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Meta-volcanosedimentary rocks in the Nautanen area, Norrbotten: preliminary lithological and deformation characteristics

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Cover: Thin to medium bedded, compositionally and texturally banded, intermediate (andesitic) metavolcaniclastic rock, Nautanen area. Photo: Edward Lynch.

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ABSTRACT

Preliminary lithological, structural and alteration characteristics of Paleoproterozoic metavolcanosedimentary rocks in the Nautanen area (Norrbotten, northernmost Sweden) are presented. The rocks form part of a regional continental arc-related volcanosedimentary succession which was deposited, deformed and metamorphosed during the Svecokarelian orogeny (c. 1.9–1.8 Ga).

The investigated sequence (part of the Muorjevaara group) is dominated by fine-grained (tuffaceous) metavolcaniclastic rocks, displaying gradational textural and compositional banding. Locally, poorly-sorted, agglomerate-like horizons containing coarser clasts (lapilli- to block-size) also occur. Interbedded sections of fine-grained, metasedimentary rocks of probable volcanic derivation display syn-depositional laminae and cross-bedding and provide field constraints for way-up and paleocurrent direction. Throughout the sequence, intercalations of phyllite, mica schist, amphibolite and rare calcareous horizons also occur. Least altered samples indicate a predominantly intermediate (basaltic andesitic to andesitic), calc-alkaline composition for the sequence.

The study area is transected by the approximately north-north-west-trending Nautanen deformation zone (NDZ), a major composite brittle-ductile structure hosting hydrothermal Cu-Au±Fe mineralisation (e.g. Nautanen deposit). Here, the bedrock is relatively intensely sheared, transposed and folded. Outside the high-strain zone, steeply plunging folds with mainly north-north-west oriented axial planes occur. Discordant brittle deformation also affects the study area.

Pervasive and vein-related hydrothermal alteration is variably developed across the area. In the Nautanen deformation zone, characteristic garnet porphyroblasts and biotite-amphibole-magnetite±sulphide banding are associated with sericite-scapolite, K-feldspar and tourmaline±apatite±sulphide assemblages. Late-stage epidote±quartz alteration also occurs. Comparison of least altered and NDZ-hosted samples (pervasively altered, mylonitic) show that the latter are relatively enriched in Cu, Ag, Au, Fe, Mo and W, and thus display typical geochemical affinities and metal abundance correlations associated with hydrothermal iron oxide-copper-gold (IOCG)-type mineralisation.

SAMMANFATTNING

Preliminära litologiska, strukturella och omvandlingsegenskaper hos paleoproterozoiska, metamorfa och vulkanosedimentära bergarter i Nautanenområdet (Norrbotten, nordligaste Sverige) presenteras. Berggrunden är en del av en lagerföljd i en regional, kontinental, magmatisk båge, som avsattes, deformerades och omvandlades under den svekokarelska orogenesen (ca 1,9–1,8 miljarder år).

Den undersökta sekvensen utgör en del av Muorjevaaragruppen och domineras av finkorniga (tuffitiska) metavulkanoklastiska bergarter med skiktvisa graderingar i textur och sammansättning. Lokalt finns dåligt sorterade, agglomeratliknande horisonter med grövre fragment (lapilli- till blockstorlek). Inlagringar av finkorniga, metasedimentära bergarter med sannolikt vulkaniskt ursprung är primärt laminerade och korsskiktade, vilket ger uppåt- och strömriktningar. Genom hela sekvensen finns skikt av lersten, glimmerskiffer, amfibolit och underordnade kalkstenar. Prover av de minst omvandlade bergarterna från den östra delen av undersökningsområdet visar på övervägande intermediär (basaltandesitisk till andesitisk), kalkalkalin sammansättning.

Undersökningsområdet genomkorsas av Nautanendeformationszonen (NDZ), en sammansatt spröd-plastisk zon som är värdbergart till hydrotermala Cu-Au±Fe-mineraliseringar (t.ex. Nautanenförekomsten). I NDZ är berggrunden relativt intensivt skjuvad, transponerad och veckad. Utanför den starkast deformerade zonen finns storskaliga veck med ungefär nordnordvästligt strykande axialplan och spröda strukturer i andra riktningar.

Penetrativa, metasomatiska–hydrotermala omvandlingar och ådror finns i varierande grad i undersökningsområdet. I NDZ är karaktäristiska granatporfyroblaster och magnetit-biotitband associerade med sericit-skapolit-turmalin±sulfidaggregat. Senare epidot±albitomvandling finns också. En jämförelse mellan prover av de minst omvandlade bergarterna och bergarterna i NDZ (som är penetrativt omvandlade och mylonitiska) visar att de senare är relativt anrikade på Cu, Ag, Au, Fe, Mo och W, och har en metallsammansättning som liknar den som finns i hydrotermala förekomster av järnoxid-koppar-guld-typ.

INTRODUCTION

The composite Svecokarelian orogeny (also referred to as Svecofennian) is recognised as a major period of crustal reworking and growth on the margins of the Fennoscandian Shield during the Paleoproterozoic (e.g. Nironen 1997, Korja et al. 2006). In northernmost Sweden (Norrbotten), c. 1.9–1.8 Ga volcanic, sedimentary and intrusive rocks (and their related structures) record a protracted and episodic tectonothermal evolution associated with Svecokarelian accretionary orogenesis and terrane amalgamation (e.g. Bergman et al. 2001, Stephens & Weihed 2013, cf. Lahtinen et al. 2005).

Regional-scale assessments of Svecokarelian-related supracrustal rocks across Norrbotten (i.e. meta-volcanosedimentary cover sequences) have helped establish a lithostratigraphic framework for the area and provide a lithotectonic context for its metallogenic evolution (e.g. Witschard 1984, Bergman et al. 2001, Martinsson 2004, Weihed et al. 2005). More detailed, local-scale investigations of specific supracrustal sequences and associated structures at key stratigraphic intervals are, however, generally lacking (cf. Edfelt et al. 2006, Wanhainen et al. 2006). Such investigations are warranted in Norrbotten, given the association of local volcanosedimentary basins and transecting deformation zones with hydrothermal base and precious metal mineralisation (e.g. Frietsch 1984, Smith et al. 2007).

In this report, we present the preliminary results of a focused investigation of Paleoproterozoic supracrustal rocks (c. 1.9 Ga) occurring in the Nautanen area, near Gällivare in northern Norrbotten (Fig. 1). The study area contains a relatively conformable succession of meta-volcanosedimentary rocks (part of the Muorjevaara group) and is transected by a major shear zone that hosts hydrothermal Cu-Au±Fe mineralisation (Nautanen deformation zone, NDZ). New outcrop observations, structural measurements, lithogeochemistry and geophysical data are integrated to ascertain a preliminary assessment of the lithological, deformation and alteration characteristics of the area.

Our ultimate aim is to develop a comprehensive lithostratigraphic appraisal of the meta-volcanosedimentary sequence in the Nautanen area and to characterise the effects of overprinting deformation and metasomatic-hydrothermal alteration. Given the area's association with iron oxide-copper-gold (IOCG) style mineralisation, its spatial proximity to the world-class Aitik Cu-Ag-Au deposit and the broad similarity between the rocks at Nautanen and the host rocks at Aitik (e.g. Monro 1988, McGimpsey 2010), constraining both primary and secondary geological processes in the area remains an important goal. Presently, shear zone-hosted hydrothermal IOCG-style mineralisation represents a significant exploration target throughout Norrbotten and northern Fennoscandia (Billström et al. 2010).

REPORT LAYOUT, STUDY APPROACH AND CONTEXT

This report firstly presents an overview of the geology, stratigraphy and geochronology of the Gällivare–Nautanen area. This is followed by an assessment of the primary (depositional) characteristics of the investigated meta-volcanosedimentary sequence based on lithological and lithogeochemical data. Subsequently, a description of geological structures and metasomatic-

Figure 1. Location of the Nautanen area (small red polygon) in Norrbotten county, northernmost Sweden. The black square corresponds to map sheet 28K Gällivare representing an area of 2500 km².

hydrothermal alteration is presented. Finally, the appendix contains some practical and logistical information about the field observations, sampling and the structural and geophysical measurements made during 2014, along with some additional geophysical data.

In this investigation, the "Nautanen area" corresponds to the study area outlined in Figure 2 and extends beyond the Nautanen Cu-Au deposit and related deformation zone. For practical, descriptive and geological reasons, we have subdivided the study area into three lithological–structural domains (Fig. 2). From east to west they are: (1) the Eastern volcanosedimentary domain (EVD, Muorjevaara to Linaälven area), (2) the central Nautanen deformation zone domain (NDZ) and (3) the Western volcanosedimentary domain (WVD, Pahtavaara–Huivijokki area). This report presents preliminary results from the Eastern volcanosedimentary domain and Nautanen deformation zone domain only. Future reports will incorporate results from the Western volcanosedimentary domain.

The work presented here forms part of SGU's ongoing *Barents Project* (2012–2016), which includes targeted geological investigations in northern Norrbotten (e.g. Lynch et al. 2014), regional bedrock mapping at 1:250 000-scale in southern Norrbotten (e.g. Nysten et al. 2014) and several focused geophysical investigations (e.g. Juhojuntti et al. 2014). The broad aim of the project, funded by the Swedish Ministry of Enterprise and LKAB, is to further our understanding of unresolved stratigraphic, structural and metallogenic processes in Norrbotten through the integration of new geological, geophysical and geochemical data. In addition, our work from the Nautanen area integrates with the ongoing SIPSTRIM research project "Multi-scale four-dimensional geological modelling of the Gällivare area" by a Luleå University of Technology

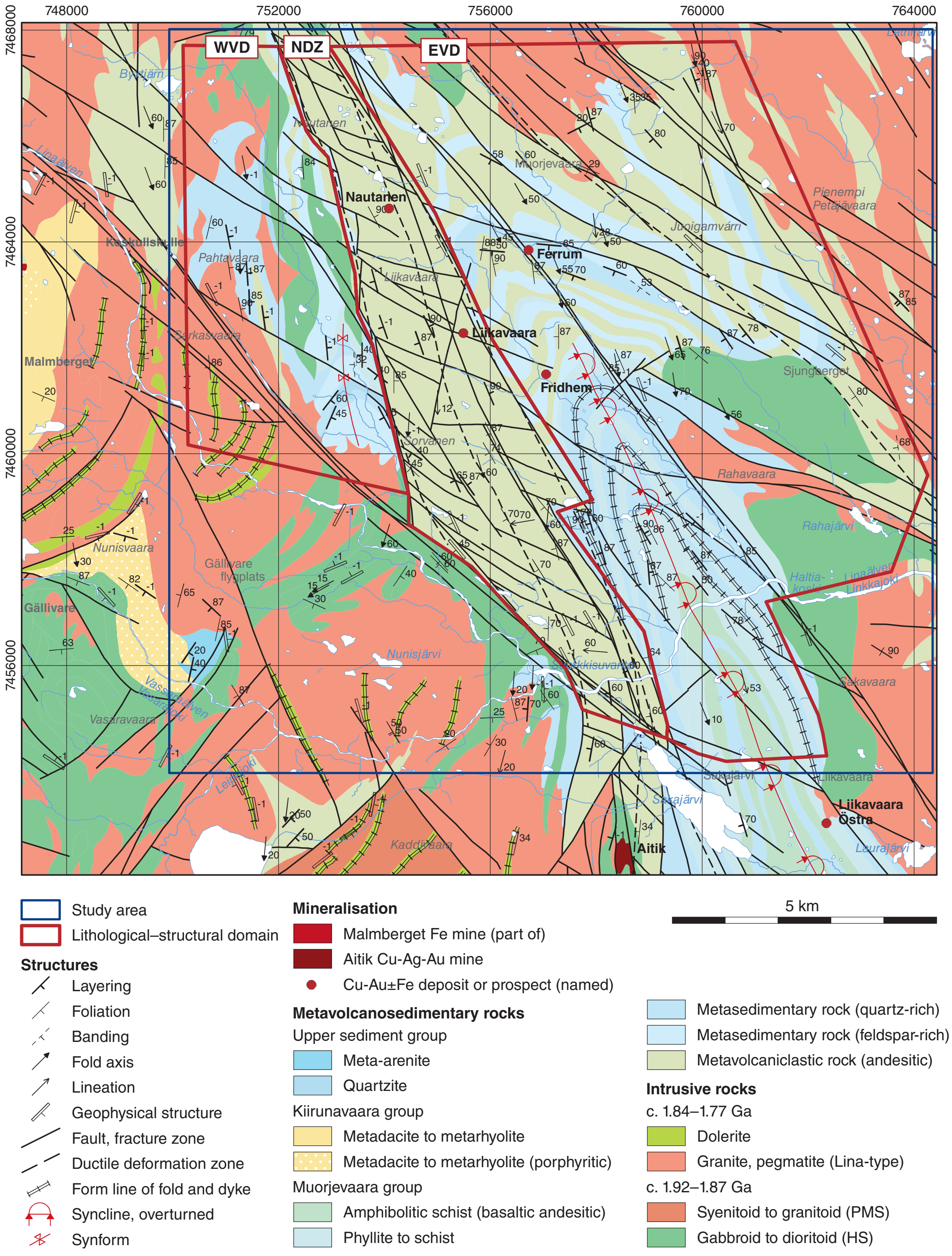

Figure 2. Geology of the Gällivare–Nautanen area (modified after Witschard 1996). Abbreviations: EVD = Eastern volcanosedimentary domain, HS = Haparanda suite, NDZ = Nautanen deformation zone domain, PMS = Perthite-monzonite suite, WVD = Western volcanosedimentary domain.

team (authors Tobias Bauer, Zimer Sarlus, Olof Martinsson and others), funded by Vinnova, Boliden and LKAB (e.g. Bauer et al. 2014).

GEOLOGY OF THE GÄLLIVARE–NAUTANEN AREA

The Gällivare–Nautanen area is centred on an approximately rectangular zone of Paleoproterozoic meta-volcanosedimentary and metavolcanic rocks that form part of a regional supracrustal succession deposited, deformed and metamorphosed during the Svecokarelian orogeny (Witschard 1996, Bergman et al. 2001, Fig. 2). Generally, the supracrustal sequence has a calc-alkaline to alkaline, andesitic to rhyolitic composition, and has undergone extensive deformation, metamorphism, recrystallisation and hydrothermal alteration (McGimpsey 2010, Tollefsen 2014). While primary lithological characteristics are often obscured by multiple overprinting events, the rocks are considered to have been deposited by volcanic, volcaniclastic and sedimentary (epiclastic) processes within an evolving continental arc-type setting (e.g. Witschard 1996, McGimpsey 2010).

Subordinate intermediate and voluminous acidic intrusive rocks also occur across the study area (Fig. 2). They primarily consist of gabbroids, dioritoids, syenitoids and granitoids assigned to the c. 1.89–1.86 Ga Haparanda and Perthite-monzonite suites (e.g. Witschard 1984, 1996), and younger c. 1.79–1.77 Ga granites of the Lina suite (Bergman et al. 2001, 2002).

Tollefsen (2014) reported pressure-temperature estimates for regional, contact and retrograde metamorphic conditions for the Nautanen area, based on mineral chemistry and thermodynamic modelling. Regional metamorphism is constrained to c. 550–660 °C and 2–5 kbar (i.e. lower to middle amphibolite facies). Contact metamorphism adjacent to Lina-type granite (forming a sillimanite-biotite-muscovite assemblage) is constrained at c. 630–710 °C and 2.0–4.4 kbar. Metamorphic retrogression occurred between c. 430 and 570 °C, and 3.0–3.5 kbar.

