



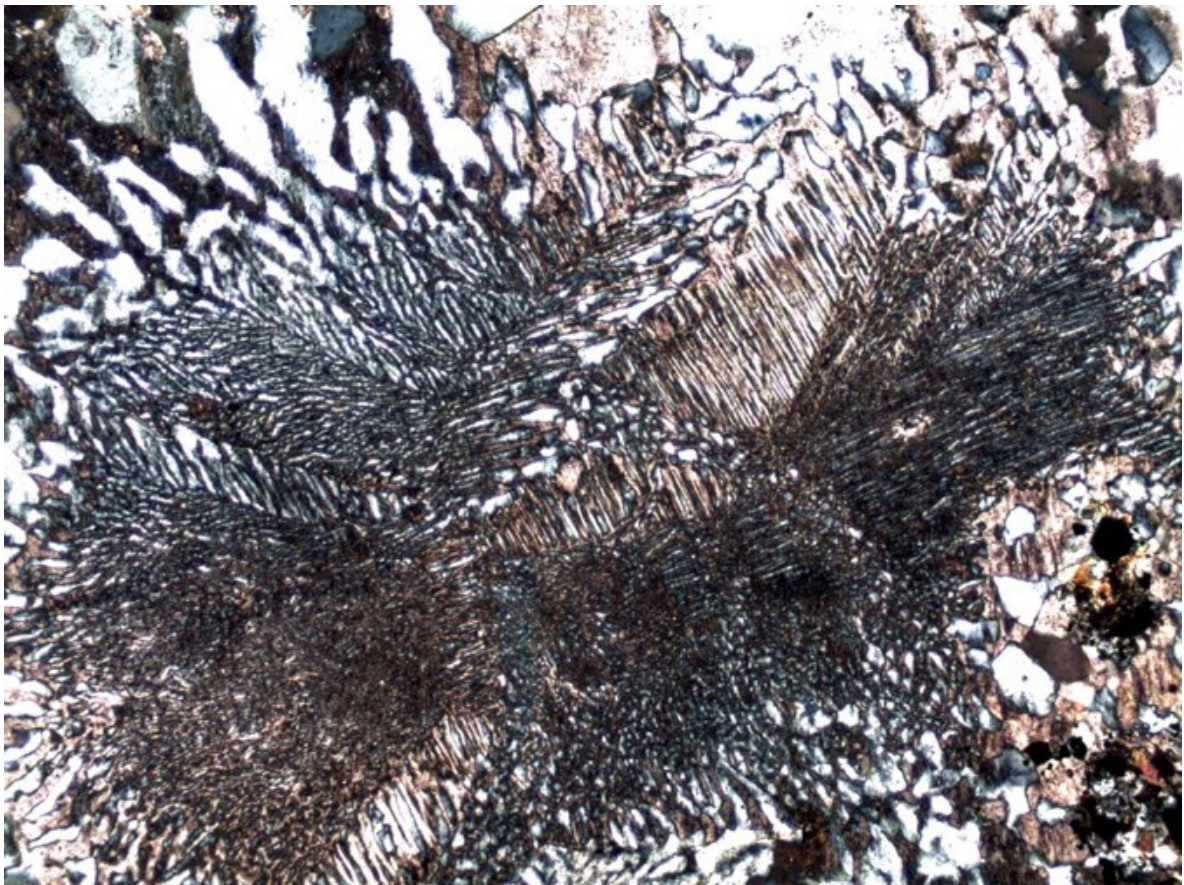
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Age and character of granophyric and composite dikes in Kiirunavaara, northernmost Sweden

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Abstract

Two sets of magmatic dikes cut the Kiirunavaara iron oxide-apatite orebody at high angle: (1) a set of 0.1-20 m wide felsic dikes, striking NW and steeply dipping to the NE, in the south, and (2) two composite mafic-felsic dikes, 2-15 m wide, striking W-NW and dipping 60-70° S-SW, in the north. The felsic rocks typically show granophyric textures. The composite dikes typically have mafic margins and felsic interiors, with bulbous contacts and mafic enclaves in the felsic centers, indicating co-intrusion and mingling of mafic and felsic magmas. Apophyses of both mafic and felsic composition are present. A granite pluton containing mafic enclaves occurs in the footwall rocks of the orebody adjacent to the dike systems.

One sample of felsic rock from each dike system was analyzed by SIMS U-Pb zircon geochronology. Zircon from the composite dike is weakly oscillatory zoned, partly metamict, and subhedral, and yields a concordia age of 1879 ± 6 Ma (MSWD = 0.8; $n = 14$). A weighted-average $^{207}\text{Pb}/^{206}\text{Pb}$ age yields 1881 ± 6 Ma (MSWD = 1.2; $n = 14$). Zircon from the southern dike is high in U, typically 1500-2500 ppm, and contains numerous small inclusions, ≤ 1 μm across, contributing to high common Pb contents and highly discordant data. Thirty-two analyses define a discordia with upper and lower intercepts at 1872 ± 14 Ma and 423 ± 14 Ma, respectively, and a MSWD of 28. One analysis is concordant at 1861 ± 10 Ma.

Strong metasomatism affecting much of the volcanic country rock has also altered many of these dikes. However, most samples in this study fall within the fields of igneous or least-altered whole-rock compositions. Geochemical classification indicates that the mafic rocks are of continental arc type, with some E-MORB influence. Both the granite and the granophyres are high-silica rocks ($>70\%$ SiO_2), although the granophyres are generally more evolved ($>75\%$ SiO_2). The granite shows a continental arc signature, whereas the granophyres extend toward within-plate fields.

We interpret these results to indicate that mafic and felsic magmas intruded during the same broad late Paleoproterozoic magmatic interval as the ore, associated volcanic rocks, and the spatially related granite pluton, within a continental arc setting. The within-plate character of the felsic dikes is best explained by crystal fractionation rather than by a separate magmatic event. A significant part of the metasomatic overprint occurred during or after dike

emplacement, consistent with previously documented later episodes of hydrothermal activity in the area.

Table of Contents

Acknowledgements	2
Abstract.....	3
List of Figures.....	7
1. Introduction	13
2. Geological Background.....	15
2.1 Regional Geology.....	15
2.2 Local Geology of Kiirunavaara.....	21
2.2.1 <i>The apatite iron ores</i>	22
2.2.2 <i>Footwall rocks</i>	24
2.2.3 <i>Hanging wall rocks</i>	25
2.2.4 <i>The dike porphyries</i>	26
2.2.5 <i>Granophyre, diabase and composite dikes</i>	27
3. Materials and Methods.....	29
3.1 Sample Selection	29
3.2 Petrography.....	29
3.3 Geochemistry	30
3.4 Geochronology	31
3.4.1 <i>BSE and CL Imaging</i>	32
3.4.2 <i>U-Pb SIMS Dating</i>	32
4. Results	33
4.1 Field Observations.....	33
4.2 Petrography.....	40
4.2.1 <i>CA-Granite (Location Code 4)</i>	40
4.2.2 <i>Granophyres in southern Kiirunavaara (Location Codes 1a–1b)</i>	41
4.2.3 <i>Konsuln Granophyres (Location Code 1c)</i>	43
4.2.4 <i>Diabases (Location Codes 2a1, 2b1 and 3)</i>	44

4.2.5 Composite dikes (<i>Location Codes 2a1, 2a2, 2b1 and 2b2</i>).....	45
4.3 Geochemistry	47
4.4 Geochronology	53
4.4.1 Sample 12-1223-1 – <i>Northern Composite Dike (granophyre core)</i>	54
4.4.2 Sample Z275-Y454 – <i>Granophyre, south (near surface)</i>	57
5. Discussion	60
6. Conclusion	74
References	76
Supplementary Material.....	85

List of Figures

- Figure 1. Simplified regional geological map of the northern Fennoscandian Shield showing the distribution of Archean, Paleoproterozoic, and younger geological units, and the location of the Northern Norrbotten Ore Province including Kiruna, Svappavaara, and Malmberget. The inset shows the principal Precambrian orogenic provinces and the younger Caledonian orogen. From Gilg & Andersson (2024).....16
- Figure 2 Simplified stratigraphic column of the Kiruna area showing the main lithostratigraphic units of the Kiruna Greenstone Group and overlying formations, together with representative lithologies and symbols used in regional geological maps. From Gilg & Andersson (2024). 18
- Figure 3. Simplified geological map of the Kiruna area (from Gilg & Andersson, 2024). 21
- Figure 4. Geological model of the Kiirunavaara deposit showing the spatial relationships among the hanging wall volcanic sequence, the dike porphyries (same color as the QP), the orebody, the CA-granite, and the granophyre, and composite dikes. Footwall rocks have been removed for clarity. The view is shown as an elevation cut; modeled units are indicated in the legend (model courtesy of H. Ergili Aydin, LKAB). 34
- Figure 5. Geological map of the southernmost part of the Kiirunavaara; horizontal section at level 130 m (below the top of the mountain), produced ~100 years ago. Red and green gridlines are spaced at 200 m. Modified from Andersson & Berglund (2024).....35
- Figure 6. Exposure in the southern wall of the Kiirunavaara open pit, viewed toward the west, showing granophyre dikes cutting footwall rocks and projecting toward the ore zone (in front, mined out). The largest individual dikes are approximately 10–20 m wide. Photo: Ulf B. Andersson. 36
- Figure 7. A. Northern Composite Dike exposed underground at Kiirunavaara, showing diabase margins flanking a granophyre core (~2 m wide) and sharp internal contacts between mafic and felsic components. Access drift, block 12/1223. Photo: Ulf B.

Andersson. B. Map of composite dike in footwall (yellow) at 12/1223. Site of geochronology sample.	37
Figure 8. A. Diabase enclaves in granophyre from the Northern Composite Dike. Drill core BRK24037. Photo: C.F. Shaw. B. Enclaves in granophyre of the Southern Composite Dike. From Y1650, level 849. Photo: Ulf B. Andersson.	38
Figure 9. Circa 7 m wide diabase dike in the subsiding hanging wall of Kiirunavaara, photographed from Förvaltningskontoret (FK). This dike has not been observed crosscutting the ore or foot wall rocks in the mine but is included in this study (sample Db Dbr1 and 2). Photo: Tomas Villegas.	39
Figure 10. CA-granite (sample CA1110) showing a feldspar-dominated framework with interstitial to discrete anhedral quartz and irregular quartz–feldspar grain boundaries. (A) PPL; (B) XPL. Approximate image widths: 2.8 mm.	41
Figure 11. 1a granophyre (sample Kii F) showing well-developed radiating to plumose granophyric intergrowths around quartz-rich centers. (A) PPL; (B) XPL.	42
Figure 12. 1b granophyre (sample Kir 23001) showing textural variation and alteration. (A) XPL, with a sericite-altered phenocryst and granophyric intergrowths. (B) XPL, from a different area of the same sample, with a chlorite-altered phenocryst, quartz, magnetite, and coarser polygonal granophyric intergrowths.	43
Figure 13. 1c granophyre (sample BPK23011.1) from the Konsuln area, showing locally developed granophyric intergrowths within a very fine-grained felsic groundmass. (A) PPL; (B) XPL.	44
Figure 14. 2b1 diabase (sample 100/792 Db) from the Northern Composite Dike, showing ophitic to sub-ophitic texture and alteration of primary clinopyroxene to chlorite. Abundant magnetite is disseminated throughout the rock. (A) PPL; (B) XPL.	45
Figure 15. 2b1+2 diabase–granophyre contact (sample 108/935 Kon) from the Northern Composite Dike, showing a sharp contact between felsic (granophyre) and mafic (diabase) domains. The two components remain texturally distinct, with no gradation across the boundary. (A) PPL; (B) XPL.	46

Figure 16. Total alkali-silica (TAS) classification diagram showing the distribution of analyzed intrusive lithologies from Kiirunavaara. Legend abbreviations denote lithology and data source: DIA = diabase, GRA = granite, GRP = granophyre, and QP = quartz porphyry; ALP denotes recent drill-core analyses available during the present study; KIR denotes legacy LKAB database analyses; and SGU denotes analyses from the Geological Survey of Sweden database. The same color and symbol conventions are retained in subsequent geochemical figures, although the populations shown vary following geochemical screening. Field boundaries after Le Maitre et al. (1989).....	48
Figure 17. Igneous spectrum diagram after Hughes (1972) showing the distribution of alteration characteristics of analyzed lithologies from Kiirunavaara. QP analyses plotting outside the Igneous Spectrum were excluded from subsequent diagrams intended to emphasize primary compositional relationships. Color and symbol conventions as in Figure 16.	49
Figure 18. IOCG-style major-element molar-ratio alteration diagram after Montreuil et al. (2013), showing the distribution of felsic and mafic intrusive rocks from Kiirunavaara across sodic, potassic, and Ca-Fe alteration fields. QP analyses plotting outside the Igneous Spectrum of Figure 17 are excluded. Color and symbol conventions as in Figure 16.....	50
Figure 19. Analyses with $Zr/Ti > 0.02$ are excluded from subsequent tectonic discrimination diagrams to ensure that only basaltic compositions are used, following the screening recommendation of Pearce (1996) for subalkaline rocks. Symbols as in Fig. 16.	52
Figure 20. Sample site for geochronology sample Z275-Y454. Blue indicates iron ore, pink granophyric dikes, and yellowish tones footwall trachyandesites. The sample was collected from the projected continuation of a granophyric dike beyond the mapped tunnel. Map modified after Andersson and Berglund (2024).....	53
Figure 21. Back-scattered electron (BSE) image of representative zircon grains from sample 12-1223-1 showing oscillatory internal zoning. Analytical spot locations and corresponding $^{207}Pb/^{206}Pb$ ages are indicated.....	54

Figure 22. Tera–Wasserburg concordia diagram for zircon analyses from sample 12-1223-1. Five excluded analyses plot outside the concordant cluster, whereas two additional excluded analyses that plot near concordia are shown in gray in the inset and were omitted from age calculation because the analytical spots intersected cracks. The remaining 14 analyses yield a Concordia age of 1879 ± 6 Ma (2σ ; MSWD = 0.8; probability of fit = 0.76). Error ellipses are shown at 2σ 55

Figure 23. Weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1882 ± 6 Ma (2σ) based on 14 analyses (MSWD = 1.15; probability = 0.31). 56

Figure 24. Back-scattered electron (BSE) images of representative zircon from sample Z275-Y454. (A) Zircon grain showing sector zoning. (B) Higher-magnification BSE image showing abundant fine inclusions; the arrow indicates an inclusion-rich area. The inset shows an EDS spectrum from analysis n7009-08b with a notable Fe signal. The circular feature labeled 8b is an analytical spot. 57

Figure 25. Tera–Wasserburg concordia diagram for zircon analyses from sample Z275-Y454. Most analyses are discordant and show significant scatter. The inset highlights the two analyses plotting closest to concordia, with $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 1861 ± 10 Ma and 1862 ± 4 Ma. Error ellipses are shown at 2σ . Diagram prepared by J. Andersson. 58

Figure 26. SiO_2 versus $100 \cdot \text{K}_2\text{O}/(\text{K}_2\text{O} + \text{Na}_2\text{O})$ diagram for felsic and mafic intrusive rocks from Kiirunavaara. Division lines at ~ 57.5 wt.% SiO_2 and $100 \cdot \text{K}_2\text{O}/(\text{K}_2\text{O} + \text{Na}_2\text{O}) = 30$ and 70 are estimated from Figure 17 and are applied only to the felsic rocks. Mafic rocks are shown for comparison only. The CA-granite compositions lie essentially within the igneous field, whereas the granophyres are partly strongly altered. QP compositions are screened to within the igneous spectrum. Legend abbreviations and symbols as in Figure 16. 61

Figure 27. Th/Yb versus Ta/Yb tectonic discrimination diagram after Schandl & Gorton (2002), modified after Pearce (1982, 1983), showing the distribution of felsic compositions from Kiirunavaara. OA = Oceanic arc; ACM = Active continental margin; WVPVZ = Within-plate volcanic zone; WPB = Within-plate basalt; MORB = Mid-ocean ridge

basalt. All data are screened to within the igneous spectrum of Figure 17. Symbols as in Fig. 16.	63
Figure 28. Felsic compositions plotted on the Hf–Rb–Ta diagram after Harris et al. (1986). Granites cluster mainly within the volcanic-arc field, whereas granophyres show a broader distribution extending toward, and locally into, the within-plate field. All data are screened to within the igneous spectrum of Figure 17. Symbols as in Fig. 16.	64
Figure 29. Yb+Ta versus Rb tectonic discrimination diagram for granites and granophyres after Pearce et al. (1984), showing volcanic arc granite (VAG), syn-collisional granite (syn-COLG), within-plate granite (WPG), and ocean-ridge granite (ORG) fields. Granophyres define a broader compositional array than granites and extend toward the within-plate field. All compositions shown are screened to within the igneous spectrum of Figure 17. Symbols as in Fig. 16.	66
Figure 30. N-MORB-normalized trace-element patterns for the Kiirunavaara diabase dikes and mafic margins of composite dikes. N-MORB, E-MORB, and OIB reference patterns are after Sun and McDonough (1989); CAV and OAV reference patterns are after Chen et al. (2023).	67
Figure 31. Mafic dike compositions plotted on the Th–Hf–Ta diagram after Wood (1980), showing clustering mainly within arc fields, particularly the continental arc basalt field. Field abbreviations: N-MORB = normal mid-ocean ridge basalt; E-MORB = enriched mid-ocean ridge basalt; VAB = volcanic arc basalt; IAT = island arc tholeiite; CAB = calc-alkaline basalt; WPT = within-plate tholeiite; WPB = within-plate basalt; Alk WPB = alkaline within-plate basalt. Symbols as in Figure 16.	68
Figure 32. Mafic dike compositions plotted on the Th/Yb versus Nb/Yb diagram after Pearce (2014), showing a trend from E-MORB toward the continental arc field. LC, MC, and UC are lower, middle, and upper crust averages, respectively, and CC is the average continental crust. Symbols as in Fig. 16.	69
Figure 33. Drill core example showing mingling between mafic and felsic components in the northern composite dike (drill core BRK24037). Sharp contacts and irregular	

interfingering relationships indicate physical juxtaposition and incomplete mixing of compositionally distinct magmas during emplacement. 70

1. Introduction

The Northern Norrbotten Ore Province in northern Sweden hosts several economically significant mineral deposits, the most notable of which is Kiirunavaara –the world's largest underground iron ore mine and the type locality for Kiruna-type iron oxide–apatite (IOA) deposits. With an annual production of approximately 25 Mt and total resources and reserves estimated at ~1600 Mt of ore (LKAB, 2025), Kiirunavaara represents Europe's largest and most strategically important source of iron ore, a position expected to be maintained for decades. Owing to its economic significance, Kiirunavaara has been the focus of extensive geological research (e.g., Geijer, 1910; Parák, 1975; Nyström & Henriquez, 1989; Nyström et al., 2008; Westhues et al., 2016; Troll et al., 2019). However, the geotectonic evolution of the area is complex, involving several episodes of deformation, metamorphism, and hydrothermal alteration that have partly obscured the primary processes responsible for ore formation.

The regional lithostratigraphy is relatively well established, comprising an Archean granitoid–gneiss basement, unconformably overlain by a Paleoproterozoic volcano–sedimentary succession (Martinsson et al., 2016). At Kiirunavaara, this sequence is crosscut by several granophyre, diabase and composite dikes. In addition, a granitic pluton, known as the Centrala anläggningar granite and hereafter referred to as the CA-granite, is exposed at depth in the footwall of the mine (Cliff et al., 1990; Westhues et al., 2016; Andersson & Berglund, 2024). Collectively, these intrusions form a distinct lithological complex that is the focus of this study.

Geijer (1910) was the first to describe the dikes at Kiirunavaara, and his mapping accurately delineated what is now referred to as the Southern Granophyre. Öhman (1986) later conducted the first detailed petrographic and mineralogical study of the Southern Composite Dike following its discovery. U–Pb zircon dating by Cliff et al. (1990) of a granophyric dike complex crosscutting the Kiirunavaara orebody yielded an age of 1880 ± 3 Ma, providing a minimum age for ore formation and key temporal constraints on the timing of magmatism relative to ore formation. Further U–Pb zircon geochronological data presented by Westhues et al. (2016) refined the chronological

framework for host rock emplacement and mineralization, yielding ages of 1884 ± 4 to 1880 ± 3 Ma for the metavolcanic footwall and hanging-wall rocks and 1877 ± 4 and 1874 ± 7 Ma for zircon from two Kiirunavaara ore samples. The dyke porphyries were found to closely overlap the hanging wall volcanic rocks in texture and geochemistry, and U–Pb zircon dating yielded a crystallization age of 1880 ± 4 Ma. These similarities, together with their field relationships, support their interpretation as feeder conduits to the hanging wall volcanism, emplaced during the waning stages of footwall and ore magmatism.

Although dikes are widely used to constrain the chronological, structural, and geochemical evolution of volcano-plutonic systems, the granophyre, diabase, and composite dikes at Kiirunavaara have not been the subject of a comprehensive study. This study aims to address this knowledge gap by (1) mapping and documenting their spatial distribution; (2) characterizing their mineralogical and petrographic features; (3) conducting lithogeochemical analyses to infer their petrogenesis within the broader magmatic framework of Kiirunavaara and the surrounding region; and (4) applying U–Pb zircon geochronology to samples from the Southern Granophyre and Northern Composite Dike to better constrain their emplacement history. The findings of this study contribute to a broader understanding of volcano-plutonic processes and their role in the formation of Kiruna-type IOA deposits

2. Geological Background

2.1 Regional Geology

The Fennoscandian Shield, which constitutes the NW part of the Baltic Shield, comprises Archean cratons, Paleoproterozoic orogenic belts, including intrusive igneous provinces that extend across parts of Sweden, Finland, Norway, and Russia (e.g., Gaál & Gorbatshev, 1987; Lahtinen et al., 2008). It is one of the world's most significant mining regions, hosting a wide variety of mineral deposits, including volcanic-hosted massive sulfides (VMS), banded iron formations (BIF), porphyry copper, orogenic gold, and layered mafic intrusions (Weihed et al., 2005; Billström et al., 2010; Eilu, 2012). In addition to these, the iron oxide–apatite (IOA) deposits at Malmberget, Svappavaara, and, foremost, Kiirunavaara are of particular economic importance. The diversity and distribution of mineral deposits in the Fennoscandian Shield reflect its complex geological evolution, particularly the extensive tectonic and magmatic activity associated with Paleoproterozoic orogenesis (e.g., Lahtinen et al., 2005, 2008).

The Northern Norrbotten Ore Province, located in the northern part of the Fennoscandian Shield, has been extensively mapped and described (Bergman et al. 2001, Bergman, 2018; Martinsson 2004; Martinsson et al., 2016, and Bergman & Weihed 2020). The regional stratigraphy consists of an Archean basement, dated to ca. 2.8–2.6 Ga (Bergman & Weihed, 2020), unconformably overlain by a Paleoproterozoic volcano-sedimentary succession that reaches a thickness of 5–10 km across most of northern Norrbotten (Bergman et al., 2001; Martinsson, 2004) (Figure 1).

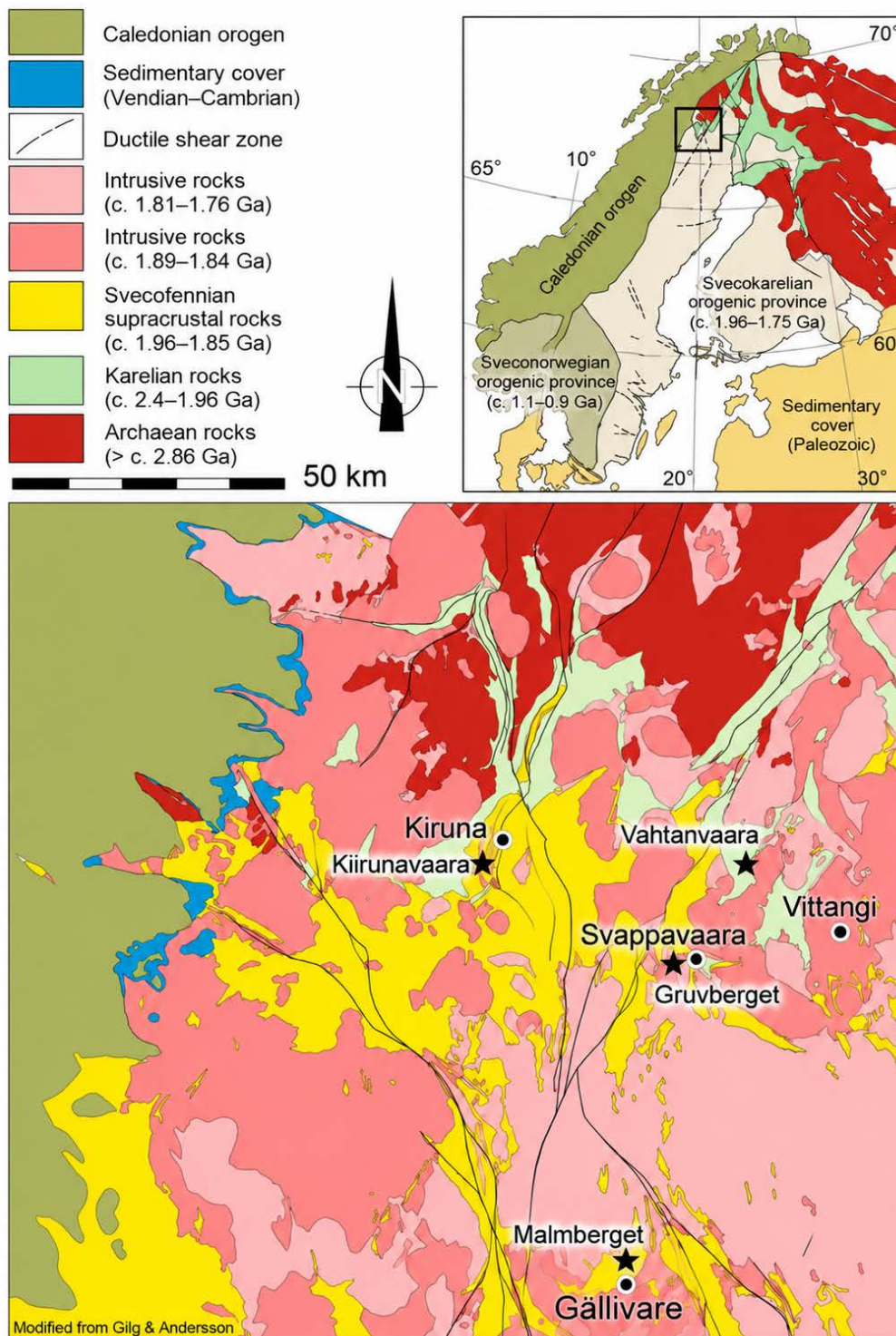


Figure 1. Simplified regional geological map of the northern Fennoscandian Shield showing the distribution of Archean, Paleoproterozoic, and younger geological units, and the location of the Northern Norrbotten Ore Province including Kiruna, Svappavaara, and Malmberget. The inset shows the principal Precambrian orogenic provinces and the younger Caledonian orogen. From Gilg & Andersson (2024).

