

地球史における花崗岩系列と関連する鉱化作用

The Granitoid Series and Related Mineralization in the Earth History

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Granitoids distributed in the Inner Zone of SW Japan were identified to have the accessory components of magnetite and ilmenite to the north, but only small amounts of ilmenite toward the south in 1971, then named later as "magnetite-series and ilmenite-series" granitoids. Associated ore deposits also show characteristic minerals. Native sulfur was mined nearly all from the Quaternary magnetite-series volcanic belts. Native Au-Ag (typically argentite AgS) deposits occur in Neogene to Quaternary magnetite-series terranes. Cu (typically chalcopyrite CuFeS_2) -Pb (galena PbS) -Zn (sphalerite, ZnS) and Mo (molybdenite, MoS_2), occur also as sulfides in vein and skarn types of the late Cretaceous to Neogene magnetite-series igneous terranes. On the other hand, the ilmenite-series ores are characterized by none sulfide mineral commodities, such as cassiterite (SnO_2) and wolframite ($(\text{Fe,Mn})\text{WO}_4$) and scheelite (CaWO_4). Therefore, distribution of sulfur in the magmatic stage is the key to the metallogeny of the two series.

Oxidation status of the earth surface has been changed in the earth history. The oldest foliated granitoids in the Greenland showed low $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios equivalent to the ilmenite series. In the Berberton region of South Africa, the Archean TTG suites appear to belong also to the ilmenite series, but pink granites younger than 3.0 Ga were found to be the first magnetite series.

In the western Australia, aeromagnetic map shows the Archean Pilbara craton of the ilmenite-series granitoids, but Proterozoic Yilgarn craton is composed dominantly of the magnetite-series.

Au-mineralized sheared zones are hosted in the green stones, with the Au-mineralizing systems: a broadly uniform, low to moderate salinity, mixed aqueous-carbonic fluid capable of carrying Au, but limited capacity to transport base metals. The oldest Sn deposits are known to occur together with biotite and aplitic granites of 1.8 - 1.6 Ga (Rb-Sr), within the Bushveld ultramafic to mafic body. These granitic magmas were found partial melting products of the middle crust by heat brought-up by the Bushveld ultramafic magmas. The oldest Li-mica pegmatite-bearing dikes (age: 2.5 Ga) have been mined in the western Australia.

キーワード：花崗岩系列、硫化物鉱化作用、酸化物鉱化作用

Keywords: Granitoid series, Sulfide mineralization, Oxide mineralization

花崗岩系列と花崗岩成因論

Granite-series and the origin of granitic magma

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磁鉄鉱系列・イルメナイト系列花崗岩類（花崗岩系列）は地域スケールで帯状配列し、活動年代によっても系統的に変化する。したがって、両系列の成因は上部地殻での局所的な現象ではなく、花崗岩質マグマの起源に密接に関連している。日本列島の花崗岩類の各種データをコンパイルすると、花崗岩類の活動度と沈み込み速度に正の相関があり、95-85Maに主にイルメナイト系列花崗岩からなる活動の極大期が認められる。イルメナイト系列の割合は110Ma頃に急上昇し、70Ma頃に急減する。イルメナイト系列のSr同位体初生値は、白亜紀に規則的に上昇するが、磁鉄鉱系列は時代にかかわらずほぼ安定している。Nd同位体初生値もほぼ同様な傾向を示す。このことは、花崗岩質マグマへの堆積岩類の同化率が白亜紀に規則的に上昇し、70Ma付近で下降することを意味する。このような現象は、海嶺の沈み込みによる下部地殻の部分溶融やマグマ溜まりと壁岩との反応では説明が困難である。