Supracrustal rocks in the Gällivare–Nautanen area host the Malmberget iron mine, Sweden's second largest iron resource after the Kiirunavaara deposit in Kiruna, and the Aitik Cu-Ag-Au deposit, one of Europe's largest copper mines. Additionally, several relatively small-tonnage, hydrothermal Cu-Au±Fe occurrences, tentatively assigned to the 'iron oxide-copper-gold (IOCG)' mineral deposit class (e.g. Carlon 2000, cf. Williams 2010) occur within a significant, approximately north-north-west-trending shear zone termed the Nautanen deformation zone (NDZ). Episodic deformation along this zone probably enhanced permeability and hydrothermal fluid flow, resulting in a relatively focused, linear zone of alteration and mineralisation (cf. Witschard 1996, Bauer et al. 2014).

Stratigraphy and regional correlations

A formally defined and consistently adopted lithostratigraphy for the Gällivare–Nautanen area has not been established (cf. Monro 1988). Likewise, the application of stratigraphic principles to the area has been somewhat hampered by the interchangeable and sometimes inconsistent use of stratigraphic terms such as 'formation' and 'group' (e.g. Zweifel 1976, Carlson 1989, Martinsson & Wanhainen 2004a). Furthermore, the use of different lithological terms for broadly similar rocks, combined with generally poor exposure and the polydeformed nature of the area, has contributed to a difficulty in defining a systematic and correlative lithostratigraphy (see Table 1 below).

Zweifel (1976) subdivided the general Gällivare–Nautanen-Aitik area into four stratigraphic units. They are (from approximately east to west): (1) the *Liikavaara group* (southern part of the Eastern volcanosedimentary domain of this study), (1) the *Muorjevaara* (Muorjevare) *group* (northern part of the Eastern volcanosedimentary domain, this study), (3) the *Nautanen group* or formation (Nautanen deformation zone domain, this study) and (4) the *Aitik group* or formation (southern extension of Nautanen deformation zone domain, not part of this study). Zweifel (1976) suggested that the Muorjevaara, Nautanen and Aitik groups are stratigraphically equivalent and represent the lowermost rocks in the area, while the Liikavaara group forms an overlying sequence. This informal stratigraphy was generally adopted by subsequent workers as a stratigraphic framework for Cu-Au exploration in the area (e.g. Ros 1980, Gustafsson 1985, Danielsson 1985, Gustafsson 1986).

Witschard (1996) assigned the bulk of the supracrustal rocks in the Gällivare–Nautanen area to the *Porphyry group*, thus adopting the stratigraphic nomenclature established in the Kiruna area (cf. Offerberg 1967). In this scheme, the meta-volcanosedimentary rocks form a basal to middle sequence within the Porphyry group, while the metavolcanic rocks at Malmberget represent the uppermost part. In addition, locally occurring quartzite units were assigned to an inferred overlying *Upper sediment group* (Figs. 2 and 3, cf. Witschard 1984). A correlation between this uppermost quartzite and the Hauki quartzite group in the Kiruna area has been proposed (Ödman 1940).

Martinsson & Wanhainen (2004a) subsequently assigned the meta-volcanosedimentary succession to an all encompassing *Muorjevaara group*, which incorporated the Muorjevaara, Nautanen, Aitik and Liikavaara groups (or formations) proposed by Zweifel (1976). In addition, the metavolcanic rocks hosting the Malmberget iron deposit were assigned to the overlying Kiruna porphyryies or *Kiirunavaara group* (cf. Martinsson & Wanhainen 2013).

For this report, we retain the basic stratigraphic framework outlined by Martinsson & Wanhainen (2004a) and incorporate some aspects proposed by Witschard (1996). A schematic outline of the stratigraphy for the area (at the stratigraphic group level) is presented in Figure 3.

In summary, Muorjevaara group rocks represent a lowermost meta-volcanosedimentary sequence. These are overlain by the Kiirunavaara group, comprised of intermediate to acidic metavolcanic rocks that host the Malmberget iron deposit. Finally, quartzites of the Upper sediment group represent the uppermost stratigraphic unit. The Muorjevaara and Kiirunavaara groups, respectively, partly correspond to the regional Porphyrite and Porphyry groups of Bergman et al. (2001). In the absence of outcropping contacts and precise geochronology (see below), the three broad stratigraphic groups are inferred to be separated by unconformities. Ongoing geological mapping and geochronology hopes to provide more robust geological and temporal constraints for this basic stratigraphic framework.

Regional correlations between Muorjevaara group rocks and equivalent meta-volcanosedimentary successions elsewhere in northern Norrbotten are permissible based on broad lithological criteria (e.g. Ros 1980, Martinsson 1995). Inferred correlative successions include (from approximately west to east, Fig. 3): (1) Kilavaara group schist, amphibolite and quartzite in the Svapavaara-Vittangi area (Eriksson & Hallgren 1975), (2) Ruutivaara and Haaravaara group paragneiss and amphibolite in the Lainio area (Witschard 1970), (3) Pahakurkio group schist, amphibolite and quartzite in the Tärendö area (Padget 1970) and (4) Sammakkovaara group schist and metavolcaniclastic rocks in the Pajala area (Padget 1977, Martinsson 2004). In the latter case, correlation with the Sammakkovaara group and related metavolcaniclastic rocks is supported by similar lithogeochemical signatures (cf. Luth et al. 2015). A correlation between the Muorjevaara group and rocks of the Kurravaara conglomerate unit in the Kiruna area has also been proposed (Ros 1980, cf. Offerberg 1967).

Age constraints

Direct radiometric dating of Muorjevaara group meta-volcanosedimentary rocks has not been conducted in the Gällivare–Nautanen area (Fig. 3). However, dating of inferred analogous units from elsewhere in Norrbotten provide approximate temporal constraints for the sequence.

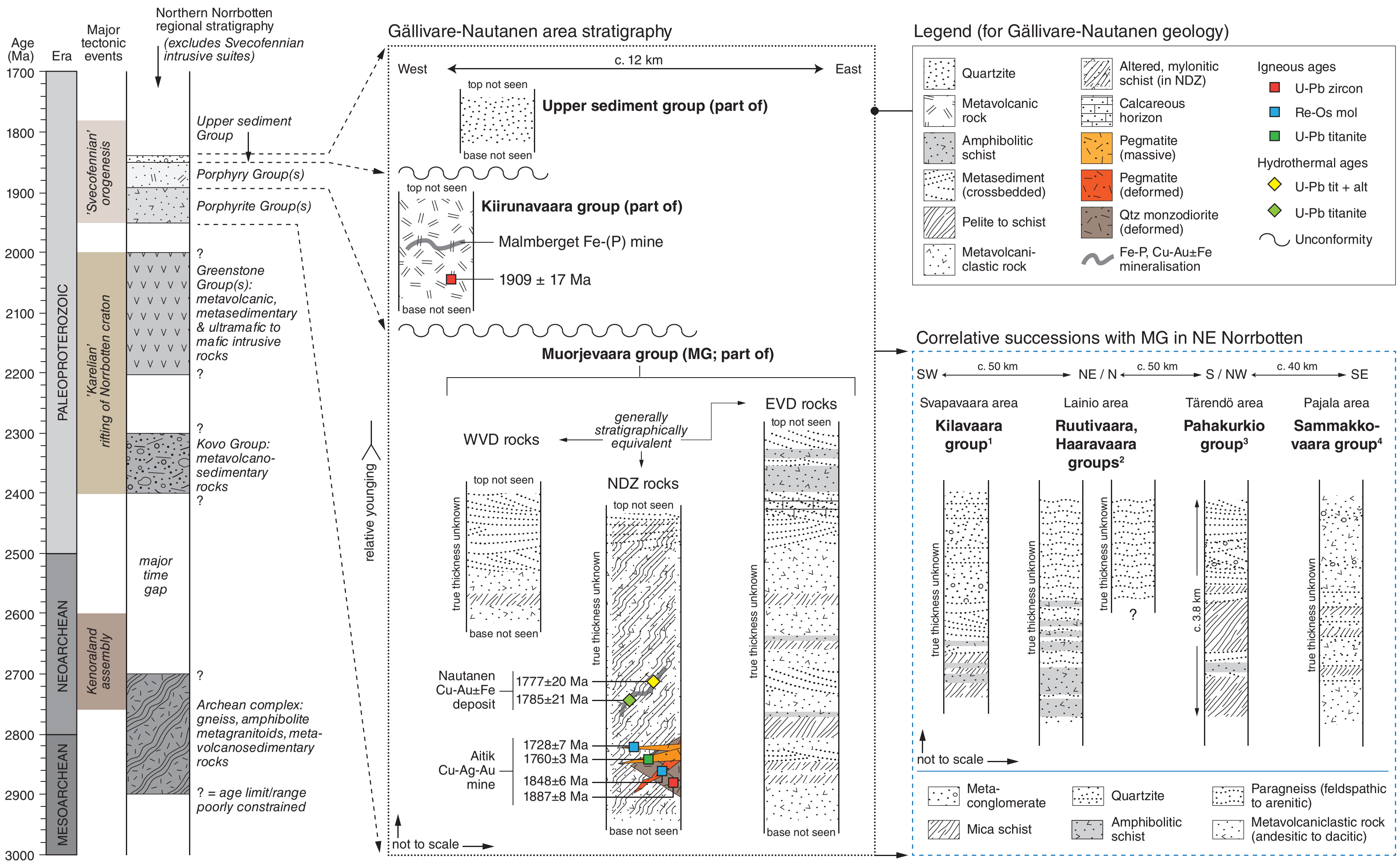

Figure 3. Summary stratigraphy of the Gällivare-Nautanen area (based on Zweifel 1976, Witschard 1996, Bergman et al. 2001, Martinsson & Wanhainen 2004a). Abbreviations: EVD = Eastern volcanosedimentary domain, MG = Muorjevaara group, NDZ = Nautanen deformation zone domain, WVD = Western volcanosedimentary domain. Geochronology references: U-Pb zircon ages = Skiöld & Cliff (1984), Wanhainen et al. (2006), Re-Os molybdenite (mol) ages = Wanhainen et al. (2005), U-Pb titanite (tit) and allanite (alt) ages = Wanhainen et al. (2005), Smith et al. (2009). Schematic stratigraphy of correlative north-east Norrbotten successions is based on: 1 = Eriksson and Hallgren 1975, 2 = Witschard 1970, 3 = Padget 1970, 1977, 4 = Martinsson 2004.

Edfelt et al. (2006) reported a U-Pb LA-ICP-MS zircon age of 1878±7 Ma for a porphyritic meta-andesite located c. 100 km north-west of Gällivare (Tjårrojåkka area), which they assigned to the regional Porphyrite group (i.e. partly Muorjevaara group equivalent). This age coincides with several ages from the Aitik deposit (Fig. 3), including a U-Pb SIMS zircon age of 1887±8 Ma for a quartz monzodiorite stock (Wanhainen et al. 2006), and a Re-Os molybdenite age of 1875±10 Ma for a barite-sulphide vein (Wanhainen et al. 2005). It also overlaps with typical c. 1.89 to 1.88 Ga igneous ages reported for Kiirunavaara group metavolcanic rocks in the Kiruna area and elsewhere in the region (e.g. Welin 1987, Romer et al. 1994, Bergman et al. 2001, Westhues et al. 2014).

As part of a dating study in the Pajala shear zone (north-east Norrbotten), Bergman et al. (2006) obtained a U-Pb SIMS age of c. 1910±12 Ma from a single zircon core obtained from Sammakkovaara group meta-volcanosedimentary rocks in the Pajala area (i.e. possible Muorjevaara group equivalent, see Fig. 3). Likewise, Lahtinen et al. (2015) report U-Pb LA-ICP-MS ages of c. 1.92–1.91 Ga for detrital zircons obtained from metasedimentary rocks in the southern Pajala shear zone. These ages at least partly correlate Sammakkovaara group and related meta-volcanosedimentary rocks with a relatively older phase of Svecokarelian-related volcanism and sedimentation and, by inference, support field relationships seen in the Nautanen area where Muorjevaara group rocks are crosscut by c. 1.89 Ga Haparanda suite intrusions (see section *Field and contact relationships*).

Skiöld & Cliff (1984) reported a U-Pb TIMS zircon age of 1909±17 Ma for Kiirunavaara group metavolcanic rocks close to Gällivare (Fig. 3), albeit using zircons derived from an aggregate sample collected from different locations across the region. Storey et al. (2007) obtained U-Pb LA-ICP-MS titanite ages of c. 2.07, 1.92 and 1.71 Ga for hanging wall metavolcanic rocks at the Malmberget iron deposit (Kiirunavaara group). While these dates suggest that multiple metasomatic events affected the area coincident with episodic Svecokarelian-related tectonothermalism, the precise timing of Kiirunavaara group volcanism remains equivocal.

The Nautanen deformation zone and related Cu-Au±Fe mineralisation

The Gällivare–Nautanen area is transected by a regionally significant, approximately north-north-west-trending shear zone termed the Nautanen deformation zone (NDZ, Witschard 1996). It represents the most conspicuous structural feature in the area and is clearly delineated on magnetic anomaly maps as a somewhat dilational, linear zone of sub-parallel and tightly banded magnetic anomalies. This coupling of high-strain deformation and magnetic banding reflects episodic metasomatic-hydrothermal fluid flow, probably enhanced by increased permeability associated with protracted and focused deformation (e.g. Pitkänen 1997, Smith et al. 2013).

Based on regional structural and magnetic lineament geometries, Bergman et al. (2001) assigned a dextral-oblique shear sense to the Nautanen deformation zone, with a south-west-side up reverse component. Earlier geological mapping and geophysical measurements within the shear zone also identified several sub-parallel, north-north-west-orientated, moderately plunging folds (e.g. Gustafsson 1984, Pitkänen 1997). Internally, the deformation zone is characterised by moderate to intense shearing, mylonitisation, structural transposition and pervasive metasomatic-hydrothermal alteration. Further details on the structural and alteration characteristics of the Nautanen deformation zone are presented below in subsequent sections.

Meta-volcanosedimentary rocks within and adjacent to the Nautanen deformation zone host several, generally small-tonnage (<2.5 Mt) replacement and vein-related (epigenetic-style) Cu-Au±Fe deposits and prospects (see reviews by Martinsson & Wanhainen 2004a, 2004b, 2013). Important examples include the Nautanen, Liikavaara and Ferrum prospects (Fig. 2). Two general styles of mineralisation are recognised (e.g. Gustafsson 1985, Martinsson & Wanhainen

2004a): (1) an inferred older phase of disseminated to semi-massive (replacement style) mineralisation occurring as locally deformed, stratiform lenses mainly within the Nautanen deformation zone (e.g. Nautanen deposit, Danielsson 1984, 1985), and (2) mineralisation associated with quartz±tourmaline±amphibole veins occurring mainly east of the Nautanen deformation zone (e.g. Ferrum prospect, Gustafsson & Johnsson 1984), or as a late-stage brittle overprint within the high-strain zone (e.g. Nautanen). Chalcopyrite with lesser bornite and chalcocite represent the main ore minerals and are typically associated with pyrite and magnetite. Gold generally occurs as inclusions and segregations in sulphide (e.g. Bark et al. 2013).

Smith et al. (2009) reported U-Pb LA-ICP-MS titanite and allanite ages ranging from c. 1.79to 1.78 Ga for hydrothermal alteration at the Nautanen deposit and inferred a temporal and genetic link between deformation, fluid mobilisation and Lina-type felsic magmatism (Fig. 3). Given the protracted and episodic nature of mineralisation seen at the Aitik deposit south of Nautanen (e.g. Wanhainen et al. 2005), it is probable that coupled deformation-hydrothermal processes within the Nautanen deformation zone may have been active over a similarly extended period.

MUORJEVAARA GROUP META-VOLCANOSEDIMENTARY ROCKS IN THE NAUTANEN AREA

This section contains a preliminary description of Muorjevaara group rocks in the study area, with an emphasis on their primary geological features. An overview of their spatial distribution, field relationships and lithological features is presented, along with some preliminary lithogeochemistry. Lithological descriptions are based on outcrop observations from the Eastern volcanosedimentary domain (EVD) and Nautanen deformation zone domain (see the appendix), while the lithogeochemistry data is from the Eastern volcanosedimentary domain only. The rock descriptions presented here complement previous accounts by Zweifel (1976), Ros (1980), Monro (1988) and Witschard (1996).