The Archean basement comprises tonalite–trondhjemite–granodiorite (TTG) suites intruding an older complex of volcanic and sedimentary rocks, including arenites and metasedimentary gneisses of arkosic and pelitic composition (Bergman et al., 2001). Emplaced between ca. 2.83 and 2.7 Ga, these TTG intrusions are interpreted as the products of magmatic activity in a maturing oceanic arc setting (Martinsson et al., 1999; Martinsson, 2004). Referred to as the Råstojaur Complex, these rocks were locally affected by Paleoproterozoic deformation and metamorphism, superimposed on an older Archean metamorphic and deformational history (Bergman et al., 2001).

The Paleoproterozoic succession unconformably overlying the Råstojaur Complex records a complex tectonic and magmatic evolution, from early intracratonic rifting to subsequent crustal shortening and accretionary tectonism during the Svecokarelian orogeny (e.g., Bergman & Weihed, 2020) (Figure 2). This evolution ultimately established the volcano-sedimentary and magmatic framework that hosts the region’s iron oxide–apatite (IOA) deposits.

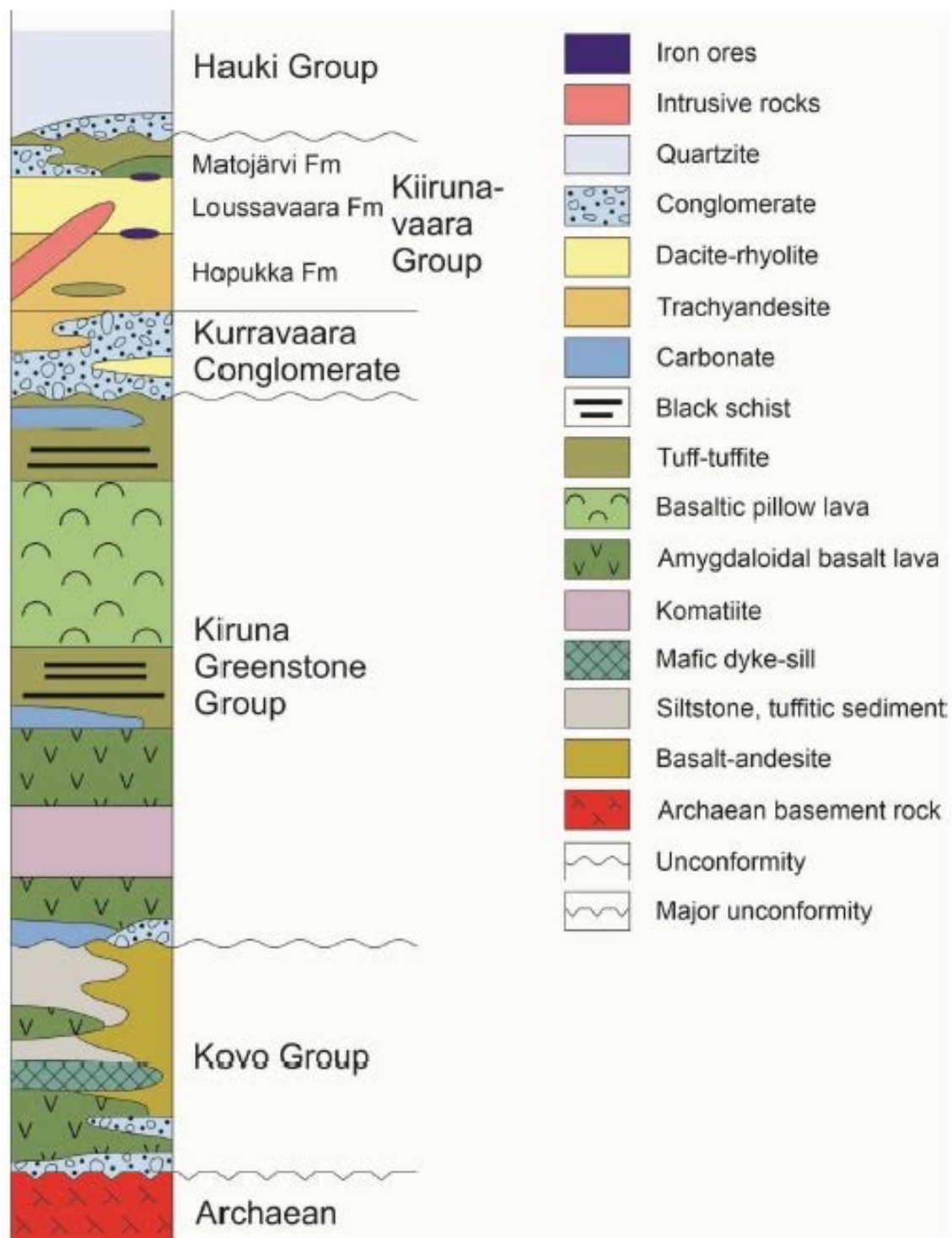


Figure 2 Simplified stratigraphic column of the Kiruna area showing the main lithostratigraphic units of the Kiruna Greenstone Group and overlying formations, together with representative lithologies and symbols used in regional geological maps. From Gilg & Andersson (2024).

Early in the Paleoproterozoic, continent Fennoscandia underwent at least two major rifting events. The first, during the Karelian orogenic cycle (ca. 2.39–2.33 Ga), resulted in deposition of the Kovo Group (Martinsson, 1997). The Lower Kovo Group comprises conglomerates, quartzites, and basaltic lavas deposited in an extensional continental rift setting, representing the early stages of basin development. The Upper Kovo Group consists of calc-alkaline basaltic to andesitic volcanic rocks, reflecting continued magmatism during rift basin evolution.

A second rifting phase, dated to ca. 2.3–2.0 Ga led to deposition of the Kiruna Greenstone Group. This 2–4 km thick sequence of mafic tholeiitic metavolcanics and subordinate metasedimentary rocks (Martinsson, 1997; Lynch et al., 2018) includes widespread pillow and amygdaloidal basalts deposited in a submarine extensional setting, together with graphite-bearing schists, carbonate rocks, clastic sediments, and ultramafic units.

Following the rifting and extensional phases affecting Fennoscandia, tectonic conditions shifted toward convergence and the onset of the Svecokarelian orogeny (ca. 2.0–1.8 Ga), marking a transition to compressional tectonics dominated by subduction, collision, and accretion, although localized extension and back-arc volcanism persisted (e.g., Bergman et al., 2001; Sarlus et al., 2018). This period was characterized by widespread volcanism and plutonism, resulting in the emplacement of several major volcano-plutonic complexes and intrusive suites.

One important magmatic phase, dated to ca. 1.89–1.86 Ga, involved emplacement of calc-alkaline magmas in continental-arc settings, producing the Haparanda Suite and Porphyrite Group volcanic rocks (Skiöld, 1986, 1987; Westhues et al., 2016; Bergman & Weihed, 2020). These units are primarily developed in the eastern part of the province and consist of intermediate to felsic volcanic and volcanoclastic rocks with associated dioritic to granodioritic intrusions.

Broadly contemporaneous magmatism, dated to ca. 1.88–1.86 Ga, produced more alkali-rich volcanic and intrusive rocks in the western part of the province, including the Porphyry Group (Kiirunavaara Group) and the Perthite Monzonite Suite (Witschard, 1984; Martinsson, 2004; Bergman et al., 2001). These units comprise mafic to felsic

volcanic and volcanoclastic rocks together with gabbroic, monzonitic, and granitic intrusions (Bergman et al., 2001; Martinsson, 2004).

The latest major magmatic event, dated to 1.81–1.77 Ga, is represented by the Lina Suite, a series of granite and pegmatite intrusions associated with regional uplift and erosion (Skiöld, 1988; Bergman et al., 2001; Sarlus et al., 2018, 2020). The Hauki Group comprises clastic sedimentary rocks that predate this magmatic event and are generally interpreted to record sedimentation during the later stages of the orogeny (Bergman et al., 2001).

Within this volcano-plutonic framework, the Kiirunavaara Group –subdivided into the Hopukka, Luossavaara, and Matojärvi Formations– forms the principal host rocks for the Kiirunavaara IOA deposit (Martinsson, 2004). The close temporal and spatial association between emplacement of these Paleoproterozoic complexes and development of IOA mineralization highlights the significance of this magmatic phase in ore formation (e.g., Geijer 1910; Westhues et al., 2016; Andersson et al., 2021; Pihl, 2024).

Following magmatism, the Paleoproterozoic succession was overprinted by deformation, metamorphism, and hydrothermal overprints in several episodes (e.g., Yan et al., 2023; Billström et al., 2025). During the Svecokarelian orogeny (ca. 1.88–1.74 Ga), the region experienced several ductile and brittle deformation phases, including at least two folding events and development of major crustal-scale shear zones such as the NNE-trending Karesuando–Arjeplog Deformation Zone (Bergman et al., 2001; Bauer & Andersson, 2023; Andersson et al., 2021). Some of these tectonic events were accompanied by regional metamorphism and pervasive metasomatic alteration. Widespread sodic alteration (albitization and scapolitization) and localized potassic metasomatism characterize the alteration associated with mineralization (e.g., Frietsch et al., 1997; Bergman et al., 2001; Martinsson, 2004; Bernal et al. 2017). Subsequent hydrothermal events at ca. 1.74–1.72 Ga, 1.64–1.62 Ga, and 1.5–1.40 Ga further overprinted earlier fabrics and contributed to extensive alteration and remobilization of mineralizing systems (Andersson et al., 2016; Palm, 2016; Westhues et al., 2017; Yan et al., 2023; Billström et al., 2025).

2.2 Local Geology of Kiirunavaara

The local geology of the Kiirunavaara area is complex, reflecting multiple phases of magmatism, tectonism, metamorphism, and hydrothermal alteration that have reworked the Paleoproterozoic rocks (e.g., Andersson et al., 2021; Yan et al., 2023; Gilg & Andersson, 2024). Although the broad lithostratigraphic framework of the district is relatively well established, interpretation of specific lithologic relationships and petrologic classifications remains obscured by ambiguous field relationships and age constraints. Despite these uncertainties, several key geological relationships provide a working framework for understanding the geological setting of the Kiirunavaara deposit. A simplified geological map of the Kiruna area is shown in Figure 3.

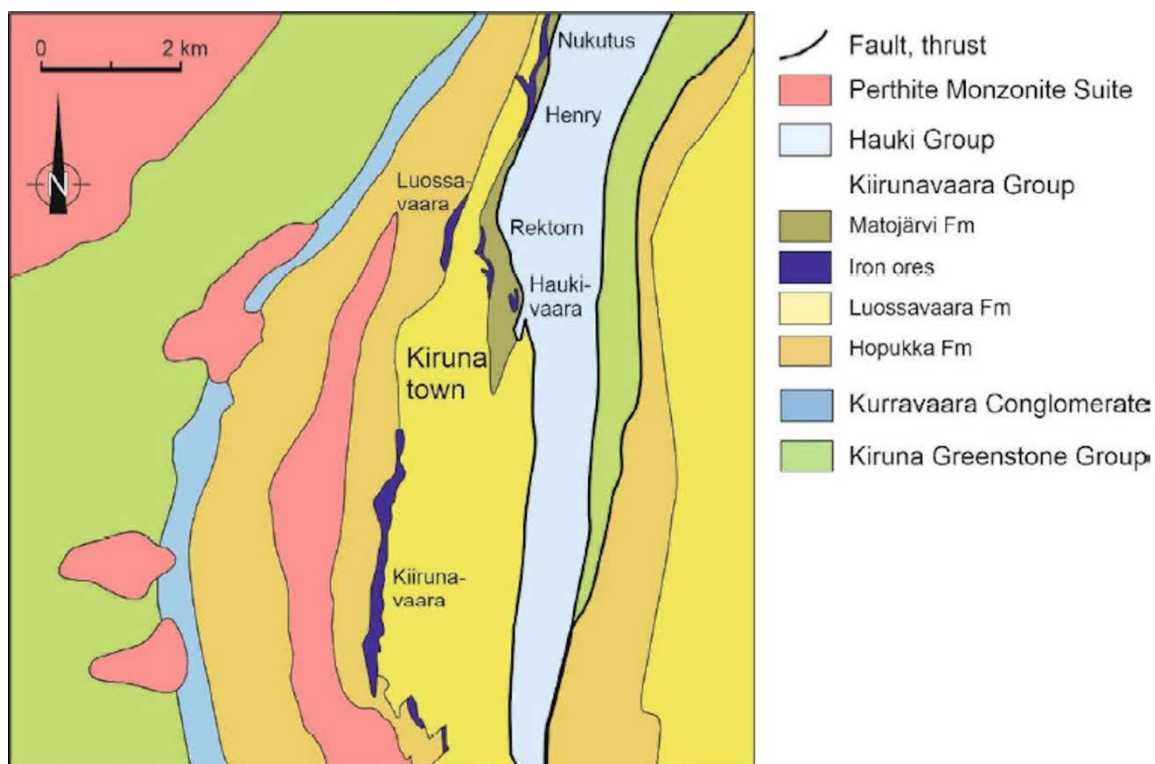


Figure 3. Simplified geological map of the Kiruna area (from Gilg & Andersson, 2024).

The Kiirunavaara stratigraphy is generally interpreted to occupy the western limb of an overturned, isoclinal fold (e.g., Wright, 1988; Andersson et al., 2021), resulting in an eastward-younging sequence. Lithologically, the stratigraphy shows an eastward transition from alkaline basaltic and andesitic volcanic rocks to more felsic, calc-alkaline dacitic and rhyolitic units (e.g., Martinsson et al., 2016). It is within this transitional volcanic environment that the massive Kiirunavaara iron oxide–apatite (IOA) deposit was emplaced.

2.2.1 The apatite iron ores

Discovered in the mid-17th century and commercially mined by Luossavaara–Kiirunavaara Aktiebolag (LKAB) since the late nineteenth century, the Kiirunavaara iron oxide–apatite (IOA) deposit is one of the largest and highest-grade deposits of its type in the world. The pre-mining total resource was estimated at approximately 2,000 Mt, with an average iron grade of 60–68 wt.% Fe (Bergman et al., 2001). The generally tabular but irregular orebody extends for about 5 km along strike, dips 60–70° to the east, and reaches depths exceeding 2 km (Niiranen, 2006; Andersson & Rutanen, 2016; Martinsson et al., 2016).

The ore is hosted within the Kiirunavaara Group, also referred to as the Porphyry Group, and occurs along the contact between trachyandesites of the Hopukka Formation in the footwall and rhyodacites of the Luossavaara Formation in the hanging wall (e.g., Geijer, 1960; Martinsson, 2004). Smaller magnetite–hematite IOA deposits, typically containing higher apatite contents, also occur along the contact between the Luossavaara and Matojärvi Formations (e.g., Paráková, 1975; Andersson et al., 2019).

The Kiirunavaara ore consists predominantly of titanium-poor, vanadium-rich magnetite accompanied by variable amounts of apatite. Vanadium enrichment, commonly reaching 0.1–0.3 wt.% V_2O_3 , represents a characteristic geochemical feature of the deposit (e.g., Loberg & Horndahl, 1983; Müller et al., 2003; Broughm et al., 2017) and is commonly interpreted as reflecting magmatic differentiation or high-temperature magmatic–hydrothermal processes (e.g., Troll et al., 2019; Reich et al., 2022).

Two principal ore types are recognized: the high-grade, low-phosphorus B-ore (typically <0.05 wt.% P) and the lower-grade, phosphorus-rich D-ore (0.8–5 wt.% P) (Niiranen, 2006; Gilg & Andersson, 2024). The B-ore is dominated by fine- to medium-grained, equigranular magnetite and is typically massive and relatively homogeneous, with only minor amounts of amphibole, mica, titanite, sulfides, sulfates, and late-stage calcite veinlets (e.g., Nordstrand, 2012). In contrast, the D-ore is characterized by abundant apatite (e.g., Aupers, 2014) and exhibits a more heterogeneous texture, commonly defined by intergrowths of magnetite and apatite. These intergrowths, together with locally developed banding and brecciation, reflect a more complex evolution and are commonly associated with evidence of hydrothermal overprinting (Harlov et al., 2002; Yan et al., 2023).

In addition to these end-member types, several textural varieties occur locally, including skeletal, dendritic, columnar, brecciated, and banded magnetite (Nyström & Henriquez, 1989, 1994; Harlov et al., 2002). Brecciation and vein-style mineralization, particularly along ore margins, further indicate a complex genetic history involving both magmatic and hydrothermal processes.

Ore–host rock contacts are generally sharp and magmatic. Alteration of the surrounding rocks is spatially zoned, with Na–Ca alteration developed proximal to the ore and K–Fe alteration occurring further outward. The sodic–calcic alteration assemblage is characterized by albite, actinolite, epidote, anhydrite, magnetite, and titanite (Paolillo & Giapis, 2021; Lupoli et al., 2022). Geochemically, the surrounding rock mass displays strong sodic–calcic alteration (e.g., Pihl, 2024; Andersson et al., 2024). In the southern part of the mine, both wall rocks and ore also exhibit localized clay alteration (Berglund & Andersson, 2013; Alexander & Andersson, 2024).

Geochronological constraints indicate an age of ore formation of 1874 ± 7 Ma, based on U–Pb zircon geochronology of ore-associated rocks (Westhues et al., 2016). Despite more than a century of study, the origin of the Kiirunavaara deposit remains debated, with current interpretations broadly divided between models involving direct emplacement

of Fe–P-rich magmatic melts (Nyström et al., 2008; Andersson, 2013; Troll et al., 2019) and those proposing precipitation of iron from hydrothermal fluids (Smith et al., 2013).

2.2.2 Footwall rocks

The footwall sequence at Kiirunavaara is between 300 and 1,400 m thick (Geijer, 1960; Gilg & Andersson, 2020) and has been interpreted as a succession of lava flows with subordinate subvolcanic intrusions (Geijer, 1910; Bergman et al., 2001; Martinsson, 2004). Stratigraphically, these rocks correspond to the lower portion of the Kiirunavaara Group, commonly referred to as the Hopukka Formation (Martinsson, 2004; Westhues et al., 2016). However, nomenclature varies in the literature, with some authors classifying these rocks as part of the Porphyry Group (Witschard, 1984; Bergman et al., 2001). In the mine they are commonly referred to as “syenite porphyries,” whereas the term *trachyandesite* is more frequently used in the scientific literature (e.g., Martinsson, 2004; Westhues et al., 2016).

The footwall rocks display a vertical transition from medium-grained syenites at depth to fine-grained syenite porphyries higher in the stratigraphy, interpreted as subvolcanic to volcanic equivalents of the rocks (Geijer, 1910). Their color varies from greenish-gray to red, and in proximity to the orebody they typically contain abundant feldspar phenocrysts 1–3 mm in size that are commonly tabular in shape. The groundmass is dominated by alkali feldspar with subordinate amphibole, magnetite, titanite, apatite, and other minor phases (Bergman et al., 2001; Martinsson, 2004; Sandberg, 2018).

Close to the orebody, mainly amphibole, magnetite, and titanite may occur as distinct nodules ranging from a few millimeters to approximately 1 dm in diameter (Geijer, 1910; Andersson, 2013; Palm, 2015). These nodules are interpreted to reflect localized magmatic or hydrothermal processes associated with ore formation. Irregular veins composed of the same mineral assemblage, commonly augmented by calcite, are also present in the footwall rocks.

Alteration of the footwall rocks is locally intense near the orebody, with epidote and chlorite occurring in areas of pervasive alteration. A distinctive alteration style, referred

to as “red-brick alteration” (Paolillo & Giapis, 2021), is characterized by intense reddening and pervasive hematite staining of the feldspars. Although poorly understood, it is thought to be related to hydrothermal fluid flow, possibly linked to early stages of mineralization (Andersson & Berglund, 2024). However, its precise origin and significance remain subjects of future study.

U–Pb zircon dating of the footwall rocks has yielded a $^{207}\text{Pb}/^{206}\text{Pb}$ weighted mean age of 1884 ± 4 Ma (Westhues et al., 2016), indicating emplacement during the main phase of Paleoproterozoic magmatism associated with IOA mineralization.

2.2.3 Hanging wall rocks

The hanging wall sequence at Kiirunavaara exceeds 800 meters in thickness (e.g., Geijer, 1960; Gilg & Andersson, 2024) and is interpreted as comprising felsic pyroclastic flows, specifically ignimbrites, deposited in a shallow marine to subaerial environment (Martinsson, 2004; Westhues et al., 2016). These volcanic units belong to the Luossavaara Formation of the Kiirunavaara Group, although terminology varies; some authors classify them within the broader Porphyry Group (Witschard, 1984; Bergman et al., 2001).

Within the mine, these rocks are traditionally referred to as “quartz porphyries” or “quartz-bearing porphyries,” designations first introduced by Geijer (1910; 1931). However, more recent studies describe them more precisely as rhyodacites (Martinsson, 2004). They typically exhibit red to gray coloration and a groundmass dominated by feldspar and quartz, with accessory phases including magnetite, amphibole, biotite, titanite, and apatite. Feldspar phenocrysts, ranging from 2 to 5 mm in size and typically equant and glomerocrystic are a distinctive feature (Sandberg, 2018; Pihl, 2024).

The contact between the hanging wall rhyodacites and the ore is variable and often complex. Ore enclaves are common within the rhyodacites (Geijer, 1968) and are suggested to indicate magma mingling or syn-emplacement mechanical interaction between the IOA mineralization and host volcanic rocks (Andersson, 2013). These relationships support a close temporal and genetic link between volcanic activity and ore formation.

Zircon is abundant in the hanging wall rhyodacites, providing precise geochronological control. U–Pb zircon ages of 1879.5 ± 7.1 Ma and 1880.5 ± 4.5 Ma indicate emplacement broadly contemporaneous with formation of the Kiirunavaara iron oxide–apatite deposit (Westhues et al., 2016).

2.2.4 The dike porphyries

Numerous dikes, originally described by Geijer (1910) as syenite porphyry dikes and more recently referred to as dike porphyries (Geijer, 1960; Pihl, 2024), occur throughout the Kiirunavaara area. These dikes generally strike east–west to ore-parallel and are concentrated in the central part of the mine. They range in size from narrow veins less than 1 dm wide to bodies exceeding 10 m in thickness (Pihl, 2024).

The dike porphyries exhibit a broad range of colors from green to red, reflecting variations in the relative abundance of clinopyroxene and amphibole in the groundmass and iron oxide staining of the fine-grained feldspar matrix (Pihl, 2024). Feldspar phenocrysts, commonly euhedral to anhedral and up to 1 cm in size, are typically abundant and frequently occur as glomerocrysts (Geijer, 1910).

Contact relationships are particularly significant in understanding their emplacement history. The dikes exhibit generally sharp but irregular contacts with the footwall rocks. Where they intersect the ore body, the contacts are commonly brecciated or display mingling textures, indicating syn- to post-ore intrusion and mechanical interaction between dike magma and the mineralized host rocks, like the ore-hanging wall relations (Andersson, 2013; Pihl, 2024). Notably, the dike porphyries have never been observed to crosscut the hanging wall rhyodacites. This spatial relationship, together with their mineralogical and textural similarities to the hanging wall units, has led to the interpretation that these dikes likely served as feeders for the overlying volcanic sequences, supported by the 1880 ± 4 Ma age determination (Pihl, 2024; Andersson et al., 2024).

These crosscutting and intrusive relationships provide key insights into the timing and evolution of the Kiirunavaara magmatic-hydrothermal system. The observation that the

dike porphyries intrude both the footwall and the ore body, but have not been observed to crosscut the hanging wall, suggests that emplacement of the ore, dike porphyries, and hanging wall rhyodacites were part of a temporally linked magmatic event. This supports models proposing that the formation of the Kiirunavaara iron oxide–apatite deposit, associated feeder dikes, and volcanic rocks of the hanging wall occurred during a single, prolonged magmatic phase, possibly associated with a volcanic caldera (Geijer & Ödman, 1974; Andersson 2013; Allen et al., 2024; Andersson, 2025).

2.2.5 Granophyre, diabase and composite dikes

The intrusive rocks at Kiirunavaara consists of two major intrusive components: (1) a granitic pluton located in the footwall of the mine, commonly referred to as the CA-granite (Cliff et al., 1990; Andersson et al., 2012), and (2) a suite of crosscutting dikes including granophyre, diabases, and composite dikes. These dikes represent the youngest intrusive phases at Kiirunavaara and cut all previously emplaced lithologies, including the iron oxide–apatite (IOA) ore body (Geijer, 1910; Öhman, 1986; Andersson & Berglund, 2024).

Granophyre dikes occur predominantly in the southern part of the Kiirunavaara mine area and are observed both at the surface and at depth, as well as in drill core, where they form a set of northwest-striking, steeply NE dipping intrusions. Many exhibit a characteristic granophyric texture, although this is not universally developed. The largest of these bodies, the so-called “Southern Granophyre”—described by Geijer (1910) as the “great dike”—extends for at least 2.4 km and attains widths of several tens of meters.