Sr-0同位体ダイヤグラムにおいて、一部の高Sr岩体を除く大部分の花崗岩類はsource contaminationを示す曲線（下に凸）に調和的である。また、Sr-Nd同位体初生値ダイヤグラムにおいても、大部分の花崗岩類は極めて枯渇した物質と堆積岩類との同化分別作用によって形成されたことを示唆する。これらのデータを整合的に説明するには、堆積岩類とマントル物質が反応しつつマグマが形成されるセッティングが必要である。この堆積岩類は、比較的均質で普遍的に存在し、マグマ形成場にまでもたらされる必要があることから、沈み込み堆積岩類と判断される。したがって、日本列島における花崗岩系列は、主としてマグマ形成場における初源マグマと沈み込み堆積岩類の反応率に依存すると推察される。また、花崗岩質マグマの原物質は、下部地殻ではなくマントル物質と反応した沈み込み堆積岩類が主体である可能性が高い。

キーワード：花崗岩、日本列島、沈み込み帯

Keywords: granite, Japan Arc, subduction zone

北海道北部・歌登金鉱床の熱水変質作用・鉱物記載と鉱床形成条件

Hydrothermal alteration, mineralogical description and ore-forming conditions of the Utanobori gold deposit in northern Hokkaido, Japan

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The Utanobori gold deposit is a low-sulfidation type epithermal gold deposit located in northern Hokkaido, Japan. In this study, we investigated geological features of gold-mineralized quartz-adularia veins and hydrothermally altered host rocks from viewpoints of mineral association and paragenetic sequences, bulk chemical compositions, mineral chemical compositions and physicochemical conditions in order to reveal characteristics of gold mineralization and ore-forming environment.

The study area and its surroundings are composed of slate of the Cretaceous to Paleogene Hidaka Supergroup, the Miocene Esashi Formation, the Kemomanai Lava, the Kinkomanai Lava, the Pliocene Penke Formation and the Quaternary terrace and alluvial deposits (Osanai et al., 1963). The gold-mineralized quartz veins are hosted in silicified conglomerate, sandstone, mudstone and tuff of the Esashi Formation. Previous studies based on K-Ar dating reported an ore-forming age of 12.1 ± 0.6 Ma on adularia from the Utanobori deposits, and a same formation-age of 12.1 ± 0.6 Ma on a bulk dacite from the Kinkomanai Lava (Ministry of International Trade and Industry (MITI), 1997). The Esashi Formation, host rocks of mineralization in the Utanobori deposit, shows hydrothermal alteration with zoning distribution such as 1) quartz + K-feldspar \pm chlorite-smectite mixed layer, 2) quartz + K-feldspar + illite \pm smectite, 3) quartz + kaolinite \pm illite \pm smectite, and 4) quartz + plagioclase + chlorite-smectite mixed layer \pm calcite, in order from the silicified zone to the periphery zone.

A representative high Au-Ag grades quartz-adularia vein shows three mineralization stages of Stages I, II and III with subdivided twelve sub-stages. Among them, the Stages I and II are the main gold mineralization stages. The veins are composed of gangue minerals of quartz and adularia and ore-minerals of electrum, naumannite, chlorargyrite and Fe-Sb-oxide or hydroxide. Quartz shows fine-grained equigranular, mosaic, microcrystalline, colloform and comb textures. Electrum shows average Au/(Au+Ag) compositions of 52.5, 65.7 and 55.5 atomic % in the Stage I-b, Stage I-d and Stage II-a, respectively. XRF spot analysis along the mineralization sequences revealed that 1) the amount of adularia gradually decreases from the Stages I to III, 2) the gold deposition is not directly associated with adularia, and 3) the highest concentrations of Au, Ag, Se and Sb were observed in a sulfide band of the Stage I-d. On the basis of the fluid inclusions microthermometry data by MITI (1997), frequent ranges of homogenization temperatures are 260-270°C and 220-230°C in the Stages I and III, respectively. Fugacity of selenium based on the electrum tarnish method was estimated to be $\log f_{\text{Se}_2} = -14.2$ to -12.8 and -13.1 to -11.6 atom for the Stages I-b and I-d, respectively.

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キーワード：歌登鉱床、浅熱水金鉱化作用、熱水変質作用

Keywords: The Utanobori deposit, Epithermal gold mineralization, Hydrothermal alteration

Geochemical mapping using surface water and stream sediments of the mineralized Lom Basin, East Cameroon.