Field and contact relationships

In the Nautanen area, Muorjevaara group rocks form a c. 10 × 15 km, approximately north-north-west-aligned, oblate to rectangular basin (Fig. 2). An assessment of the true thickness of the sequence is complicated by the lack of exposed contacts with underlying and overlying successions, along with polyphase folding and shearing in the area. However, based on the 1:50 000-scale geological cross-sections presented by Witschard (1996), a minimum thickness of c. 1.3–2.5 km is estimated for the succession.

To the north, east and west of the study area, the succession is intruded by aerially extensive plutonic rocks (Fig. 2). These consist of (1) subordinate, generally foliated and locally folded, gabbroic, dioritic and granodioritic plutons assigned to the c. 1.89 Ga Haparanda suite, and (2) more voluminous, weakly deformed to massive granitic intrusions assigned to the c. 1.79 Ga Lina suite (e.g. Witschard 1996, Bergman et al. 2002). Additional intrusive rocks occur to the west and south-west outside the study area and include c. 1.88 Ga PMS-related monzonite and <1.8 Ga doleritic dykes and sills (Witschard 1996, Bergman et al. 2001).

To the south of the Nautanen area, the meta-volcanosedimentary sequence narrows toward a c. 2 km wide 'pinch zone' adjacent to the Aitik deposit (Fig. 2). Beyond Aitik, analogous Muorjevaara group rocks continue south along two general south-south-west- and south-south-east-trending belts that are covered by the1:50 000-scale 27K Nattavaara map sheet (Claeson & Antal Lundin 2012).

Overall, the meta-volcanosedimentary sequence shows a degree of spatial variability across the study area. In the northern part of the Eastern volcanosedimentary domain, metavolcaniclastic units dominate with locally occurring and interbedded metasedimentary horizons (Fig. 2). In the southern part of the Eastern volcanosedimentary domain, coincident with a prominent north-north-east-aligned synform, metasedimentary rocks (of probable volcanic derivation) are more common, with lesser metavolcanic horizons. In the Western volcanosedimentary domain (WVD, Fig. 2), metasedimentary rocks, similar to those in the southern part of the Eastern volcanosedimentary domain, most commonly occur. Across the area as a whole, phyllitic, schistose and rare gneissic varieties of the main rock types occur as intercalated zones or horizons (cf. Table 1).

SGU's 1:50 000-scale mapping has not delineated internal lithologic variation within the Nautanen deformation zone (NDZ) domain due to the relatively intense, transposed nature of the deformation zone and pervasive metasomatic-hydrothermal alteration (Witschard 1996, cf. Fig. 2). However, NDZ-hosted rocks in several lower-strain zones have outcrop-scale characteristics similar to the main rocks units occurring in the eastern and Western volcanosedimentary domains (e.g. laminated to bedded forms, generally mesocratic and compositionally intermediate appearance, local volcaniclastic and sedimentary textures). These features, combined with their lithogeochemical signatures and the general discordant and transecting nature of the Nautanen deformation zone, suggest the deformed and altered rocks in the Nautanen deformation zone domain form an integral part of the Muorjevaara group succession and probably had similar internal variability to that seen to the east and west, prior to shear zone transposition and hydrothermal overprinting (see below for further discussion).

Where visible, inter-unit relationships are generally gradational and interbedded, suggesting a broadly contemporaneous and relatively conformable depositional sequence. However, folding and faulting across the area has resulted in structural dismemberment of the package, which has complicated the stratigraphy. At outcrop scales, the gradational and intercalated nature of the sequence is apparent as centimetre- to metre-scale, textural and compositional banding, as well as variable deformation and foliation intensities. In general, internal variability at the outcrop scale appears to reflect the banded, interbedded and layered lithological and geophysical anomaly patterns seen in both geological and magnetic anomaly maps.

Rare intrusive contacts in the Nautanen area provide field evidence for the temporal relationship between intrusive rocks and Muorjevaara group units and help establish the number and sequence of intrusive events (Fig. 4). Dioritic and granitic bodies of varying size intrude the sequence typically parallel to primary bedding and dominant foliations (sills), or as discordant veins or dykes with moderate to high angles relative to the principal planar fabrics (Figs. 4A–B).

In the Eastern volcanosedimentary domain, fine- to medium-grained (c. 0.5–3 mm), dioritic dykes and veins intrude metavolcaniclastic rocks with sharp contacts (Fig. 4A). These minor intrusions resemble larger-scale, medium- to coarse-grained (c. 1–8 mm), diorite to quartz monzodiorite bodies in the area, and contain similar textural and lithological features (e.g. mafic enclaves, Figs. 4A–E). At the Aitik deposit to the south of the study area, a monzodioritic stock that is petrologically similar to the crosscutting dioritic intrusions in the Nautanen area has yielded a crystallisation age of c. 1.89 Ga (Wanhainen et al. 2006). This age thus provides an inferred minimum age for the Muorjevaara group succession in the Nautanen area (i.e. approximately 1.89 Ga or older, cf. Fig. 3).

Granitic rocks also crosscut the meta-volcanosedimentary sequence with sharp, igneous contacts and typically intrude parallel to primary and overprinting structures (Fig. 4). They occur as relatively abundant, c. 1–15 m thick, medium- to coarse-grained (c. 1–10 mm), granitic to locally pegmatitic, sill-like bodies (Figs. 4B–C) and minor, c. 1–5 cm thick, fine- to medium-grained (c. 0.5–5 mm) aplite veins and segregations (Fig. 4D). Where present, granitic veins consistently

Table 1. Summary of the main Muorjevaara group meta-volcanosedimentary units in the Nautanen area (listed by decreasing relative abundance).

Field term (with textural, metamorphic qualifiers; inter-unit relationships)	**Protolith term (with textural, compositional qualifiers) 1**	**Historical, literature term (with reference)**
In the Eastern volcanosedimentary domain (EVD):		
1. Metavolcaniclastic rock (tuffaceous, recrystallised, locally schistose, local volcanic and lithic clasts, compositionally banded, laminated, transitional or interbedded with 2, 3 and 4).	Andesitic to dacitic (intermediate), well-sorted, fine to very coarse tuff to lapilli-tuff. Locally poorly sorted lithic tuff and agglomeritic (volcanic breccia) horizons.	Leptite (Geijer 1918) Biotite gneiss (Ros 1980) Basic to intermediate, calc-alkaline to alkaline, metavolcanic rock, tuff (Witschard 1996) Metaandesite (Bergman et al. 2000)
2. Metasedimentary rock (recrystallised appearance, laminated, locally cross-bedded, more texturally and compositionally uniform compared to 1, interbedded with 1).	Andesitic to rhyodacitic (intermediate) fine to coarse tuff or volcanic siltstone to sandstone (volcanogenic epiclastic rock).	Meta-arenite (Zwifel 1976) Metaarkose (Ros 1980) Meta-arenite (Witschard 1996) Metaarenite, quartzite (Bergman et al. 2000)
3. Mica schist (weathers proud, micaceous sheen, generally intercalated or transitional with 1 and 2, possible compositional variant of 1).	Basaltic andesitic to andesitic (intermediate), fine to very coarse tuff.	Mica schist (Geijer 1918) Pelitic intercalation (Ros 1980) Phyllite to biotite schist (Witschard 1996) Pelite (Martinsson & Wanhainen 2004)
4. Amphibolitic schist (dark greenish grey, foliated, aligned grains, intercalated with 1 and 2, major unit in Lina river synform hinge zone).	Basaltic andesitic (basic to intermediate), fine to very coarse tuff, to fine lapilli-tuff	Amphibolitic rock (Zwifel 1976) Greenstone intercalation (Ros 1980) Amphibolitised andesite, dacite, trachyandesite (Witschard 1996) Metabasalt (Bergman et al. 2000)
In the Nautanen deformation zone (NDZ) domain:		
5. Mica±amphibole schist (conspicuous garnet porphyroblasts, pervasive sericite±scapolite and K-feldspar altered with local biotite-amphibole-magnetite and tourmaline banding. Locally mylonitic. NDZ-hosted equivalent to 1, 3 and possibly 2).	Andesitic to dacitic (intermediate) fine to very coarse tuff, locally agglomeritic tuff (breccia). Variably sheared, transposed, metasomatised and altered.	High magnetic, biotite-garnet±amphibole schist to gneiss (Zwifel 1976) Biotite-muscovite-garnet gneiss (Ros 1980) Variably magnetic, basic-intermediate, calc-alkaline-alkaline, metavolcanic rock, tuff (Witschard 1996) Metaandesite (Bergman et al. 2000) Shoshonitic metavolcanic rock (McGimpsey 2010)

1 = protolith terms follow volcaniclastic nomenclature of White & Houghton (2006) and incorporate preliminary lithogeochemical results.

± = locally occurring.

Figure 4. Muorjevaara group and intrusive rock field relationships. **A.** Bedding view (to the north-east) of well sorted, laminated, metavolcaniclastic rock cut by west-north-west-aligned, dioritic veins. Note elongate mafic enclaves in the veins (arrows) that are compositionally similar to the enclave shown in E. **B.** Along-strike view (to the south-east) of contact (dashed line) between massive granite sill and amphibole-mica schist. **C.** View to the north-north-east of contact (dashed line) between reddish-pink, massive granite sill and mica schist. **D.** Bedding view (to the south-west) of north-west-aligned, laminae-parallel, aplitic veins crosscutting magnetite-altered, biotite schist. **E.** View to the south-west of weak to moderately foliated monzodiorite with mafic microgranular enclave (arrow). Crosscutting, north-west-aligned, granitic vein is seen near the top. **F.** View to the south-west of north-west-aligned aplite vein crosscutting monzodiorite.

crosscut larger dioritic bodies and thus reflect inferred absolute ages for the two main intrusive suites in the general Gällivare–Nautanen area (Figs. 4E–F).

Overall, field and contact relationships in the Nautanen area provide indirect constraints for the geological and temporal evolution of Muorjevaara group meta-volcanosedimentary rocks and adjacent intrusive bodies, consistent with previous studies (e.g. Witschard 1996).

Lithological features

Based on outcrop observations in the Eastern volcanosedimentary domain and the Nautanen deformation zone domain, four broad lithological units are recognised. They are: (1) metavolcaniclastic rocks, (2) metasedimentary rocks, (3) mica schist horizons and (4) amphibolitic schist. Units 1 and 2 are most common, while units 3 and 4 represent less common lithologies. In general, units 1, 2 and 3 represent compositionally similar lithologies and are primarily distinguished based on textural, structural and deformation intensity criteria. In the Nautanen deformation zone domain, deformed and altered mica-amphibole-feldspar schist (unit 5 in Table 1) is inferred to represent a composite metavolcaniclastic unit comprised of one or more of the other units. Summary descriptions of the different units are presented below and in Table 1. Volcaniclastic terminology in this section is based on White & Houghton (2006).

Metavolcaniclastic rocks

In the central Eastern volcanosedimentary domain, the dominant rock type is a medium to dark grey, fine- to medium-grained (c. 0.1–3 mm), laminated and locally compositionally banded, metavolcaniclastic rock (Figs. 5–6). It forms planar to weakly wavy, generally sub-parallel, medium to very thick (c. 0.1–1 m), laterally continuous beds (Figs. 5A–B). Inter-bed contacts are narrowly gradational to sharp. Internal textural and compositional consistency is somewhat variable and includes generally homogeneous, well sorted and granular units (fine to coarse tuff), and banded, layered and laminated sequences (Figs. 5C–E). Locally, the tuffaceous, granular sections grade into somewhat irregular and wavy weathered beds consisting of mica-rich schist (equivalent to unit 3 in Table 1, cf. Fig. 8) or relatively coarse (c. 1–4 mm) feldspathic-rich bands and seams (Fig. 5B). The former tend to have a strongly developed micaceous sheen, while the latter may partly represent more compositionally felsic horizons. Locally, tuffaceous sections display multiple, repeat grading sequences that alternate between very coarse tuff at the base (locally containing somewhat pumiceous, felsic clasts) to fine tuff at the top (thus, possible reverse density grading, Fig. 5E). In addition, local horizons display cross-laminae that indicate a general younging direction toward the south-west (Fig. 5F).

The metavolcaniclastic rock mainly consists of feldspar, amphibole, biotite and lesser quartz and muscovite within a fine-grained, intergranular (granoblastic) to foliated (lepidoblastic) matrix. Feldspar occurs as anhedral and sub-rounded tabular grains, and is generally sericitised. Locally, feldspar also forms remnant, medium-grained (c. 3–5 mm) phenocrysts (c. 5–8 vol.%). Anhedral prismatic amphibole (hornblende) is intergrown with biotite and feldspar as irregular, matted, elongate and cleaved grains. Local magnetite disseminations or thin bands and veinlets (<1 cm) also occur. Generally, biotite and feldspar occur in approximately equal proportions (c. 30–45 vol.%). Locally however, biotite±sericite dominates (up to c. 60–70 vol.%) and thus imparts a more obvious mica schist appearance to the rock (see unit description below). These latter intercalations may also locally represent more altered horizons. In general, prismatic and tabular matrix grains tend to exhibit a preferred sub-parallel alignment (generally parallel to primary structures and foliations). Within the Eastern volcanosedimentary domain, a median magnetic susceptibility for relatively fresh (least altered) metavolcaniclastic rocks is 853×10^{-5} SI units (n = 32).

Figure 5. Metavolcaniclastic rocks in the Nautanen area. **A.** Along-strike view (to the south-east) of medium- to thickly-bedded, intermediate, fine to coarse tuff. **B.** Bedding view to the south-west of thin- to medium-bedded, compositionally and texturally banded, intermediate metavolcaniclastic rock. **C.** View to the east-south-east of recrystallised, intermediate fine to coarse tuff. **D.** View to the north-east of intermediate metavolcaniclastic unit (tuff) with steeply dipping, sub-parallel amphibole-magnetite veinlets. **E.** Bedding view (to the north-east) of thinly laminated, well sorted, fine to coarse tuff. Slightly coarser, epidote-altered layers (arrows) with rare sub-rounded clasts indicate possible normal grading to the north-east. **F.** Bedding view (to the south-west) of finely laminated, well-sorted, intermediate tuff with remnant elongate (feldspathic) clast. Dashed lines indicate orientation of laminae (cross-lamination) indicating younging direction.