In the northern part of the mine, diabase dikes are prevalent and commonly occur together with granophyres in composite dikes or as apophyses of these dikes (Öhman, 1986). Two composite dikes have been identified in the northern part of Kiirunavaara: the Northern Composite Dike and the Southern Composite Dike (Andersson & Berglund, 2024). Despite its name, the Southern Composite Dike is also located within the northern sector of the orebody and is termed “Southern” only relative to the Northern Composite Dike.

In addition to the dike suite, a granitic pluton –the CA-granite– is exposed at depth (from level 775 and downwards) in the footwall of the mine (Andersson, 2009; Andersson & Berglund, 2024). It has been interpreted as a diapiric intrusion (Talbot & Koyi, 1995), though its full extent is still unknown. A similar granite body intrudes both the Kiruna Greenstone Group and the Kurravaara Conglomerate northwest of Kiruna (Westhues et al., 2016), suggesting a broader distribution of this intrusive phase. The CA-granite has been dated at 1874 ± 4 Ma and interpreted as related to the Perthite Monzonite Suite (Cliff et al., 1990; Westhues et al., 2016), further supporting the interpretation of a prolonged and complex magmatic history at Kiirunavaara.

Together, the granophyres, diabases, composite dikes, and the CA-granite represent the youngest intrusive phases recognized in the Kiirunavaara area. Their field relationships, whole-rock geochemistry, and geochronological constraints form the basis for evaluating the timing, petrogenesis, and tectonomagmatic setting of the late intrusive phases in relation to iron oxide–apatite mineralization and the structural evolution of the Kiruna mining district.

3. Materials and Methods

3.1 Sample Selection

A total of 35 samples were collected for petrographic analysis out of which 17 were selected for geochemical analysis: eight granophyres, five diabases, and four CA-granite samples (Table S1). Samples were obtained from several locations within the Kiirunavaara mine area as well as from the nearby Konsuln locality southeast of the deposit to represent the principal intrusive lithologies examined in this study. These include granophyres from the southern part of Kiirunavaara and the Konsuln area, samples from the Northern and Southern Composite Dikes, a diabase dike exposed in the Kiirunavaara open pit, and samples of the CA-granite.

Samples were selected to capture variations in depth and to include key lithological relationships, including contacts between granophyric interiors and diabase margins as well as contacts between intrusive rocks and surrounding wall rocks.

Two samples –one from the Southern Granophyre and one from the granophyric center of the Northern Composite Dike– were selected for U–Pb zircon geochronology.

3.2 Petrography

Petrographic analysis was conducted on samples from all six locations using transmitted and reflected polarized light microscopy (Table S2). A total of 35 thin sections were examined, 13 of which were newly prepared for this study. Two samples were previously examined by Lindgren (2013). Thin section analysis was carried out at LKAB in Kiruna, Stockholm University, and the Swedish Museum of Natural History (NRM). Mineral identification, textural relationships, and alteration features were documented during petrographic examination. Reflected light microscopy was used for the identification of opaque minerals. The petrographic observations were used to characterize the textural and mineralogical features of the felsic and mafic intrusive rocks at Kiirunavaara and their relationships at thin-section and outcrop scales.

3.3 Geochemistry

Whole-rock geochemical analyses were undertaken to characterize the composition of the intrusive rocks and to place the study samples within the context of regional geochemical datasets from LKAB and the Geological Survey of Sweden (SGU). Analytical work was conducted by ALS Scandinavia AB, where analytical accuracy and reproducibility are monitored using certified reference materials and duplicate analyses. Seventeen samples were analyzed in this study and are reported in Tables S3a and S3b.

To ensure complete digestion of refractory minerals, samples were subjected to lithium borate fusion followed by acid dissolution. Major elements were analyzed using inductively coupled plasma atomic emission spectroscopy (ICP-AES; ALS method ME-ICP06), and trace elements were measured using inductively coupled plasma mass spectrometry (ICP-MS; ALS method ME-MS81). Results are reported in wt% for major elements and ppm for trace elements. Typical detection limits are on the order of 0.01 wt% for major elements and <0.1 ppm for trace elements (ALS, 2023).

The analytical results from this study were compared with historical and current geochemical datasets from LKAB and the Geological Survey of Sweden (SGU). In addition to the 17 study samples analyzed here, the LKAB database contributed 120 granophyre, 231 diabase (including 5 from the hanging wall), and 94 CA-granite analyses produced using the same ALS analytical methods. Five additional recent drill-core analyses logged as diabase (DIA_ALP), available during this study, were included for comparison. Legacy LKAB analyses are designated KIR. Three additional datasets representing relatively unaltered (QP), sodically altered (QP_KN), and potassically altered (QP_K_KN) varieties of the quartz-bearing porphyry hanging wall rocks (felsic volcanic rocks) were extracted from the LKAB database for comparison. From the region, 28 samples of mafic intrusive rocks (gabbros-ultramafic rocks) mapped as belonging to the perthite-monzonite suite of rocks, interpreted as possibly related to the diabbases of this study, were selected from the database of the Geological Survey of Sweden for comparison. Reported analytical methods for this dataset are limited or unavailable.

Prior to interpretation, the compiled dataset was screened to minimize the influence of ore contamination and strong hydrothermal overprinting. Samples with $\text{Fe}_2\text{O}_3 > 10 \text{ wt}\%$ were excluded from the LKAB dataset, and mafic analyses with $\text{SiO}_2 < 35 \text{ wt}\%$ were removed. A further filter based on the Hughes (1972) Igneous Spectrum was applied to distinguish igneous compositions from strongly metasomatized rocks, particularly among the quartz porphyries (QP). QP analyses plotting outside the Igneous Spectrum were excluded from subsequent diagrams, whereas dike rocks and granites were retained unless otherwise stated. Additional selection criteria were applied to individual diagrams where appropriate, including thresholds on specific elements or element ratios (e.g., Ti, trace-element concentrations) to ensure valid application of classification schemes and to minimize the influence of analytical artifacts or non-representative compositions. Such criteria are applied on a diagram-by-diagram basis and are described where relevant.

Data processing, visualization, and geochemical classification were carried out using Microsoft Excel for Mac (Version 16.95.1) and ioGAS Version 8.2 (IMDEX).

3.4 Geochronology

Zircon U–Pb geochronology was conducted to constrain the timing of felsic magmatism associated with the granophyric intrusions at Kiirunavaara. Two samples were selected for analysis: one from near the surface of the Southern Granophyre (level 275), and the other from the granophyric center of the Northern Composite Dike (at level 1223). Data are reported in Table S4.

The mineral separation was performed at Stockholm University and the Swedish Museum of Natural History in Stockholm. Approximately 0.5 kg of crushed sample was milled to a rock powder using a swing mill. Heavy mineral separation was performed using a full-size Wilfley panning table, after which magnetic phases were removed using a hand magnet. Zircon was then handpicked under a binocular microscope, mounted on double-sided tape, embedded in 25 mm transparent epoxy pucks, and polished to expose

grain interiors. The mounts were first coated with a 5 nm gold layer for pre-analysis backscattered electron imaging to guide the location of analytical spots.

3.4.1 BSE and CL Imaging

Backscattered electron (BSE) and cathodoluminescence (CL) images were obtained using a FEI Quanta 400 scanning electron microscope (SEM) at the Swedish Museum of Natural History. Imaging was used to examine zircon grain morphology and internal structures and to assist in selecting analytical sites for U–Pb SIMS analysis. In several cases, CL images provided limited resolution of internal zircon zoning and were therefore used primarily for analytical targeting rather than for detailed interpretation of growth structures.

3.4.2 U–Pb SIMS Dating

In situ U–Pb zircon analyses were carried out using the Cameca ims1280 high-resolution ion microprobe at the NordSIMS facility at the Swedish Museum of Natural History. Analytical protocols followed Whitehouse et al. (1999) and Whitehouse & Kamber (2005). The zircon standard 91500 (1065 Ma; Wiedenbeck et al., 1995) was used for calibration.

Data reduction and common Pb correction were performed using in-house software developed by Martin Whitehouse at the Swedish Museum of Natural History. When measured ^{204}Pb counts exceeded background by more than three standard deviations, corrections were applied using the model Pb isotope composition of Stacey & Kramers (1975).

U–Pb data are presented using Tera–Wasserburg (inverse concordia) diagrams ($^{238}\text{U}/^{206}\text{Pb}$ vs. $^{207}\text{Pb}/^{206}\text{Pb}$) generated in Isoplot 3.0 (Ludwig, 2003). Concordia ages, weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ ages, and discordia regressions were calculated using Isoplot where appropriate. Reported uncertainties are given at the 2σ (95%) confidence level. Decay constants follow Steiger & Jäger (1977).

Analytical results are provided in Table S4.

4. Results

4.1 Field Observations

Field, underground, and drill-core observations in Kiirunavaara document a suite of late intrusive dikes that crosscut both the orebody and its volcanic host sequence. These include felsic granophyre dikes, mafic diabase dikes, and composite mafic–felsic dikes. In addition, the felsic granite pluton (CA-granite) occurring in the footwall is spatially associated with the dike systems, although direct contact relationships between the granite and the dikes have not been established. The observations summarized below define the spatial framework and geometric relationships that underpin the petrographic, geochemical, and geochronological results presented in subsequent sections.

The overall spatial distribution of the late intrusive rocks in Kiirunavaara is illustrated by a geological model of the mine area (Figure 4). The model provides a deposit-scale view of the relationships among the orebody, the hanging wall volcanic sequence, the footwall rocks, the CA-granite, and the late intrusive rocks examined in this study.

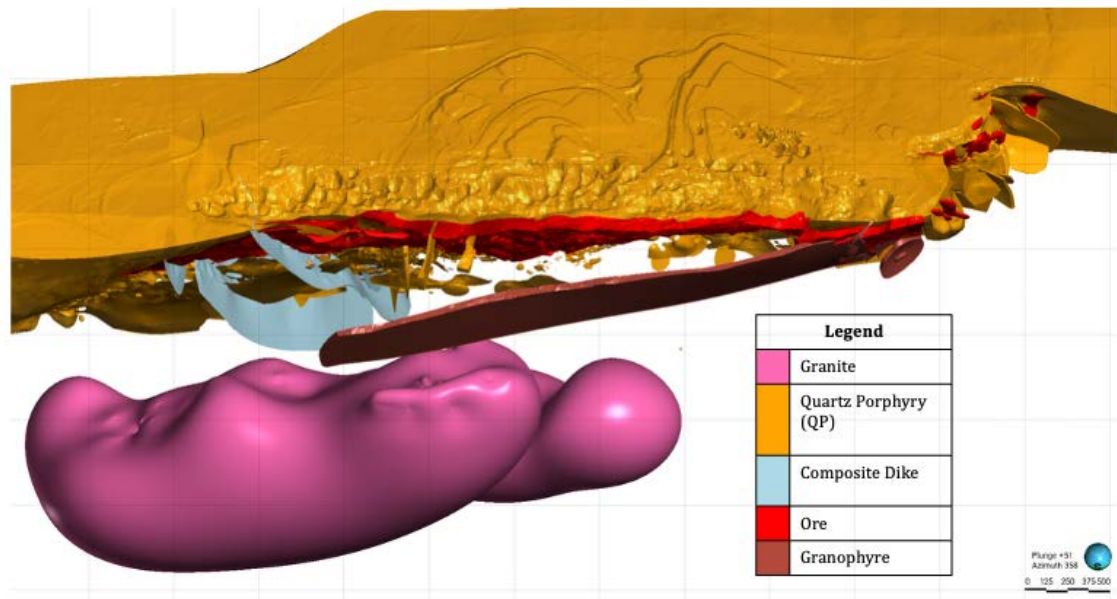


Figure 4. Geological model of the Kiirunavaara deposit showing the spatial relationships among the hanging wall volcanic sequence, the dike porphyries (same color as the QP), the orebody, the CA-granite, and the granophyre, and composite dikes. Footwall rocks have been removed for clarity. The view is shown as an elevation cut; modeled units are indicated in the legend (model courtesy of H. Ergili Aydin, LKAB).

The distribution of granophyric dikes in the southern sector of Kiirunavaara is shown in a historical geological map of the open pit (Figure 5). The map is a horizontal section at approximately 130 m below the top of the mountain and shows relationships between the hanging wall, orebody, and footwall. Granophyric dikes form a set of northwest-striking, steeply northeast-dipping intrusions that crosscut both the orebody and its volcanic host rocks. Individual dikes range from decimeter-scale veins to bodies up to ~20 m wide.

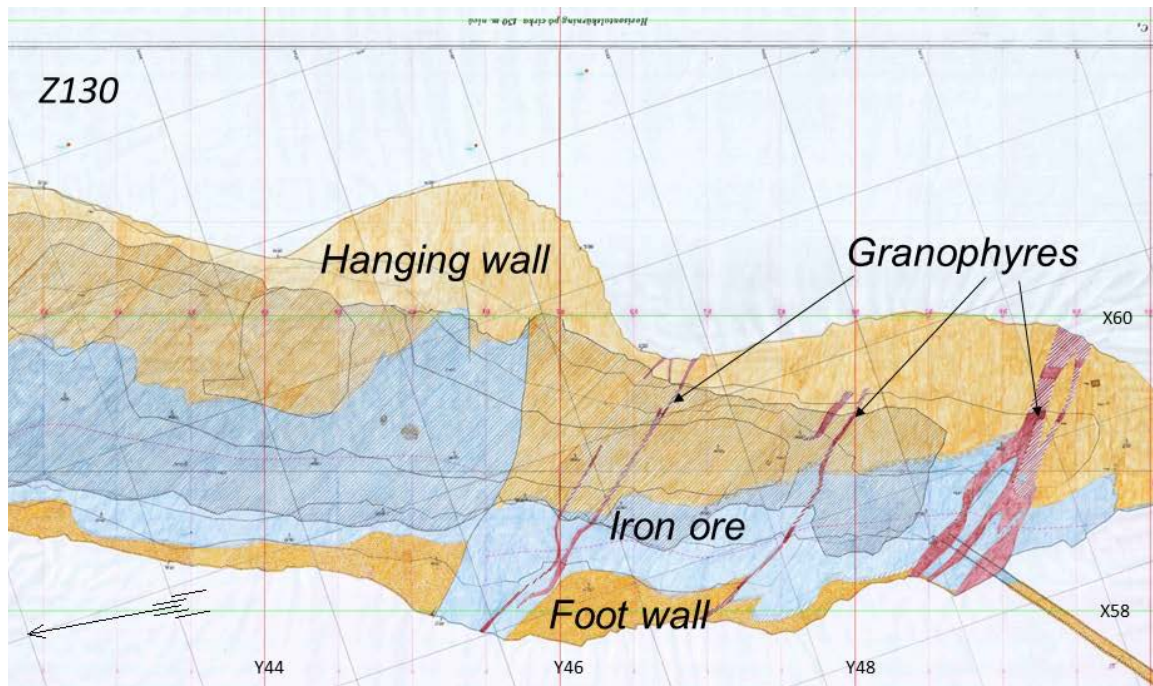


Figure 5. Geological map of the southernmost part of the Kiirunavaara; horizontal section at level 130 m (below the top of the mountain), produced ~100 years ago. Red and green gridlines are spaced at 200 m. Modified from Andersson & Berglund (2024).

Exposures in the original open pit preserve these relationships at outcrop scale (Figure 6). In the pit wall, granophyre dikes cut footwall rocks and project toward the ore zone, now largely removed by mining. The dikes form light-colored bodies against darker host rocks and can be traced across major lithologic boundaries. They display normally sharp contact relationships against both ore and host rocks, although locally unsharp contacts do occur. In outcrop, the dikes commonly contain quartz and feldspar phenocrysts set in a finer felsic matrix. Chilled margins are observed.



Figure 6. Exposure in the southern wall of the Kiirunavaara open pit, viewed toward the west, showing granophyre dikes cutting footwall rocks and projecting toward the ore zone (in front, mined out). The largest individual dikes are approximately 10–20 m wide. Photo: Ulf B. Andersson.

In contrast to the southern granophyre dike set, the intrusive rocks in the northern part of the Kiirunavaara orebody include both diabase dikes and composite mafic–felsic dikes. Two principal composite dikes are recognized: the Northern Composite Dike and the Southern Composite Dike. These dikes are typically 2–15 m wide and strike west–northwest, dipping approximately 60–70° to the south–southwest. The Northern Composite Dike is exposed underground and displays a relatively regular internal architecture, with diabase margins enclosing a central granophyre core typically a few meters wide (Figure 7). The southern composite dike also is exposed underground from level 441 and downwards, but without mapped granophyre for the first c. 100 m. Further,

it is associated with smaller apophyses of diabase, as well as significant deformation along particularly its southern contact (Andersson & Berglund, 2024) and has proven to be a negative factor for mine stability (e.g., Mawson et al., 2022; Ylmefors, 2023).

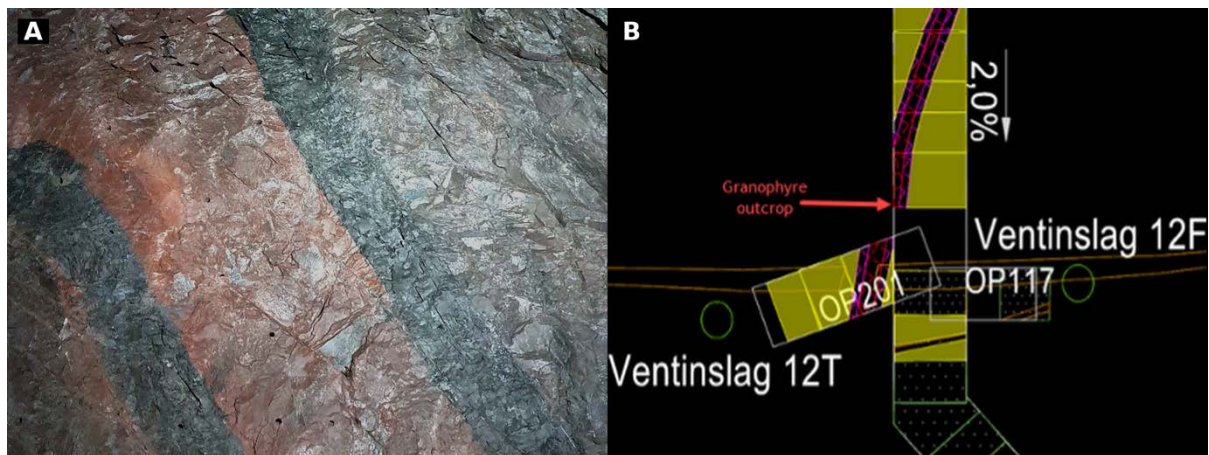


Figure 7. A. Northern Composite Dike exposed underground at Kiirunavaara, showing diabase margins flanking a granophyre core (~2 m wide) and sharp internal contacts between mafic and felsic components. Access drift, block 12/1223. Photo: Ulf B. Andersson. B. Map of composite dike in footwall (yellow) at 12/1223. Site of geochronology sample.

Observations from the Composite Dikes show felsic–mafic relationships at the hand-sample scale (Figure 8). Granophyre encloses darker, fine-grained diabase domains that occur as rounded to irregular enclaves. These enclaves lack internal brecciation and in some cases are bounded by thin biotite or amphibole rims. Contacts between the enclaves and granophyre appear sharp at outcrop scale but are planar to slightly lobate at hand-sample and drill-core scale.

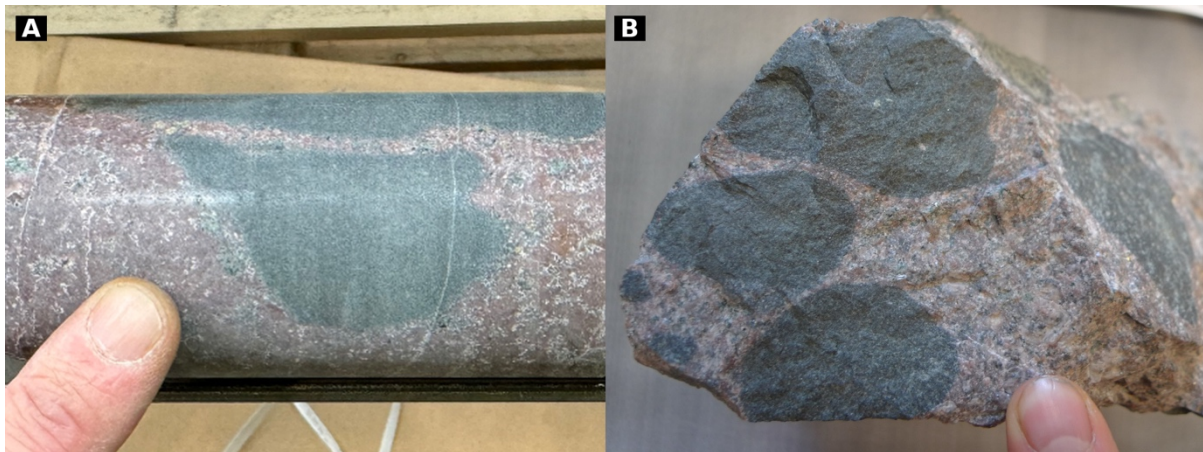


Figure 8. A. Diabase enclaves in granophyre from the Northern Composite Dike. Drill core BRK24037. Photo: C.F. Shaw. B. Enclaves in granophyre of the Southern Composite Dike. From Y1650, level 849. Photo: Ulf B. Andersson.

Diabase dikes also occur separately from the composite bodies in several parts of the deposit and range in size from ~1 dm to several meters, including one c. 7 m wide dike in the hanging wall of the open pit (Figure 9). It has not been possible to relate these scattered occurrences to the composite dikes; however, they share similar dark green to black color and mafic mineralogy with the composite dike margins.



Figure 9. Circa 7 m wide diabase dike in the subsiding hanging wall of Kiirunavaara, photographed from Förvaltningskontoret (FK). This dike has not been observed crosscutting the ore or foot wall rocks in the mine but is included in this study (sample Db Dbr1 and 2). Photo: Tomas Villegas.

The spatial distribution and internal characteristics of the late intrusive rocks at Kiirunavaara are summarized above. Granophyre dikes occur primarily in the southern part of the deposit, whereas composite mafic–felsic dikes and diabase dikes are recognized in the northern sector. These intrusions consistently crosscut the orebody

and its volcanic host sequence, establishing a field-based lower age limit on volcanism and ore emplacement. The CA-granite pluton, occurring at depth in the footwall below the dike occurrences is partly even-grained and partly weakly porphyritic and contains mafic enclaves (Andersson, 2009; Andersson et al., 2012). Together, these relationships provide the framework for the petrographic descriptions (Section 4.2), whole-rock geochemistry (Section 4.3), and U–Pb zircon geochronology (Section 4.4) presented below.

4.2 Petrography

Thin-section petrography documents systematic textural and mineralogical variation among the CA-granite, granophyres, diabases, and composite dikes. Observations emphasize grain size, the style and abundance of quartz–feldspar intergrowths, the abundance of opaque and other minerals, and the distribution of alteration features. To maintain consistency with field relationships and sample context, petrographic descriptions are organized by location and lithology (Table S1): CA-granite (location 4); granophyres from southern Kiirunavaara (locations 1a, near-surface, and 1b, deeper levels); granophyres from the Konsuln area (location 1c); diabases, including discrete dikes (location 3) and the mafic components of composite dikes (locations 2a1 and 2b1); and the felsic components of composite dikes (locations 2a2 and 2b2).

4.2.1 CA-Granite (Location Code 4)

The CA-granite (Location Code 4) forms a felsic pluton exposed in a large volume of the footwall (the central facility area/centrala anläggningarna) and intersected in drill core. In thin section, the rock is generally medium-grained, although it is sometimes phenocrystic (cf. Andersson et al., 2012; Lindgren, 2014), with some larger feldspar and subordinate quartz grains, and is composed predominantly of quartz and feldspar (Figure 10). Feldspar occurs as subhedral to anhedral grains forming the main framework of the rock. Quartz is present as anhedral grains, commonly interstitial between feldspar crystals but also as larger discrete grains. Quartz–feldspar grain boundaries are irregular and do not form micrographic or granophyric intergrowths. Strong undulose extinction

is common in quartz. Mafic minerals are minor and occur as scattered grains and small aggregates within the felsic matrix.

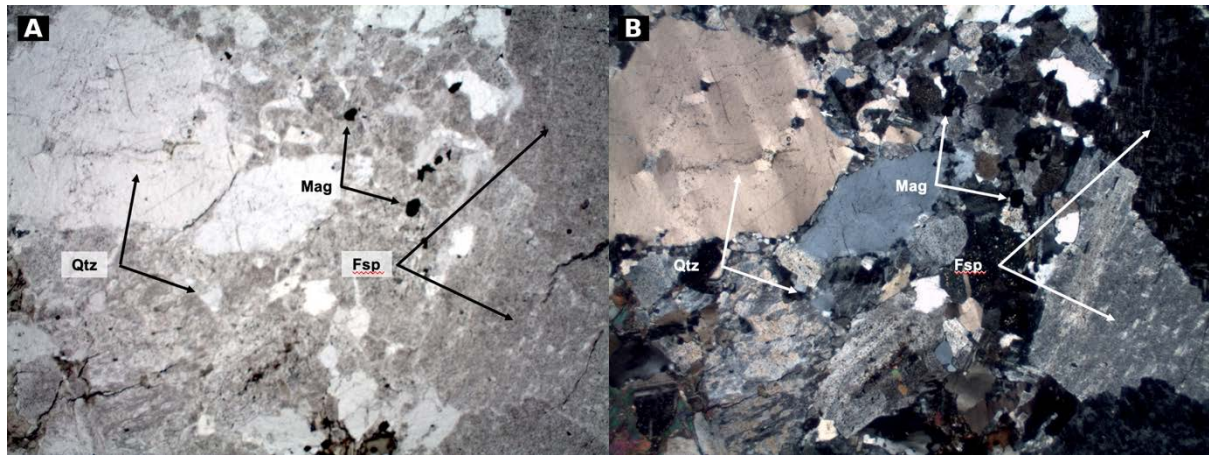


Figure 10. CA-granite (sample CA1110) showing a feldspar-dominated framework with interstitial to discrete anhedral quartz and irregular quartz–feldspar grain boundaries. (A) PPL; (B) XPL. Approximate image widths: 2.8 mm.

