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Petrogenesis, Geochemical Evolution, and Cryospheric Interactions of Alkaline Complexes in Greenland: Implications for Mineralization and Paleoclimate Reconstruction

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Abstract

Greenland hosts some of the most significant alkaline igneous complexes in the North Atlantic region, representing key archives of mantle processes, crustal evolution, hydrothermal alteration, and glacial–climatic interactions. These complexes, including Kangerdlugssuaq, Ilímaussaq, Grønnedal-Íka, and Qassiarsuk, provide valuable insights into magmatic differentiation, isotopic evolution, mineralization, and water–rock interactions. In addition, glacial retreat studies and sedimentary investigations from East Greenland and beyond contribute to understanding post-magmatic surface processes and paleoclimatic transitions. This review synthesizes petrological, mineralogical, geochemical, isotopic, and cryospheric research to evaluate the evolution of Greenland's alkaline systems and their broader geodynamic and environmental implications. Emphasis is placed on magma genesis, fractional crystallization, carbonatite association, ikaite formation, aerosol iron transport, and ice-sheet retreat history. The integration of magmatic and surface-process studies provides a comprehensive framework for understanding lithosphere–hydrosphere–cryosphere interactions in high-latitude tectonic settings.

Keywords : Alkaline igneous complexes, Greenland petrogenesis, Kangerdlugssuaq intrusion, Ilímaussaq complex, carbonatite magmatism

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1. Introduction

Alkaline igneous complexes represent products of low-degree partial melting of enriched mantle sources, commonly associated with rift tectonics and plume-related magmatism. Greenland's Gardar Province and East Greenland margin preserve exceptional exposures of these systems, making them ideal natural laboratories for studying petrogenesis and crust–mantle interaction. Early isotopic and petrological investigations of the Kangerdlugssuaq alkaline intrusion demonstrated complex magmatic differentiation histories and crustal assimilation processes (Kempe & Deer, 1976; Pankhurst et al., 1976). These studies revealed the importance of strontium and oxygen isotopes in deciphering mantle versus crustal contributions to magma evolution.

Subsequent mineralogical syntheses of the Ilímaussaq complex emphasized extreme magmatic differentiation and rare-element enrichment (Marks & Markl, 2015). The association of carbonatite and alkaline silicate volcanism in South Greenland further refined models of mantle metasomatism and rift-related magmatism (Andersen, 1997). More recent petrological modeling of the Grønnedal-Íka complex has expanded understanding of hydrothermal water–rock interaction and ikaite precipitation mechanisms (Aðalsteinsdóttir et al., 2025).

Beyond magmatic systems, sedimentological and geochemical studies, including analyses of magnetic microspherules near the Younger Dryas boundary (Andronikov et al., 2016), provide insight into high-energy depositional and potential impact-related processes. Atmospheric studies of aerosol iron transport (Gao et al., 2020) contribute to understanding geochemical fluxes linking continental sources and polar environments. Additionally, reconstructions of East Greenland Ice Sheet retreat offer critical constraints on post-magmatic landscape evolution and sediment redistribution (Anderson et al., 2025).

This review integrates petrogenetic, mineralogical, isotopic, hydrothermal, and cryospheric research to provide a comprehensive understanding of Greenland's alkaline systems and their broader environmental implications.

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2. Geological Setting and Tectonic Framework

Greenland's alkaline complexes are primarily associated with the Mesoproterozoic Gardar Rift system and the Paleogene North Atlantic Igneous Province. The Gardar rift reflects extensional tectonics that facilitated mantle-derived magmatism and emplacement of alkaline plutons and carbonatites. The Kangerdlugssuaq intrusion in East Greenland exemplifies layered alkaline plutonism linked to lithospheric extension (Kempe & Deer, 1976).

Isotopic investigations of Kangerdlugssuaq revealed enriched mantle signatures combined with crustal contamination effects (Pankhurst et al., 1976). These findings support models of plume–lithosphere interaction during continental rifting. The Ilímaussaq complex, another hallmark of the Gardar province, displays extreme differentiation and peralkaline magmatism (Marks & Markl, 2015).

The Qassiarsuk carbonatite–alkaline silicate volcanic complex further demonstrates the coexistence of silica-undersaturated and carbonate-rich magmas within rift environments (Andersen, 1997). Collectively, these complexes record mantle metasomatism, lithospheric thinning, and volatile-rich magmatic processes.

The tectonic evolution of East Greenland also influenced post-emplacement glacial modification. Ice-sheet dynamics have reshaped exposures, influencing erosion, sediment transport, and fjord development (Anderson et al., 2025). Thus, Greenland's alkaline systems must be interpreted within both magmatic and glacial tectonic contexts.

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3. Petrogenesis and Magmatic Differentiation

Petrogenetic models for Greenland's alkaline complexes emphasize fractional crystallization, magma mixing, and volatile enrichment. Experimental and field evidence from Kangerdlugssuaq indicates progressive differentiation from basaltic parental magmas to syenitic and nepheline syenitic compositions (Kempe & Deer, 1976). Isotopic data confirm variable crustal assimilation during this evolution (Pankhurst et al., 1976).

The Ilímaussaq complex represents one of the most evolved peralkaline systems globally. Mineral assemblages such as arfvedsonite, eudialyte, and sodalite indicate high alkali activity and extreme differentiation (Marks & Markl, 2015). These processes concentrate rare elements including REEs, Zr, and Nb, making such complexes economically significant.