Locally, metavolcaniclastic parts contain coarser clastic material (>3 mm) that forms fine- to medium-grained lapilli-tuff horizons (Fig. 6B). In addition, poorly-sorted sections containing coarse, blocky clasts form local agglomeritic (volcanic breccia-like) horizons (Figs. 6A,

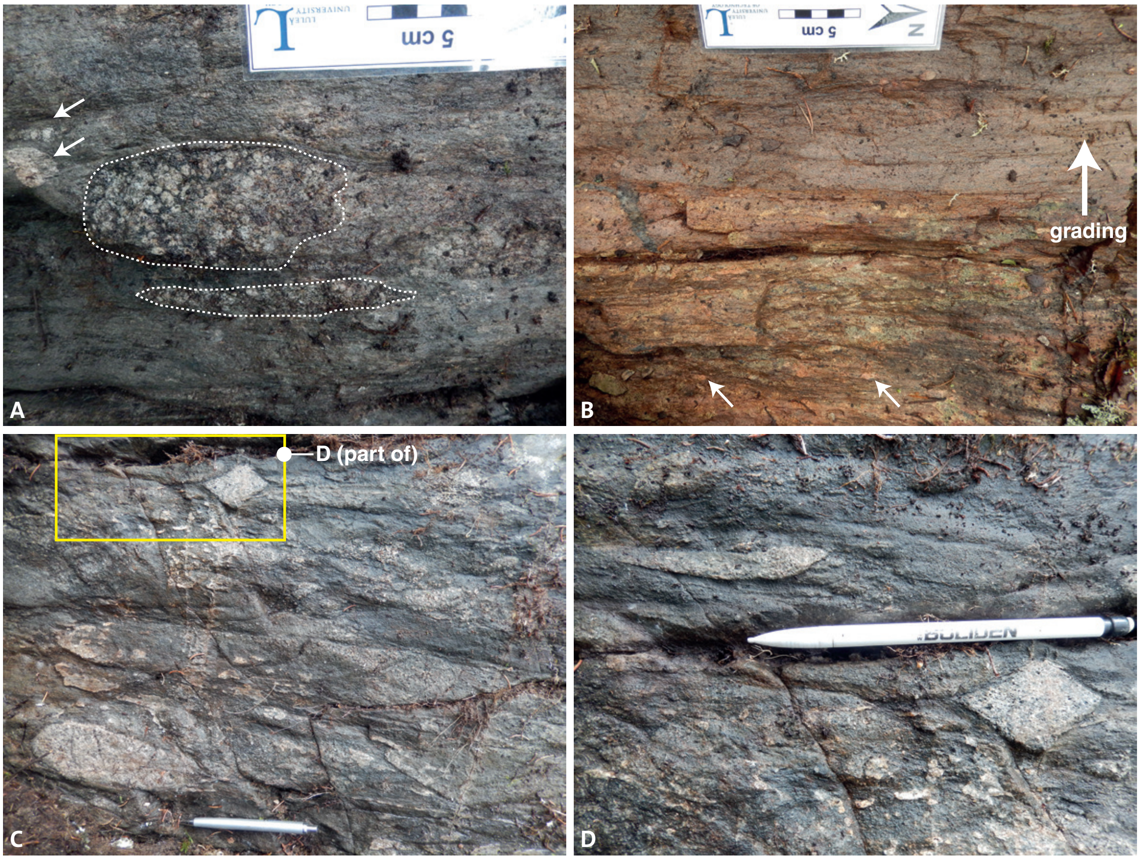

Figure 6. Metavolcaniclastic rocks with lithic and volcanic (juvenile) clasts. **A.** Bedding view (to the south-west) of variably biotite-magnetite altered and schistose, fine to coarse, lithic tuff. Two types of deformed clasts are visible: aggregated granular clasts (dashed outline) and relatively homogeneous felsic clasts (arrows). **B.** Bedding view (to the south-west) of poorly sorted, metavolcaniclastic unit containing irregular felsic clasts (arrows) grading into well sorted and laminated, fine-grained volcaniclastic unit. **C–D.** Bedding view (to the west-south-west) of poorly sorted and foliated volcaniclastic (agglomeritic) unit containing a mixture of deformed, angular to sub-rounded coarse (lapilli and block-sized) granular (intrusive?) and fine-grained felsic clasts.

6C–D). Two broad clasts types are recognised: fine-grained (<0.5 mm), sub-rounded to elongate or flattened, compositionally uniform felsic clasts (possible juvenile volcanic clasts, Figs.6A–B), and medium- to coarse-grained (c. 0.1–10 cm), aggregated granular types (probably lithic clasts, Figs. 6C–D). In poorly sorted sections, the latter clasts are locally up to 8 cm in size (Figs. 6C–D).

Overall, the metavolcaniclastic rocks display a degree of compositional and textural variability across the sequence that reflects the generally interbedded nature of the Eastern volcanosedimentary domain and the geophysical anomaly patterns seen across the area.

Metasedimentary rocks (of probable volcanic derivation)

Throughout the Eastern volcanosedimentary domain, interbedded sections of medium-grey, well-sorted, fine- to medium-grained (c. 0.1–3 mm), generally arkosic to locally arenitic, metasedimentary rocks occur (Fig. 7). Locally, the interbedded sections transition into relatively thick sequences (c. 500–800 m apparent thickness) where metasedimentary rock dominates.

In the Muorjevaara area (northern Eastern volcanosedimentary domain, cf. Fig. 2), a relatively well exposed c. 150 m long, stratified metasedimentary sequence occurs (Fig. 7A). Here the rocks form planar, parallel to locally non-parallel, thin to thick (c. 0.03–0.4 m) and generally laterally continuous beds (Figs. 7A–D). Inter-bed contacts are either narrow diffuse or distinctive and sharp (e.g. Fig. 7C). Internally, the beds contain planar to locally wavy, generally parallel and laterally continuous, thin to medium (c. 0.1–0.3 cm) laminae. Locally, however, parallel and

Figure 7. Metasedimentary rocks in the Eastern volcanosedimentary domain. **A.** View to the west of planar, sub-parallel and laterally continuous, thin to medium bedded, arkosic metasediment (volcanic siltstone to sandstone). **B.** Detail view from A with younging direction toward the south-west. **C.** Bedding view (to the south-west) of fine-grained, medium to thick bedded metasedimentary rock. **D.** Detailed view from C showing sub-parallel, planar beds. **E.** Bedding view (to the south-west) of thin to thickly bedded, planar to curved (non-parallel) metasedimentary rock. **F.** Interpretive sketch of E showing nine bedding co-sets. Sets 4, 5, 8 and 9 contain inclined (ripple) foresets indicating low-angle trough cross-lamination (sets 4 and 5) and herringbone cross-lamination (sets 8 and 9).

lenticular non-parallel beds exhibit inclined cross-laminae (tabular to trough-style, respectively, Figs. 7E–F). Additionally, local co-sets display bi-directional, herringbone-type cross-lamination (Fig. 7F). In general, topset laminae and bedding contacts truncate low-angle (tangential) ripple foresets toward the south-west, providing constraint for way-up and younging direction. Likewise, in the central and southern Eastern volcanosedimentary domain, on the eastern limb of a large synform, cross-stratification suggests general younging toward the south-west (i.e. towards the hinge zone of the fold). These way-up markers are locally supported by rare, normal graded sequences (Fig. 7C). Ripple foreset patterns indicate paleocurrent directions mainly towards the north-north-west, or locally towards the south-south-east.

At the outcrop scale, the metasedimentary rocks appear relatively homogeneous and more lithologically consistent compared to other volcaniclastic and schistose sections, and consist of intergranular (granoblastic) feldspar and quartz with minor amphibole and rare muscovite. Locally, some beds are affected by patchy to banded amphibole-biotite-magnetite and epidote±feldspar alteration. The latter assemblage is the more prevalent and appears to preferentially overprint coarser (coarse to very coarse sand) horizons.

In general, a typical stratified sequence (c. 0.5–2 m thick) consists of alternating very fine to coarse sand (c. 0.1–1 mm) within planar and parallel laminated beds (Figs. 7C–F). These locally grade into wavy and cross-laminated horizons, more typically consisting of coarse to very coarse sand (c. 1–2 mm) These general depositional characteristics are relatively consistent with medium-grained turbidite sequences (cf. Tucker 1991). Other minor features include siliceous, sub-rounded concretions (c. 3–5 cm) locally developed at bedding contacts, and amphibole, epidote and quartz veins. In the Eastern volcanosedimentary domain, a median magnetic susceptibility value for relatively fresh metasedimentary rock is 200×10^{-5} SI units (n = 56), while local biotite-magnetite±amphibole altered outcrops have a median susceptibility value of 2150×10^{-5} SI units (n = 34).

In general, the rocks display sedimentary structures consistent with sub-aqueous deposition. In terms of formational processes, the metasedimentary rocks may represent either volcaniclastic material re-deposited within an active volcanosedimentary basin (i.e. syn-eruptive re-deposition as defined by McPhie et al. 1993), or the product of eroded and re-deposited older lithified material (volcanic ± plutonic) during volcanically inactive periods (i.e. epiclastic rocks in the terminology of Fisher 1961, cf. White & Houghton 2006). Evidence for a dominantly volcanic provenance includes the interbedded and gradational nature of the metasedimentary rocks with other metavolcaniclastic sequences, the common occurrence of feldspar in the matrix, and the general intermediate (andesitic) geochemical composition, similar to volcaniclastic units within the sequence.

Mica schist and other minor units

Intercalations of mica schist locally occur throughout the main meta-volcanosedimentary package in the Eastern volcanosedimentary domain (Fig. 8). They typically form 0.3–1.5 m thick, planar to laterally dilational units, with generally narrow, gradational contacts. At the outcrop scale, they are recognised as texturally distinctive horizons that typically exhibit a more micaceous (lustrous), weathering proud and more obvious schistose appearance, when compared to the more granular and recrystallised metavolcaniclastic and metasedimentary rocks (Figs. 8A and 8C). The intensity of schistosity ranges from phyllitic to gneissic types, with the latter consisting of thinly spaced (c. 1–5 mm), compositionally variable (mesocratic–melanocratic) banding (Fig. 8D). This textural variation probably reflects local contrasts in grain size, deformation intensity, mineralogy and composition, and somewhat mimics the broader lithological variability seen throughout the meta-volcanosedimentary sequence as a whole.

Figure 8. Minor intercalated units in the Nautanen area. **A.** View to the west-south-west of mica schist outcrop. **B.** Bedding view (to the east-north-east) of biotite schist with foliation-parallel feldspathic layers and veins showing tight, recumbent intrafolial folds. **C.** Bedding view (to the east-north-east) of biotite schist with garnet porphyroblasts. **D.** Example of a recrystallised metavolcaniclastic rock displaying schistose to gneissic texture. **E.** View to the north-north-west of amphibolite schist. **F.** Thin calcareous horizon (c. 70 cm wide) with a somewhat vuggy (dolomitic?) texture occurring within an overall metavolcaniclastic unit. View to the north-west.

Mica schist horizons consist of fine-grained (<1 mm), intergranular biotite and feldspar, with lesser muscovite, amphibole and quartz (Figs. 8A–B). Mica grains are aligned and flattened parallel to the main schistosity and sub-parallel to inferred bedding. Locally, medium-grained (c. 3–5 mm) garnet, andalusite and possible cordierite porphyroblasts occur (Fig. 8C). Where garnet and andalusite occurs, secondary hematite-goethite is typically exposed on weathered surfaces. Pervasive, weak to moderately intense sericite alteration is also locally developed. In addition, thin seams and veinlets of feldspathic material are locally developed and are typically orientated parallel to the main schistosity and sometimes tightly folded (Fig. 8B). In general, mica schist horizons have a low degree of magnetism. A median magnetic susceptibility value for mica schist horizons in the Eastern volcanosedimentary domain is 64×10^{-5} SI units (n = 135).

Rare calcareous horizons form local intercalations within the meta-volcanosedimentary pile (Fig. 8F). Typically, they occur as light to medium grey, fine-grained (<1 mm), generally narrow laminated units (<1 m thick), with a somewhat vuggy (dolomitic?) appearance. Narrow gradational contacts with the enclosing volcaniclastic material are generally sub-parallel, weakly lenticular and laterally continuous. Minor intercalations of amphibole schist also occur, which locally become thicker (up to c. 400 m) and form the dominant rock unit (see below).

Amphibolitic schist

In the southern Eastern volcanosedimentary domain, within the hinge zone of a major south-south-east-plunging synform, an amphibolitic schist unit occurs (Fig. 6D). The rock is dark grey to dark greenish-grey and is generally aphanitic to locally amphibole-phyric (c. 3–7 vol.% phenocrysts). It consists of medium- to coarse-grained (c. 1–8 mm), generally sub-rounded, anhedral platy to elongate (subhedral prismatic) amphibole (c. 40–50 vol.%) within a fine-grained (<1 mm), plagioclase-amphibole-biotite±magnetite matrix (c. 35–45%). Recrystallisation of plagioclase and secondary phases such as biotite and chlorite (replacing amphibole) are common. Locally, scapolite appears to replace plagioclase.

The rock has a relatively strongly developed deformation fabric that imparts an overall schistose appearance. The schistosity is typically sub-vertical, north-north-west-orientated and steeply dipping (Fig. 6D). Locally, thin feldspathic lenses and veinlets occur, sub-parallel to the main fabric.

Along the northern bank of the Lina river (Linaälven area) the unit has a relatively low magnetism, with a measured median magnetic susceptibility of 955×10^{-5} SI units (n = 26). Across the Eastern volcanosedimentary domain as a whole, analogous amphibolitic units locally occur as relatively thin (<1 m) intercalations within the main volcaniclastic package. In addition, similar rocks have been observed in the central part of Nautanen deformation zone and at the Salmijärvi Cu-Au prospect, c. 2 km south-south-east of the Aitik mine (Sarlus 2013).

Mica-amphibole-feldspar schist in the Nautanen deformation zone domain (composite meta-volcanosedimentary unit)

The bedrock in the Nautanen deformation zone domain has been affected by relatively intense mylonitisation, folding and metasomatic-hydrothermal alteration. Thus, primary lithological characteristics are commonly obscured or masked by overprinting processes and remain somewhat equivocal (cf. Witschard 1996). However, local lower-strain zones provide some petrographical insights into the primary nature of the rocks in this area and facilitate comparisons with mapped units in the Eastern volcanosedimentary domain.

The dominant lithology is a medium to dark grey, fine- to medium-grained (c. 0.1–3 mm), well-sorted, medium to thickly bedded (c. 0.1–0.5 m) and internally laminated, biotite-amphibole-feldspar schist. Locally, more weakly laminated varieties have a recrystallised, granoblastic appearance and appear more feldspar-rich (up to 40–50 vol.%). Inferred bed forms are generally laterally continuous, sub-parallel and planar. Anhedral and platy biotite and lesser amphibole grains (c. 15–20 and 5–10 vol.%, respectively) are aligned parallel to the dominant penetrative cleavage and are intergrown with feldspar. Throughout the area, local horizons containing coarser (felsic) clasts (c. 5–15 mm), elongate and stretched lensoidal patches (remnant clasts?), and composite, aggregated fragments (lithic clasts?) occur. These features are consistent with a possible volcaniclastic derivation (e.g. Fig. 6). Locally, the schist grades into more quartz-rich sections consisting of fine-grained (<1 mm), granular and anhedral quartz (c. 10–20 vol.%) which forms banded zones and aggregated, irregular to sub-rounded clasts.

Throughout the Nautanen deformation zone domain, the rock has a moderate penetrative foliation, is pervasively altered, and locally contains distinctive reddish-pink, medium- to coarse-grained (c. 1–10 mm), garnet porphyroblasts (c. 3–12 vol.%). Magnetite is a ubiquitous alteration phase. It typically occurs as fine- to medium-grained (c. 0.1–2 mm), anhedral tabular and elongate platy grains within foliation planes. It also forms fracture-filling inclusions and patchy rims around garnet porphyroblasts. Consequently, the bedrock throughout the domain is magnetically anomalous. A calculated median magnetic susceptibility value for potassic altered schist within the Nautanen deformation zone domain is $2\,970 \times 10^{-5}$ SI units (n = 47). Secondary hematite-goethite commonly replaces magnetite, while chlorite replaces biotite and is associated with epidote.

Preliminary lithogeochemistry

Preliminary lithogeochemistry results for meta-volcanosedimentary rocks from the Eastern volcanosedimentary domain are shown in Figure 9. Although the Nautanen area is affected by variably intense hydrothermal alteration, rocks within the Eastern volcanosedimentary domain are generally less pervasively altered compared to those in the Nautanen deformation zone domain. From a total of 32 analyses, a subset (n = 24) of relatively fresh or 'least altered' Eastern volcanosedimentary domain samples were used to geochemically characterise the meta-volcanosedimenatry rocks in the area (Fig. 9A, shaded area). The subset includes a sample of fine-grained, medium grey rock (labelled 'metavolcanic' in Fig. 9A) that contains remnant feldspar phenocrysts and an elevated Na_2O concentration of 6.98 wt.%.