4.2.2 Granophyres in southern Kiirunavaara (Location Codes 1a–1b)

Granophyres from the southern part of Kiirunavaara constitute the most abundant felsic intrusive rocks examined in this study. For descriptive purposes, they are subdivided into two informal groups (1a and 1b) based on relative depth within the mine. In thin section, both groups are dominated by quartz and feldspar and are characterized by granophyric intergrowth textures that define the overall fabric, although the degree of development varies between the two groups.

Granophyres classified as 1a, corresponding to shallower levels, display the most well-developed granophyric textures observed in this study (Figure 11). Quartz–feldspar intergrowths are pervasive and fabric-defining, forming fine-grained groundmass domains with radiating to plumose patterns. Under crossed polars, intergrowths commonly extend from quartz-rich centers into branching networks of quartz and

feldspar. In the illustrated sample, individual intergrowth domains are generally fine-grained and commonly up to about 0.5 mm across. Magnetite is sparse and fine-grained, and minor biotite is present. Alteration is limited.

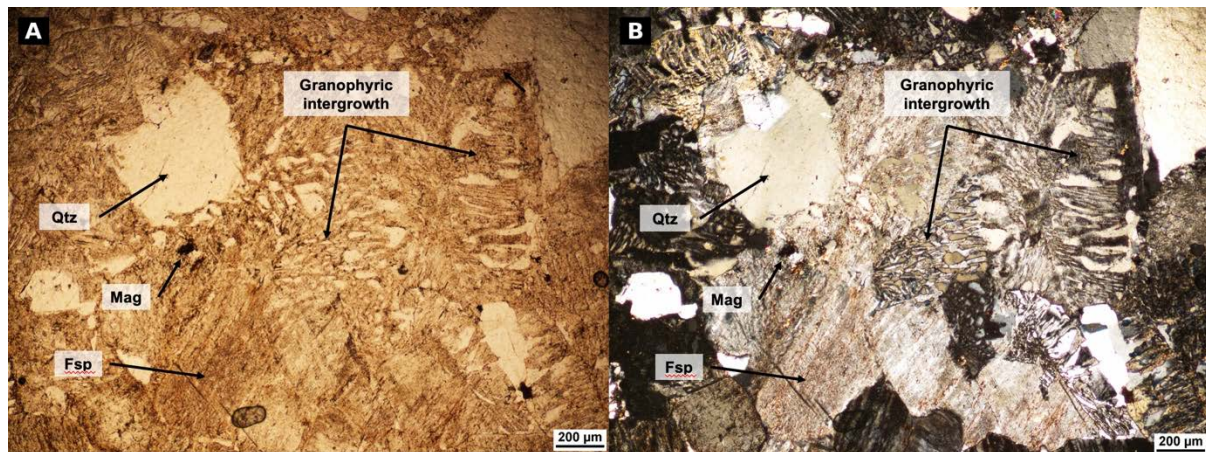


Figure 11. 1a granophyre (sample Kii F) showing well-developed radiating to plumose granophyric intergrowths around quartz-rich centers. (A) PPL; (B) XPL.

In contrast, granophyres classified as 1b, sampled at deeper levels in the south and considered to be part of the same dike system, show less pervasive and more heterogeneously distributed granophyric intergrowths (Figure 12). Intergrowths occur in broader, more equant and polygonal domains and are less commonly organized into radiating patterns. A greater proportion of discrete quartz and feldspar grains occurs between intergrowth domains, and the felsic groundmass appears more even-grained than in 1a samples. Magnetite is more abundant than in 1a and occurs as disseminated grains and aggregates. Altered phenocrysts are prominent and contain sericite or chlorite.

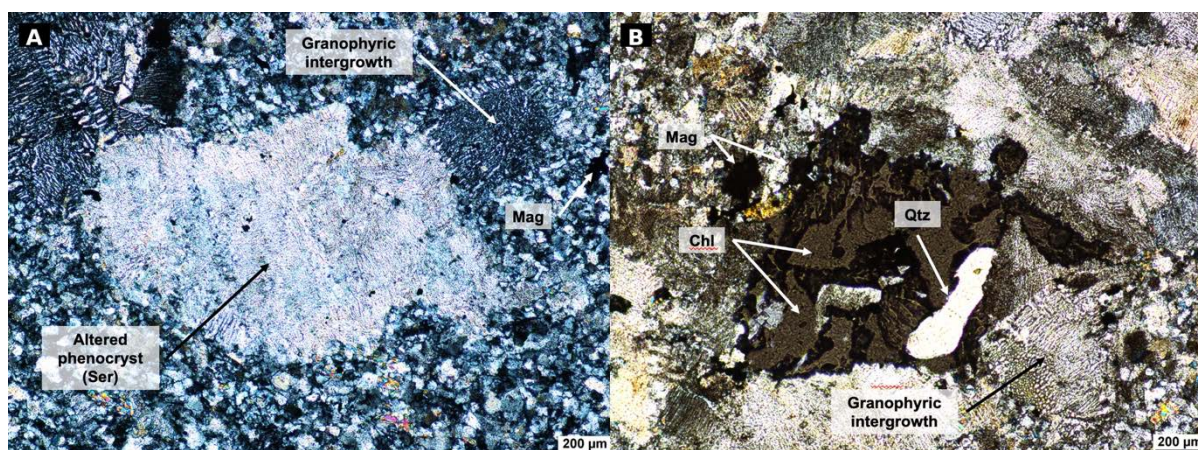


Figure 12. 1b granophyre (sample Kir 23001) showing textural variation and alteration. (A) XPL, with a sericite-altered phenocryst and granophyric intergrowths. (B) XPL, from a different area of the same sample, with a chlorite-altered phenocryst, quartz, magnetite, and coarser polygonal granophyric intergrowths.

The transition between 1a and 1b granophyres is gradational rather than sharply defined, and both groups share a consistent felsic mineral assemblage. The subdivision therefore reflects textural variation rather than mineralogical differences.

4.2.3 Konsuln Granophyres (Location Code 1c)

Granophyres from the Konsuln area (location code 1c) display textures that differ from the other southern granophyres (1a–1b), although they share a felsic mineral assemblage dominated by quartz and feldspar. In thin section, the rock is composed of a very fine-grained felsic groundmass in which granophyric textures are weakly developed or restricted to small, irregular domains, although locally larger granophyric intergrowths occur around quartz-rich centers (Figure 13). Quartz and feldspar otherwise form a fine-grained, equigranular mosaic rather than the pervasive radiating or plumose intergrowth domains characteristic of 1a. Magnetite is more abundant than in 1a–1b and occurs as finely disseminated grains and small interstitial clusters. Minor biotite and chlorite are present, and thin late-stage veinlets locally crosscut the rock.

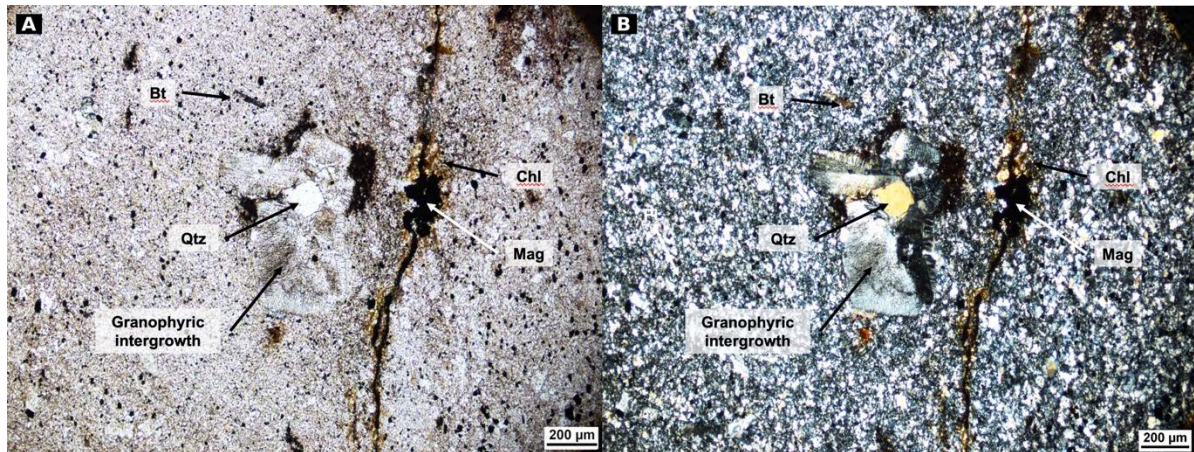


Figure 13. 1c granophyre (sample BPK23011.1) from the Konsuln area, showing locally developed granophyric intergrowths within a very fine-grained felsic groundmass. (A) PPL; (B) XPL.

4.2.4 Diabases (Location Codes 2a1, 2b1 and 3)

Diabases associated with the late intrusive suite at Kiirunavaara occur both as discrete mafic dikes (location code 3) and as the mafic components of the Southern and Northern Composite Dikes (location codes 2a1 and 2b1, respectively). In thin section, the rocks are dominated by plagioclase and clinopyroxene, with abundant magnetite and variable chlorite alteration (Figure 14).

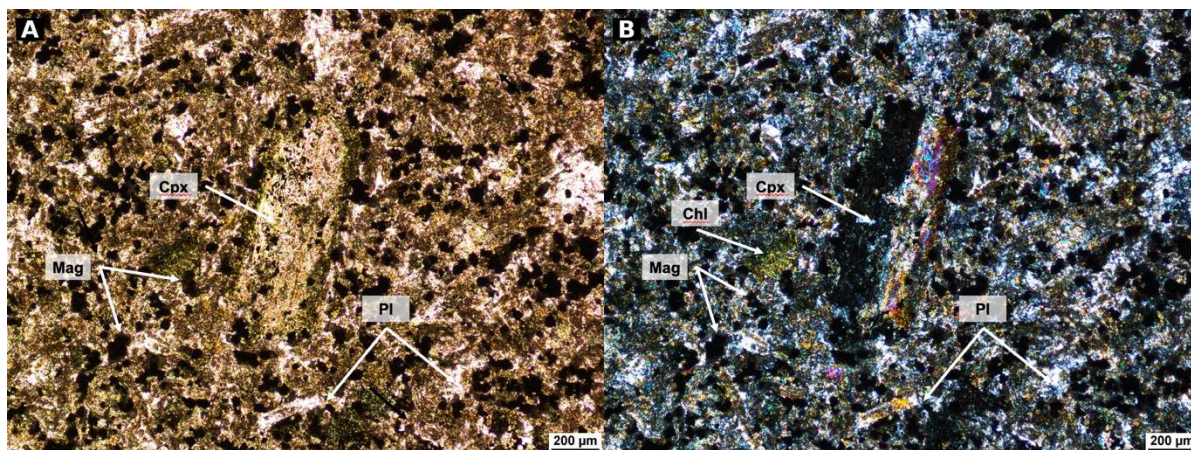


Figure 14. 2b1 diabase (sample 100/792 Db) from the Northern Composite Dike, showing ophitic to sub-ophitic texture and alteration of primary clinopyroxene to chlorite. Abundant magnetite is disseminated throughout the rock. (A) PPL; (B) XPL.

Plagioclase occurs predominantly as elongated to irregular subhedral crystals that define ophitic to sub-ophitic textures. Mafic minerals consist primarily of clinopyroxene, which is variably preserved but commonly altered to amphibole and chlorite. Primary pyroxene grain shapes are locally obscured by alteration, although original crystal outlines remain recognizable. Minor biotite is also locally present.

Opaque minerals, dominantly magnetite, are abundant and occur as disseminated grains and interstitial clusters between plagioclase crystals. Accessory phases include apatite and titanite, and secondary minerals such as chlorite, amphibole, and epidote reflect alteration of primary mafic phases. Overall, the diabases are texturally similar across the different occurrences, including the open pit samples, and together define a clear mafic end-member for comparison with the associated granophyres.

4.2.5 Composite dikes (Location Codes 2a1, 2a2, 2b1 and 2b2)

The composite dikes described here are the Northern Composite Dike (location codes 2b1 and 2b2) and the Southern Composite Dike (location codes 2a1 and 2a2), both located in the northern part of Kiirunavaara. These consist of associated felsic granophyre and mafic diabase within single intrusive bodies. In thin section, felsic domains are composed

predominantly of quartz and feldspar and locally display micrographic to granophyric intergrowths. Mafic and felsic components occur in direct contact and remain texturally distinct, with sharp boundaries between the two domains (Figure 15).

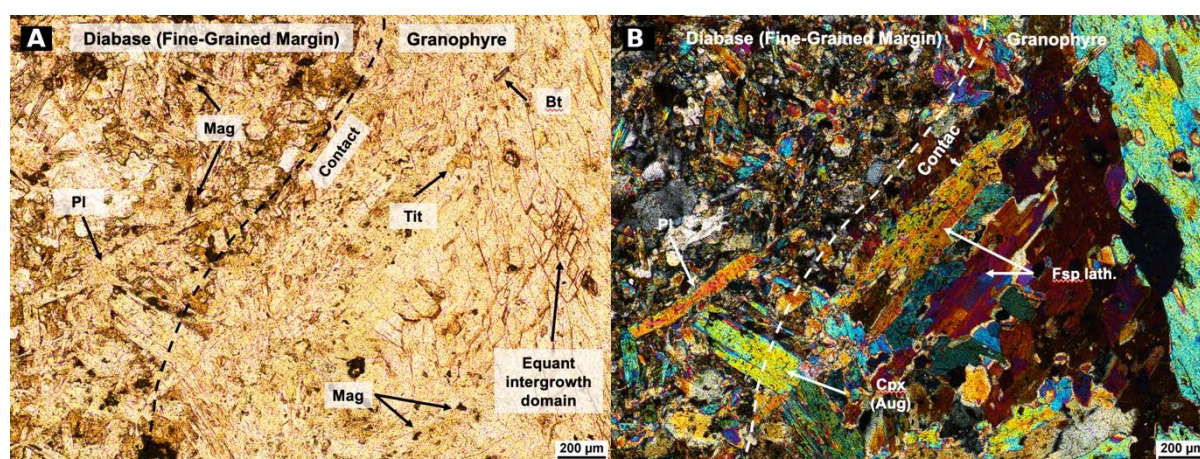


Figure 15. 2b1+2 diabase–granophyre contact (sample 108/935 Kon) from the Northern Composite Dike, showing a sharp contact between felsic (granophyre) and mafic (diabase) domains. The two components remain texturally distinct, with no gradation across the boundary. (A) PPL; (B) XPL.

Quartz–feldspar intergrowths are confined to the felsic domains, where they form coherent granophyric textures where developed. In contrast, adjacent mafic domains consist predominantly of elongated to irregular plagioclase crystals and mafic minerals arranged in ophitic to sub-ophitic textures. Clinopyroxene is variably altered to amphibole and chlorite but retains recognizable primary crystal shapes.

Contacts between felsic and mafic domains are sharp at the thin-section scale and range from planar to slightly irregular. No continuous mineralogical or textural gradation is observed across these boundaries. Quartz–feldspar intergrowths terminate abruptly against mafic domains, and mafic plagioclase crystals do not extend into the felsic portions. In some sections, small mafic enclaves occur within felsic material, preserving rounded to irregular margins at the scale observed. Grain size commonly decreases

toward these contacts, and locally developed fine-grained margins are observed along the boundaries between felsic and mafic domains.

Opaque minerals are locally concentrated near felsic–mafic contacts, occurring as disseminated grains and small clusters within both domains. Despite their close spatial association, felsic and mafic domains retain distinct internal fabrics and mineral assemblages.

4.3 Geochemistry

Whole-rock geochemical data define the compositional range of the intrusive rocks at Kiirunavaara and document their distribution in commonly used classification and alteration-screening diagrams. The dataset includes both analyses from this study and supplementary current and legacy data from the LKAB and SGU databases, encompassing granophyres, diabases, and granites, with quartz-bearing porphyries of the hanging wall included for comparison. The color and symbol scheme used to distinguish lithological groups and data sources is shown in Figure 16 and is retained in the subsequent geochemical diagrams, although the populations shown vary following the geochemical screening described below.

In total alkali-silica (TAS) space, the intrusive rocks define two dominant compositional groupings (Figure 16). Granophyres (GRP) and granites (GRA) form felsic clusters concentrated mainly in the trachydacite-rhyolite part of the diagram, whereas diabases (DIA) and related mafic intrusions are distributed largely across the basalt to basaltic trachyandesite fields. Few analyses occupy intermediate compositions, and felsic and mafic groups remain compositionally distinct. Many analyses display dispersion toward alkali-enriched fields, with some extending into more alkaline compositions. This spread is most pronounced among the mafic rocks, the quartz porphyries (QP), and in parts of the legacy datasets.

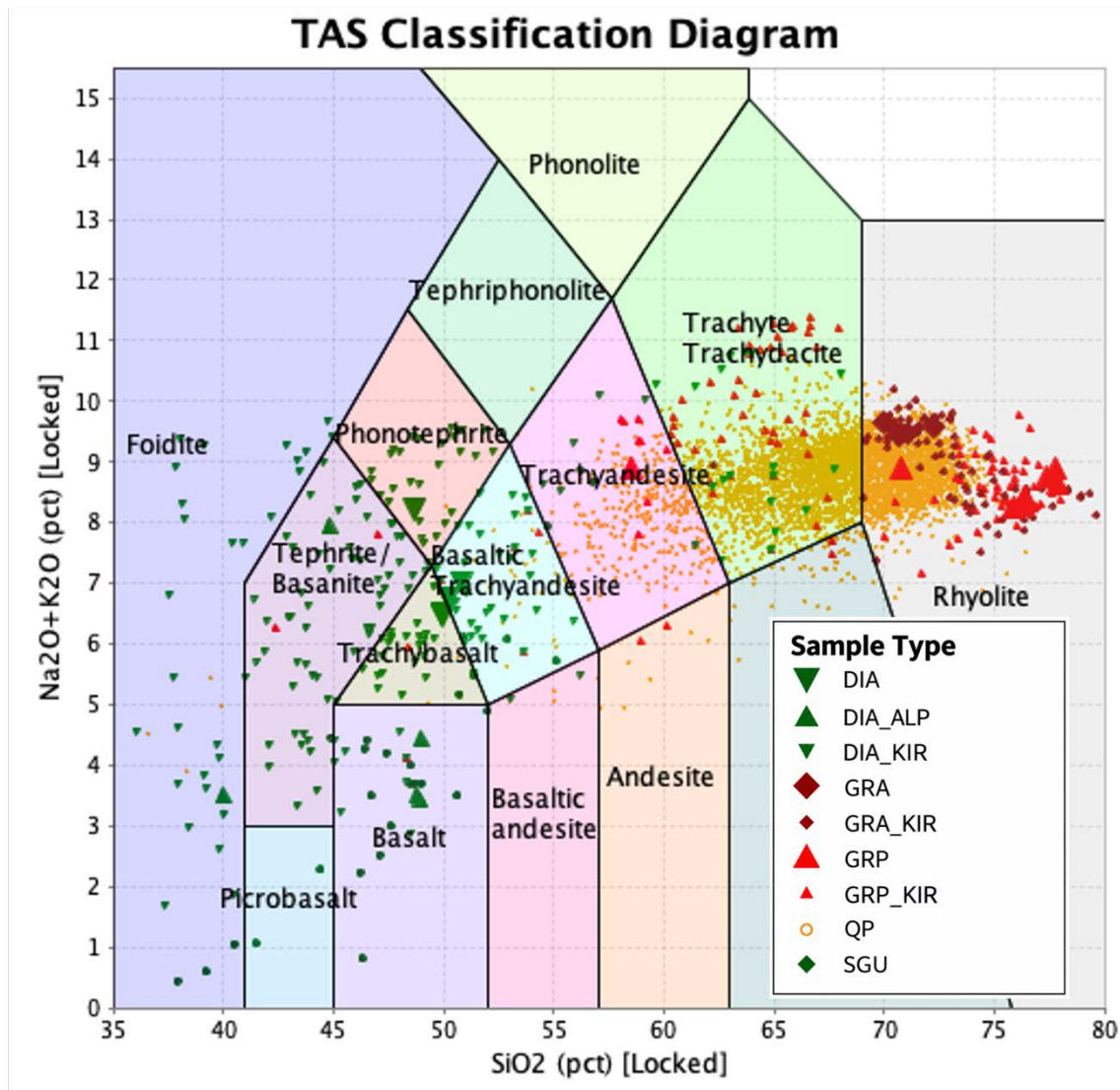


Figure 16. Total alkali-silica (TAS) classification diagram showing the distribution of analyzed intrusive lithologies from Kiirunavaara. Legend abbreviations denote lithology and data source: DIA = diabase, GRA = granite, GRP = granophyre, and QP = quartz porphyry; ALP denotes recent drill-core analyses available during the present study; KIR denotes legacy LKAB database analyses; and SGU denotes analyses from the Geological Survey of Sweden database. The same color and symbol conventions are retained in subsequent geochemical figures, although the populations shown vary following geochemical screening. Field boundaries after Le Maitre et al. (1989).

Many analyses display dispersion toward alkali-enriched fields, with some extending into more alkaline compositions. This spread is most pronounced among the mafic rocks, the quartz porphyries (QP), and in parts of the legacy datasets.

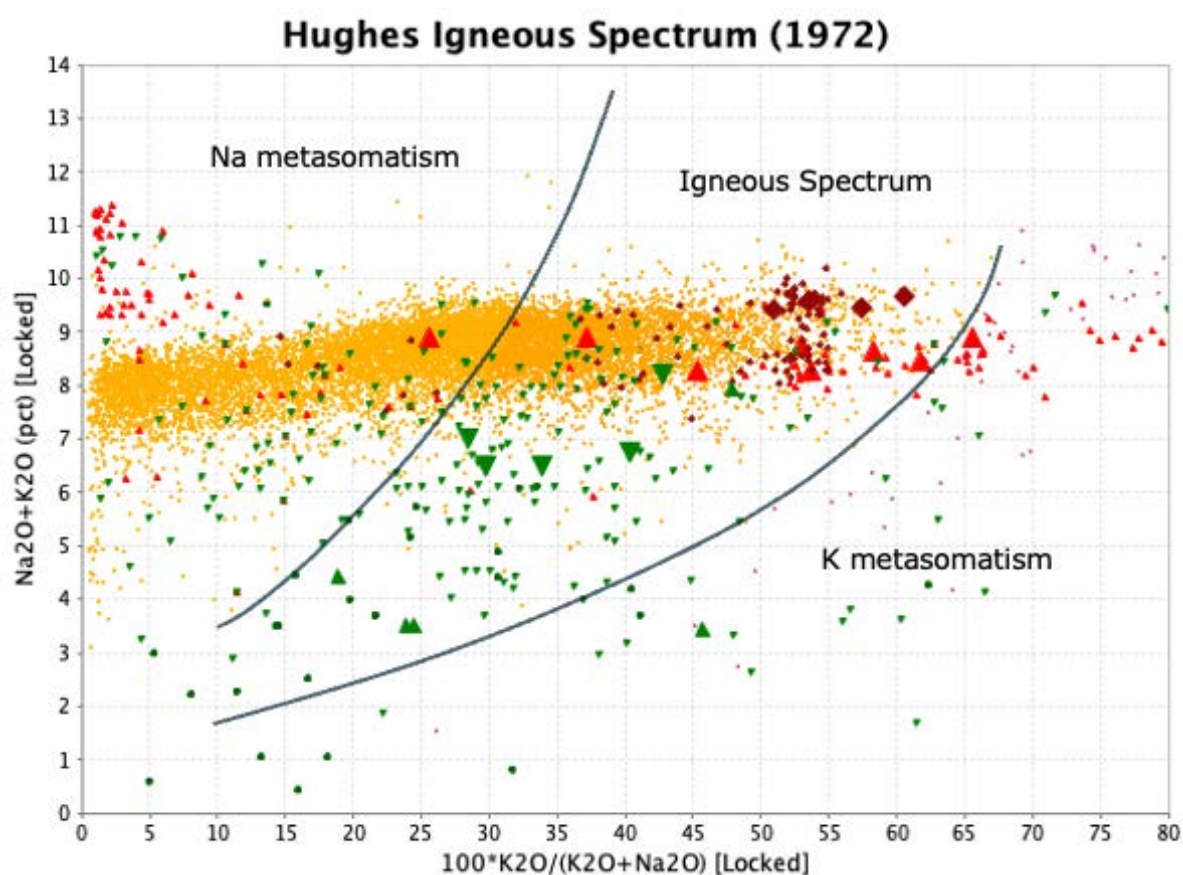


Figure 17. Igneous spectrum diagram after Hughes (1972) showing the distribution of alteration characteristics of analyzed lithologies from Kiirunavaara. QP analyses plotting outside the Igneous Spectrum were excluded from subsequent diagrams intended to emphasize primary compositional relationships. Color and symbol conventions as in Figure 16.

Major-element molar-ratio relationships were examined using an IOCG-style alteration diagram after Montreuil et al. (2013) (Figure 18). The data show a strong concentration of samples within and adjacent to the sodic and weakly altered fields, with additional populations extending into K-altered and Ca-Fe-altered fields. Mafic intrusions display a

broader spread toward Ca-Fe compositions, whereas felsic rocks are more tightly clustered. Most samples from this study plot within or near the weakly altered fields.