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The Lom Basin is heavily mineralized especially in gold owing to its regional geological setting. Consequently, most research in this region have reported either the rock type, age, and the formation history or the reconnaissance gold investigations. However, the geochemical database of the area is scanty and no regional geochemical mapping has been performed. Although this area has a long artisanal mining history and is a major target for industrialized mining, pollution studies have received limited attention. The present study seeks to i) conduct a systematic stream water and bottom sediment sampling in the area based on the International Geological Correlation Programme (IGCP, 1995) recommendations; ii) determine trace element levels in the sediments and natural water systems and iii) develop geochemical/risk maps of the study area. We target to sample 50 surface water and sediments of streams and major rivers draining the catchment. The geochemical background shall be determined by analysing surface water samples for cations by AAS and anions by Ion Chromatography (IC); and sediments for trace metals using ICP-MS. It is expected that the geochemical baselines and toxic levels of both sampling media shall be established for the construction of a geochemical/risk map of the area. This is important in environmental monitoring. Preliminary results shall be presented in this talk.

Keywords: Geochemical mapping, Surface water, Stream sediments, Lom Basin, East Cameroon

フィリピン・ディナガット南部地域のニッケルラテライト鉱床におけるレアアース濃集帯の酸化還元状態に関する地化学的な研究

Geochemical Study on Redox Conditions of REE Zone in Nickel Laterite Deposit, South Dinagat Island, Philippines

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Recently, the demand of REE is increasing but its production of REE is limited to a few countries. Therefore it is important to look for alternative sources of REE production. It is economically effective to produce REE as by-product of other resource deposits. Nickel laterite deposits, which account for over 60% of global nickel supply, are being investigated as a possible REE resource because weathering of nickel laterite produces significant concentration of REE, especially Sc. One of the factors that control the geochemical behavior of REE during weathering process is soil pH and redox condition. The objectives of this study are to describe the geochemical characteristics of REE during the formation of nickel laterite in South Dinagat Island and to propose a practical and convenient on-site geochemical tool for REE exploration in nickel laterite deposits.

The harzburgite is considered to be the bedrock in this area, and thin section observation revealed that it mainly consists of olivine, orthopyroxene, lizardite, saponite and garnierite. In this study, laterite samples are classified as limonite (FeO>60%), earthy saprolite (30%<FeO<60%) and rocky saprolite (FeO<30%).

The XRF and ICP-MS analysis revealed that there is no apparent correlation between nickel, which is main product of nickel laterite deposits, and scandium, which is investigated as by-product. Nickel is concentrated in the fractures of lower limonite and saprolite as secondary formed hydrous Mg silicate. On the other hand, Sc exhibits correlation with immobile elements such as Fe and Al resulting in Sc concentration in the shallower zone. Weathering caused the Sc concentration to increase about 5.6 times, up to 75ppm, in the shallower zone compared with Sc content in bedrock because mobile elements percolate downward during weathering. Y and the lanthanides, except for Ce, showed different behavior from Sc. Y and Ln are concentrated in the negative Ce anomaly zone in the chondrite-normalized REE pattern. In oxidizing conditions, soluble Ce³⁺ is oxidized to Ce⁴⁺, which easily precipitates as very insoluble CeO₂. However, the other REE is drained from the shallower zone and percolates downward. Consequently, positive Ce anomaly is observed in the shallower zone and negative Ce anomaly is observed in the deeper zone. Y and Ln are concentrated to increase up to 57ppm in negative Ce anomaly zone. Combined above geochemical data with on-site soil pH and Eh analyses, there is possibility to practically extract REE concentration zone. ΣREE (Sc, Y and Ln) is concentrated to increase about 3.2 times up to 126ppm in the horizon where pH values shows less than 7.0 compared with ΣREE content in the horizon where pH values shows more than 7.0. Furthermore limonite and earthy saprolite, where Sc is concentrated, show pH values less than 6.5 and reveal Eh values more than 550mV.