Carbonatite associations at Qassiarsuk suggest mantle-derived carbonate melts coexisted with silicate magmas (Andersen, 1997). This dual-magmatic system highlights the role of volatile components, particularly CO_2, in magma evolution. Carbonatitic activity also enhances metasomatic alteration of surrounding lithologies.

Hydrothermal overprinting further modifies primary magmatic signatures. Fluid circulation can remobilize alkalis and trace elements, altering mineral stability fields. Integrated petrological and geochemical modeling thus remains essential for understanding the complete magmatic history.

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4. Water–Rock Interaction and Hydrothermal Processes

Hydrothermal systems within alkaline complexes significantly influence mineral precipitation and geochemical cycling. Detailed petrological modeling of the Grønnedal-Íka complex demonstrates that interaction between alkaline magmas and circulating fluids promotes ikaite ($CaCO_3 \cdot 6H_2O$) deposition in Ikka Fjord (Aðalsteinsdóttir et al., 2025). Such processes require highly alkaline, carbonate-rich fluids under low-temperature conditions.

Water–rock interaction alters primary igneous minerals and generates secondary carbonate and zeolite assemblages. These reactions are sensitive to fluid composition, temperature gradients, and host-rock mineralogy. The Grønnedal-Íka system provides a rare example where modern hydrothermal discharge links deep magmatic processes to surface carbonate precipitation.

Isotopic and geochemical modeling confirms that hydrothermal fluids derive from a combination of magmatic and meteoric sources. Such mixing influences pH, redox conditions, and carbonate saturation states. These interactions contribute to unique mineral deposits and geomorphological features.

Hydrothermal alteration also plays a role in rare-element redistribution, affecting economic potential. Thus, integrating petrology and hydrochemistry enhances understanding of post-magmatic evolution.

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5. Surface Processes, Aerosol Iron, and Sedimentary Signatures

Surface processes provide additional context for interpreting magmatic terrains. Magnetic microspherules identified near the Younger Dryas boundary in New Mexico demonstrate how high-energy depositional processes can produce distinctive mineralogical signatures (Andronikov et al., 2016). Although geographically distinct from Greenland, such studies illustrate how microspherules and geochemical anomalies can serve as stratigraphic markers.

Atmospheric transport of mineral dust and iron plays a key role in polar biogeochemical cycles. Research over the Antarctic Peninsula highlights particle-size distribution and solubility controls on aerosol iron deposition (Gao et al., 2020). Similar mechanisms likely influence Greenland's glacial and marine systems.

Iron-bearing aerosols contribute to ocean fertilization and influence primary productivity. In high-latitude settings, glacial grinding enhances production of fine particulates that can enter atmospheric and marine pathways. Thus, lithospheric processes indirectly affect cryospheric and biospheric systems.

These interconnected processes underscore the importance of integrating sedimentology, atmospheric science, and petrology when studying polar alkaline provinces.

6. Ice Sheet Retreat and Landscape Evolution

Deglaciation studies in East Greenland provide insights into the interaction between tectonics, magmatism, and climate-driven erosion. Reconstruction of the East Greenland Ice Sheet retreat during the last deglaciation indicates dynamic glacier behavior and fjord-based ice-stream retreat (Anderson et al., 2025).

Glacial erosion has exposed deep crustal sections of alkaline intrusions, improving access to petrological records. Simultaneously, glacial retreat influences sediment flux and geochemical transport to marine basins. Isostatic rebound and fjord incision further modify regional geomorphology.

The integration of glacial chronology with magmatic history allows improved reconstruction of long-term landscape evolution. Ice-sheet retreat also affects hydrothermal circulation patterns by altering surface water infiltration and pressure regimes.

Understanding cryospheric dynamics is therefore essential for contextualizing Greenland's alkaline geological record within Quaternary climate change.

7. Discussion

Greenland's alkaline complexes illustrate the interplay between mantle melting, crustal assimilation, fractional crystallization, and hydrothermal alteration. Isotopic constraints (Kempe & Deer, 1976; Pankhurst et al., 1976) highlight enriched mantle sources and crustal contributions. Extreme differentiation in Ilímaussaq (Marks & Markl, 2015) demonstrates how peralkaline systems evolve toward rare-element enrichment.

Carbonatite associations (Andersen, 1997) confirm volatile-rich magmatic regimes in rift environments. Hydrothermal modeling (Aðalsteinsdóttir et al., 2025) bridges magmatic and surface processes through water–rock interaction and carbonate deposition. Surface and atmospheric studies (Andronikov et al., 2016; Gao et al., 2020) emphasize sedimentary and geochemical linkages beyond purely magmatic frameworks.

Finally, glacial retreat reconstructions (Anderson et al., 2025) integrate climate forcing into geological interpretation. Collectively, these studies demonstrate that alkaline provinces function as coupled lithosphere–hydrosphere–cryosphere systems.

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8. Conclusion

Greenland's alkaline complexes represent integrated records of mantle processes, magmatic differentiation, hydrothermal alteration, and glacial modification. Petrogenetic models reveal enriched mantle sources and complex differentiation histories. Hydrothermal systems facilitate carbonate deposition and rare-element redistribution. Surface processes and atmospheric transport connect lithospheric activity to polar biogeochemical cycles. Ice-sheet retreat further shapes exposure, sediment flux, and landscape evolution. A multidisciplinary framework combining petrology, isotope geochemistry, hydrothermal modeling, sedimentology, and cryospheric science is essential for fully understanding these dynamic geological systems.

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