals filling pores or between rock-forming minerals, fractures that provide space for REE mineral deposition, and fluorite. The shape of euhedral crystals in rock-forming minerals indicates that their formation coincided with early magma crystallization. REE mineral inclusions filling pores between rock-forming minerals are interpreted as REE precipitated at an intermediate stage. Fracture-infilling veins indicate that there is room for the circulation of mineralization-carrying solutions and their deposition (Jia & Liu, 2020), in the context of the studied area, it is interpreted as intermediate stages. The presence of quartz veins containing cassiterite and tourmaline mineralization is interpreted as the final stage of the hydrothermal solution.

From the results of fluid inclusion studies on quartz veins, which are in contact with the parent granitic rocks (sample TBL-21MN/05E/R), there are two types of fluid inclusions consisting of type V (vapor) with the main components H$_2$O, CO$_2$, CH$_4$ dan N$_2$, and type L (liquid or fluid) with the main component H$_2$O (Fig. 19). These data indicate that there is a separation process between fluid and gas during hydrothermal activity or boiling (Shepherd, 1985). This corresponds to the composition of the vapor inclusions. The temperature of mineralization formation associated with hydrothermal fluid can be interpreted from the homogenization temperature data. Referring to the histogram in Fig. 20, the temperature of the formation of tin mineralization and REE minerals (parisite, monazite, and zircon) is estimated to be in the range of 210–316°C.

A plot of the salinity vs temperature homogenization (Fig. 20) shows that the curve partially overlaps with the metamorphic fluid region. Referring to field data, the sample (TBL-21MN/05E/R) is located at the
contact between metamorphic rocks (phyllite, schist, and quartzite) of the Pemali Complex and Kelabat Granite (Fig. 1). So, the composition of the hydrothermal solution may be influenced by the metamorphic solution.

Referring to the homogenization temperature range and salinity, there are three mineralization phases. The initial phase is magmatic crystallization which produces a magmatic-hydrothermal solution with an estimated temperature range of > 316 °C – 316°C. At this early stage, pyrite is formed along with a small amount of chalcopyrite and REE minerals (monazite and xenotime). In the second stage which is magmatic-hydrothermal, it is estimated that at a temperature range of < 316°C – 210 °C metallic sulfide and REE minerals (monazite, parisite, bastnasite, and allanite) are formed. In the third stage, the temperature of formation of sulfide minerals (pyrite-py, sphalerite-sf) within the mineralized quartz veins (TBL-21MN/05E/R Air Gegas) can be estimated using the formula: 

\[
T = \frac{(0.55 \pm 0.04) \times 10^3}{\Delta_{py-sf}} - 273 \degree C \quad \text{atau } \Delta_{py-sf} = 0.30 \times 10^6 / T^2 - 273 \degree C \quad \text{(Ohmoto & Rye, 1970; Seal, 2006).}
\]

From the calculation, temperature (T) value is 190 °C. In terms of mineral paragenesis in the study area, sulfide minerals are formed up to the final stage of the hydrothermal solution with the temperature range of < 210 °C – 190 °C, by which pyrite, sphalerite, monazite, parisite, and bastnasite are formed. Hence, the sequence of mineral paragenesis can be arranged as shown in Fig. 24.

6. Conclusion

Primary REE mineral types which are the main source of REE in South Bangka can be divided into three groups, namely REE phosphate consisting of monazite, xenotime, and apatite, REE carbonate consisting of parisite, allanite, and bastnasite, and other REE-bearing minerals such as thorite and zircon but coincidentally they are generally classified as radioactive minerals. The REE phosphate mineral group is hosted in granite which is formed in the early magmatic crystallization and magmatic-hydrothermal stages. While monazite seems to have formed in quartz veins together with cassiterite. The main granite host rocks are peraluminous and S-type.

The carbonate REE group is thought to have formed from the intermediate magmatic-hydrothermal to the late hydrothermal stage. Cassiterite, stannite, chalcopyrite, and sphalerite are interpreted to form at the same stage as REE. However, the highest total REE values were found in the Toboali mineralized granite parent rock, but not in the granite as a host of mineralized quartz veins. Research on REE deposits within hydrothermal solutions is an interesting program for finding primary REE deposits of economic value in the future. However, REE with granite has more potential for weathering products, in both alluvial and weathering deposits.

The sulfur isotope composition is thought to originate from granite rocks which are part of the Klabat Granite emplacement. While the oxygen isotope composition is a meteoric mixture but it seems also to have been influenced by metamorphic fluids. This is thought to be related to the metamorphic rocks of the Pemali Metamorphic Complex. Research on the existence of this metamorphic rock and its effect on REE deposition is necessary to follow up in the future.
Declarations

Competing interests: The authors declare that they have no competing interest in connection to publishing the manuscript.