ミャンマー南部の花崗岩類中の軽希土類と重希土類の分別：重希土類に富む花崗岩への影響
Fractionation between LREE and HREE in granitic rocks in southern Myanmar: Implications
for HREE-rich granite

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希土類元素(REE)の中でも、重希土類(HREE)はYを除くと軽希土類(LREE)に比べ地殻存在量が少なく、市場での価格も高い。現在採掘可能なHREEに富む鉱床は、イオン吸着型鉱床の一部(例えば、中国のLongnan)にほぼ限定されている。これらの原岩は極度に分化したカルクアルカリ花崗岩(> 74 -75 % SiO₂)であり、HREEに富みLREEに乏しい。本研究では、SiO₂含有量67 -76 %の花崗岩類をミャンマー南部から採取し、全岩化学組成とREE含有鉱物の産出を調べた結果を基に、HREEに富む花崗岩の特徴を論じる。

マグマ中ではHREEに比べてイオン半径が大きいLREEがより不適合元素として挙動するため、部分熔融度の低いマグマから形成されたアルカリ岩は一般にLREEに著しく富むがHREEには若干富む程度である。HREEに富む花崗岩の形成には、部分熔融度よりもマグマの分化に伴うREE含有鉱物の分別が重要な役割を果たす。本研究においてミャンマー南部で採取した白亜紀後期-始新世の花崗岩類を分析した結果、SiO₂含有量が74%程度を超える分化した花崗岩はHREEに富む傾向が見られた。この境界は全岩化学組成よりも、REE含有鉱物の産出によって明確に決められる。SiO₂含有量が74%以下の花崗岩はチタン石と褐レン石の片方または両方を含むのに対し、SiO₂含有量が74%以上の花崗岩にはこれらの鉱物をほとんど含まない。EPMAによる化学組成分析の結果、いくつかのチタン石はHREEに富んでいることが分かった。チタン石はジルコンと同様に花崗岩の主要なHREE含有鉱物であるため、チタン石が晶出しないと、メルトは最終的にHREEに富むようになる可能性がある。極度に分化した花崗岩(SiO₂ > 74%程度)中ではチタン石はほとんど見られなかったが、シンキス石-(Y)といった様々なHREE含有鉱物が確認された。

本研究結果は、イオン吸着型鉱床の原岩に代表されるようなHREEに富む花崗岩は、マグマの分化過程で主要なHREE含有鉱物であるチタン石を晶出しない条件で形成されたことを示唆している。花崗岩類の全岩化学組成および特定のREE含有鉱物の産出は、HREE鉱床の探査の指標になるかもしれない。

キーワード：重希土類、軽希土類、花崗岩、チタン石、褐レン石、鉱床

Keywords: HREE, LREE, Granite, Titanite, Allanite, Deposit

重希土類資源としてのアパタイトの可能性

Heavy rare earth potential of apatite resources

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Phosphorous is one of the three major nutrients (N, K, P) required by plants and 80-90% of the phosphate mined in the world is used to produce chemical fertilizers. Securing stable supply of phosphate fertilizers is essential to a sustainable food production considering a continuing rapid growth of world population (Van Kauwenbergh et al., 2013). The world resources of phosphate rocks are more than 300 billion tons (U.S. Geological Survey, 2015). "Phosphate rock" is the term generally used in industry to describe mineral assemblages with a high concentration of phosphate minerals, commonly francolite ($\text{Ca}_5(\text{PO}_4, \text{CO}_3)_3(\text{OH}, \text{F}, \text{Cl})$) - apatite ($\text{Ca}_5(\text{PO}_4)_3(\text{OH}, \text{F}, \text{Cl})$) series. There are two main types of phosphate deposits: sedimentary and igneous. The former deposits sometimes are called phosphorite and contain varieties of francolite (CO_2 -rich fluorapatite), the latter mainly consist of fluorapatite (F-rich apatite) (Ihlen et al. 2014).