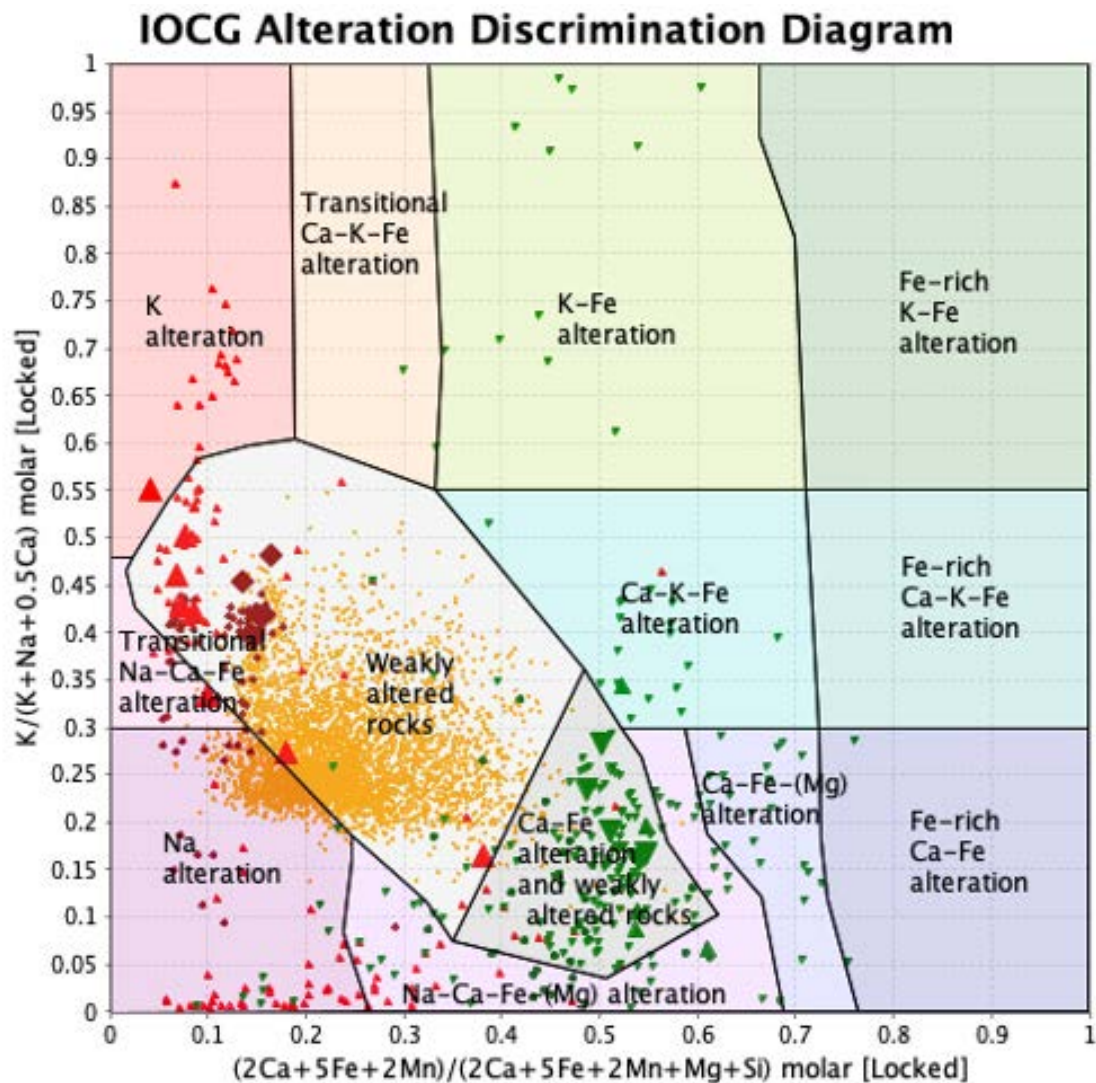


Figure 18. IOCG-style major-element molar-ratio alteration diagram after Montreuil et al. (2013), showing the distribution of felsic and mafic intrusive rocks from Kiirunavaara across sodic, potassic, and Ca-Fe alteration fields. QP analyses plotting outside the Igneous Spectrum of Figure 17 are excluded. Color and symbol conventions as in Figure 16.

Trace-element relationships were examined using relatively immobile element ratios in the Nb/Y versus Zr/Ti diagram of Pearce (1996) to reduce the effects of metasomatism

on classification (Figure 19). Felsic intrusive rocks plot mainly in rhyolitic-dacitic compositional fields near the subalkaline-alkaline boundary, with the granophyres predominantly in the alkali-rhyolite field. Mafic intrusions plot mainly in the basaltic field. Few rocks plot in the intermediate field; thus, compared to the major-element classification, this diagram shows a more distinct separation between felsic and mafic intrusive rocks. The few rocks falling in the intermediate field may reflect misidentification during logging, for example where intermediate footwall lithologies were included (cf. Pihl, 2024), or mixed-rock compositions. One sample among the presently studied granophyres was later recognized as a mislabeled footwall rock (plotting intermediate in the diagrams). Analyses with $Zr/Ti > 0.02$ were excluded from this diagram because such evolved compositions fall outside the range for which this modified classification is most appropriately applied.

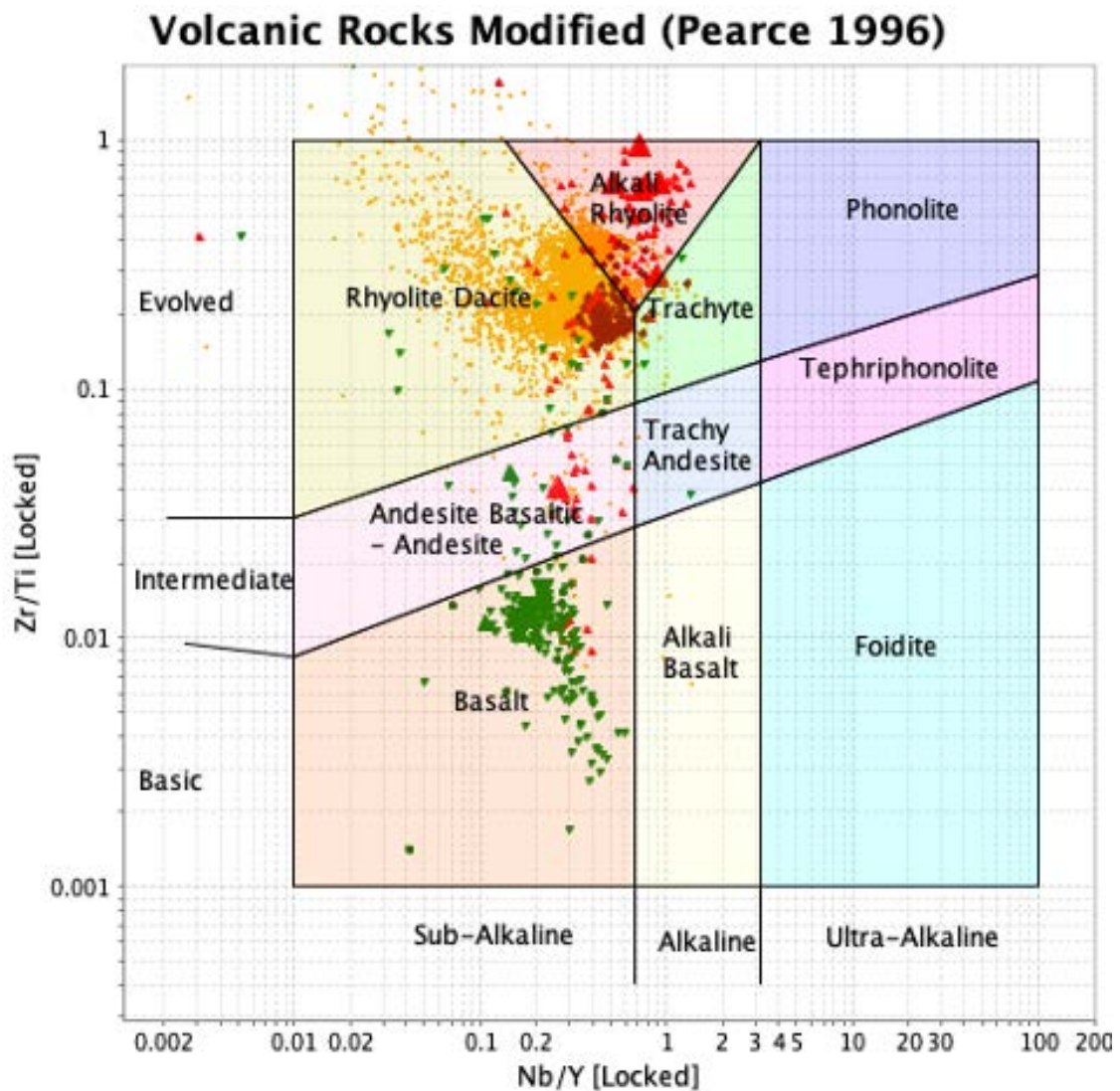


Figure 19. Analyses with $Zr/Ti > 0.02$ are excluded from subsequent tectonic discrimination diagrams to ensure that only basaltic compositions are used, following the screening recommendation of Pearce (1996) for subalkaline rocks. Symbols as in Fig. 16.

The geochemical data define distinct felsic and mafic compositional groupings and document variability in composition across the intrusive suite. These relationships, together with comparison to the felsic volcanic rocks of the hanging wall, provide a framework for evaluating magmatic processes within the system. In the following

section, U–Pb zircon geochronology is used to constrain the age of selected intrusive units.

4.4 Geochronology

U–Pb zircon geochronology constrains the timing of felsic magmatism associated with the late intrusive systems at Kiirunavaara. Two granophyre samples were selected for analysis. Sample 12-1223-1 was collected from the granophyre-dominated core of the Northern Composite Dike (see Figure 7), whereas sample Z275-Y454 represents a granophyre from the southern dike set sampled underground at level 275 (Figure 20). Together, these samples provide age constraints on felsic intrusion in the northern and southern parts of Kiirunavaara. Analytical methods, data reduction procedures, and criteria for excluding discordant or common Pb-affected analyses are described in Section 3.4, and the analytical data are reported in Table S4.



Figure 20. Sample site for geochronology sample Z275-Y454. Blue indicates iron ore, pink granophyric dikes, and yellowish tones footwall trachyandesites. The sample was collected from the projected continuation of a granophyric dike beyond the mapped tunnel. Map modified after Andersson and Berglund (2024).

4.4.1 Sample 12-1223-1 – Northern Composite Dike (granophyre core)

Zircon grains from sample 12-1223-1 are predominantly euhedral to subhedral and range from elongate prismatic crystals to more equant forms. Back-scattered electron (BSE) imaging was used to document internal textures and guide placement of analytical spots. The zircon displays oscillatory zoning, consistent with magmatic growth (Figure 21). Zoning patterns are generally regular, and inclusions are sparse. Analytical spot locations and corresponding $^{207}\text{Pb}/^{206}\text{Pb}$ ages are shown in Figure 21.

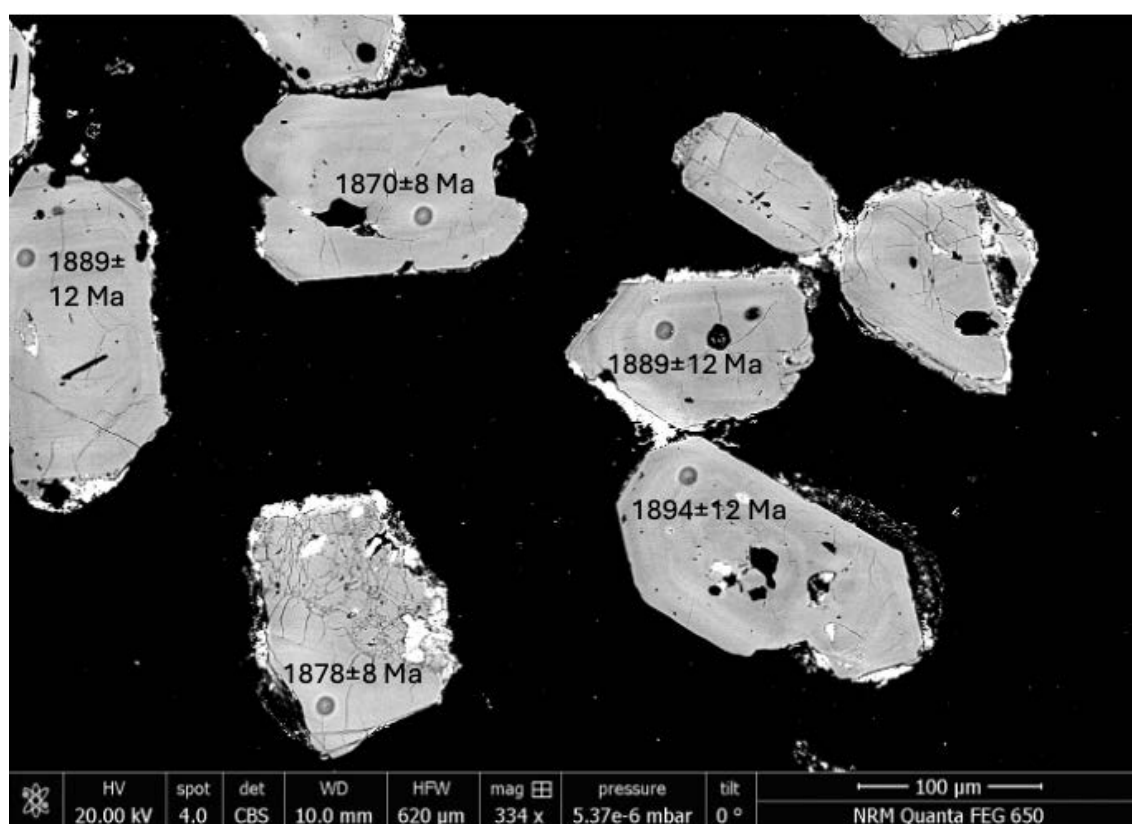


Figure 21. Back-scattered electron (BSE) image of representative zircon grains from sample 12-1223-1 showing oscillatory internal zoning. Analytical spot locations and corresponding $^{207}\text{Pb}/^{206}\text{Pb}$ ages are indicated.

A total of 21 zircon analyses were obtained from sample 12-1223-1. Seven analyses were excluded from further age calculations. Five of these excluded analyses are characterized

by low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios (<4000), indicating a significant contribution of common Pb, and are associated with elevated uranium concentrations (>1200 ppm). Two additional analyses plot near concordia but were excluded because the analytical spots were misplaced and intersected cracks in the zircon grains. The remaining 14 analyses define a coherent population on a Tera–Wasserburg diagram (Figure 22), yielding a Concordia age of 1879 ± 6 Ma (2σ ; MSWD = 0.8; probability of fit = 0.76).

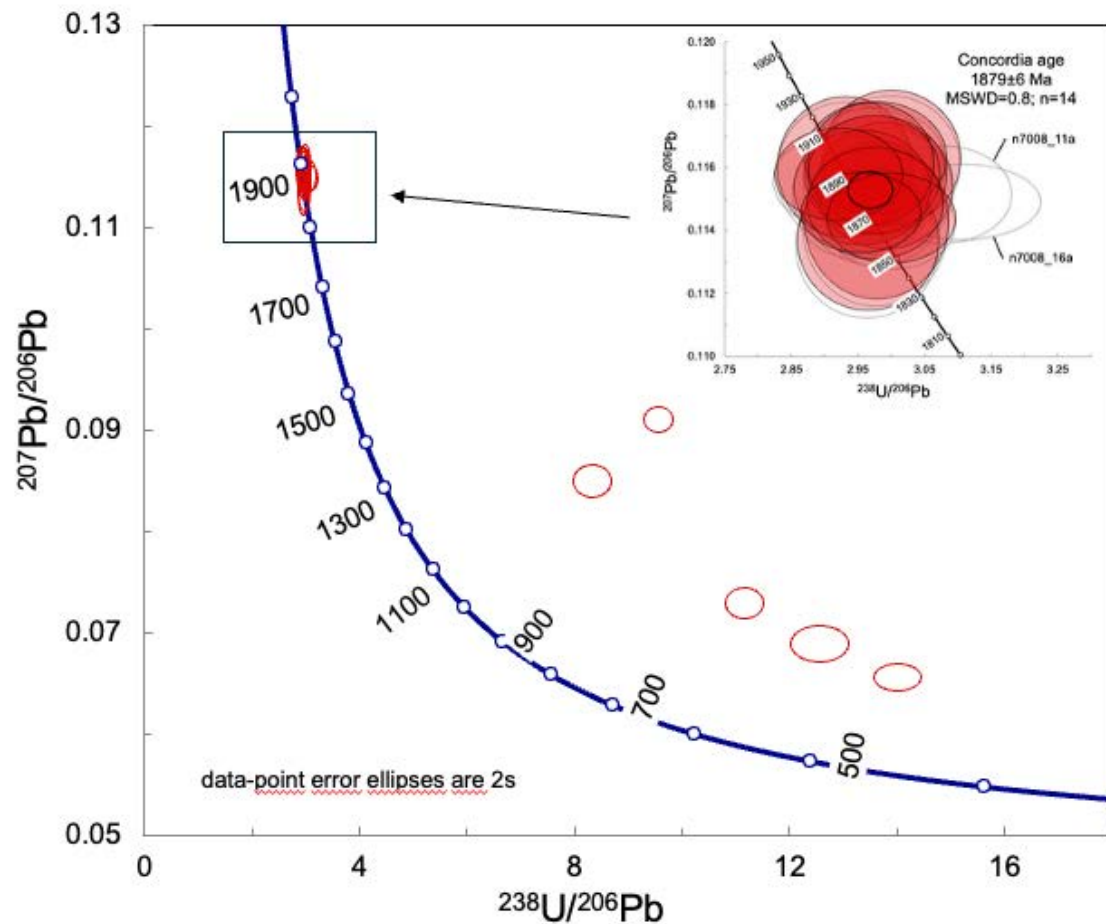


Figure 22. Tera–Wasserburg concordia diagram for zircon analyses from sample 12-1223-1. Five excluded analyses plot outside the concordant cluster, whereas two additional excluded analyses that plot near concordia are shown in gray in the inset and were omitted from age calculation because the analytical spots intersected cracks. The remaining 14 analyses yield a Concordia age of 1879 ± 6 Ma (2σ ; MSWD = 0.8; probability of fit = 0.76). Error ellipses are shown at 2σ .

Using the concordant population ($n = 14$), a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1882 ± 6 Ma (2σ) was calculated (Figure 23). The MSWD is 1.15 with a probability of 0.31, indicating that the observed scatter is within analytical uncertainty. The weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1882 ± 6 Ma for the 14 concordant analyses is consistent with the Concordia age of 1879 ± 6 Ma and supports crystallization of igneous zircon, and therefore emplacement of the granophytic intrusion, at ca. 1.88 Ga.

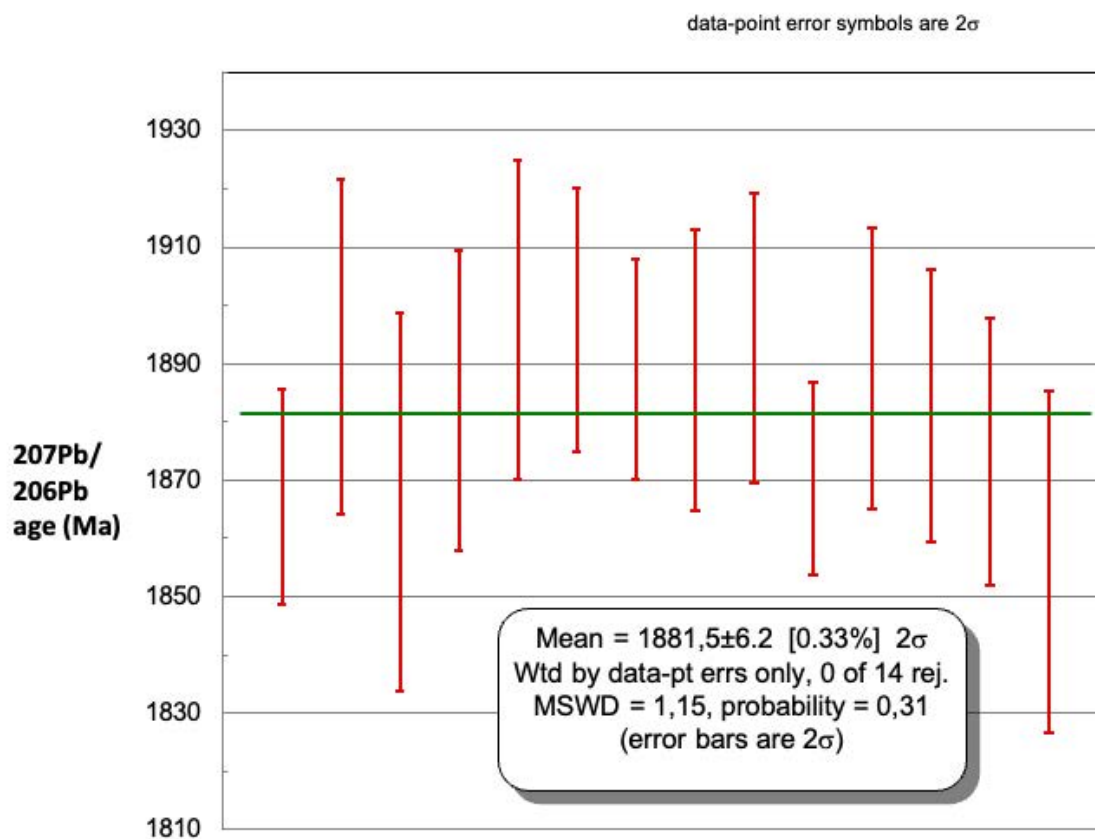


Figure 23. Weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1882 ± 6 Ma (2σ) based on 14 analyses (MSWD = 1.15; probability = 0.31).

4.4.2 Sample Z275-Y454 – Granophyre, south (near surface)

Zircons from sample Z275-Y454 differ from those in sample 12-1223-1 in both internal texture and analytical behavior. BSE imaging reveals predominantly sector-zoned zircon grains that commonly contain abundant small inclusions (Figure 24). A higher-magnification BSE image highlights numerous fine inclusions, typically on the order of $\sim 1\ \mu\text{m}$ or smaller. EDS analyses indicate that these inclusions are variably enriched in Fe and Ca, although some individual analyses are dominated by Fe. The elevated common Pb content in this sample is consistent with the abundance of inclusions in the zircon, but further characterization of these inclusions is beyond the scope of this study.

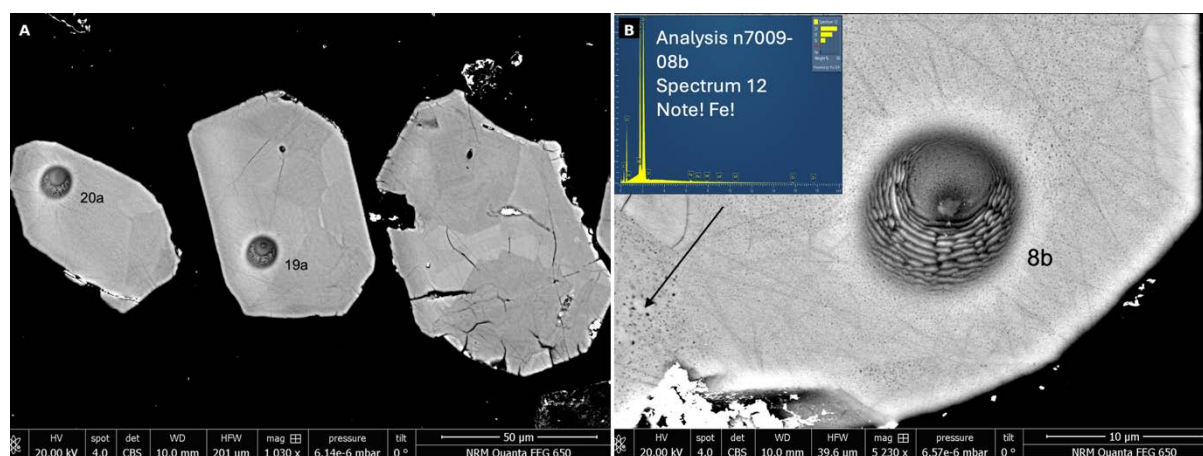


Figure 24. Back-scattered electron (BSE) images of representative zircon from sample Z275-Y454. (A) Zircon grain showing sector zoning. (B) Higher-magnification BSE image showing abundant fine inclusions; the arrow indicates an inclusion-rich area. The inset shows an EDS spectrum from analysis n7009-08b with a notable Fe signal. The circular feature labeled 8b is an analytical spot.

A total of 32 zircon analyses were obtained from sample Z275-Y454. In contrast to sample 12-1223-1, many analyses are discordant and display relatively large analytical uncertainties. On a Tera–Wasserburg concordia diagram (Figure 25), the analyses define a broad, scattered array rather than a single coherent concordant population. A discordia regression fitted through all analyses yields an upper intercept age of $1871 \pm 15\ \text{Ma}$ and

a lower intercept age of 425 ± 14 Ma (MSWD = 6.9; $n = 32$). Only a small subset of analyses plots close to concordia. As shown in the inset to Figure 24, the two analyses plotting closest to concordia yield $^{207}\text{Pb}/^{206}\text{Pb}$ ages of approximately 1.86 Ga.