Based on the classification plot of Winchester & Floyd (1977), least altered Eastern volcanosedimentary domain-hosted meta-volcanosedimentary rocks have a sub-alkaline, generally basaltic andesitic to andesitic signature (Fig. 9B), while high field strength element bivariate plots indicate a dominantly calc-alkaline composition (Figs. 9C–D). Metavolcaniclastic, metasedimentary, mica schist and amphibolitic schist samples generally have similar calc-alkaline, intermediate compositions, suggesting a broadly similar volcanic source region and petrogenetic history. The feldspar porphyritic sample (metavolcanic rock, Fig. 9A) plots close to the andesite–dacite boundary and overlaps with the general composition of the other samples.

The geochemical signatures of the Eastern volcanosedimentary domain meta-volcanosedimentary rocks partly overlap with the compositions of altered and mylonitic metavolcaniclastic rocks occurring in the Nautanen deformation zone domain hosting the Nautanen Cu-Au deposit (Fig. 9B, McGimpsey 2010). These latter units have a broader compositional range compared to Eastern volcanosedimentary domain samples that includes dacitic, rhyodacitic and more alkaline trachyandesitic (shoshonitic) varieties. However, the presence of alkaline rocks within the Nautanen deformation zone domain may partly reflect the high degree of pervasive potassic alteration and skarn banding in the area. Similar apparent alkaline enrichment is reported for the metavolcaniclastic rocks hosting the Aitik deposit (Monro 1988, McGimpsey 2010), which also compositionally overlap with both the Eastern volcanosedimentary domain and Nautanen deformation zone domain meta-volcanosedimentary rocks (Fig. 9B).

Overall, the lithogeochemistry data confirm that the rocks within the Nautanen deformation zone domain represent a more intensely deformed and hydrothermally altered variety of the sequence occurring in the Eastern volcanosedimentary domain and that the Muorjevaara group sequence in the Nautanen area is similar to the metavolcaniclastic rocks (biotite-amphibole-feldspar gneiss) hosting Cu-Ag-Au mineralisation at Aitik (cf. Martinsson & Wanhainen 2004a).

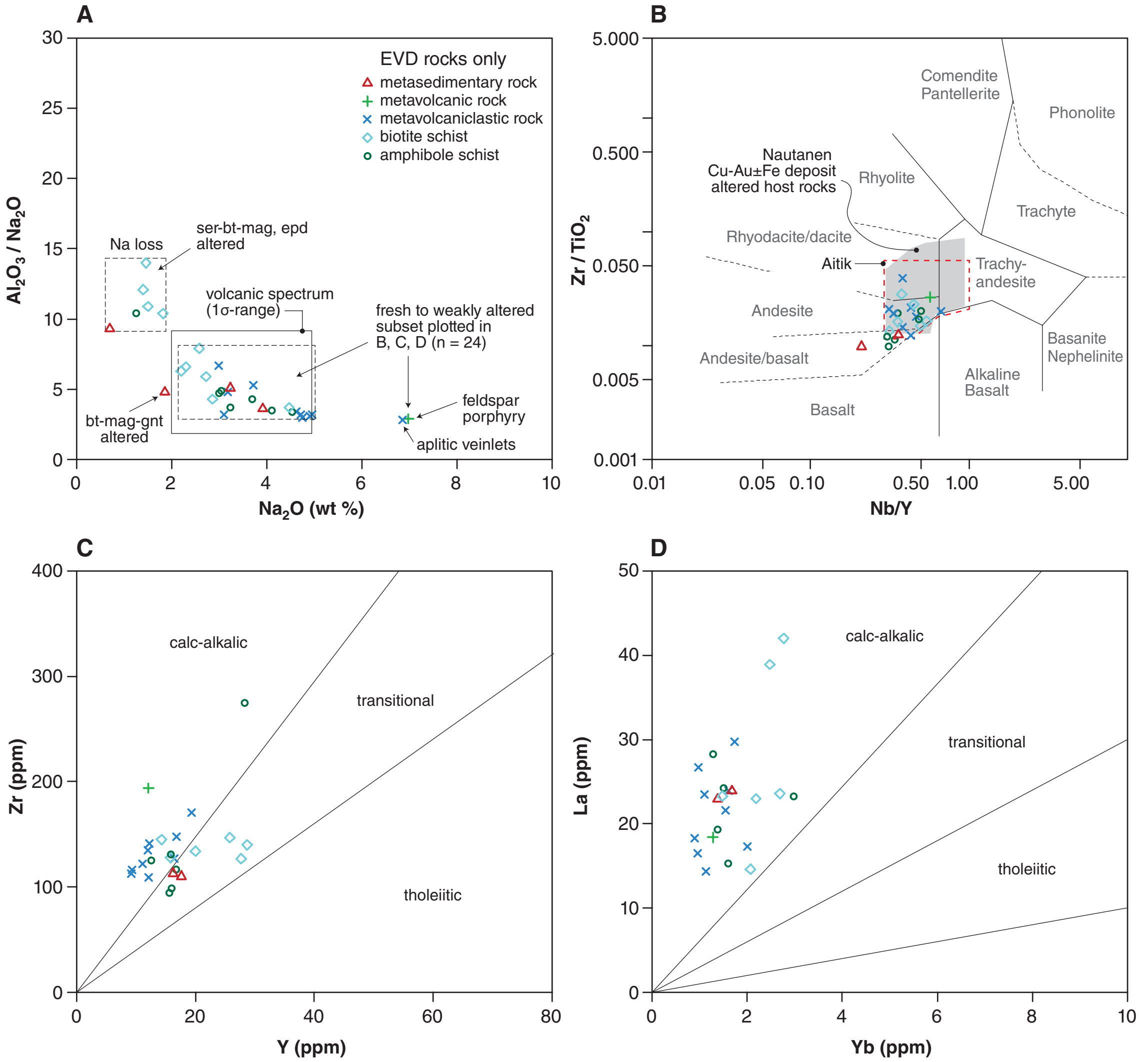

Figure 9. Geochemical classification of Muorjevaara group meta-volcanosedimenatry rocks from the Eastern volcanosedimentary domain, Nautanen area. **A.** Spitz-Darling type plot (Spitz & Darling 1978) delineating weakly altered samples used for the other classification plots shown in B, C and D. The spectrum for fresh volcanic rocks (basalt to rhyolite) is derived from the average and 1σ-range of 6491 analyses reported by Le Maitre (1976). **B.** Incompatible-HFSE classification plot (Winchester & Floyd 1977) showing lithologic-compositional range of Eastern volcanosedimentary domain meta-volcanosedimentary rocks. Shaded area represents the range reported by McGimpsey (2010) for altered metavolcaniclastic rocks hosting the Nautanen Cu-Au±Fe deposit, while the dashed red line represents the approximate range for metavolcaniclastic rocks hosting the Aitik Cu-Ag-Au deposit (cf. Monro 1988). **C–D.** Incompatible-HFSE bivariate plots (after Barrett & MacClean 1999) indicating a predominantly calc-alkalic signature (i.e. equivalent to medium to high K, low to medium Fe, intermediate rocks).

The lithogeochemistry results tentatively support lithostratigraphic correlations between Muorjevaara group rocks in the Nautanen area and meta-volcanosedimentary successions in north-eastern Norrbotten (Pajala shear zone). Luth et al. (2015) report sub-alkaline, mainly andesitic to rhyodacitic compositions for metavolcanic and metavolcaniclastic rocks assigned to the *Suorsa group* in the Pajala area. Certain units within this local group may be equivalent to the Pahakurkio and Sammakkovaara groups in adjacent areas, and are inferred to belong to the regional Porphyrite group of Bergman et al. (2001).

STRUCTURAL GEOLOGY AND DEFORMATION

Structures in the Eastern volcanosedimentary domain

The Eastern volcanosedimentary domain contains a variety of superimposed ductile and brittle structures that record a protracted, multiphase deformation history (Figs. 10 and 11). The most commonly observed fabric is a variably intense, planar penetrative foliation, here designated S1 (e.g. Figs. 10A–B). It is generally north-west- to north-north-west-aligned, moderate to steeply south-west- to west-south-west-dipping, and tends to parallel primary bedding, laminae and compositional banding (Figs. 10–11). Additionally, S1 has a similar orientation to planar foliations in dioritic intrusions hosted by the Eastern volcanosedimentary domain (Fig. 11). The intensity of S1 varies between outcrop and lithology, and where it forms a schistose to gneissic texture, S1 may be a composite fabric (cf. Fig. 6). Locally, S1 is axial planar to tight to isoclinal, asymmetric, intrafolial folds (Fig. 10B).

The Eastern volcanosedimentary domain is characterised by tight to isoclinal folding of primary bedding, compositional banding, alteration banding and foliations. To the immediate east of the Nautanen deformation zone domain (i.e. southern Eastern volcanosedimentary domain) a distinct, large-scale, asymmetrical and overturned syncline is the dominant structure (Fig. 11). The western limb appears to be truncated by approximately north-north-west trending shear zones and faults related to the Nautanen deformation zone. Fold vergences are typically eastward, with axial surfaces aligned approximately north to north-north-west (sub-parallel to the Nautanen deformation zone) and generally steeply dipping towards the west (Fig. 11). The fold shapes are non-cylindrical and fold axes are locally curvilinear. The larger scale fold structures are accompanied by parasitic, asymmetric small-scale folding. In the southern part of the Eastern volcanosedimentary domain, parasitic fold axes commonly plunge with moderate angles towards the south-south-west, whereas in the northern parts fold axes have doubly plunging geometries (typically north-west and south-east). Mineral lineations are gently plunging and have varying orientations.

A discordant, approximately bedding plane-orthogonal crenulation cleavage, here designated S2, also occurs in the Eastern volcanosedimentary domain (Figs. 10D–F). It is generally aligned north to north-north-east, sub-vertical and is axial planar to gentle, upright, moderate south to south-south-east plunging F2 folds (Figs. 10C and 11). The S2 cleavage is associated with L2 intersection lineations that typically have a moderate plunge to the south and south-south-east, similar to F2 fold axes (Fig. 11). Locally, near the hinge zones of larger-scale folds, relatively intense S2/L2 deformation has developed elongate and stretched L-tectonites that form mullion-like features along bedding surfaces (Fig. 10G). Additionally, in eastern limb areas, local bedding plane surfaces with L2 lineations contain slicken-side notches that indicate top-block reverse movement towards the north and north-north-west (Fig. 10H).

Brittle deformation in the Eastern volcanosedimentary domain consists of (1) locally developed spaced cleavage and fracture sets that tend to follow earlier planar structures, (2) numerous north-north-west- to east-aligned, generally sub-vertical amphibole and quartz vein sets (Fig. 11), of which the latter are locally sulphide-bearing (e.g. Ferrum Cu-Au prospect), and (3) joint sets developed in intrusive rocks. Additionally, discordant north- to north-north-east-aligned brittle deformation zones (faults?) are inferred from aeromagnetic data (Fig. 11). These cross-cutting, locally NDZ-related high strain zones segment the Eastern volcanosedimentary domain into several blocks.

Structures in the Nautanen deformation zone

The Nautanen deformation zone (NDZ) is an important regional-scale, composite shear zone in northern Norrbotten and is the most prominent large-scale structural feature in the study

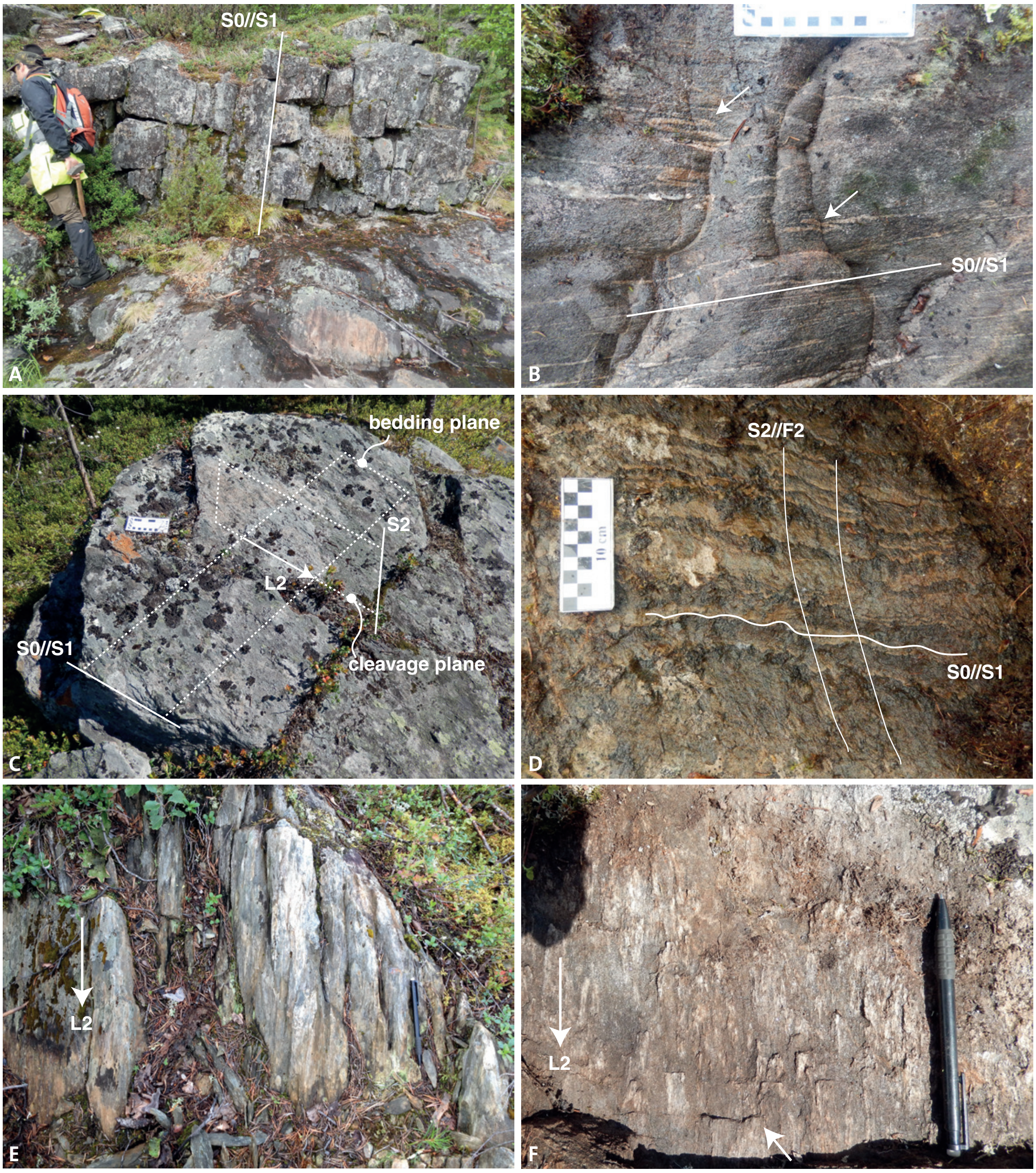

Figure 10. Structures in the Eastern volcanosedimentary domain. **A.** North-north-east view of steeply west-south-west dipping, medium bedded, metavolcaniclastic rocks with bedding parallel S1 foliation. Zimer Sarlus for scale. **B.** Side surface view (to the east-north-east) of laminated and compositionally banded mica schist with dominant bedding parallel S1 foliation. Arrows indicate tight to isoclinal, recumbent, interfolial folding (F1?) of feldspathic bands and veins. **C.** View to the north-east of mica schist showing bedding-cleavage relationship and related south-south-east plunging, L2 intersection lineations. **D.** Top surface view (to the north-north-east) of compositionally banded metasediment showing bedding parallel S1 foliation affected by steep S2 cleavage, axial planar to gentle, upright, south-south-east plunging F2 folds. **E.** Top surface view (to the north-north-west) of mica schist with stretched south-south-east plunging, L2 intersection lineation associated with mullion-like features. **F.** Bedding surface view (to the north) showing moderate, south to south-south-east plunging L2 intersection lineations. Arrow marks slicken-side notches that suggest top block movement toward the north.