Apatites contain a variety of REEs in concentrations from several thousands of ppm to several wt.%. They are generally enriched in LREEs (e.g., Roeder et al., 1987), however, some apatites are rich in HREEs: apatites in sedimentary phosphate rocks (Emsbo et al. 2015) and deep sea mud (e.g., Kon et al. 2014), and igneous phosphate rocks (e.g., Hoshino et al., 2015). In addition, both Th and U contents in apatite are very low in contrast to common REE minerals such as monazite and xenotime, and this may be a big advantage over the other types of REE deposits (e.g., alkaline REE deposits). In view of the future of HREE supply (considering both feasibility and sustainability), one of the most promising sources of HREEs is apatite ores that are mined for fertilizer production, because apatite ores are sufficient in reserves and contain enough amounts of the whole REEs that can cover the world demand.

キーワード：アパタイト、重希土類資源

Keywords: apatite, HREE resources

The Origin of the Nangarhar Talc Deposits in the Spin-Ghar Block, Afghanistan

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Talc deposits in the E-W trending Spin-ghar block, southeastern part of Afghanistan, were formed in Paleoproterozoic carbonate rocks. There are two types of talc mineralization in the study area, one in the western part (Dar, Kherwas and Janinaw deposits) and other in the eastern part (Mamond Dara deposits) of the block, hosted by magnesite and dolomite marbles, respectively. The objective of this study is to describe the talc mineralization on the basis of field observations, microscopic observation, XRD, XRF, ICP-MS and SEM-EDS analyses.

In the western part of the block, talc is parallel to sub parallel to magnesite rock and cross cut by intrusive igneous rocks of diabase. Metamorphic rocks of quartz chlorite schist are parallel to sub parallel to talc ore body and magnesite. Massive layers of tremolite about one meter thick were observed at Kherwas. Intrusive rocks have not been identified and a thin layer of talcose quartz has been marked within talc veins at Janinaw. A thick layer of talc contains needle like macroscopic tremolite crystals in the matrix of talc at Janinaw. In the Mamond Dara area at the most eastern part of the block, parallel alternating layers of talc and dolomite marbles occur with quartz chlorite schist mostly altered to chlorite. Massive gneiss occurs at the contact of these talc, dolomite marbles and quartz chlorite schist. Mineral assemblages in the western part are (a) talc + tremolite + calcite, and (b) talc ± cordierite, while those in the eastern deposits are (c) talc + dolomite + calcite ± quartz ± apatite and (d) talc + dolomite + calcite. Talc was formed by alteration of tremolite and magnesite in Dar and Kherwas deposits, while in Janinaw and Mamond Dara, talc was formed by alteration of dolomite and tremolite and by alteration of dolomite, respectively. Total REE contents of talc bodies, magnesite and dolomite marbles range from 0.9, 5.3 and 13.0 ppm, respectively. The SiO₂ contents of carbonates and talc bodies range from 1.6 to 33.3 wt% and from 52.9 to 65.1wt %, respectively, while MgO contents of carbonate and talc bodies range from 18.4 to 48.1 wt% and from 29.4 to 34.0 wt%, respectively. The CaO contents in talc bodies and magnesite are less than 1 wt%, while those of dolomite marbles ranges from 18.0 to 26.0 wt%. The concentration of Al, Ta, Hf, Zr, Th and REE in talc ore and carbonates rocks is very low and inconsistent with a felsic igneous rock protolith, whereas the low concentrations of Cr, Ni, and Co are inconsistent with a mafic igneous protolith. On the basis of this low concentration of trace elements and REE, the Mg-rich carbonate rock is likely the protoliths of talc ore. Magnesium has been derived from pre-existing Mg-rich carbonate host rocks, i.e., magnesite and dolomite marbles.

