ABSTRAK

MODEL PENGAYAAN SKANDIUM DALAM LATERIT NIKEL DI KONAWE UTARA, SULAWESI TENGGARA

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Skandium merupakan unsur tanah jarang strategis dengan nilai ekonomi tinggi dan permintaan global yang terus meningkat. Namun demikian, perilaku geologinya dalam sistem laterit nikel tropis masih belum terdefinisi secara memadai, khususnya terkait peran relatif komposisi batuan induk, intensitas pelapukan, serta fase mineral pembawa. Sebagian besar studi terdahulu memperlakukan skandium sebagai penjejak geokimia sekunder atau unsur ikutan, tanpa membangun kerangka genetik berbasis proses yang mampu menjelaskan redistribusi vertikal dan mekanisme akumulasi selama proses lateritisasi. Penelitian ini secara eksplisit menjawab keterbatasan tersebut dengan mengembangkan model implementatif pengayaan skandium pada laterit nikel, berbasis integrasi data geologi, mineralogi, dan geokimia dari wilayah Konawe Utara, Sulawesi Tenggara, Indonesia.

Penelitian difokuskan pada empat blok laterit—Tapunopaka, Lalindu, Mandiodo, dan Bahubulu—yang berkembang di atas batuan ultramafik dari Kompleks Ofiolit Sulawesi Timur. Pendekatan metodologi meliputi pemetaan geologi dan profil laterit, pengambilan sampel sistematis dari inti bor dan singkapan, pengamatan petrografi dan mineragrafi, analisis geokimia unsur utama dan jejak menggunakan ICP-OES dan XRF, karakterisasi mineralogi berbasis XRD, analisis spektral ASD–VNIR–SWIR, serta studi mikrotekstur dan asosiasi unsur menggunakan SEM–EDS. Mobilitas dan tingkat pengayaan skandium dievaluasi melalui indeks geokimia unsur *immobile* dikorelasikan secara kuantitatif dengan intensitas pelapukan (UMIA), serta diuji secara statistik terhadap Fe_2O_3 dan Al_2O_3 untuk mengidentifikasi faktor dominan pengontrol pengayaan skandium.

Hasil penelitian menunjukkan bahwa pengayaan skandium pada laterit nikel dikontrol secara sistematis oleh kandungan skamdium pada magma asal, komposisi batuan asal dan progresivitas pelapukan. Batuan induk ultramafik—khususnya, lherzolit, harsburgit, dunit, dan klinopiroksenit—merupakan sumber utama skandium, dengan kadar pada batuan asal berkisar antara 3 hingga 16 ppm, dan kadar tertinggi tercatat pada harsburgit, namun batuan asal yang menghasilkan laterit paling tebal dengan kadar skandium tertinggi mencapai 123 ppm adalah lherzolit. Seiring peningkatan intensitas pelapukan, skandium mengalami konsentrasi residu yang semakin meningkat ke arah bagian atas profil dan mencapai

kadar maksimum pada zona limonit. Rata-rata kadar skandium di wilayah penelitian mencapai 100,35 ppm pada Blok Tapunopaka, 100,18 ppm pada Mandiodo, 86,23 ppm pada Lalindu, dan 81,13 ppm pada Bahubulu, dengan nilai puncak melebihi 110 ppm pada beberapa interval limonit. Zona saprolit menunjukkan kadar yang lebih rendah dan lebih bervariasi, sedangkan zona batuan dasar (*bedrock*) secara konsisten memperlihatkan kadar terendah.

Kebaruan ilmiah yang kritis dan dapat dipertanggungjawabkan dari penelitian ini terletak pada pembuktian bahwa skandium terdapat pada harsburgit dan lherzolit di dalam augit yang memiliki tekstur lamelar augit-diopsid. Aluminium mempunyai pengaruh yang lebih kuat terhadap retensi skandium daripada pengaruh besi dan magnesium karena aluminium dan skandium mempunyai kesamaan valensi alami (3^+). Skandium dalam laterit terutama terikat dalam gutit dan hematit melalui mekanisme adsorpsi dan substitusi. Temuan ini mengindikasikan bahwa skandium berperilaku relatif tidak mobil pada tahap awal pelapukan, kemudian mengalami konsentrasi residu dan rekonsentrasi pada zona limonit seiring pelindian progresif unsur-unsur mobil seperti Mg, Si, dan Ca.

Model pengayaan yang diusulkan memberikan penjelasan berbasis proses mengenai pengayaan skandium, mulai dari keterikatannya dalam ikatan kristal mineral primer pembawa yaitu piroksen dan olivin pada batuan ultramafik, pelepasannya selama proses serpentinisasi dan lateritisasi, hingga akumulasi residu dan stabilisasinya dalam mineral oksida besi–aluminium pada zona limonit. Model ini menunjukkan bahwa pengayaan skandium pada laterit nikel tropis dikontrol oleh interaksi antara mineralogi batuan induk, intensitas pelapukan, kestabilan kimia larutan, serta kondisi geomorfologi dan sistem pengaliran. Dengan mengaitkan secara eksplisit mineral pembawa, lateritisasi, dan laterit dalam satu kerangka genetik, penelitian ini memberikan kontribusi konseptual terhadap pemahaman pengayaan skandium serta menyediakan dasar ilmiah untuk eksplorasi skandium dalam laterit nikel secara lebih terarah.