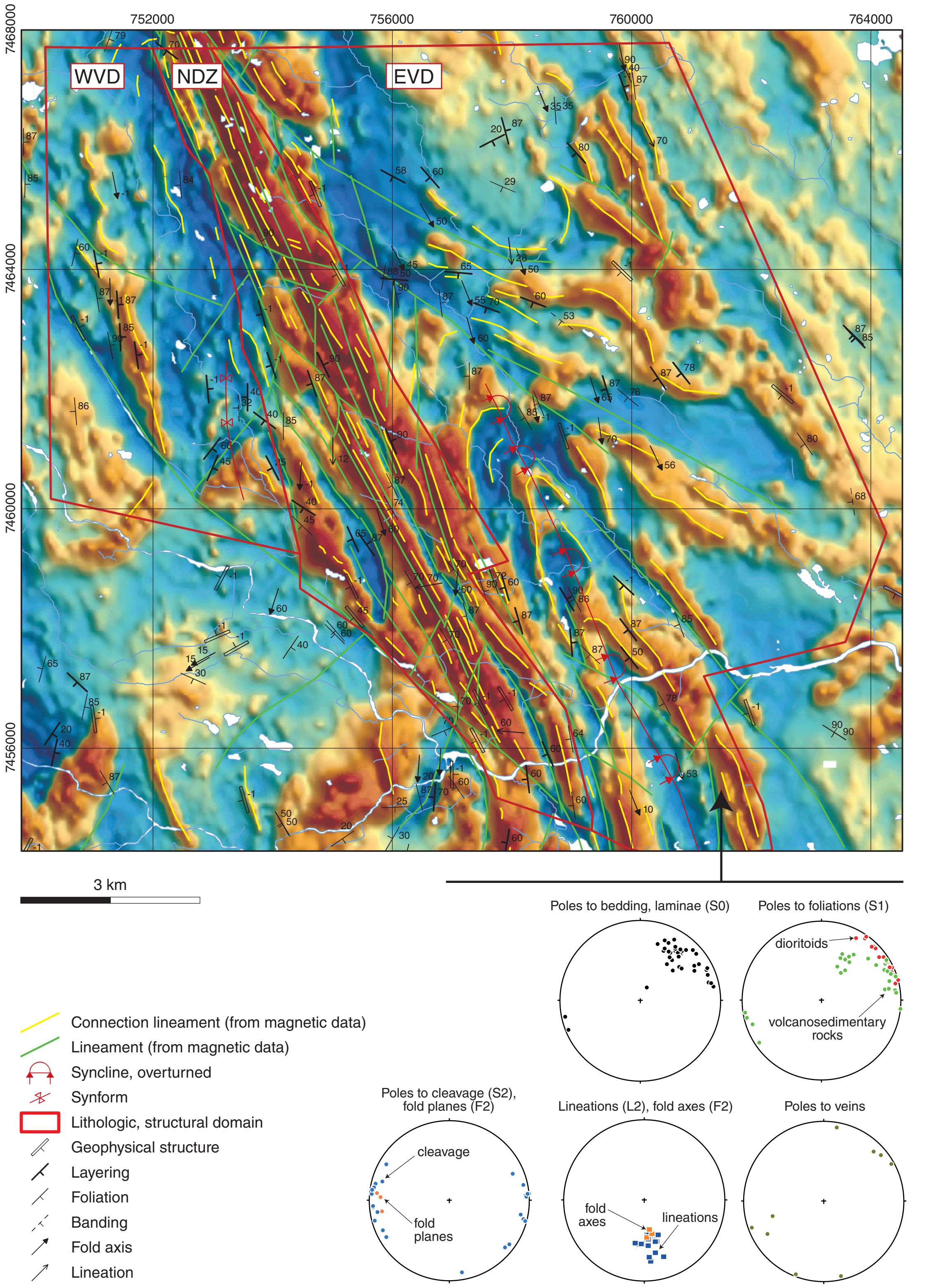

Figure 11. Airborne-derived magnetic anomaly map showing interpreted magnetic connections and structural lineaments. Equal-area, lower hemisphere stereonets with plotted structural measurements from Eastern volcanosedimentary domain meta-volcanosedimentary rocks are also shown. EVD = Eastern volcanosedimentary domain, NDZ = Nautanen deformation zone, WVD = Western volcanosedimentary domain.

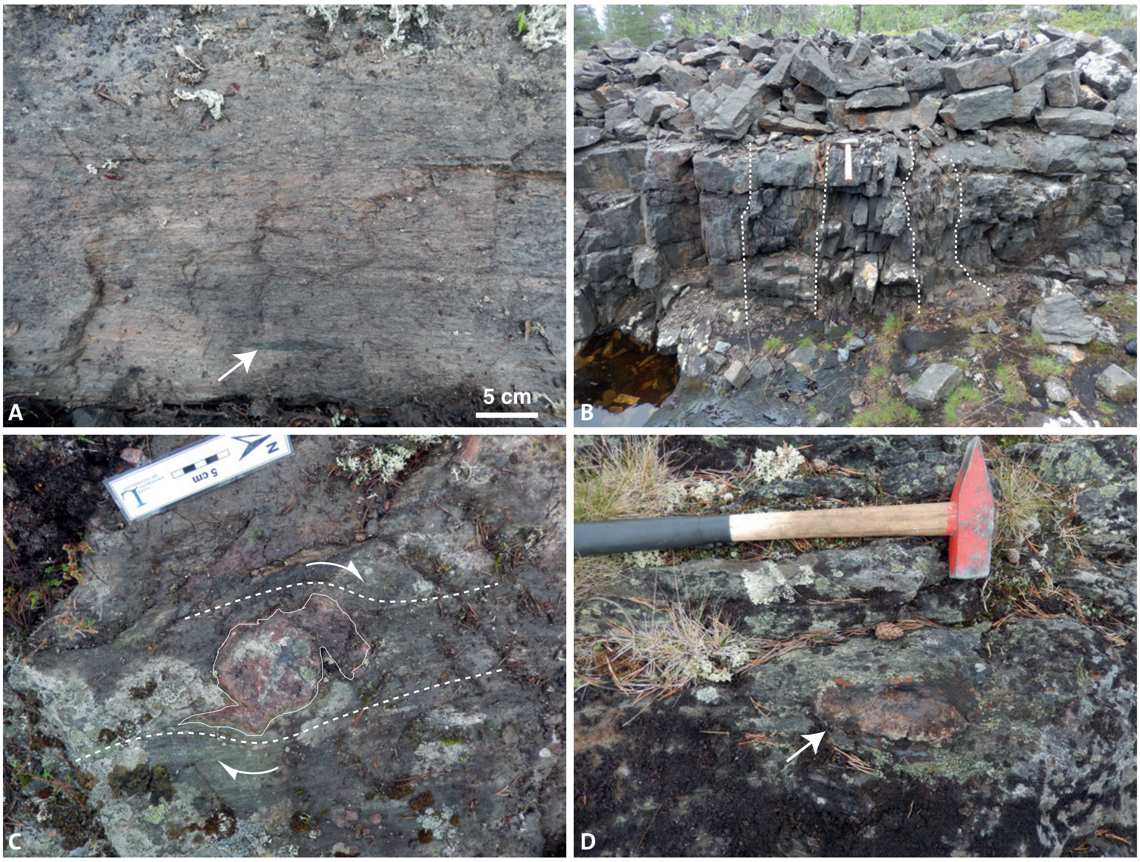

Figure 12. Structures related to the Nautanen deformation zone. **A.** Top surface, bedding view (to the west-south-west) of dominant bedding parallel, steeply west-south-west dipping, penetrative S1 schistosity affecting biotite-magnetite altered metavolcaniclastic rocks. Arrow indicates altered and stretched clast replaced by biotite. **B.** Top surface view (to the west) of late-stage garnet porphyroblast partly deflecting S0–S1 fabrics in schist. Deflection pattern and garnet growth tails indicate possible dextral rotation sense. **C.** Top surface view (to the west-south-west) of elongate (stretched?) garnet porphyroblast (arrow) in biotite-magnetite-altered schist. **D.** Along strike side view (to the south-south-east) showing localised high-strain shearing (dashed lines) of altered schist.

area (e.g. Bergman et al. 2001). Here, it occurs as a c. 300 m to 2 km wide, distinct high strain deformation zone, characteristically delineated on aeromagnetic maps by planar, sub-parallel, approximately north-north-west striking positive magnetic anomalies (e.g. Fig. 11).

Structurally, the Nautanen deformation zone is characterised by a conspicuous north-north-west to north-west oriented, steep to locally moderate, generally west-dipping, penetrative foliation with varying but generally strong intensity (Figs. 12A–B). Locally observed primary bedding, compositional banding and alteration banding are typically transposed into steep orientations parallel to the dominant foliation and locally produce a composite fabric.

The dominant shearing direction strikes approximately north-north-west and shows mainly west-block up reverse kinematics and common oblique dextral and less common sinistral components evident as asymmetric foliation deflection around garnet porphyroblasts (Figs. 12C–D) and local asymmetric kink bands (Fig. 13A). Minor asymmetric folding related to shearing is mainly evident from folded hornblende-, magnetite- and epidote-filled veinlets (Fig. 13B). To the south of the study area, at the Aitik deposit (cf. Fig. 2), the shear zones are orientated more north–south and dip moderately towards the west with distinct west-plunging mineral lineations.

Figure 13. Kinematic indicators in the Nautanen deformation zone. **A.** View to the south-west of small-scale dextral kink bands (arrow) in mica schist. **B.** View to the south-south-west (along strike) of asymmetric folding of magnetite-filled veinlets in a mica-amphibole schist.

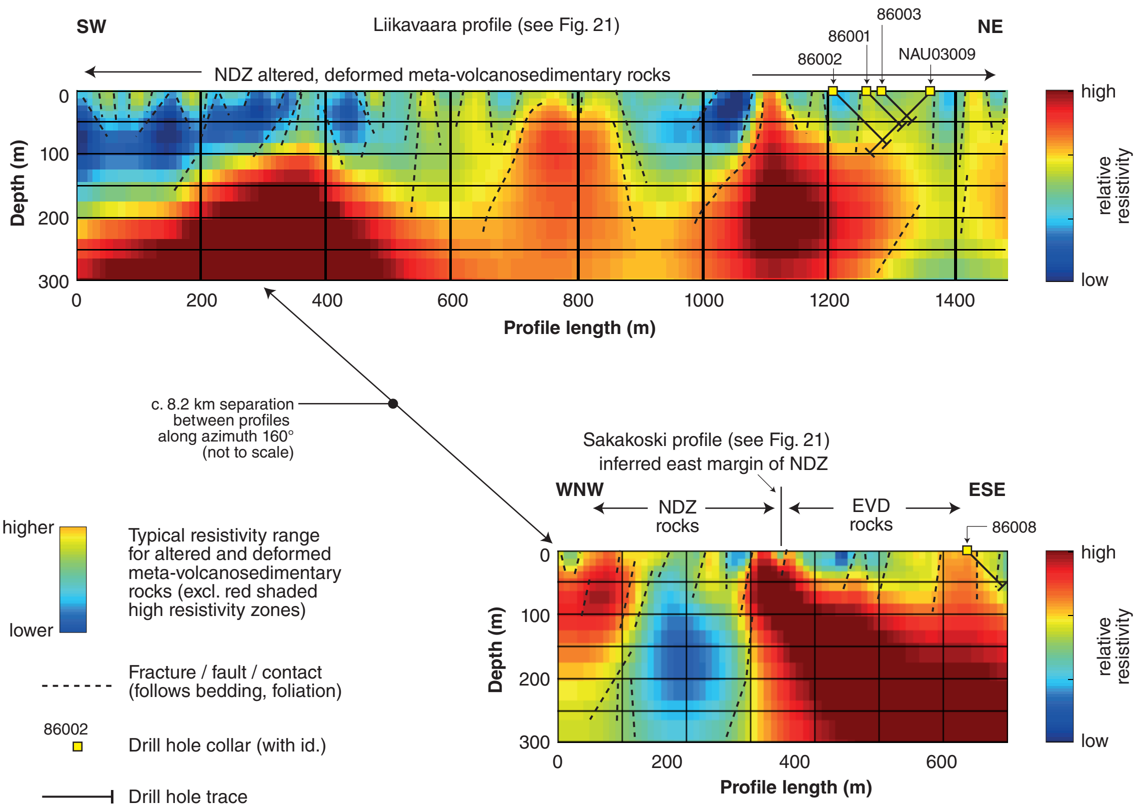

Figure 14. VLF resistivity models for two profiles in the Liikavaara and Sakakoski areas of the Nautanen deformation zone (profile lines are shown in Figure 21). Note the variation in the profile orientations. See text for discussion. NDZ = Nautanen deformation zone, EVD = Eastern volcanosedimentary domain.

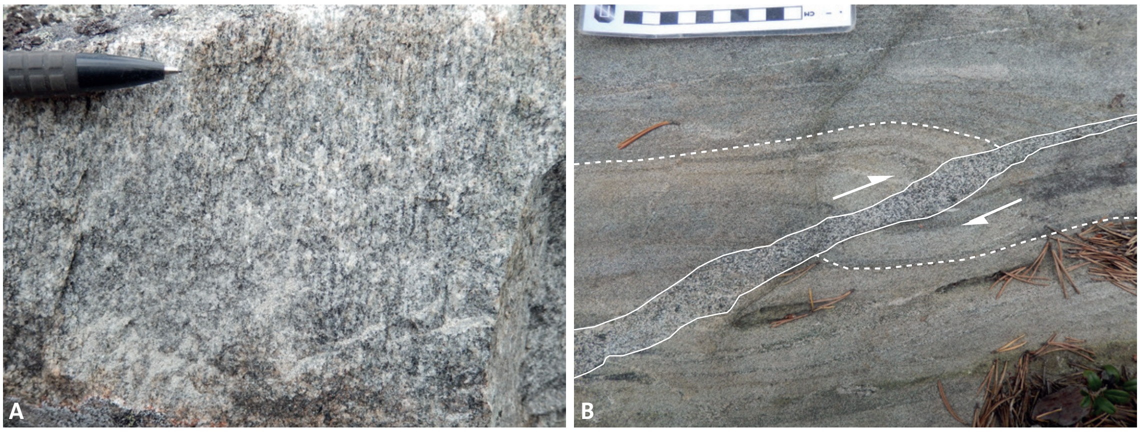

Figure 15. A. Side view to the north-north-west of sub-vertical foliation in a medium-grained, monzodioritic intrusion. B. Top view to the south-west of a dioritic dyke crosscutting steeply south-south-west-dipping, thinly laminated, metavolcaniclastic rock. Laminae appear dextrally offset and associated with possible syn-emplacement drag fold (dashed lines).

Mineral lineations in the Nautanen deformation zone are defined by stretching of minerals and their orientations are variable. In general, lineations plunge moderately towards the south and south-west. Local deviations with gentle to horizontal plunges were also observed.

The dominant shearing pattern and composite schistosity in the Nautanen deformation zone is evident in VLF-resistivity imaging across the shear zone (Fig. 14). Two ground-based VLF-resistivity profiles (northern Liikavaara and southern Sakakoski profiles), orientated approximately orthogonal to the dominant structural grain in the Nautanen deformation zone, illustrate relative resistivity variations in the sheared and altered Muorjevaara group rocks transected by the Nautanen deformation zone (see the appendix for profile locations and orientations).

Based on a preliminary interpretation, numerous relatively shallow resistivity breaks occur that mostly dip steeply to the south-west and west. These features appear to follow the dominant orientation of primary bedding and the dominant shear zone fabric (Fig. 11). The rocks in the shallow sub-surface also correspond to zones of relatively lower resistivity (i.e. perhaps higher permeability, more fractured?), although higher resistivity blocks also occur at depth. The Sakakoski profile (Fig. 14) transects the mapped contact between the eastern margin of the Nautanen deformation zone and adjacent Eastern volcanosedimentary domain meta-volcanosedimentary rocks. Here, a steep west-dipping zone of low resistivity (higher fracture permeability, alteration?) coincides with Nautanen deformation zone shearing and extends further down dip with depth.