Keywords: Nangarhar, Spin-Ghar, Talc, Magnesite, Tremolite, Dolomite marble

高取鉬床における熱水の進化 - 鉄マンガン重石の交代組織について

Evolution of the hydrothermal fluid at the Takatori deposit, Japan - Replacement texture at the rim of wolframite

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高取鉬床は鉬脈型のタングステン鉬床であり、タングステン鉬石として採掘されていた鉄マンガン重石((Fe, Mn)WO₄)は鉄とマンガンの固溶体である。これまでの研究で、結晶の内部で鉄とマンガンの比率が変化していることがあり、それらは後期ステージの熱水との反応による交代組織であるとされている。しかしながら、この交代組織をもたらした熱水の特徴については未だ明らかになっていない。そこで、本研究の目的は高取鉬床におけるこの後期熱水の特徴を明らかにすることである。

試料は7番鍾の-4レベル(海拔60m)と-7レベル(海拔-30m)の2箇所から得られたものを使用し、それぞれ中部試料(middle sample)と深部試料(lower sample)とした。

SEM-EDSを用いた元素マッピングにより、鉄マンガン重石結晶の外縁部で交代組織が見られたため、EPMAを用いて測定を行った。その結果、中部試料での結晶の中心部のMn/Fe比は40-50 mole%であったが、黄鉄鉬を伴う試料ではリム部分で70 mole%まで増加していた。

これらの交代組織は、鉄マンガン重石中の鉄と、鉄マンガン重石の形成後に流入した後期熱水に含まれていたマンガンが置換して形成されたものであると考えられている。そのため、この後期の熱水は鉄マンガン重石結晶の周囲を流れることで交代組織を形成したと考えられる。

下部試料ではSEM-EDSマッピングとEPMAにより黄鉄鉬や他の硫化鉬物を伴う複雑な組織を示したが、Mn/Fe比の変化が中部試料と同じであることから、これらも交代組織であると考えられる。従って、この複雑な組織は後期熱水が結晶中のひび割れを通ることで形成されたと推測される。

相図より、この後期熱水は鉄マンガン重石を形成した初期ステージの熱水よりも低温であると考えられる。この環境では鉄重石(FeWO₄)が不安定となりマンガン重石と黄鉄鉬が安定となる領域が生じるため、硫化鉬物を伴う鉄マンガン重石(MnWO₄)で交代組織が発達したと推測できる。また、交代組織の形成にはpHと酸素フガシティーの変化も必要であったと考えられる。

キーワード：高取鉬床、鉄マンガン重石、交代組織、熱水性鉬床

Keywords: Takatori deposit, wolframite, replacement texture, hydrothermal deposit

沖縄トラフ伊平屋北海丘より採取されたコア試料を用いた流体包有物研究

Fluid inclusion study of core samples collected from the Iheya North Knoll in the Okinawa Trough

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From July 9 to 26 in 2014, the dive expedition (Exp. 907, CK14-04) was performed at the Iheya North Knoll in the middle Okinawa Trough to confirm hydrothermal seafloor mineralization. The core samples used in this study were obtained from Hole C9015B and C9016B of the research target area. Microscopic observation and fluid inclusion microthermometry were mainly focused to reveal the ore formation condition. The objective of this study is to clarify geochemical characteristics and the point of similarity between Kuroko deposits and seafloor hydrothermal deposits.

The characteristics of the ores collected from Iheya North Knoll are as follows: C9015B samples are pyrite rich but chalcopyrite is minor, therefore, the characteristic of sulfide assemblage is not similar to yellow ore of Kuroko deposits. C9016B samples are divided into two groups. a) At the upper portion, from 29.6 to 32.7 mbsf, only framboidal pyrite could be observed. b) At the lower portion, from 38.1 to 42.1, pyrite is minor, while galena and sphalerite is abundant like Kuroko of Kuroko deposits.

Homogenization temperatures of fluid inclusions in quartz of C9015B range from 266.7 to 338.4°C and the salinity ranges from 0.00 to 6.30 wt. % NaCl eq. Homogenization temperatures of fluid inclusions in anhydrite of C9016B range 271.1 to 348.5°C and the salinity range from 3.2 to 6.1 wt. % NaCl eq. Both the data of fluid inclusion microthermometry of C9015B and C9016B samples are well plotted on the boiling curve of seawater. The fact that low salinity fluid can be observed may support the occurrence of boiling during the formation of the ore in Iheya North Knoll, Okinawa Trough.