

MAGMATIC FE-TI OXIDE DEPOSITS ASSOCIATED WITH MAFIC-ULTRAMAFIC INTRUSIONS IN MOZAMBIQUE: INSIGHTS INTO THEIR NATURE, GENESIS, AND EVOLUTION

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(モザンビークにおける苦鉄質—超苦鉄質貫入岩に伴われるマグマ
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学 位 論 文 の 要 旨

The origin and evolution of mafic-ultramafic intrusions and related Fe-Ti oxide deposits have been discussed over the decades without reaching agreed conclusions. This research focuses on the Mazua ultramafic intrusion and the Tete Suite, which are the most important Fe-Ti oxide-bearing intrusions in Mozambique, aiming to address their nature, origin, and evolution. The study serves as a guiding reference for future exploration projects for such types of deposits in Mozambique.

Chapter I overviews the geology of Mozambique and associated Fe-Ti oxides deposits. It also introduces the motivation, objectives, and significance of the research and the structure of the thesis.

Chapter II discusses the nature and origin of the Mazua ultramafic intrusion and related Fe-Ti oxide ores on the basis of whole-rock and mineral chemistry. The Fe-Ti oxide ores are mainly composed of ilmenite occurring as lenses, veins, and layers, either massive or disseminated in hornblende pyroxenite. Textural and structural evidences support a cumulate origin for these rocks, including the occurrence of relict cumulate textures, layering of alternating oxides and silicate-rich rocks, and size-grading of silicate-rich layers. Primary magmatic features have, however, largely been overprinted by subsolidus processes. The occurrence of the cumulate assemblage (Fe-Ti oxides and clinopyroxene), without plagioclase and olivine, suggests that the magma underwent differentiation before its emplacement. The high TiO_2 concentrations (> 4 wt.%) of the evolved magma, by magmatic differentiation, are interpreted as the main factors controlling the crystallization of Fe-Ti oxides. It is proposed that the ores formed from the crystallization and settling of Fe-Ti oxide minerals from an evolved basaltic magma. This model is consistent with (1) the occurrence of Fe-Ti oxides and clinopyroxene as cumulates coexisting with amphibole, (2) the layering structures of alternating oxides and silicate matrix, (3) the scarcity of apatite supported by the extremely low whole-rock P_2O_5 concentrations, and (4) the restricted occurrence of ore veins, excluding the formation from immiscible oxide melts.

Chapter III tracks the lost mafic body related to the Mazua ultramafic intrusion on the basis of whole-rock geochemical data of some spatially related rocks. It is shown that the amphibolite enclaves and the hornblende pyroxenites are comagmatic. Due to the similarities in their trace element geochemistry, the amphibolite enclaves would represent the remains of a possible mafic body of the Mazua ultramafic-mafic system.

Chapter IV constraints the emplacement conditions of the Mazua intrusion on the basis of the geochemistry of amphibole. Two different types of amphiboles occur within the pyroxenite: (1) amphibole filling the interstices between the cumulate ilmenite and clinopyroxene and (2) the amphibole blebs replacing grains of clinopyroxene. The interstitial amphibole is interpreted to be magmatic in origin and therefore it was used to constrain the emplacement conditions of the Mazua intrusion. Pressure-Temperature (P-T) conditions for

the interstitial amphibole were estimated at 230–280 MPa and 819–827 °C, respectively, using amphibole-only thermobarometers. These conditions represent depths of 8.7–10.6 km and delineate the emplacement conditions, which occurred within the upper crust.

Chapter V discusses the nature and origin of the Tete Suite, with particular attention to the Fe-Ti oxides and related sulfides, based on mineral geochemistry. The Fe-Ti oxides, mainly ilmenite and magnetite, are predominantly interstitial to the silicate assemblage. Pyroxene crystals host lamellae of Fe-Ti oxides. The Fe-Ti oxides are characterized by prominent negative Ni and Co anomalies in the olivine melanogabbro-normalized patterns. These negative anomalies are ascribed to the early crystallization of olivine at depths, rather than the early sulfide segregation, as the sulfur saturation was achieved at the last stage of differentiation, consistent with the occurrence of Cu-Fe-rich and Ni-poor sulfide assemblage in the Tete Suite. The Fe-Ti oxides are interpreted to have formed from evolved Fe-Ti rich melt, which was enriched by magmatic differentiation. That is consistent with the pMELTS modeling results, run under a pressure of 300 MPa, an oxygen fugacity (fO_2) of FMQ+1 (1 log unit above the fayalite-magnetite-quartz buffer), and water content of 0.2 wt.%. The bulk composition of melanogabbro LDA11 [Mg-number = 80, defined as $100 \times \text{MgO}/(\text{MgO} + \text{FeO}_{\text{Total}})$, molar], was chosen as the starting composition for modeling. According to the model, olivine is the first phase to crystallize at 1475 °C, followed by plagioclase at 1189 °C, clinopyroxene at 1168 °C, Ti-rich magnetite at 1110 °C, and finally orthopyroxene at 1096 °C. The pMELTS modeling results predicted that the crystallization of Ti-rich magnetite occurs at a condition where the liquid is in equilibrium with olivine [Forsterite content = 81, defined as $100 \times \text{Mg}/(\text{Mg} + \text{Fe} + \text{Ni} + \text{Co} + \text{Mn} + \text{Ca})$, mol.%], plagioclase [Anorthite content = 81, defined as $100 \times \text{Ca}/(\text{Ca} + \text{Na} + \text{K})$, mol.%], and clinopyroxene [Mg-number = 65, defined as $100 \times \text{Mg}/(\text{Mg} + \text{Fe})$, atomic], consistent with the crystallization sequence and the composition of minerals in the gabbro of the Tete Suite. The early segregation of chromite is interpreted to be responsible for the Cr depletion in Fe-Ti oxides. Similarities between the Tete Suite and well-known intrusions that host chromite layers at their base, such as the Bushveld Complex, are suggested. However, the Tete Suite may represent the upper part of an original larger intrusion that was tectonically transported to the current position, implying that such chromite-rich bodies are mostly to be found where the root of the Tete Suite is located. The rocks underwent subsolidus re-equilibration during their cooling history. The QUILF program was used to quantify the T- fO_2 conditions at which coexisting magnetite and ilmenite were last equilibrated. Temperature and oxygen fugacities vary from 422 to 545 °C and FMQ-2 to FMQ+4 (2 log units below the FMQ buffer to 4 units above the FMQ buffer), respectively were constrained, representing subsolidus conditions.

Chapter VI presents the general conclusions of the research on the Mazua intrusion and the Tete Suite. (1) The two intrusions were formed from Fe-Ti rich melts evolved by magmatic differentiation. (2) The absence of sulfides at Mazua and the trace occurrence of sulfides (< 0.1 vol.%) in the Tete Suite indicates the sulfur undersaturated nature of the parental melt and the insignificant influence of crustal contamination during magma ascent. (3) The Fe-Ti oxides in the Tete Suite followed a cooling path that is parallel to the ulvöspinel isopleths in titanomagnetite solid solution, while in the Mazua intrusion, the oxides followed a trend that is parallel to the ilmenite isopleths in ilmenite-hematite solid solution. These cooling paths are explained by different proportions of the Fe-Ti oxides prior to subsolidus re-equilibration in the Tete Suite, composed mainly of Ti-rich magnetite and ilmenite, and in the Mazua intrusion, consisting solely of ilmenite.