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Tables 1-2, 6

Tables 1-2 and Table 6 are available in the Supplementary Files section.

Tables 3-5, 7, And 8

Table 3. Chemical composition results measured by EPMA on sample TBL21 KP-07/F (spot KP 9- REE-1 and KP 9-REE-2), Toboali, and TBL-21MN/14/R Air Gegas.
<table>
<thead>
<tr>
<th>Chemical compounds</th>
<th>(KP7-REE-2) TBL-21 KP 07/F</th>
<th>(KP9-REE-1) TBL-21 KP 07/F</th>
<th>(KP9-REE-2) TBL-21 KP 07/F</th>
<th>(MN-3-REE-1) TBL-21 MN14/R</th>
</tr>
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<tr>
<td>Al₂O₃</td>
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<tr>
<td>SiO₂</td>
<td>30.95</td>
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<td>6.78</td>
</tr>
<tr>
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<td>0.03</td>
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<td>0.61</td>
<td>0.46</td>
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<tr>
<td>CaO</td>
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<td>0.29</td>
</tr>
<tr>
<td>FeO</td>
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<td>20.55</td>
<td>18.86</td>
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</tr>
<tr>
<td>Y₂O₃</td>
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<td>0.51</td>
<td>0</td>
</tr>
<tr>
<td>La₂O₃</td>
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<td>8.76</td>
<td>2.30</td>
<td>5.49</td>
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<td>Ce₂O₃</td>
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<td>10.14</td>
<td>4.84</td>
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<td>2.35</td>
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<td>Ho₂O₃</td>
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<td>Er₂O₃</td>
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<td>Yb₂O₃</td>
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<td>0</td>
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<td>0</td>
</tr>
<tr>
<td>Lu₂O₃</td>
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<td>0</td>
<td>0</td>
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<tr>
<td>ThO₂</td>
<td>0.30</td>
<td>1.12</td>
<td>0.28</td>
<td>4.42</td>
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<tr>
<td>TOTAL</td>
<td>90.30</td>
<td>70.58</td>
<td>70.87</td>
<td>63.99</td>
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Mineral: Allanite, Allanite, Monazite

**Table 4.** Chemical composition of EPMA at thorite spots of sample TBL-21MN/02B/R Toboali and TBL-21MN/05E/R Air Gegas
<table>
<thead>
<tr>
<th>Chemical Compounds</th>
<th>TBL-21MN/02B/R-Th-1</th>
<th>TBL-21MN/02B/R-Th-2</th>
<th>21MN/05E/R Th-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>1.30</td>
<td>5.10</td>
<td>0.00</td>
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<tr>
<td>Al₂O₃</td>
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<td>0.30</td>
<td>0.00</td>
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<td>SiO₂</td>
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<td>P₂O₅</td>
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<td>0.00</td>
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<tr>
<td>CaO</td>
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<td>FeO</td>
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<td>La₂O₃</td>
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<td>Ce₂O₃</td>
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<td>Pr₂O₃</td>
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<tr>
<td>Nd₂O₃</td>
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<td>Gd₂O₃</td>
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<tr>
<td>Ho₂O₃</td>
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<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>ThO₂</td>
<td>59.28</td>
<td>79.58</td>
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<tr>
<td>Total</td>
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<tr>
<td>Mineral</td>
<td>Thorite</td>
<td>Thorite</td>
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</table>

**Table 5.** Chemical analysis of EPMA sample TBL 21KP-16/F (laboratory code KP-10)
### Table 7. Data of eutectic and disappeared clathrate temperatures.

<table>
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<tr>
<th>Eutectic temperature (°C)</th>
<th>Disappeared clathrate temperature (°C)</th>
<th>Salinity (wt.%NaCl)</th>
<th>Partial homogenization temperature (°C)</th>
<th>Final Homogenization temperature (°C)</th>
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</thead>
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<tr>
<td>-76</td>
<td>+8.0</td>
<td>3.96</td>
<td>+26.8</td>
<td>317</td>
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</table>

### Table 8. Stable isotope values of oxygen and sulfur.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mineral</th>
<th>δ(^{18})O-PDB</th>
<th>δ(^{18})O-SMOW</th>
<th>δ(^{34})S(_{V-CDT})/‰</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBL-21MN/05E/R</td>
<td>Quartz</td>
<td>-17.3</td>
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<tr>
<td></td>
<td>Pyrite</td>
<td>-</td>
<td>-</td>
<td>5.3</td>
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<td>Sphalerite</td>
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<td>-</td>
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<td>TBL-21MN/14/R</td>
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<td>-17.6</td>
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<td></td>
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</tr>
</tbody>
</table>

**Figures**
Figure 1

Geology of the South Bangka and locations of rock sampling (modified from Crow & Van Leeuween, 2005; Hutchison, 2014).