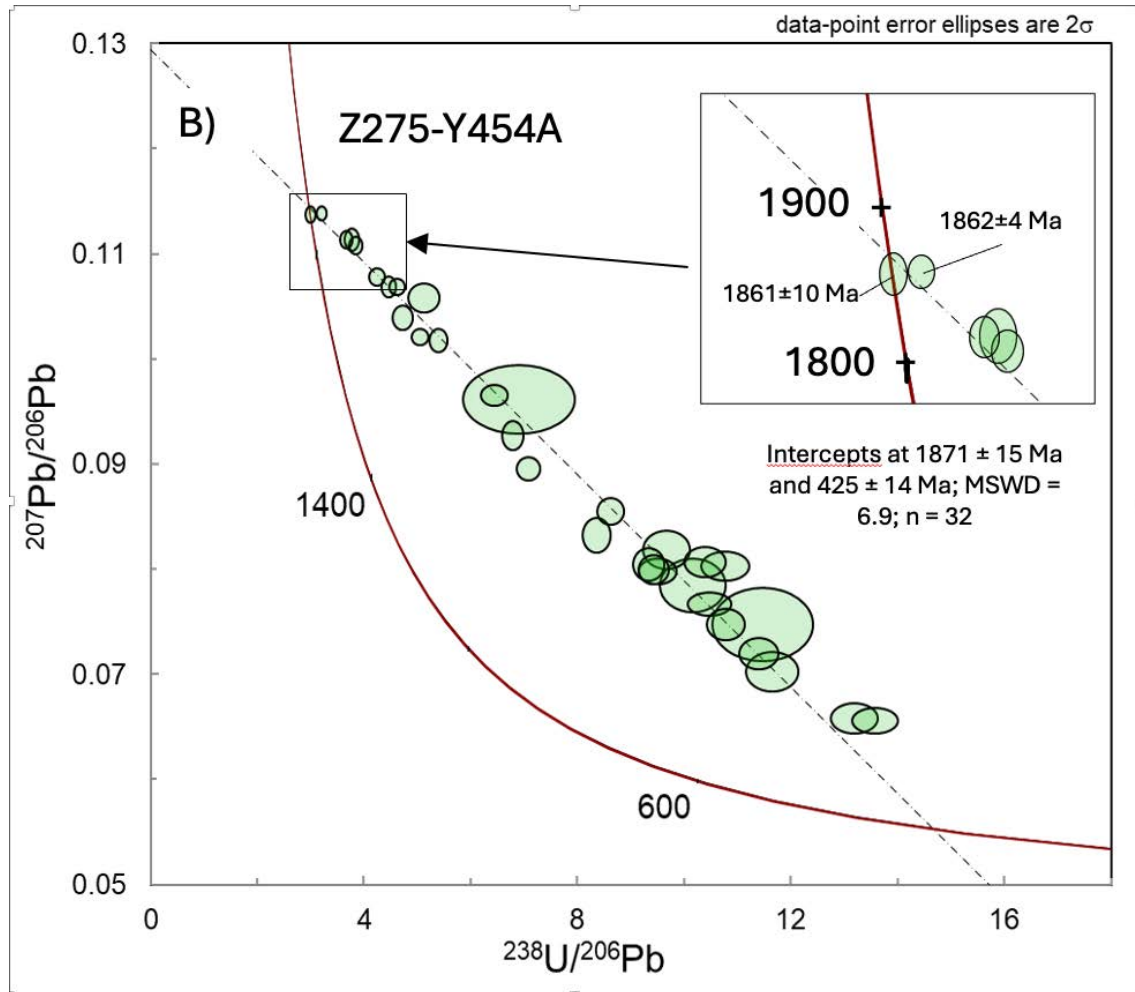


Figure 25. Tera-Wasserburg concordia diagram for zircon analyses from sample Z275-Y454. Most analyses are discordant and show significant scatter. The inset highlights the two analyses plotting closest to concordia, with $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 1861 ± 10 Ma and 1862 ± 4 Ma. Error ellipses are shown at 2σ . Diagram prepared by J. Andersson.

Overall, the two analyzed samples yield Paleoproterozoic zircon ages in the range of approximately 1880–1860 Ma. Sample 12-1223-1 defines a coherent near-concordant

zircon population, whereas sample Z275-Y454 is markedly more discordant and analytically complex. Despite this contrast, both samples indicate felsic magmatism at Kiirunavaara during at between 1880 Ma and 1860 Ma.

5. Discussion

The whole-rock geochemical data presented in Section 4.3 define the compositional characteristics of the intrusive suite at Kiirunavaara and provide a basis for evaluating magma evolution and tectonomagmatic setting. Major- and trace-element relationships are discussed below, with particular emphasis on the effects of alkali modification and on the distinction between felsic and mafic components of the system.

Whole-rock compositions indicate pervasive alkali modification across the deposit, consistent with field and petrographic evidence for hydrothermal alteration (Paolillo & Giapis, 2021; Lupoli et al., 2022; Andersson et al., 2024). These processes variably disturb primary Na and K budgets, complicating direct tectonic interpretation based on mobile major elements. The extent of this modification in felsic compositions is illustrated using the relationship between SiO_2 and $100 \cdot \text{K}_2\text{O} / (\text{K}_2\text{O} + \text{Na}_2\text{O})$ (Figure 26), which distinguishes compositions that follow primary igneous trends from those displaced by metasomatic processes.

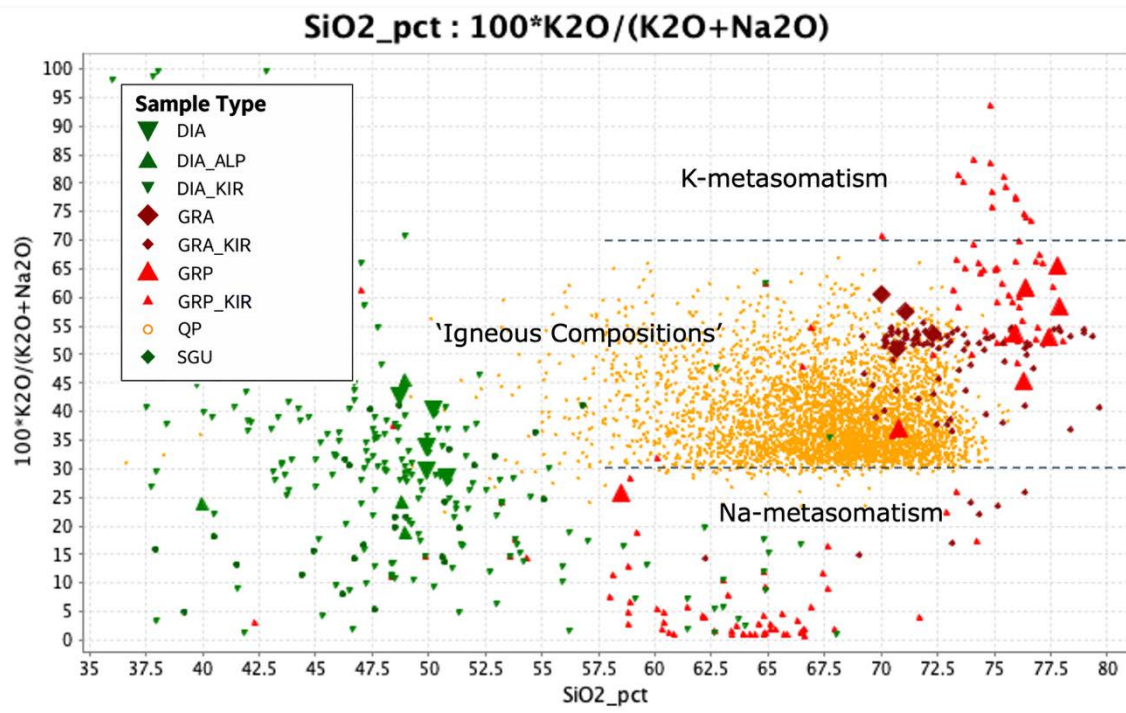


Figure 26. SiO_2 versus $100 \cdot \text{K}_2\text{O}/(\text{K}_2\text{O} + \text{Na}_2\text{O})$ diagram for felsic and mafic intrusive rocks from Kiirunavaara. Division lines at ~ 57.5 wt.% SiO_2 and $100 \cdot \text{K}_2\text{O}/(\text{K}_2\text{O} + \text{Na}_2\text{O}) = 30$ and 70 are estimated from Figure 17 and are applied only to the felsic rocks. Mafic rocks are shown for comparison only. The CA-granite compositions lie essentially within the igneous field, whereas the granophyres are partly strongly altered. QP compositions are screened to within the igneous spectrum. Legend abbreviations and symbols as in Figure 16.

The SiO_2 versus $100 \cdot \text{K}_2\text{O}/(\text{K}_2\text{O} + \text{Na}_2\text{O})$ diagram shows that although a subset of samples exhibits significant alkali redistribution, most compositions are not, including nearly all samples analysed in the present study except the misidentified trachyandesite. Together with the alteration relationships shown in Figure 18, these data indicate that most displaced analyses follow sodic trajectories, with more limited evidence for K enrichment and localized Ca-Fe alteration, consistent with the metasomatic overprinting documented in the Kiruna district (Pihl, 2024; Blein et al., 2025). Because metasomatism has variably modified mobile major elements, subsequent tectonic discrimination emphasizes relatively immobile trace-element signatures.

Following this screening, tectonomagmatic affinity was evaluated using immobile element systematics on a Th/Yb versus Ta/Yb diagram after Schandl & Gorton (2002) (Figure 27). The data define a broad distribution from oceanic arc to within-plate volcanic fields, although most analyses cluster within the active continental margin field. This pattern is consistent with an overall arc-related affinity while also indicating compositional variability within the felsic suite.

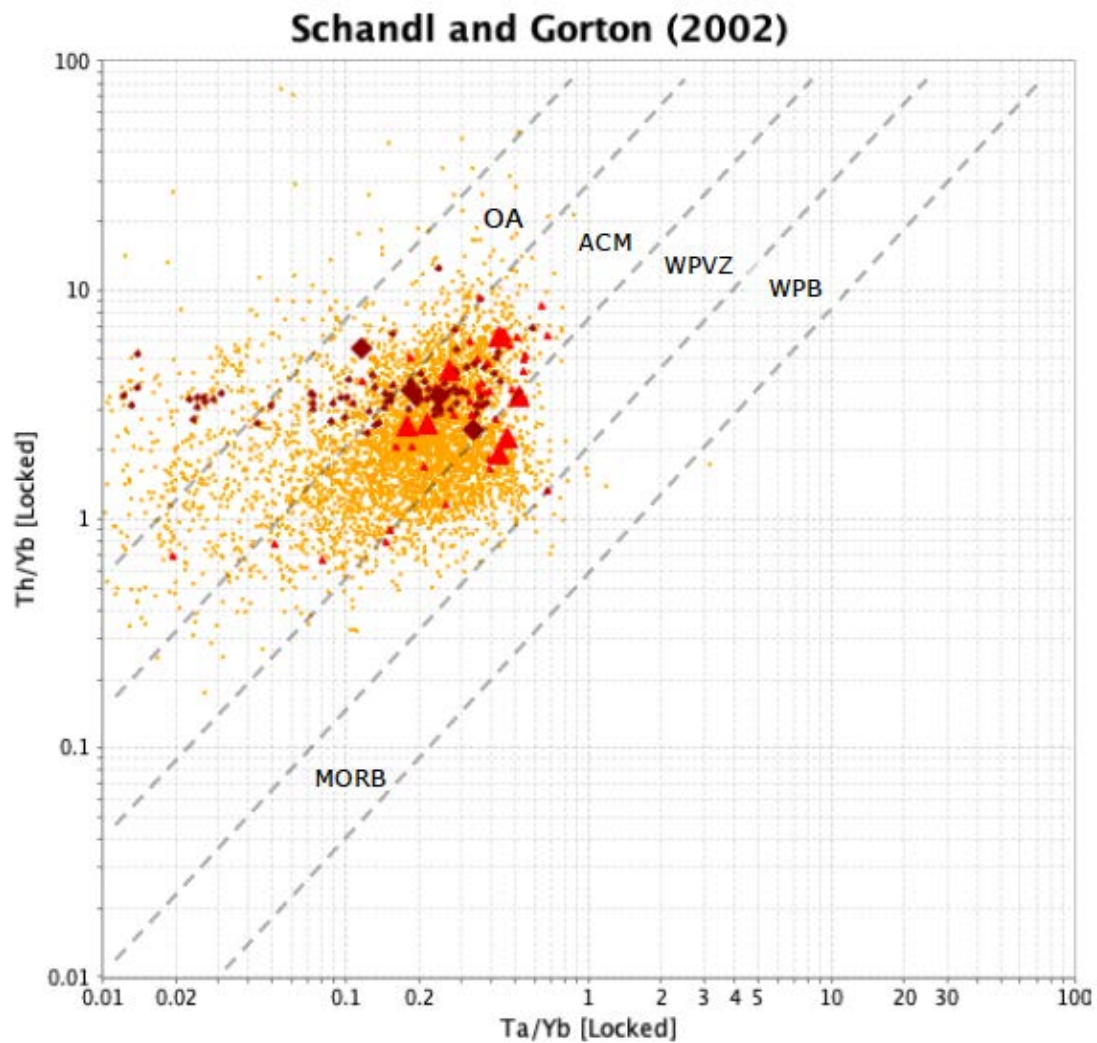


Figure 27. Th/Yb versus Ta/Yb tectonic discrimination diagram after Schandl & Gorton (2002), modified after Pearce (1982, 1983), showing the distribution of felsic compositions from Kiirunavaara. OA = Oceanic arc; ACM = Active continental margin; WPVZ = Within-plate volcanic zone; WPB = Within-plate basalt; MORB = Mid-ocean ridge basalt. All data are screened to within the igneous spectrum of Figure 17. Symbols as in Fig. 16.

Felsic compositions were also evaluated using the Rb–Hf–Ta classification diagram after Harris et al. (1986) (Figure 28). The granites plot predominantly within the volcanic-arc field, whereas the granophyres define a broader distribution that extends toward, and locally into, the within-plate field. Despite this dispersion, most analyses remain within arc-related domains. The felsic volcanic rocks are generally more tightly clustered than

the plutonic rocks, whereas the granites and granophyres show broader dispersion toward higher relative Rb and Ta contents.

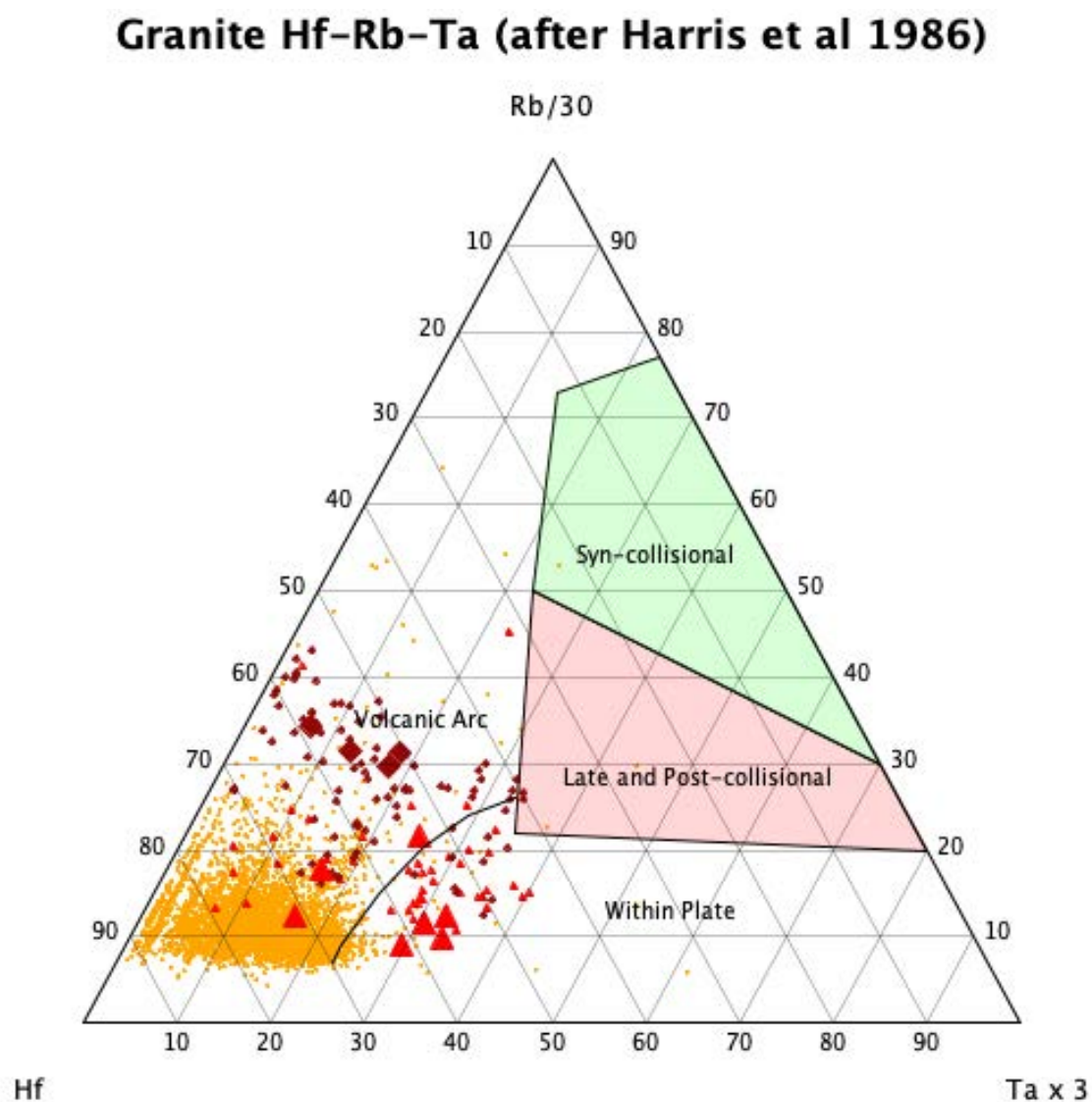


Figure 28. Felsic compositions plotted on the Hf-Rb-Ta diagram after Harris et al. (1986). Granites cluster mainly within the volcanic-arc field, whereas granophyres show a broader distribution extending toward, and locally into, the within-plate field. All data are screened to within the igneous spectrum of Figure 17. Symbols as in Fig. 16.

As in the preceding diagrams, the granites and granophyres partly overlap but also show a degree of separation, although intermediate compositions indicate that the overall trend is essentially continuous. The shift from the volcanic-arc field toward the within-plate field is accompanied by a relative decrease in Hf and increase in Ta.

The Yb+Ta versus Rb discrimination diagram of Pearce et al. (1984) provides further insight into felsic magma evolution (Figure 29). Granophyres define a broader and more evolved compositional array than the granites, extending toward fields traditionally classified as within-plate granites. When considered together with the dominant arc-related clustering observed on the Hf-Rb-Ta diagram (Figure 28) and the effects of metasomatic modification discussed above, this dispersion is more plausibly interpreted as the result of progressive differentiation within a shared magmatic system rather than a fundamental shift in tectonic setting. The more evolved character of the granophyres is consistent with derivation from a granitic parent magma through continued fractionation.

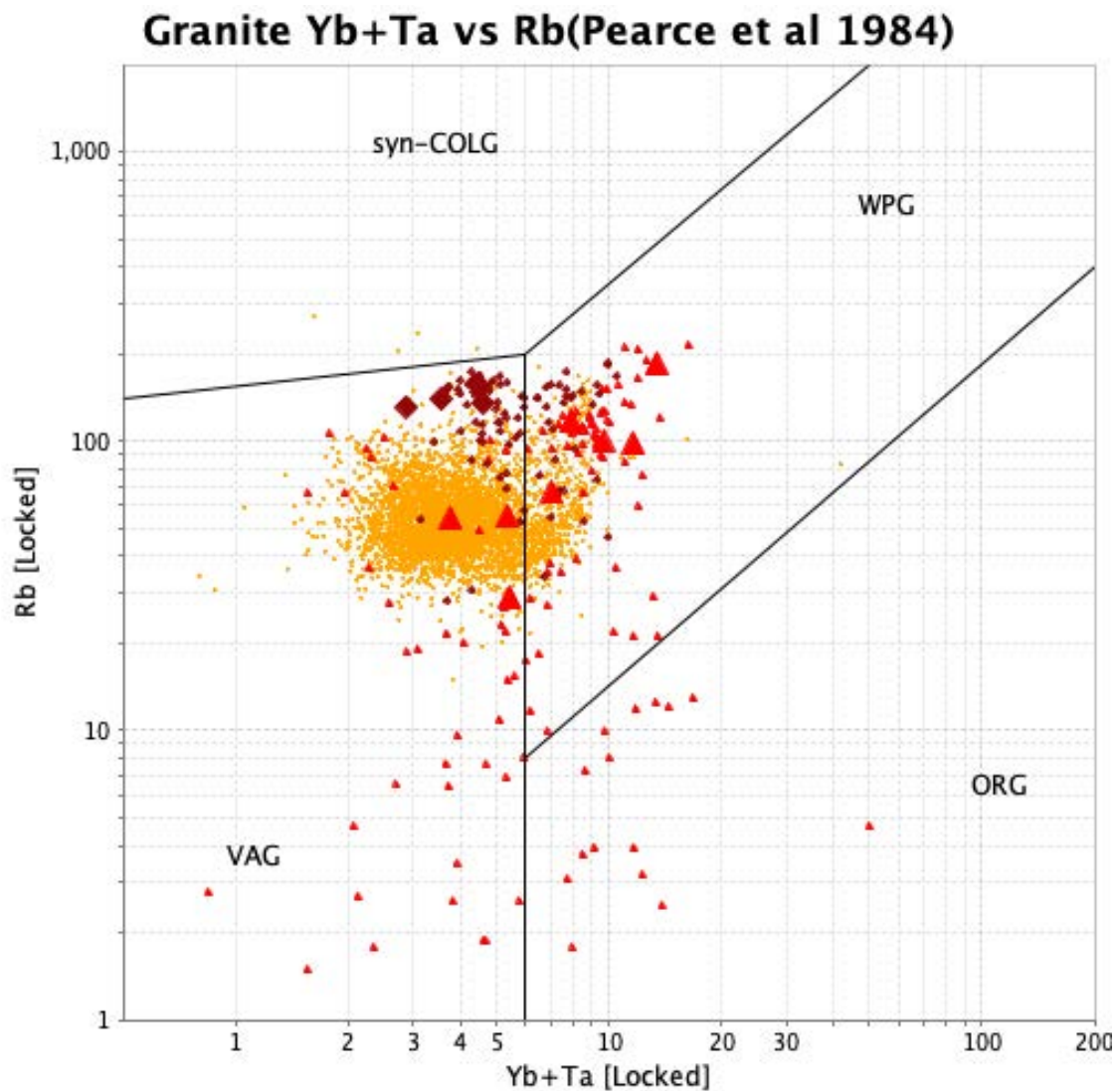


Figure 29. Yb+Ta versus Rb tectonic discrimination diagram for granites and granophyres after Pearce et al. (1984), showing volcanic arc granite (VAG), syn-collisional granite (syn-COLG), within-plate granite (WPG), and ocean-ridge granite (ORG) fields. Granophyres define a broader compositional array than granites and extend toward the within-plate field. All compositions shown are screened to within the igneous spectrum of Figure 17. Symbols as in Fig. 16.

The mafic dikes and mafic components of the composite intrusions provide complementary constraints on magma source characteristics. N-MORB-normalized trace-element patterns (Figure 30) show enrichment in large-ion lithophile elements relative to high-field-strength elements, together with pronounced negative Nb-Ta

anomalies. Comparison with the N-MORB, E-MORB, and OIB reference patterns of Sun and McDonough (1989) and the continental arc volcanic (CAV) and oceanic arc volcanic (OAV) reference patterns of Chen et al. (2023) indicates that these features are most consistent with an overall continental arc affinity and derivation from a mantle source modified by subduction-related processes.

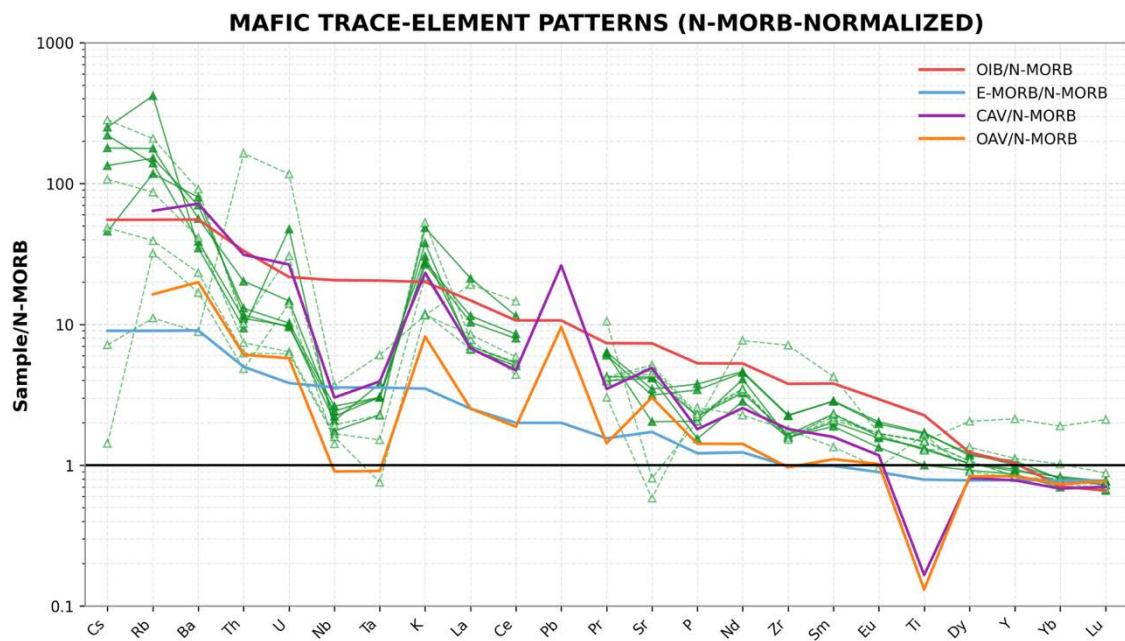


Figure 30. N-MORB-normalized trace-element patterns for the Kiirunavaara diabase dikes and mafic margins of composite dikes. N-MORB, E-MORB, and OIB reference patterns are after Sun and McDonough (1989); CAV and OAV reference patterns are after Chen et al. (2023).

Mafic compositions plotted on the Th-Hf-Ta diagram after Wood (1980) (Figure 31) cluster predominantly within arc fields, particularly within the continental arc basalt field. This distribution is consistent with an arc-related affinity for the mafic magmas.