Throughout the Nautanen deformation zone, the main north-north-west striking shear zones are connected by additional local, approximately north–south trending, generally vertical to sub-vertical high strain zones. These relay zones show mainly dextral and minor sinistral kinematics, mainly seen as weak to moderate foliation deflections around garnet porphyroblasts. Minor east-north-east striking shear zones also occur that locally correspond to inferred fault zone lineaments seen in magnetic anomaly data (e.g. Fig. 11). Additionally, local tensional features such as quartz-filled tension gashes and en-echelon quartz veins were observed along the western margin of the Nautanen deformation zone.

Structures associated with intrusive rocks

Intrusive rocks in the area have varying strain intensities that reflect their relative ages and emplacement histories. In Haparanda-type dioritic to granodioritic intrusions, a general penetrative foliation is observable (Fig. 15A). In the Eastern volcanosedimentary domain, it strikes predominantly north-north-east to north-west, dips steeply south-west, and tends to follow the orientation of dominant S1 foliations seen in the country rocks (cf. Fig. 11). Locally, dioritic dykes intruding metavolcaniclastic rocks display evidence of dextral-oblique emplacement associated with folding (e.g. Fig. 15B), while high strain zones cutting through the dioritic intrusions can cause a strong transposition of the penetrative foliation, suggesting local pre-shearing emplacement. Along the western margin of the Nautanen deformation zone, dioritic intrusions occur as narrow, elongate, north-north-west-aligned bodies that are orientated sub-parallel to and deflected by folding and shearing related to the Nautanen deformation zone (cf. Fig. 2). Overall, the foliated character of the dioritic rocks, combined with their general orientation and intrusive patterns, suggest a probable syn-kinematic emplacement (cf. Witschard 1996).

Lina-type granitic rocks and subordinate aplite-pegmatite bodies typically occur as sheet-like intrusions, sills and veins that intrude parallel to planar structures (cf. Fig. 4). A varying degree of strain is observed in these granitic rocks, ranging from penetratively foliated to non-foliated (massive). This suggests episodic emplacement of several generations of granitic rocks in the area and indicates that not all granitic intrusions may strictly belong to the Lina association (cf. Bergman et al. 2001).

Variably deformed granitic rocks are also known from the broader Gällivare area. For example, Wanhainen et al. (2005) report radiometric ages for both deformed and undeformed pegmatitic dykes occurring at the Aitik deposit, south of Nautanen. A deformed pegmatite dyke yielded an age of c. 1.85 Ga, while undeformed dykes have ages from c. 1.76 to 1.73 Ga. In addition, Bergman et al. (2002) obtained an age of c. 1.77 Ga from a weakly foliated Lina granite c. 30 km north-west of the Nautanen area. These data, combined with observations presented here, support the occurrence of both syn- and post-kinematic granitic magmatism in the general Gällivare–Nautanen area.

METASOMATIC–HYDROTHERMAL ALTERATION

Meta-volcanosedimentary rocks in the Nautanen area have been affected by varying degrees of metasomatic-hydrothermal alteration (e.g. Martinsson & Wanhainen 2004a, McGimpsey 2010, Tollefsen 2014). Using magnetic mineral occurrences as a proxy for hydrothermal fluid flow, magnetic anomaly maps show that relatively intensely developed alteration is confined to the Nautanen deformation zone domain, coincident with high-strain deformation and structurally-channelled hydrothermal Cu-Au±Fe mineralisation (e.g. Figs. 11 and 21). Outside the Nautanen deformation zone domain, alteration intensity is generally lower and where it is higher, it is locally associated with vein-hosted Cu-Au mineralisation.

In general, two broad alteration styles occur across the study area. They are (1) semi-conformable (pervasive to selectively pervasive) alteration consisting of irregular to linear (banded) replacement-type zones and patches, and (2) alteration associated with hydrothermal veins (selectively developed). This section summarises the general style and character of alteration in the Nautanen area, including a preliminary, comparative geochemical assessment between altered rocks from the Nautanen deformation zone domain and less altered rocks from the Eastern volcanosedimentary domain.

Semi-conformable (pervasive) alteration

Pervasive to selectively-pervasive (semi-conformable) alteration within the Nautanen deformation zone domain consists of a moderate to intense biotite-amphibole-magnetite-garnet-K-feldspar-tourmaline±apatite±sulphide assemblage forming ubiquitous bands and linear zones (Figs. 16–17). Locally, this banded ‘potassic’ assemblage appears to overprint a more pervasive (earlier?) sericite-scapolite±feldspar assemblage (Figs. 16A and C). The potassic banding consists of individual

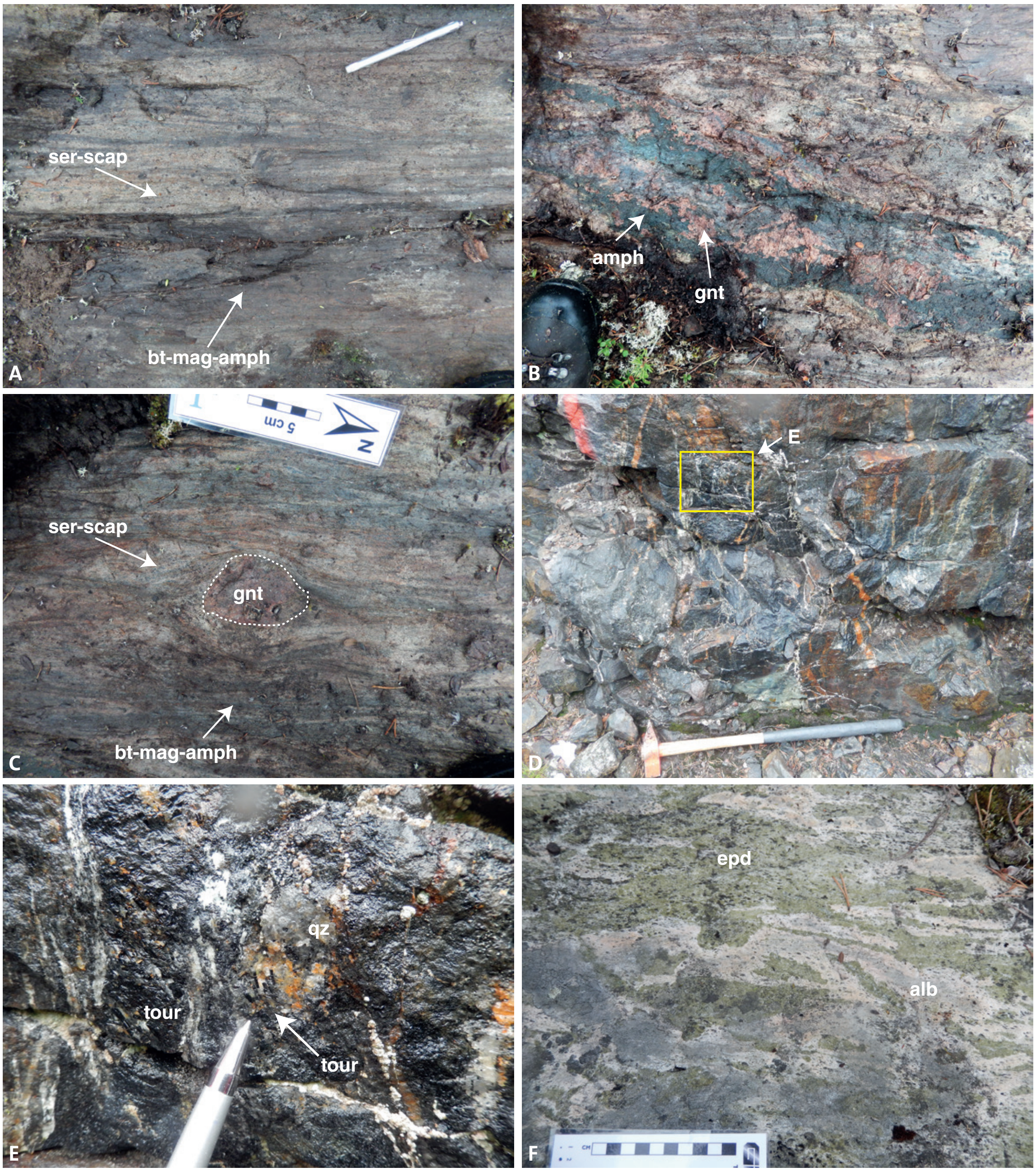

Figure 16. Semi-conformable (pervasive) alteration in the Nautanen area. **A.** Bedding view (to the west-south-west) of banded, moderate to intense, magnetite-biotite-amphibole alteration of foliated metavolcaniclastic rock. **B.** View to the south-west of somewhat discordant amphibole-garnet-magnetite band within a generally sericite-scapolite altered metavolcaniclastic rock. **C.** Bedding view (to the west-south-west) of garnet porphyroblast in a biotite-amphibole-magnetite altered metavolcaniclastic rock. Almandine porphyroblasts deflect S1 suggesting late syn-deformational growth. **D.** Along-strike view (to the north-north-west) of tourmaline-amphibole-quartz alteration zone close to the Nautanen deposit. **E.** Detailed view from D showing tourmaline-quartz alteration with prismatic tourmaline grains. **F.** View to the north-east of patchy to pervasive, intense epidote-albite alteration, Eastern volcanosedimentary domain. Abbreviations: alb = albite, amph = amphibole, bt = biotite, epd = epidote, gnt = garnet, mag = magnetite, scap = scapolite, ser = sericite, tour = tourmaline.

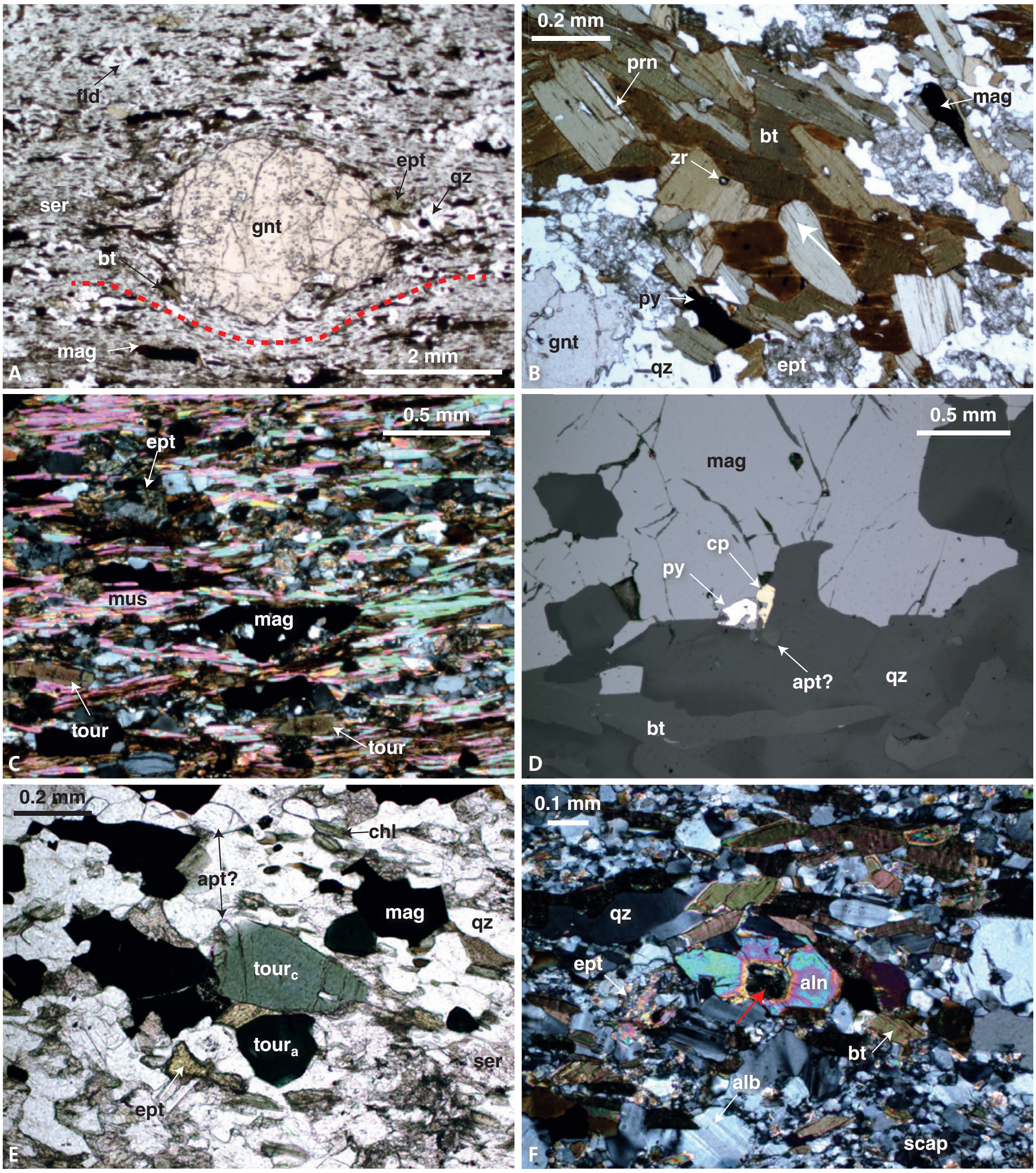

Figure 17. Photomicrographs of hydrothermal alteration in the Nautanen area. **A.** Plane polarised light view. Lepidoblastic quartz-feldspar-biotite schist with garnet porphyroblast. Moderate deflection of schisosity (dashed line) is attributed to late-stage (?), metasomatic garnet growth. **B.** Plane polarised light view. Shreddy biotite associated with magnetite adjacent to garnet porphyroblast with late-stage epidote. **C.** Cross polarised light view of lepidoblastic muscovite-sericite schist associated with lenticular magnetite and tourmaline. Tourmaline grains partly overprint muscovite and are also preferentially aligned. **D.** Reflected light view of magnetite with associated pyrite and chalcopyrite. **E.** Plane polarised light view of tourmaline in magnetite-sericite altered schist. Image shows both basal (tour$_a$) and prismatic (tour$_c$) tourmaline sections. **F.** Cross polarised light view. Allanite grain in scapolite. Core of allanite displays metamict texture (red arrow). Abbreviations: gnt = garnet, ept = epidote, bt = biotite, prn = phrenite, qz = quartz, scap = scapolite, mag = magnetite, py = pyrite, cp = chalcopyrite, tour = tourmaline, alb = albite, apt = apatite, aln = allanite, ser = sericite.

mm- to cm-scale, laterally continuous layers that merge to form broader (tens of metres) linear alteration zones. Magnetite abundance typically ranges from 3 to 10 vol.% and is locally associated with disseminations and thin (<5 mm thick), stringer-like seams of fine- to medium-grained (<0.1–3 mm) pyrite and chalcopyrite (Fig. 17D). Sulphide abundance is typically 1–2 vol.%, but locally increases to c. 5–8 vol.%. Both pyrite and chalcopyrite are intergrown with magnetite, and occur on the margins of garnet porphyroblasts. Amphibole forms 1–10 mm thick dilational bands associated with biotite and magnetite.

A conspicuous feature of altered Nautanen deformation zone domain rocks is the presence of disseminated porphyroblasts and irregular aggregated (granoblastic) zones of reddish pink garnet (almandine-spessartine varieties, Tollefsen 2014). Garnet porphyroblasts generally range from 0.2 to 5 cm in size (rarely up to 30 cm), are typically subhedral, and often appear flattened and stretched parallel to the dominant foliation (Fig. 16C, cf. Fig. 12D). Locally, garnet porphyroblasts gently deflect the main schistosity, indicating (late?) syn-kinematic metasomatic growth (Figs. 16C and 17A). Rare curving and partly folded garnet tails, combined with asymmetric foliation deflections, suggest a degree of oblique grain rotation, mostly with a dextral sense (see Fig. 12C). Fracture-hosted inclusions of magnetite, epidote and quartz also suggest that garnet porphyroblasts partly predate the dominant potassic-magnetite alteration banding.