Figure 2

Sample location of TBL-21MN/2B/R, Toboali. Granite boulder with faneric texture, gray color, relatively fresh, compact (left), composed of quartz, feldspar, biotite, hornblende, and mica (right).

Figure 3

(a). Sampling location TBL-21MN/05E/R at Air Gegas tin mine pit, 20 m depth. (b). Relics of feldspar, biotite and quartz within weathered granite. (c). The quartz vein hosted in the granite, showing the weathering of cream-colored feldspar and cloudy white quartz, containing metallic sulfides and cassiterite.
Figure 4

Sample location of TBL-21MN/14/R. a) Laterite profile in the granite, Geology of the South Bangka and locations of rock sampling (modified from Crow & Van Leeuween, 2005; Hutchison, 2014). Air Gegas Area. b) Quartz vein of 5 cm thick in the weathered granite (position N 300 E/60). c) Vein with quartz (white) and tourmaline (black).

Figure 5

Photomicrograph of sample TBL-21MN/02BR on cross nicol (A and B), Toboali, consist of orthoclase (Oth), biotite (Bt), plagioclase (Plg), hornblende (Hbl), microcline (Mkr), clay (Cly), zircon (Zr), and opaque (Opq) (A), in addition, quartz (Qz) and monazite (Mz) (B). Sample TBL-21MN/5E/R (parallel nicol C and cross nicol D), Air Gegas, consist of quartz (Qz), microcline (Mkr), zircon (Zr), and opaque (Opq) (C, parallel nicol), in addition, orthoclase (Oth), and monazite (Mz) (D). Sample TBL21 KP-14/R Toboali (E, parallel nicol, and F, cross nicol) consisting of quartz (Qz), orthoclase (Oth), muscovite (Msv), chlorite (Chl), plagioclase (Plg), and opaque (Opq). Micrograph of sample TBL 21MN/14/R (G, parallel nicol, and H, cross nicol) Air Gegas, consisting mainly of quartz (Qz), cassiterite (Cst), pyroxene (Px), and opaque (Opq). Magnification 50x

Figure 6

Photomicrograph of polished section sample TBL-21MN/02B/R consisting of pyrite (Py) 2%, kalkopirit (Cp) < 0,5%, stannite (Stn) < 0,5%, magnetite (Mgt) (trace), and sphalerite (Sp) (trace). Mag. 50x
Figure 7

Photomicrograph of polished section sample TBL-21MN/05E/R Air Gegas, composed of cassiterite (Cst) 20% and hydrous iron oxide 3%. Mag. 50x

Figure 8

Photomicrograph of the polished section of the granite sample TBL-21MN/14/R Air Gegas nicol cross (1) shows the color of reflection in cassiterite (Cst) and appears to have holes and cracks in the rock mass (2). Contains ore minerals cassiterite (25 %), hematite (trace), and hydrous iron oxide (1 %). Mag. 50x

Figure 9

Major elements data of granitic rocks from Toboali and Air Gegas, South Bangka. (a). Plotting the SiO₂ versus Na₂O + K₂O binary diagram (Middlemost, 1994), most of the samples are in granite areas. (b). K₂O
versus SiO₂ wt.% using Paccerilo & Taylor diagram (1976); (c). Alumina saturation index diagram: The A/CA (molar Al₂O₃/(CaO + Na₂O + K₂O)) ratio is greater than 1.1, and the granite is categorized as peraluminous and S-type (Shand, 1943); (d). Y + Nb versus Rb diagram showing the tectonic setting (Pearce et al., 1984) of the South Bangka granitic rocks. Syn-COLG = syncollisional granites; VAG = volcanic-arc granites; WPG = within-plate granites; ORG = oceanic ridge granites

Figure 10

Chondrite normalized rare earth elements (REE) diagram (a) and primitive mantle normalized trace element diagram (b) Normalized multi trace element values for Bangka Selatan granites (Sun & McDonough, 1989)

Figure 11

BSE images of sample TBL-21MN/02B/R, Toboali, showing allanite (Aln) < 2 µm in biotite (Bt) (a), parisite (Par) filling the fracture, bastnasite (Bsn) (40 µm) in plagioclase (Pl) (b), thorite and monazite (Mon) inclusions (< 2 µm) in biotite (c), xenotime and zircon inclusions (< 2 µm) in biotite (d), parisite inclusions, zircon (50 µm), and thorite (< 2 µm) in biotite (e), inclusions of monazite and thorite (< 2 µm)
and parsite filling in the cleavage of biotite (f). In addition, chalcopyrite (Ccp), sphalerite (Sp) and ilmenite (Ilm) were also seen in biotite

Figure 12

Photomicrograph of sample TBL21 KP-07/F, Toboali. (a). BSE image of allanite grain (Aln) (100 µm) with thorite inclusion (< 10 µm) in biotite (Bt). (b). Secondary electron image of REE-bearing mineral (allanite). (c). REEs compositional SEM of allanite.