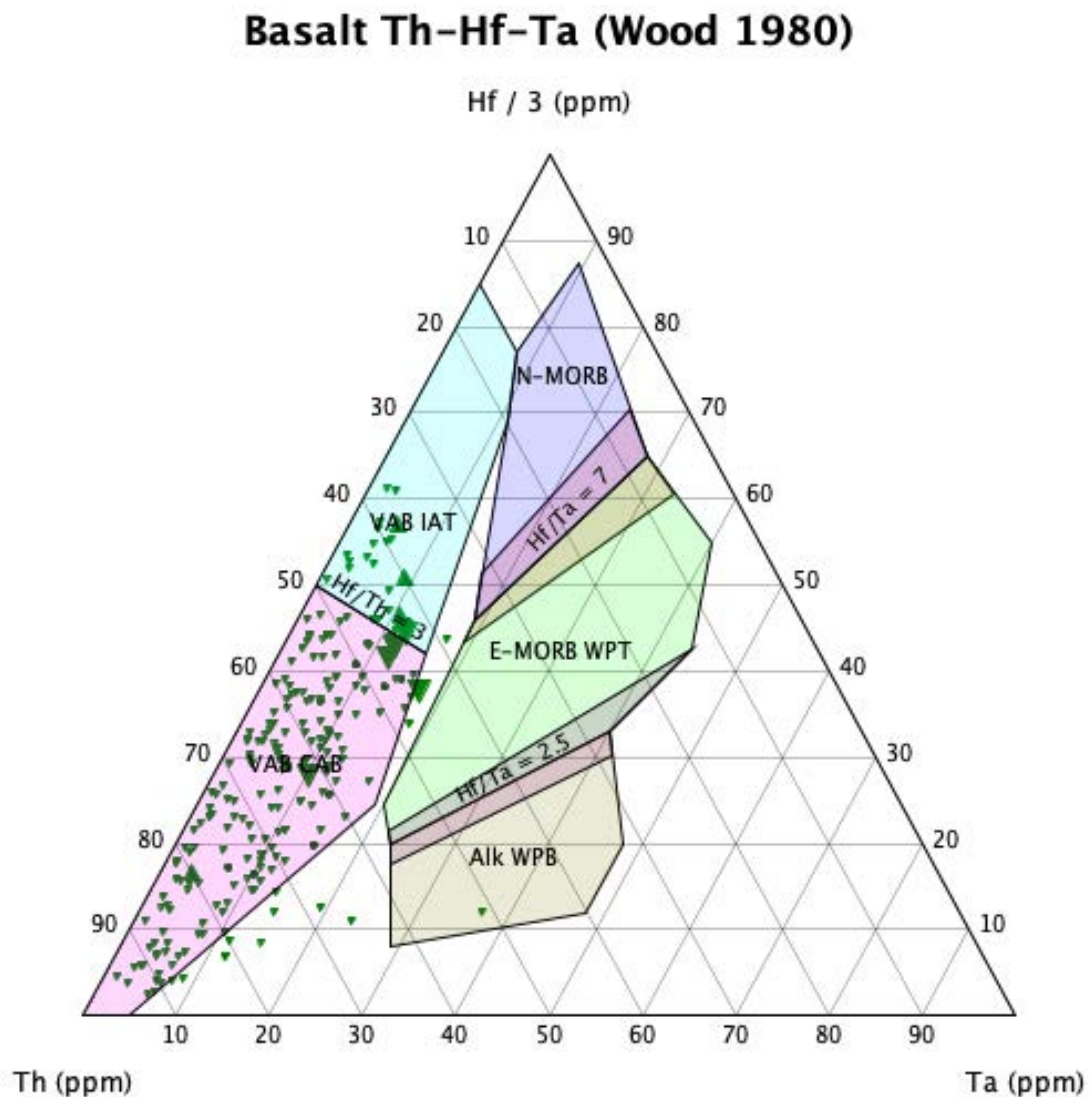


Figure 31. Mafic dike compositions plotted on the Th-Hf-Ta diagram after Wood (1980), showing clustering mainly within arc fields, particularly the continental arc basalt field. Field abbreviations: N-MORB = normal mid-ocean ridge basalt; E-MORB = enriched mid-ocean ridge basalt; VAB = volcanic arc basalt; IAT = island arc tholeiite; CAB = calc-alkaline basalt; WPT = within-plate tholeiite; WPB = within-plate basalt; Alk WPB = alkaline within-plate basalt. Symbols as in Figure 16.

Th/Yb versus Nb/Yb systematics after Pearce (2014) (Figure 32) show that the mafic rocks define a trend from E-MORB toward the continental arc field. This distribution is consistent with derivation from a subduction-modified mantle source with E-MORB-like

affinity for the dike suite. A contribution from lower crustal contamination cannot be excluded.

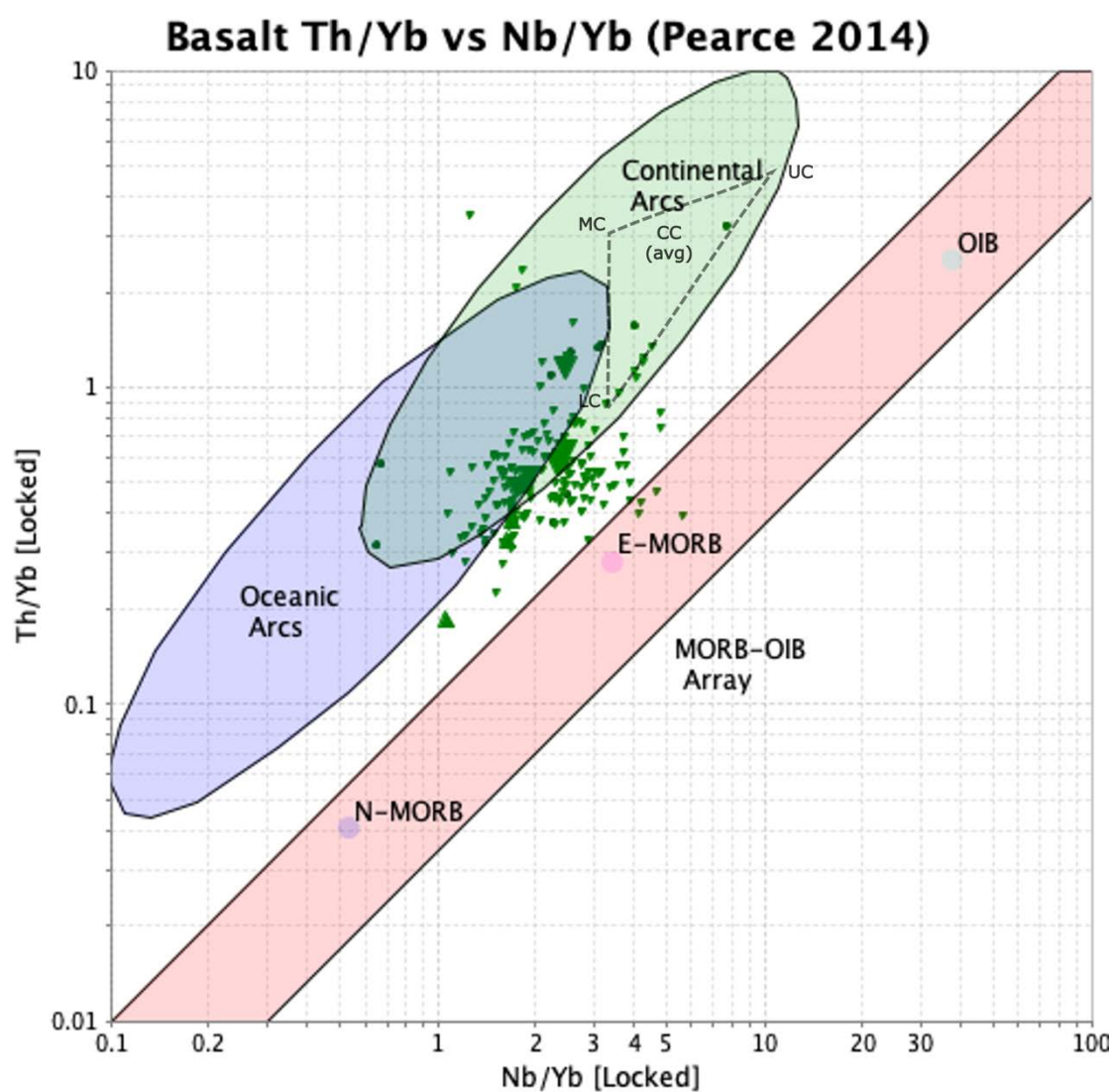


Figure 32. Mafic dike compositions plotted on the Th/Yb versus Nb/Yb diagram after Pearce (2014), showing a trend from E-MORB toward the continental arc field. LC, MC, and UC are lower, middle, and upper crust averages, respectively, and CC is the average continental crust. Symbols as in Fig. 16.

Composite dikes preserve sharply defined mafic margins and granophyric cores, indicating magma mingling with limited chemical hybridization. The occurrence of mafic enclaves within the associated granite pluton (e.g., Andersson et al., 2012) further supports contemporaneous interaction between compositionally distinct mafic and felsic magmas. These relationships are consistent with mechanical mingling between contrasting magmas, where thermal equilibration outpaces chemical diffusion (e.g., Sparks & Marshall, 1986; Frost & Mahood, 1987). Direct evidence for this interaction is observed at the hand-sample and drill-core scale (Figure 33).

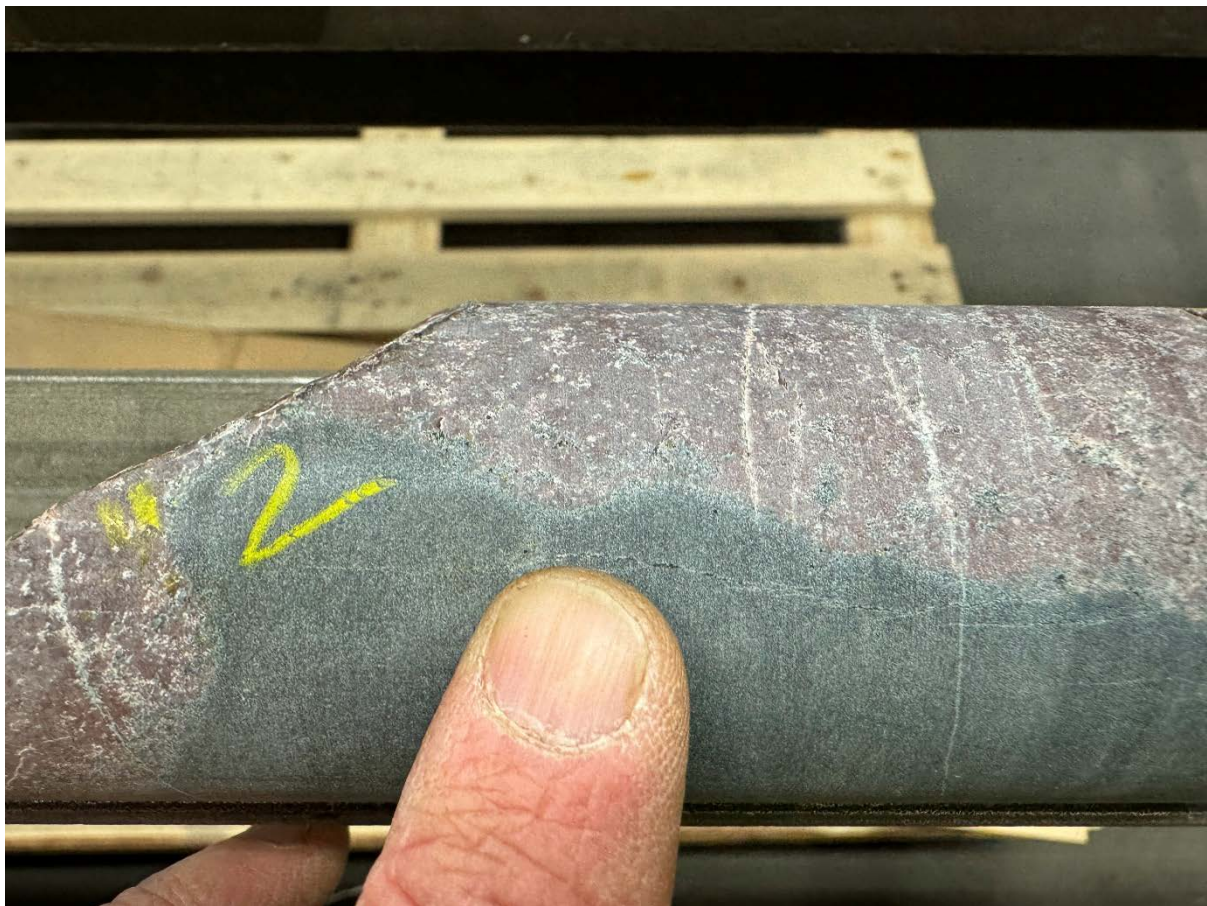


Figure 33. Drill core example showing mingling between mafic and felsic components in the northern composite dike (drill core BRK24037). Sharp contacts and irregular interfingering relationships indicate physical juxtaposition and incomplete mixing of compositionally distinct magmas during emplacement.

The micrographic to granophyric and locally fine-grained textures characteristic of the granophyres are consistent with relatively rapid cooling. The development of granophyric intergrowths and fine crystalline groundmass textures suggests crystallization in the upper crust following intrusion into cooler host rocks. These textural relationships support shallow crustal emplacement of the felsic dikes, but do not in themselves imply different emplacement levels among the granophyre occurrences.

The zircon U–Pb geochronology indicates that emplacement of the northern composite dikes and the southern granophyres overlapped within analytical uncertainty, although the northern set may be marginally older. The ages obtained here for the intrusive dikes also overlap within uncertainty with previously reported ages for granophyric intrusions and the CA-granite, as well as with ages reported for the ore and volcanic rocks they cut (Cliff et al., 1990; Westhues et al., 2016). These relationships indicate that the granite and dike intrusions formed during the same broad late Paleoproterozoic magmatic interval as the ore and volcanic host succession. Together, the temporal and spatial relationships are consistent with a relatively short interval of magmatism, intrusion, and ore formation between ca. 1890 and 1870 Ma within an evolving continental arc system.

Sample 12-1223-1 yields low MSWD values (0.8–1.2), indicating that dispersion among the concordant analyses is consistent with analytical uncertainty and supporting interpretation of the calculated age as a robust crystallization age. In contrast, the southern granophyre sample yields a very high MSWD value of 28, reflecting scatter far in excess of analytical uncertainty and pronounced disturbance of the zircon population. This dispersion may reflect variable Pb loss, common-Pb incorporation, and radiation damage associated with elevated U concentrations, while the inclusion-rich zircon textures indicate additional analytical complexity. The pronounced difference between the two samples indicates that the southern zircon population experienced substantially greater post-crystallization disturbance.

The orientations and geometry of the dikes indicate emplacement during a period of regional NNE–SSW extension, consistent with recent structural interpretations for

Kiirunavaara (Andersson & Berglund, 2024). The steeply dipping felsic dikes in the southern part of the deposit and the composite dikes with mafic margins and felsic interiors in the northern sector suggest that magma ascent exploited pre-existing crustal anisotropies, possibly reusing structures developed during the volcanic activity (cf. Andersson & Berglund, 2024). Within this framework, the dike system represents a late component of the Kiruna magmatic system that postdates emplacement of the ore and volcanic host succession and formed during the waning stages of magmatic activity within an evolving continental arc crust.

Elevated magnetite contents observed in the Konsuln (1c) granophyres introduce additional complexity to the felsic suite. These oxide enrichments may reflect primary magmatic variation, secondary modification during metasomatic or hydrothermal overprinting, or a combination of both. Considering the pervasive metasomatic modification documented at Kiirunavaara (Pihl, 2024; Yan et al., 2023), some contribution from late-stage alteration is plausible. However, the available data do not allow these alternatives to be distinguished with confidence.

Taken together, the geochemical, petrographic, and geochronological data indicate that the intrusive suite at Kiirunavaara represents a bimodal magmatic system developed within a continental arc setting. The coexistence of mafic and felsic endmembers, together with evidence for mechanical mingling and limited chemical hybridization, reflects contemporaneous interaction between compositionally distinct mafic and felsic magmas during the waning stages of magmatic activity. Textural evidence for shallow emplacement, combined with crosscutting field relationships and overlapping U–Pb ages, further supports a close temporal and genetic relationship between the ore and volcanic host rocks and the final intrusive phases of the Kiruna magmatic system.

However, uncertainties remain regarding the relationship between the studied dike suite and the broader felsic magmatic framework, particularly with respect to the granophyres and their possible link to the underlying CA-granite. Andersson and Berglund (2024) interpreted the granophyres as apophyses of the magma pluton represented by the CA-granite. However, a direct spatial connection between the dikes and the granite has not

yet been confirmed by underground mapping. The available evidence therefore suggests, but does not yet demonstrate, that the granophyres may represent fractionated late-stage magma offshoots from a crystallizing granite pluton that interacted with coeval diabase magmas during extension in the waning stages of magmatic activity at Kiirunavaara.

6. Conclusion

Field relationships demonstrate that the granophyric and composite dikes at Kiirunavaara crosscut all major lithologic units, including the orebody, thereby establishing that mineralization predates dike emplacement at 1882 ± 6 Ma. Zircon U-Pb geochronology further shows that dike emplacement overlaps, within analytical uncertainty, the ages of the ore, associated volcanic rocks, and the spatially related granite pluton at depth. These data support a relatively short interval of magmatism and ore formation between ca. 1890 and 1870 Ma and indicate that dike intrusion occurred during the waning stages of early Svecokarelian arc magmatism rather than during a distinctly younger tectonomagmatic episode.

Petrographic evidence from the composite intrusions, including sharply defined mafic margins and granophyric cores, demonstrates contemporaneous interaction between compositionally distinct mafic and felsic magmas. Mafic enclaves in the associated granite provide additional evidence for mafic–felsic interaction within the broader magmatic system. The preservation of granophyric textures and limited chemical hybridization reflects mechanical mingling under conditions in which thermal equilibration outpaced chemical diffusion. Geochemically, screened whole-rock data place both felsic and mafic components predominantly within continental arc tectonic fields. Although the granophyres display more evolved compositions approaching within-plate fields, this dispersion is consistent with advanced fractional crystallization within a shared magmatic system rather than requiring a change in tectonic setting.

The dike suite, like the volcanic rocks, records the effects of pervasive metasomatic modification within parts of the Kiirunavaara rock mass. Alkali redistribution records metasomatic modification, while elevated magnetite contents in parts of the felsic suite and contrasting zircon Pb-loss behavior indicate additional complexity within the intrusive system. Taken together, these observations indicate that the granophyric and composite dikes represent the final intrusive expressions of a continental arc magmatic-hydrothermal system closely associated with iron oxide-apatite mineralization at Kiirunavaara. These late intrusions record the closing stages of magmatism in the

Kiirunavaara system and help constrain the timing, evolution, and structural framework of iron oxide-apatite mineralization in the district.

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Supplementary Material

Table S1. Summary of samples used for petrographic and geochemical analysis (samples 56 and 61b from Lindgren (2013) have been reused). Underground locations labelled according to Kiirunavaara coordinate system.

Sample/Location	Code	Lithology	Location / Description	Petrog.	WR Geochem
Kii F 753205/718091*	1a	Granophyre	Southern Kiirunavaara	yes	yes
Z275-Y454 (geochron)	1a	Granophyre	South, near surface	yes	yes
Z275-Y472	1a	Granophyre	SP contact, Z275	yes	no
GRP/SP 1 753178/718194*	1a	Granophyre	SP contact, southern Kiirunavaara	yes	no
GRP/SP 2 753178/718194*	1a	Granophyre	Southern Kiirunavaara (~30 cm from contact)	yes	no
GRP S. KOJ 1 753177/718179*	1a	Granophyre	South, near surface	yes	yes
496/1137	1b	Granophyre	Southern KUJ	yes	yes
499/1137 H	1b	Granophyre	Southern KUJ	yes	yes
500/1108 H	1b	Granophyre	Southern KUJ	yes	no
Kir23001 (508/1108)	1b	Granophyre	Southern KUJ	yes	no
BPK23002	1c	Granophyre	Konsuln	yes	no
BPK23008	1c	Granophyre	Konsuln	yes	no
BPK23011.1	1c	Granophyre	Konsuln	yes	no
BPK23011.2.1	1c	Granophyre + xenolith	Konsuln	yes	no
BPK23011.2.2	1c	Granophyre + xenolith	Konsuln	yes	no
BPK23012	1c	Granophyre	Konsuln	yes	no
BPK23013	1c	Granophyre	Konsuln	yes	no
Db Dbr 1 753529/719127*	3	Diabase	Open pit, center	yes	existing
Db Dbr 2 753529/719127*	3	Diabase	Open pit, margin	yes	no

Sample/Location	Code	Lithology	Location / Description	Petrog.	WR Geochem
176/993	2a1	Diabase	Southern Composite Dike (Z993)	yes	yes
176/1051	2a1	Diabase	Southern Composite Dike (Z1051)	yes	yes
16/907	2a1	Diabase	Southern Composite Dike (Z907)	yes	yes
100/792 Db	2b1	Diabase	Northern Composite Dike, margin	yes	yes
108/935 Kon	2b1+2	Diabase-granophyre contact	Northern Composite Dike	yes	no
12/1223 2	2b1	Diabase	Northern Composite Dike, margin	yes	yes
100/792 Grp	2b2	Granophyre	Northern Composite Dike, center	yes	yes
108/935 Grp	2b2	Granophyre	Northern Composite Dike, center	yes	no
12/1223 1 (geochron)	2b2	Granophyre	Northern Composite Dike, center	yes	yes
16/849	2a2	Granophyre	Southern Composite Dike, center	yes	yes
BRK24033 (18.77-18.9 m)	2b1+2	Mingling zone	Northern Composite Dike	yes	no
Z849-Y1650	2a1+2	Mingling zone	Southern Composite Dike	yes	no
56**	4	CA-granite	-	yes	yes
61b**	4	CA-granite	-	yes	yes
CA1110	4	CA-granite	-	yes	yes
CA1465	4	CA-granite	-	yes	yes

Codes: 1a = granophyres (south, near surface); 1b = granophyres (south, deep); 1c = granophyres (Konsuln); 2a1 = diabase (Southern Composite Dike); 2a2 = granophyre (Southern Composite Dike); 2b1 = diabase (Northern Composite Dike); 2b2 = granophyre (Northern Composite Dike); 3 = diabase (open pit); 4 = CA-granite. Approximate surface sample locations in SWEREF 99 TM. **) Sample locations reported in Lindgren (2013).

Table S2. Petrographic observations for all thin-section samples.

Sample Info	Minerals	Description
Kii F (1a, Granophyre, Southern Kiirunavaara)	Qtz, Fsp, Mag, Bt	Fine- to medium-grained granophyre with well-developed radiating to plumose quartz–feldspar intergrowths. Magnetite is sparse and fine-grained, and minor biotite is present. Alteration is limited.
Z275-Y454 (geochron) (1a, Granophyre, South, near surface)	Qtz, Kfs, Plag, Mag, Chl	Fine- to medium-grained granophyre with abundant granophyric to spherulitic quartz–feldspar intergrowths. Magnetite is sparse and dispersed, with minor chlorite alteration.
Z275-Y472 (1a, Granophyre, SP contact, Z275)	Qtz, Kfs, Plag, Mag	Fine- to medium-grained granophyre with locally preserved micrographic texture. Brittle fractures and thin oxide-rich veinlets crosscut the rock, and magnetite is dispersed throughout the felsic groundmass.
GRP/SP 1 (1a, Granophyre, SP contact, southern Kiirunavaara)	Qtz, Plag, Mag, Chl	Sharp contact between granophyre and trachyandesitic footwall. The granophyre consists of quartz in a fine-grained felsic matrix with weak granophyric texture and minor magnetite. The footwall contains aligned plagioclase laths, abundant magnetite, and chlorite-filled fractures.
GRP/SP 2 (1a, Granophyre, Southern Kiirunavaara (~30 cm))	Qtz, Kfs, Plag, Mag, Chl	Fine- to medium-grained granophyre with locally developed quartz–feldspar intergrowths and scattered quartz and feldspar crystals. Magnetite is sparse, and chlorite alteration is present.
GRP S. KOJ 1 (1a, Granophyre, South, near surface)	Qtz, Kfs, Plag, Mag, Chl	Fine-grained granophyre with a micrographic felsic matrix and scattered quartz and feldspar crystals. Magnetite is sparse and fine-grained, with minor chlorite alteration.
496/1137 (1b, Granophyre, Southern KUJ)	Qtz, Kfs, Plag, Mag	Fine- to medium-grained granophyre with weak, heterogeneous, polygonal quartz–feldspar intergrowths and discrete quartz and feldspar grains. Magnetite is present.
499/1137 H (1b, Granophyre, Southern KUJ)	Qtz, Kfs, Plag, Mag	Fine- to medium-grained granophyre with moderately developed, heterogeneous, polygonal quartz–feldspar intergrowths and discrete quartz and feldspar grains. Magnetite is present.

Sample Info	Minerals	Description
500/1108 H (1b, Granophyre, Southern KUJ)	Qtz, Kfs, Plag, Mag, Chl, Ser	Fine- to medium-grained granophyre with weak, heterogeneous quartz–feldspar intergrowths. Magnetite is relatively abundant. Sericite and chlorite alteration and local veinlets are present.
Kir23001 (508/1108) (1b, Granophyre, Southern KUJ)	Qtz, Fsp, Mag, Ser, Chl	Fine- to medium-grained granophyre with heterogeneous quartz–feldspar intergrowths and discrete quartz and feldspar grains. Magnetite is relatively abundant. Altered phenocrysts contain sericite or chlorite.
BPK23002 (1c, Granophyre, Konsuln)	Qtz, Kfs, Plag, Mag, Chl	Fine-grained granophyre with larger quartz crystals in a fine-grained felsic matrix. Granophyric texture is weakly developed. Magnetite and minor chlorite alteration are present.
BPK23008 (1c, Granophyre, Konsuln)	Qtz, Kfs, Plag, Mag	Very fine-grained granophyre with larger quartz and feldspar crystals in a fine-grained felsic matrix. Granophyric texture is weakly developed. Magnetite and thin veinlets are present.
BPK23011.1 (1c, Granophyre, Konsuln)	Qtz, Fsp, Mag, Bt, Chl	Very fine-grained granophyre with locally developed quartz–feldspar intergrowths. Magnetite is relatively abundant. Minor biotite and chlorite and thin veinlets are present.
BPK23011.2.1 (1c, Granophyre + xenolith, Konsuln)	Qtz, Kfs, Plag, Mag, (Py), (Cal), (Ser)	Very fine-grained granophyre containing areas of coarser crystalline material. Granophyric texture is locally developed, and magnetite is concentrated near the coarser areas. Trace pyrite is present.
BPK23011.2.2 (1c, Granophyre + xenolith, Konsuln)	Qtz, Kfs, Plag, Mag, (Ser), (Chl)	Fine-grained granophyre containing areas of coarser crystalline material. Magnetite occurs as disseminated grains and clusters and is locally concentrated near the coarser areas.
BPK23012 (1c, Granophyre, Konsuln)	Qtz, Kfs, Plag, Mag, Ser	Very fine-grained granophyre with locally developed coarser quartz–feldspar intergrowths. Magnetite is disseminated throughout, and sericite alteration is present.
BPK23013 (1c, Granophyre, Konsuln)	Qtz, Kfs, Plag, Mag, Ser	Very fine-grained granophyre with larger quartz crystals and altered feldspar in a fine-grained matrix. Magnetite is finely disseminated, and sericite alteration is present.