Kata kunci: unsur tanah jarang, skandium, pengayaan, nikel, laterit

ABSTRACT

SCANDIUM ENRICHMENT MODEL IN THE MANDIODO NICKEL LATERITE, NORTH KONAWE, SOUTHEAST SULAWESI

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Scandium is increasingly recognized as a critical rare earth element of substantial strategic and economic importance owing to its expanding applications in aluminium–scandium alloys, aerospace engineering, advanced transportation systems, and emerging low-carbon energy technologies. Despite its growing economic relevance, the geological behaviour of scandium within tropical nickel laterite systems remains inadequately constrained, particularly regarding the relative controls exerted by protolith composition, weathering intensity, and mineralogical host phases on scandium redistribution and enrichment. Previous studies have predominantly treated scandium as a subordinate geochemical tracer or incidental by-product element, with limited emphasis on the development of an integrated process-based genetic framework capable of elucidating the mechanisms governing its vertical redistribution, retention, and enrichment during lateritization. This study addresses these unresolved issues through the formulation of an implementative genetic model for scandium enrichment in nickel laterites, established through the integration of geological, mineralogical, petrographic, and geochemical datasets from North Konawe, Southeast Sulawesi, Indonesia.

The investigation was conducted across four representative lateritic blocks—Tapunopaka, Lalindu, Mandiodo, and Bahubulu—which developed over ultramafic lithologies of the East Sulawesi Ophiolite Complex. The analytical framework incorporated detailed geological and laterite-profile mapping, systematic drill-core and outcrop sampling, petrographic and mineragraphic characterization, major and trace element analyses using ICP–OES and XRF, mineralogical identification by XRD, ASD–VNIR–SWIR spectral characterization, and microtextural as well as elemental association analyses utilizing SEM–EDS. Scandium mobility and enrichment behaviour were quantitatively evaluated using immobile-element geochemical indices correlated with the Ultramafic Mafic Index of Alteration (UMIA), followed by statistical assessment against Fe_2O_3 and Al_2O_3 concentrations to determine the dominant geochemical controls governing scandium retention and enrichment.

The results demonstrate that scandium enrichment in tropical nickel laterites is fundamentally controlled by the initial scandium inventory of the parental magma,

the mineralogical composition of the ultramafic protolith, and the progressive evolution of lateritic weathering. Lherzolite, harzburgite, dunite and clinopyroxenite represent the principal primary lithological sources of scandium, with primary bedrock concentrations ranging from 3 to 16 ppm. Although harzburgite exhibits the highest primary scandium abundance, lherzolite-derived lateritic profiles generated the thickest weathering mantles and the highest scandium enrichment, reaching concentrations of up to 123 ppm. Progressive weathering promotes residual scandium concentration toward the upper portions of the laterite profile, culminating in maximum enrichment within the limonite horizon. Average scandium concentrations reached 100.35 ppm in the Tapunopaka Block, 100.18 ppm in Mandiodo, 86.23 ppm in Lalindu, and 81.13 ppm in Bahubulu, with localized limonitic intervals exceeding 110 ppm. In comparison, the saprolite horizon exhibits lower and more heterogeneous scandium distributions, whereas the bedrock zone consistently records the lowest concentrations.

A critical and scientifically robust novelty of this study resides in the identification of scandium occurrence within augite displaying augite–diopside lamellar textures hosted by harzburgite and lherzolite. The findings further demonstrate that aluminium exerts a stronger influence on scandium retention than iron or magnesium, principally due to the comparable trivalent ionic behaviour shared by Al^{3+} and Sc^{3+}. Within the laterite profile, scandium is preferentially associated with goethite and hematite through adsorption and lattice-substitution mechanisms. These observations indicate that scandium behaves as a relatively immobile element during the early stages of weathering, prior to undergoing progressive residual concentration and reconcentration within the limonite zone in response to the continued leaching of mobile components such as Mg, Si, and Ca.

The genetic enrichment model proposed herein provides a comprehensive process-based interpretation of scandium behaviour during tropical lateritization. Scandium is initially incorporated within the crystal lattices of primary ferromagnesian minerals, particularly pyroxene and olivine, hosted by ultramafic rocks, subsequently liberated during serpentinization and lateritic alteration, and ultimately concentrated and stabilized within iron–aluminium oxide assemblages in the limonite horizon. The model demonstrates that scandium enrichment in tropical nickel laterites is governed by the coupled interaction of parent-rock mineralogy, weathering intensity, aqueous geochemical stability, geomorphological evolution, and hydrological drainage conditions. By explicitly integrating primary host mineralogy, lateritization processes, and laterite evolution into a unified genetic framework, this study contributes a significant conceptual advancement toward the understanding of scandium enrichment mechanisms and establishes a scientifically defensible foundation for more predictive and targeted scandium exploration within tropical nickel laterite provinces.

Keywords: *rare earth elements, scandium, enrichment, nickel laterite, ultramafic rocks*