Figure 13

BSE images of a granite sample of TBL21 KP-07/F (spot KP-9-7), Toboali. (a). Allanite (Aln) with 20 µm size, overgrowth with biotite (Bt) along with zircon inclusions (Zrn) with 25 µm size (b). BSE images of sample TBL-21KP 07/F containing thorite with 25 µm size
Figure 14

BSE images of sample TBL-21MN/02B/R, Toboali. (a) Secondary electron image of parisite (Par). (b). SEM compositional map of parisite. (c). Fine inclusions of the parasite, zircon and fluorite (Fl) in quartz and monazite in biotite (d) Secondary electron image of monazite. (e). SEM compositional map of monazite.

Figure 15

BSE images of sample TBL-21MN/05E/R, (a). Parasite (Par-1) filling in cleavage of biotite (Bt) and apatite inclusion. (b). Parasite filling in cleavage of biotite, along with zircon and apatite inclusions in biotite, and monazite (Mon) inclusion (10 µm) in quartz vein. (c). Cassiterite (>600 µm) in quartz vein. (d). Apatite (Ap) rimmed by monazite, chromite (Chr), zircon (Zrn) replaced by fluorite (Fl) in Plagioclase (Pl).

Figure 16

BSE images of sample TBL-21MN/02B/R, Toboali, showing inclusions of thorite and monazite (Mon) (< 2 µm) in biotite (A), Inclusions of monazite and thorite (< 2 µm) and biotite cleavage-filling parisite (B). In addition, chalcopyrite (Ccp) and ilmenite (Ilm) were seen in biotite
Figure 17

BSE image of sample TBL-21MN/14/R (spot MN-3-REE-1), Air Gegas, showing monazite inclusions in quartz. The REE oxide values from the EPMA analysis is shown in Table 3.

Figure 18

BSE images of sample TBL 21KP-16/F (laboratory code KP-10), Toboali, in the form of zircon inclusions (Zm) with the size from > 10 µm (left) until 10 or 20 µm (right).

Figure 19

(a). Fluid inclusion type L+V (top photo) with the main components of H₂O, CO₂, CH₄ and N₂. Top curve, inclusion of type V fluid (vapour) with the main components H₂O, CO₂, CH₄ and N₂. The lower curve shows the Raman spectrum of the inclusion of an L-type fluid (liquid), with the main component of H₂O. (b). Fluid inclusions of type L+V (top photo) with the main components H₂O and CO₂. Top curve, the inclusion of type V fluid (vapor), with CO₂ and H₂O components. Bottom curve, Raman spectrum inclusions type L fluid (liquid), with the main component of H₂O. Compositional analysis of L+V type inclusions in quartz by Laser Raman spectroscopy.

![Figure 19](image)

Figure 20


![Figure 20](image)
**Figure 21**

(a). Plot of fluid inclusions in the study area (shading) fall into the low temperature hydrothermal field that may come from metamorphic fluid (modified from Rajesh & Pankaj, 2014). (b). All fluid inclusion data are also within Au and Sn-W field (modified from Randivel et al., 2014).

**Figure 22**

(a). Interpretation curve for mineralization depth in Air Gegas, South Bangka using the relation of homogenization temperature versus depth (Hass, 1971) (b) and fluid inclusion groups representing immiscibility and evolved mineralizing fluid.

**Figure 23**

Sulfur isotope composition of sphalerite and pyrite of samples from Air Gegas (Mirza & Rashid, 2019)

<table>
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<th>Minerals</th>
<th>Early stage magmatic crystallization ($\geq 316^\circ$C)</th>
<th>Medium stage (magmatic-hydrothermal) ($&lt; 316^\circ$C–$200^\circ$C)</th>
<th>Late stage hydrotermal ($&lt; 210^\circ$C–$190^\circ$C)</th>
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<td>- Pyrite</td>
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- : Abundant, ----- : Common, ........ : Minor

**Figure 24**

Paragenetic mineral sequences

**Supplementary Files**
This is a list of supplementary files associated with this preprint. Click to download.

- Tables126.docx