Sample Info	Minerals	Description
Db Dbr 1 (3, Diabase, Open pit, center)	Plag, Cpx, Amph, Mag, Chl, (Ser)	Diabase with lath-like plagioclase and interstitial clinopyroxene and amphibole. Magnetite is disseminated throughout. Chlorite and sericite alteration are present.
Db Dbr 2 (3, Diabase, Open pit, margin)	Plag, Cpx, Amph, Mag, Chl	Fine-grained diabase with lath-like plagioclase and interstitial clinopyroxene and amphibole. Magnetite is disseminated throughout, and chlorite alteration is present.
176/993 (2a1, Diabase, Southern Composite Dike (Z993))	Plag, Cpx, Amph, Mag	Diabase with well-developed ophitic texture defined by plagioclase laths and clinopyroxene and amphibole. Magnetite occurs as disseminated and interstitial grains.
176/1051 (2a1, Diabase, Southern Composite Dike (Z1051))	Plag, Cpx, Mag, (Amph), Chl	Fine- to medium-grained diabase with ophitic to sub-ophitic texture. Plagioclase laths occur with larger clinopyroxene and amphibole grains. Magnetite is disseminated throughout.
16/907 (2a1, Diabase, Southern Composite Dike (Z907))	Plag, Cpx, Amph, Mag, Chl, (Ser)	Fine-grained, altered diabase with partially preserved ophitic texture. Plagioclase, clinopyroxene, and amphibole are variably altered, and magnetite is disseminated throughout..
100/792 Db (2b1, Diabase, Northern Composite Dike, margin)	Plag, Cpx, Mag, Chl	Fine-grained diabase with ophitic to sub-ophitic texture. Clinopyroxene is variably altered to chlorite. Magnetite is abundant and occurs as disseminated grains and interstitial clusters.
108/935 Kon (2b1-2, Diabase-granophyre contact, Northern Composite Dike)	Qtz, Fsp, Plag, Cpx, Mag	Sharp contact between granophyre and diabase. The granophyre contains quartz-feldspar intergrowths, whereas the diabase displays ophitic to sub-ophitic texture. Magnetite occurs in both domains and is locally concentrated near the contact.
12/1223 2 (2b1, Diabase, Northern Composite Dike, margin)	Plag, Cpx, Amph, Mag, Chl, (Ser), (Cbt), (Sulfides)	Fine-grained, altered diabase with partially preserved ophitic texture. Chlorite, sericite, and carbonate alteration are present. Magnetite and sulfides are disseminated throughout.

Sample Info	Minerals	Description
100/792 Grp (2b2, Granophyre, Northern Composite Dike, center)	Plag, Kfs, Qtz, Mag, Chl, (Ser), (Py)	Granular granophyre composed of quartz and feldspar, with no clear granophyric intergrowths. Magnetite occurs as both coarse and finely disseminated grains.
108/935 Grp (2b2, Granophyre, Northern Composite Dike, center)	Plag, Kfs, Qtz, Mag, Chl, (Ser)	Coarse-grained, granular granophyre composed of quartz and feldspar, with no clear granophyric intergrowths. Magnetite occurs mainly as coarse grains.
12/1223 1 (geochron) (2b2, Granophyre, Northern Composite Dike, center)	Plag, Kfs, Qtz, Mag, Chl, (Ser)	Granular granophyre composed of quartz and feldspar, with no clear granophyric intergrowths. Chlorite and sericite alteration are present. Magnetite is mainly fine-grained and disseminated.
16/849 (2a2, Granophyre, Southern Composite Dike, center)	Plag, Kfs, Qtz, Bt, Mag, Chl, (Ser)	Granular granophyre composed mainly of quartz and feldspar, with locally developed fine-grained intergrowths. Minor biotite is present. Magnetite occurs as coarse and disseminated grains.
BRK24033 (18.77-18.9 m) (2b1+2, Mingling zone, Northern Composite Dike)	Data unavailable	Data unavailable
Z849-Y1650 (2a1+2, Mingling zone, Southern Composite Dike)	Plag, Kfs, Qtz, Mag, Chl, (Ser)	Granular felsic rock with altered feldspar and no clear granophyric intergrowths. Magnetite occurs as coarse and disseminated grains, with chlorite and sericite alteration. Although sampled from the mingling zone, no mingling texture or diabase component is observed in the thin section.
56 (4, CA-granite)	Plag, Qtz, Bt (altered), Mag, Chl, (Ser)	Altered CA-granite containing quartz, plagioclase, altered biotite, and magnetite. Chlorite and sericite alteration are present.
61b (4, CA-granite)	Qtz, Kfs (Microcline), Plag, Bt (altered), Mag	CA-granite containing quartz, feldspar, biotite, and magnetite. Microcline shows characteristic tartan twinning, and biotite is variably altered.

Sample Info	Minerals	Description
CA1110 (4, CA-granite)	Qtz, Fsp, Mag	Medium-grained CA-granite dominated by quartz and feldspar. Quartz occurs both between feldspar grains and as larger grains and commonly shows strong undulose extinction. Magnetite is sparse.
CA1465 (4, CA-granite)	Qtz, Kfs (Microcline), Plag, Mag, (Ser)	Coarse-grained CA-granite dominated by quartz and feldspar. Magnetite is present, with minor sericite alteration.

Table S3a. Whole-rock major-element geochemical data for analyzed samples, with oxides and totals determined by ALS ICP06 and LOI by ALS OA-GRA05.

Sample ID	SiO2 (%)	Al2O3 (%)	Fe2O3 (%)	CaO (%)	MgO (%)	Na2O (%)	K2O (%)	Cr2O3 (%)	TiO2 (%)	MnO (%)	P2O5 (%)	SrO (%)	BaO (%)	LOI (%)	Total (%)
Kii F	76.4	11.75	1.32	0.6	0.11	3.23	5.22	0.	0.09	0.02	<0.01	<0.01	0.03	1.06	99.83
176/993	49.9	15.6	12.6	6.82	6.57	4.29	2.2	0.02	1.64	0.12	0.26	0.04	0.03	1.33	101.42
176/1051	48.7	15.25	13.15	4.26	6.54	4.7	3.51	0.02	1.68	0.08	0.24	0.02	0.02	1.16	99.33
16/907	50.2	15.45	11.2	6.59	6.22	4.03	2.73	0.02	1.27	0.15	0.18	0.04	0.04	1.27	99.39
100/792 Db	49.9	13.2	14.45	6.57	4.52	4.55	1.93	0.01	2.16	0.12	0.4	0.03	0.06	0.89	98.79
100/792 Grp	58.5	13.95	8.11	3.55	2.52	6.61	2.28	<0.002	1.26	0.05	0.61	0.01	0.03	0.57	98.05
496/1137	77.4	12.	1.76	0.25	0.01	4.11	4.64	0.	0.08	0.01	0.01	<0.01	0.01	0.55	100.83
499/1137 H	77.9	11.8	0.93	0.99	0.1	3.6	5.04	0.	0.06	0.03	<0.01	<0.01	0.04	1.22	101.71
56	70.7	13.8	2.78	0.8	0.43	4.63	4.8	0.	0.3	0.01	0.06	<0.01	0.05	1.24	99.6

Sample ID	SiO2 (%)	Al2O3 (%)	Fe2O3 (%)	CaO (%)	MgO (%)	Na2O (%)	K2O (%)	Cr2O3 (%)	TiO2 (%)	MnO (%)	P2O5 (%)	SrO (%)	BaO (%)	LOI (%)	Total (%)
61b	71.1	13.65	2.4	1.	0.4	4.03	5.44	0.01	0.26	0.01	0.05	<0.01	0.06	1.6	100.01
16/849	70.8	13.55	3.78	0.61	0.24	5.59	3.31	<0.002	0.3	0.02	0.02	<0.01	0.05	1.08	99.35
Z275-Y454	77.8	11.55	0.74	0.23	0.02	3.06	5.83	0.04	0.1	0.01	0.02	<0.01	0.03	0.7	100.13
12/1223 1	76.3	11.7	1.44	1.41	0.27	4.54	3.76	0.04	0.12	0.01	0.02	0.01	0.03	2.11	101.76
12/1223 2	50.8	13.2	14.05	6.79	4.6	5.02	2.	0.	2.12	0.09	0.44	0.03	0.05	0.92	100.11
CA1110	72.3	13.55	3.13	0.87	0.37	4.45	5.13	<0.002	0.3	0.02	0.1	0.01	0.06	1.01	101.3
CA1465	70.	13.35	3.01	1.19	0.34	3.81	5.85	0.	0.29	0.01	0.03	0.01	0.06	1.74	99.69
GRP S. KOJ 1	75.9	11.45	1.42	0.28	0.04	3.83	4.44	<0.002	0.08	0.01	<0.01	<0.01	0.02	0.82	98.29

Table S3b. Whole-rock trace-element geochemical data for analyzed samples, determined by ALS MS81.

Element	Unit	Kii F	Z275-Y454 (geochron)	GRP S. KOJ 1	496/1137	499/1137 H	176/993	176/1051	16/907	100/792 Db	12/1223 2	100/792 Grp	12/1223 1 (geochron)	16/849	56	61b	CA1110	CA1465
Ba	ppm	258	221	198.5	61.1	383	245	220	356	504	441	244	248	386	468	495	494	487
Ce	ppm	37.9	34.5	22.2	93.6	25	39.8	86.2	38.1	59.6	64	127	21.4	63.7	108	97.8	127.5	97.8
Cr	ppm	5	293	9	11	19	121	131	126	48	32	<5	313	9	13	49	11	9
Cs	ppm	0.14	0.17	0.16	0.36	0.05	1.54	1.76	1.25	0.32	0.94	0.05	0.16	0.08	0.4	0.38	0.3	0.2
Dy	ppm	8.72	8.47	8.01	13.45	4.8	4.67	4.66	4.19	5.32	5.49	7.67	4.71	3.01	5.52	4.16	5.32	4.07
Er	ppm	6.13	6.8	6.42	10.25	3.68	2.74	2.34	2.24	2.87	2.88	4.53	3.14	2.24	3.79	2.24	3.26	2.56
Eu	ppm	0.44	0.22	0.23	0.35	0.23	1.63	1.59	1.36	2.07	2	1.85	0.17	0.61	0.96	1.04	0.75	0.84
Ga	ppm	23.9	23	24.5	24.2	22.9	23.9	23.4	20.9	22.8	22.7	19.7	20.8	22	19.4	17.8	18.9	17.7
Gd	ppm	6.16	5.49	5.94	10.15	3.99	5.67	6.12	4.89	7.18	6.71	8.34	2.81	3.06	6.14	5.27	6.08	4.73
Hf	ppm	14.45	18.85	14.8	15.4	15.1	3.31	3.2	3.29	4.31	4.18	7.1	9.08	10.45	8.02	7.48	9.26	7.51
Ho	ppm	2.01	2	1.86	3.08	1.1	0.89	0.85	0.83	1.11	1.01	1.6	1.04	0.64	1.08	0.78	1.16	0.87
La	ppm	15.5	19.9	10	41.8	11.2	17.5	53.1	16.6	25.9	28.7	75.3	12	33.1	53.8	37.6	69.1	40.3
Lu	ppm	0.94	1.22	0.96	1.64	0.69	0.35	0.35	0.3	0.33	0.35	0.8	0.58	0.43	0.56	0.38	0.53	0.43
Nb	ppm	37.5	47.7	42.3	51.5	22.3	4.83	4.07	5.19	5.64	6.11	12.15	23.7	8.68	15.85	14.45	15.1	13.6

Element	Unit	Kii F	Z275-Y454 (geochron)	GRP S. KOJ 1	496/1137	499/1137 H	176/993	176/1051	16/907	100/792 Db	12/1223 2	100/792 Grp	12/1223 1 (geochron)	16/849	56	61b	CA1110	CA1465
Nd	ppm	18.5	16.1	11.8	39	12.2	23.8	29.7	20.7	33.1	33.8	49.5	9.5	21.2	43	42	46.1	37.1
Pr	ppm	4.88	4.09	2.91	11.2	3.16	5.61	8.23	5.24	7.96	8.37	13.6	2.34	6.66	12.2	11.95	13.2	11.35
Rb	ppm	118	98.7	100	186.5	66.6	78	235	99.4	65.8	84.7	29.1	54.9	54.3	136	132	156.5	139.5
Sc	ppm	0.7	<0.5	0.8	<0.5	0.8	32.1	31.4	29.6	35.8	34.5	16.9	0.7	2.6	3.9	2	2.2	3.4
Sm	ppm	4.79	4.21	3.65	9.38	3.36	6.07	5.31	4.95	7.52	7.46	8.48	2.55	4.06	7.73	6.94	7.29	6.56
Sn	ppm	2.3	1.8	2	4	1	1.8	1.7	0.9	1.3	1.4	3	1.1	1.6	1.8	1.8	1.9	2.8
Sr	ppm	14.7	12.6	13.2	13.1	30.2	380	183.5	374	283	312	52.9	68.4	28	51.7	67	58.4	57.1
Ta	ppm	1.2	3.7	2.9	2.4	2.4	0.5	0.3	0.4	0.4	0.4	0.8	1.6	0.8	0.9	0.3	0.7	0.9
Tb	ppm	1.14	1.16	1.17	1.92	0.67	0.84	0.69	0.66	0.98	0.88	1.15	0.59	0.43	1	0.65	0.87	0.64
Th	ppm	17.05	17.95	12.95	28.6	15.95	1.32	1.13	2.43	1.4	1.56	7.32	23.4	13.25	12.7	14.4	13.75	6.56
Ti	%	0.06	0.06	0.05	0.05	0.04	1.02	1.05	0.79	1.32	1.29	0.79	0.07	0.17	0.18	0.16	0.17	0.18
Tm	ppm	1.02	1.09	0.93	1.63	0.56	0.34	0.35	0.34	0.4	0.35	0.66	0.5	0.38	0.52	0.32	0.52	0.38
U	ppm	4.21	6.3	4.32	9.84	5.22	0.46	2.23	0.69	0.45	0.48	4.09	4.8	2.82	3.24	3.01	3.47	4.9
V	ppm	<5	9	<5	<5	<5	322	313	262	458	452	123	13	27	15	15	14	14
W	ppm	1.5	3.4	1.8	1.4	1	2.1	1.1	1.5	2.5	1.6	1.2	6.3	1.8	1.9	1.9	1.1	2
Y	ppm	50.7	51.4	54.4	98.7	31.1	25.4	26.3	24.1	30.1	28.1	45.9	26.9	20.6	34.8	24.3	34.1	27.2

Element	Unit	Kii F	Z275-Y454 (geochron)	GRP S. KOJ 1	496/1137	499/1137 H	176/993	176/1051	16/907	100/792 Db	12/1223 2	100/792 Grp	12/1223 1 (geochron)	16/849	56	61b	CA1110	CA1465
Yb	ppm	6.71	7.94	6.76	11	4.64	2.53	2.34	2.12	2.43	2.47	4.62	3.75	2.98	3.7	2.57	3.77	2.66
Zr	ppm	339	408	319	323	340	122	116	117	166	168	303	205	414	306	281	363	293

Table S4a. SIMS U-Pb geochronology data for sample 12/1223 1 (geochron).

Spot ID	$^{207}\text{Pb}/^{235}\text{U}$	$\pm s$ (%)	$^{206}\text{Pb}/^{238}\text{U}$	$\pm s$ (%)	$^{207}\text{Pb}/^{206}\text{Pb}$	$\pm s$ (%)	$^{207}\text{Pb}/^{206}\text{Pb}$ age (Ma)	$\pm s$ (Ma)	$^{206}\text{Pb}/^{238}\text{U}$ age (Ma)	$\pm s$ (Ma)	U (ppm)	Pb (ppm)	Th/U	f ²⁰⁶ %	Disc. (2 σ) (%)
n7008_01a	5.2494	1.42	0.3334	1.32	0.1142	0.51	1867.3	9	1854.8	21	404	173	0.59	{0.01}	
n7008_02a	5.4495	1.63	0.3412	1.43	0.1158	0.80	1892.8	14	1892.5	23	159	68	0.46	{0.01}	
n7008_03a	0.8988	1.54	0.0894	1.30	0.0729	0.83	1010.9	16	552.1	6	1590	190	0.86	0.51	-41.4
n7008_03b	0.6456	1.50	0.0714	1.26	0.0656	0.81	793.4	17	444.5	5	2681	269	1.11	0.55	-38.6
n7008_04a	5.2868	1.75	0.3360	1.49	0.1141	0.90	1866.2	16	1867.2	24	127	56	0.68	{0.01}	
n7008_05a	5.3138	1.57	0.3344	1.40	0.1152	0.72	1883.6	12	1859.8	22	200	88	0.68	{0.00}	
n7008_06a	5.3385	1.62	0.3334	1.43	0.1161	0.76	1897.4	13	1854.9	23	176	73	0.45	{0.01}	
n7008_07a	5.3812	1.60	0.3361	1.47	0.1161	0.63	1897.5	11	1867.7	23	260	112	0.58	{0.01}	
n7008_08a	1.3127	1.24	0.1045	1.10	0.0911	0.57	1448.8	10	640.8	6	1776	256	0.98	0.23	-55.2
n7008_09a	0.7556	2.05	0.0796	1.75	0.0688	1.07	894.2	22	493.7	8	1594	170	0.89	0.65	-38.1
n7008_09b	1.4068	1.85	0.1201	1.69	0.0850	0.74	1315.3	14	730.9	11	1211	197	0.91	0.56	-42.3
n7008_10a	5.4588	1.45	0.3425	1.35	0.1156	0.53	1889.1	9	1898.7	22	383	168	0.57	{0.01}	
n7008_11a	5.1580	1.47	0.3249	1.36	0.1151	0.55	1882.1	9	1813.6	21	371	161	0.76	{0.02}	-0.5
n7008_12a	5.3564	1.62	0.3361	1.47	0.1156	0.67	1888.8	12	1868.1	23	227	111	1.18	{0.01}	
n7008_13a	5.3843	1.48	0.3368	1.31	0.1159	0.69	1894.4	12	1871.5	21	210	89	0.50	{0.02}	
n7008_14a	5.3403	1.33	0.3386	1.25	0.1144	0.46	1870.2	8	1880.0	20	491	234	1.02	{0.02}	
n7008_15a	5.3603	1.53	0.3363	1.37	0.1156	0.67	1889.2	12	1868.9	22	224	95	0.49	{0.00}	
n7008_16a	5.0999	1.61	0.3219	1.55	0.1149	0.42	1878.5	7	1798.9	24	619	257	0.61	0.03	-1.3
n7008_17a	5.3748	1.56	0.3384	1.42	0.1152	0.65	1882.7	11	1879.1	23	244	116	0.98	{0.02}	
n7008_18a	5.3144	1.55	0.3361	1.41	0.1147	0.63	1874.9	11	1867.9	22	246	103	0.45	{0.00}	
n7008_19a	5.2792	1.68	0.3374	1.47	0.1135	0.81	1856.0	14	1874.0	23	153	65	0.52	{0.01}	

f²⁰⁶% = percentage of common ^{206}Pb in measured ^{206}Pb , estimated from ^{204}Pb assuming a present-day Stacey and Kramers (1975) model. Values are given in braces when no correction has been applied. Th/U = calculated ratio. w.e. = concordant within error (2 σ).

Table S4b. SIMS U-Pb geochronology data for sample Z275-Y454 (geochron).

Spot ID	$^{207}\text{Pb}/^{235}\text{U}$	$\pm s$ (%)	$^{206}\text{Pb}/^{238}\text{U}$	$\pm s$ (%)	$^{207}\text{Pb}/^{206}\text{Pb}$	$\pm s$ (%)	$^{207}\text{Pb}/^{206}\text{Pb}$ age (Ma)	$\pm s$ (Ma)	$^{206}\text{Pb}/^{238}\text{U}$ age (Ma)	$\pm s$ (Ma)	U (ppm)	Pb (ppm)	Th/U	f206%	Disc. (2 σ) (%)
n7009_01a	1.0640	2.84	0.0983	2.50	0.0785	1.34	1159.4	26	604.5	14	2646	338	0.74	0.5	-41.1
n7009_02a	2.7861	1.34	0.1979	1.31	0.1021	0.31	1663.0	5	1163.9	13	2584	675	0.75	0.12	-30.4
n7009_03a	3.5008	1.53	0.2355	1.50	0.1078	0.31	1762.8	5	1363.3	18	2859	920	0.89	0.16	-22.4
n7009_04a	1.3677	1.32	0.1159	1.17	0.0856	0.61	1328.7	11	707.0	7	1851	285	0.82	0.38	-45.6
n7009_05a	1.1678	2.07	0.1034	1.86	0.0819	0.91	1244.0	17	634.2	11	1641	224	0.80	0.5	-45.5
n7009_06a	3.0341	1.68	0.2116	1.62	0.1040	0.44	1696.2	8	1237.6	18	1711	478	0.75	0.03	-26.6
n7009_07a	2.5964	1.36	0.1850	1.28	0.1018	0.45	1656.5	8	1094.5	12	1382	334	0.70	0.24	-34.1
n7009_08a	4.1763	1.29	0.2720	1.25	0.1114	0.30	1821.9	5	1550.8	17	2385	855	0.72	0.01	-14.2
n7009_08b	5.2298	1.42	0.3333	1.39	0.1138	0.29	1860.9	5	1854.4	22	1329	578	0.66	0.01	
n7009_09a	0.8985	3.87	0.0872	3.36	0.0748	1.91	1062.3	38	538.7	17	2385	263	0.64	0.11	-37.8
n7009_10a	0.9564	1.58	0.0927	1.35	0.0748	0.81	1062.9	16	571.7	7	2322	286	0.84	0.84	-42.6
n7009_11a	1.9192	6.37	0.1446	6.22	0.0962	1.38	1552.3	26	870.8	50	2359	469	0.95	0.43	-37.0
n7009_12a	1.0080	1.69	0.0953	1.58	0.0767	0.59	1112.8	11	587.0	8	1627	200	0.72	{0.02}	-45.2
n7009_12b	1.0281	1.86	0.0928	1.72	0.0804	0.71	1205.8	14	572.0	9	2218	265	0.69	0.11	-50.1
n7009_13a	0.6664	1.48	0.0736	1.27	0.0657	0.76	795.6	15	457.8	5	3181	320	0.99	0.54	-37.5
n7009_14a	1.3731	1.48	0.1195	1.23	0.0833	0.82	1276.4	16	727.9	8	1333	204	0.66	0.94	-40.3
n7009_15a	3.9677	1.28	0.2597	1.25	0.1108	0.30	1812.7	5	1488.3	16	1929	651	0.65	0.03	-17.6
n7009_16a	1.1692	1.41	0.1060	1.21	0.0800	0.72	1197.5	14	649.3	7	1397	191	0.70	0.24	-43.4
n7009_17a	1.8840	1.34	0.1473	1.18	0.0928	0.63	1483.1	12	885.8	9	958	184	0.72	0.28	-39.4
n7009_17b	2.0625	1.64	0.1549	1.59	0.0966	0.42	1559.4	7	928.1	13	2725	576	0.91	0.24	-40.6
n7009_18a	0.8698	1.57	0.0876	1.32	0.0720	0.84	985.6	17	541.5	6	1734	198	0.77	0.56	-40.8
n7009_19a	1.0714	1.69	0.0962	1.53	0.0808	0.73	1215.8	14	592.2	8	1574	201	0.84	0.44	-48.8
n7009_20a	1.1870	1.51	0.1070	1.29	0.0805	0.78	1208.3	15	655.3	8	1639	236	0.90	0.81	-43.0
n7009_21a	1.7447	1.37	0.1413	1.27	0.0896	0.51	1416.3	9	851.9	10	1674	339	1.16	0.28	-39.4

n7009_22a	0.8317	2.06	0.0858	1.73	0.0703	1.12	937.4	22	530.6	8	1562	175	0.76	0.63	-36.8
n7009_23a	3.1873	1.25	0.2162	1.21	0.1069	0.30	1747.7	5	1261.7	13	2469	718	0.82	0.19	-28.4
n7009_24a	4.0662	1.55	0.2648	1.50	0.1114	0.39	1822.1	7	1514.2	20	2369	840	0.79	0.1	-15.9
n7009_24b	3.2943	1.30	0.2234	1.25	0.1069	0.38	1747.8	6	1300.0	14	1516	445	0.71	0.11	-25.7
n7009_25a	0.6880	1.65	0.0758	1.37	0.0658	0.91	801.2	19	470.9	6	1885	187	0.80	0.5	-35.1
n7009_26a	4.8942	1.27	0.3116	1.25	0.1139	0.23	1862.5	4	1748.8	19	2581	1088	0.83	0.01	-4.4
n7009_27a	2.8444	2.40	0.1949	2.35	0.1058	0.52	1729.1	9	1147.8	24	2775	738	0.89	0.17	-32.8
n7009_28a	1.1575	1.67	0.1051	1.55	0.0798	0.62	1193.3	12	644.5	9	1453	197	0.69	0.13	-44.1

$f^{206}\%$ = percentage of common ^{206}Pb in measured ^{206}Pb , estimated from ^{204}Pb assuming a present-day Stacey and Kramers (1975) model. Values are given in braces when no correction has been applied. Th/U = calculated ratio. w.e. = concordant within error (2σ).