Irregular to linear, aggregated bands and lenses of generally fine- to coarse-grained (<1 cm) garnet associated with amphibole, biotite, magnetite and rare sulphide also occur (Fig. 16B). These zones have a gradational to locally sharp (vein-like) appearance, and have formed discordantly to the main alteration banding and foliation. Here, garnet is more typically subhedral to euhedral and less deformed, suggesting that two broadly contemporaneous generations of garnet may be present within the Nautanen deformation zone domain.

Tourmaline (probably schorl to dravite series, cf. Frietsch et al. 1997) is a relatively common alteration phase across the study area, and within the Nautanen deformation zone domain the banded potassic alteration locally grades into tourmaline-rich zones (Figs. 16D–E). These zones are typically 0.3–2 m thick and are associated with amphibole, magnetite, quartz and sulphide (Figs. 16D–E). Locally, prismatic tourmaline grains are typically oriented sub-parallel to dominant foliations and locally overprint sericite-muscovite grains (Fig. 17C). In both the Eastern volcanosedimentary domain and Nautanen deformation zone domain, tourmaline also occurs within quartz±amphibole±sulphide veins (see below).

Ubiquitous, late-stage, epidote±quartz alteration occurs throughout the Eastern volcanosedimentary domain and Nautanen deformation zone domain (e.g. Fig. 16F). In general, it forms 0.01–1 m wide irregular patches, bands and zones and is locally associated with epidote-amphibole±quartz±feldspar veinlets. Epidote generally forms fine-grained (<1 mm), anhedral and granular aggregates and disseminations associated with rare (c. 1–2 vol.%) subhedral to euhedral allanite grains (Fig. 17F).

In general, rock units in the Eastern volcanosedimentary domain are less pervasively altered compared to analogous units in the Nautanen deformation zone domain. Where present, pervasive alteration is generally of low to moderate intensity and restricted to patchy, irregular zones of sericite-amphibole-magnetite-tourmaline±biotite and epidote±quartz±feldspar alteration.

The geochemical characteristics of meta-volcanosedimentary rocks from the Eastern volcanosedimentary domain and Nautanen deformation zone domains reflect bulk differences in the degree of alteration and mineralisation between the two domains and thus provide insights into metasomatic-alteration processes across the study area (cf. Tollefsen 2014). In Figure 18, bivariate plots of Cu concentrations relative to Ag, Au, W, Mo and Fe abundances are shown for samples hosted by the Nautanen deformation zone and the Eastern volcanosedimentary domain. In general, the more intensely altered and mylonitic samples from the Nautanen deformation zone

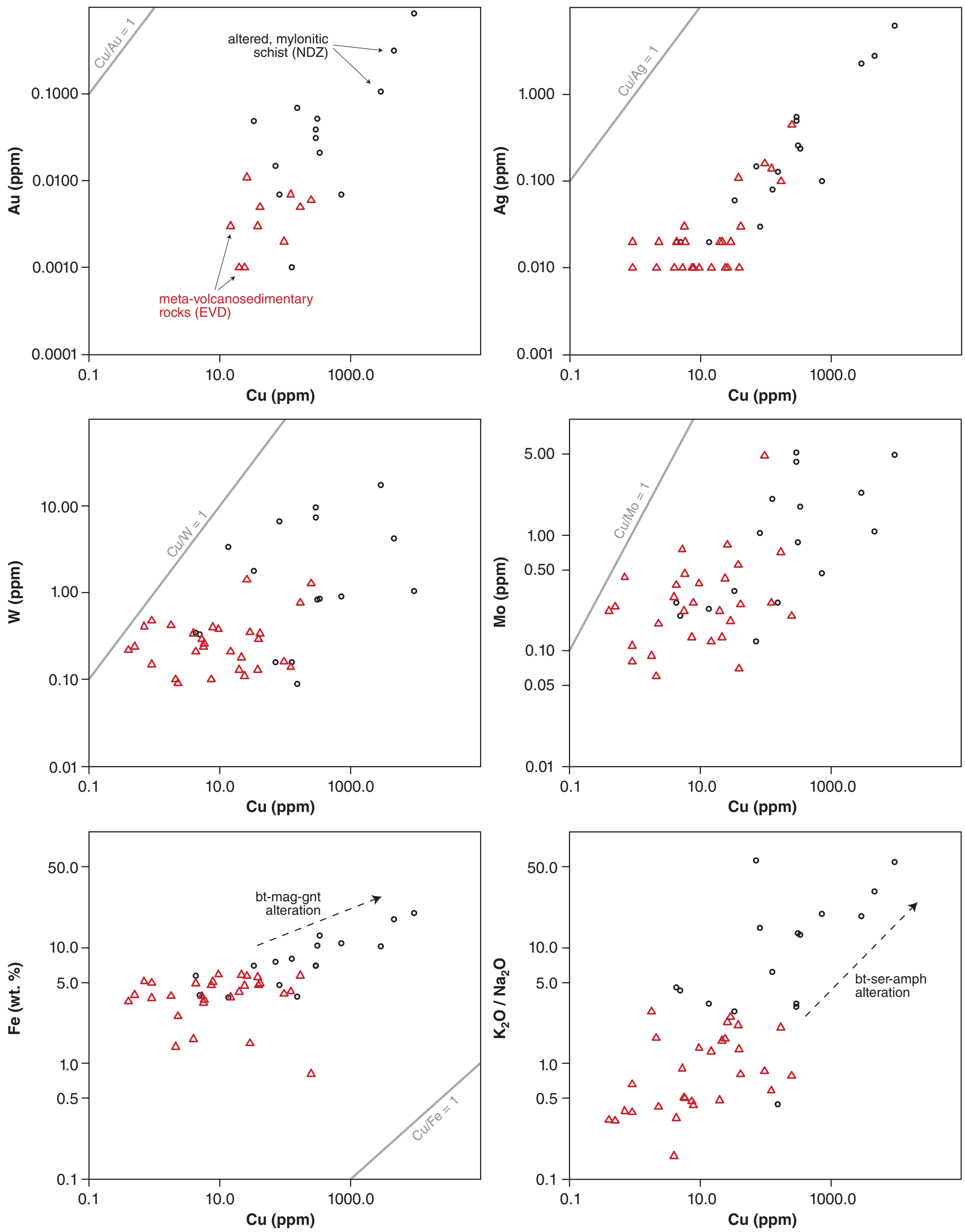

Figure 18. Metal association plots showing relative enrichment and positive abundance correlations between Cu and other selected elements for Nautanen deformation zone altered and Eastern volcanosedimentary domain 'less altered' meta-volcanosedimentary rocks.

domain have elevated metal concentrations relative to the less altered and less sheared Eastern volcanosedimentary domain samples. These data correspond to a generally increased abundance of hydrothermal-related phases within the Nautanen deformation zone such as sericite, magnetite, biotite, garnet, pyrite and chalcopyrite. Figure 18 indicates a positive linear correlation between Cu and Au, Ag and Fe concentrations, while a somewhat more scattered correlation is evident between Cu and W and Mo abundances.

For samples hosted by the Nautanen deformation zone, the relative enrichment in Fe and higher K_2O/Na_2O values reflect the generally higher intensity of biotite-amphibole-magnetite-garnet-sericite alteration, while higher K_2O/Na_2O values suggest that potassic alteration may be preferential controlled by the replacement of feldspar (i.e. albite destruction). Tollefsen (2014) also reports increased abundances of Ba and Mn for rocks transected by the Nautanen deformation zone, compared to meta-volcanosedimentary units to the east (cf. Ros 1980). In the former case, elevated Ba values may be partly due to the presence of barite veins (not seen), which are relatively common at the Aitik deposit (Monro 1988). Mn abundance is probably controlled by garnet.

Overall, the elevated concentrations of Cu, Ag, Au, Fe, W and Mo within the Nautanen deformation zone reflect the effects of mineralising metasomatic-hydrothermal crustal fluids that were preferentially channelled through the deformation zone, resulting in relatively higher alteration intensity and associated sulphide abundance (cf. Smith et al. 2013). Likewise, the broad geochemical signature and metal associations seen in the Nautanen area correspond to the typical geochemical characteristics and metal enrichment patterns associated with metasomatic-hydrothermal-related IOCG-style mineralisation (e.g. Barton 2014).

Vein types and vein-related (selective) alteration

A variety of hydrothermal veins occur throughout the study area (Fig. 19 and Table 2). Generally, quartz veins are more abundant within the Eastern volcanosedimentary domain, while magnetite±amphibole veinlets are more prevalent within the Nautanen deformation zone domain. Weak to moderately developed alteration haloes are generally confined to within 1–2 cm of vein margins, although the degree of alteration intensity is quite variable. Overall, vein sets are typically aligned sub-parallel to bedding and laminae (north-west to north-north-west) or are locally discordant with an approximate east–west orientation (see Fig. 11). The majority of veins dip steeply (>80°).

In the Nautanen deformation zone domain, magnetite-amphibole veinlets form sheeted to stockwork and local breccia-like vein networks (Fig. 19A). They are spatially associated with pervasive biotite-amphibole-garnet-magnetite±sulphide banding and, locally, they are moderately to tightly folded and sheared (Fig. 13B). Amphibole±magnetite±garnet veinlets also occur here and thus a continuum of amphibole- and magnetite-rich veinlets associated with the pervasive alteration banding occurs along the deformation zone. In the Eastern volcanosedimentary domain, distinctive amphibole±quartz±tourmaline veins with albitic haloes occur (Fig. 19B). Quartz is generally confined to the centre of these veins and may have been precipitated during a later phase of vein opening.

Quartz veins occurring in both the Eastern volcanosedimentary domain and Nautanen deformation zone domain include (1) planar to often wavy (folded?), quartz-magnetite veins that locally crosscut foliations and alteration banding (Fig. 19C) and (2) generally planar quartz-tourmaline±amphibole veins (and patchy segregations) that are locally sulphide-bearing (Fig. 19D). The latter vein type is associated with weak amphibole haloes. In addition, generally thick (c. 0.2–1 m), undeformed quartz veins comprised of coarse (c. 5–15 mm), milky-white anhedral and blocky grains, may represent a late-stage (sulphide-barren?) quartz vein type.

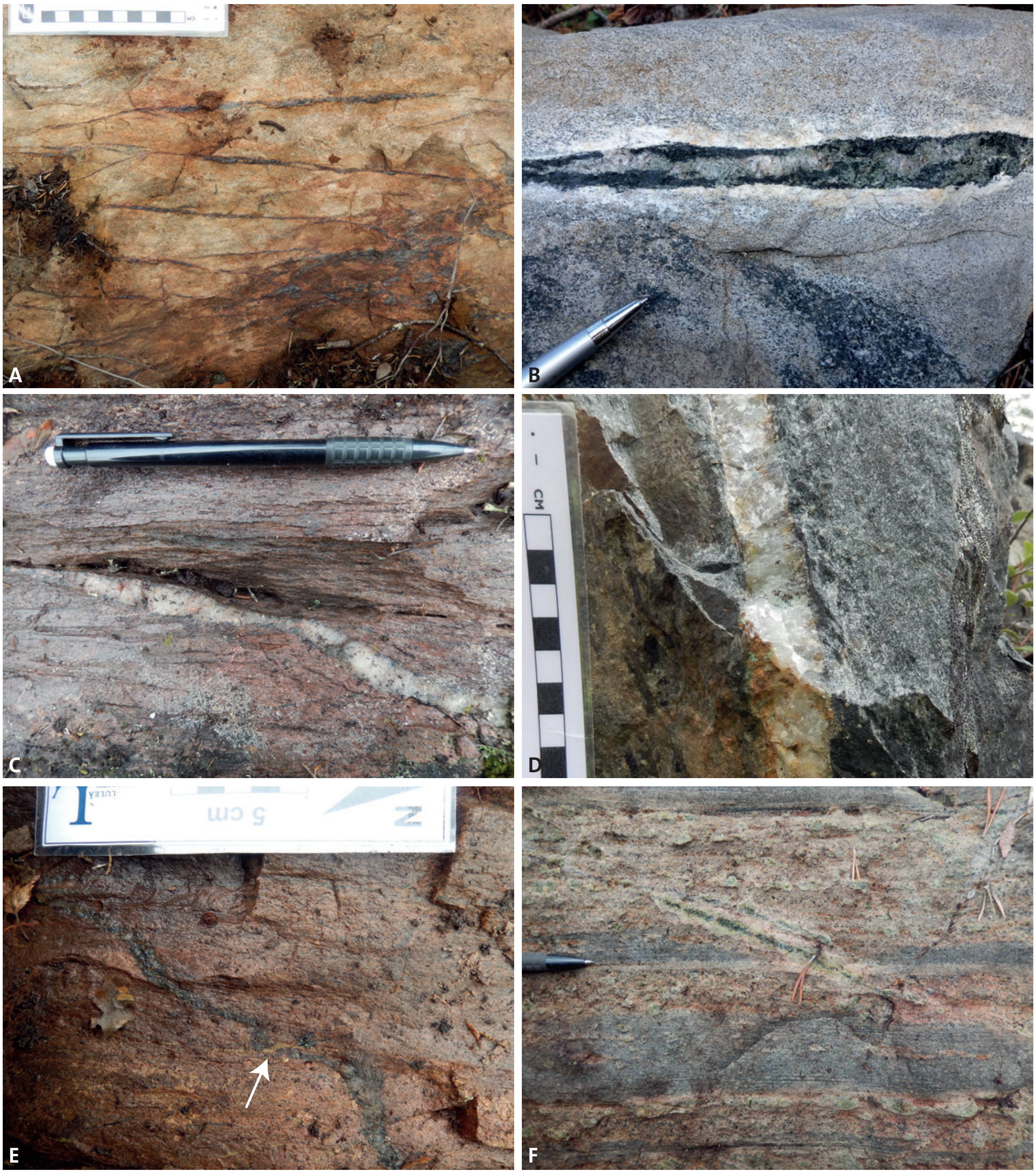

Figure 19. Vein types and vein-related alteration in the Nautanen area. **A.** View to the west-south-west of sub-parallel, steeply-dipping, north-north-west orientated magnetite-amphibole veins crosscutting mica schist. Secondary hematite staining replacing magnetite. **B.** View to the west-south-west of an amphibole-quartz vein with albite halo. **C.** Bedding view (to the west-south-west) of steep, north-east aligned, quartz-magnetite vein. **D.** View to the east-north-east of a quartz-pyrite-chalcopyrite vein with weak, discontinuous, amphibole halo. **E.** View to the south-west of an epidote veinlet crosscutting wavy quartz-magnetite vein (arrow). **F.** Bedding view (to the south-west) of discontinuous epidote±amphibole±quartz veinlets crosscutting compositionally banded metavolcaniclastic unit.

Throughout the study area, epidote±amphibole±feldspar veinlets associated with weak to moderate epidote±albite haloes occur (Figs. 19E–F). In general, they crosscut other veins and foliations, and are locally discordant with inferred primary structures. A summary of the different vein

Table 2. Summary of hydrothermal vein characteristics in the Nautanen area.

Vein type [1]	Brief description	Alteration characteristics
1. Magnetite-amphibole±garnet ± pyrite ± quartz	<1 cm thick, irregular planar, locally folded, sub-parallel to schistosity in NDZ (syn-shearing?), locally forms breccia-like zones, 0.5–1 m thick	Associated with moderate biotite ± magnetite banding, seams of stringer sulphide in the NDZ. Abundant secondary Fe-oxides
2. Amphibole±garnet±magnetite± sulphide (possible variety of 1)	c. 0.5–30 cm thick, planar to irregular patchy zones (replacement style?). In NDZ, magnetite-rich zones associated with thin quartz-sulphide veinlets	Moderate amphibole ± biotite halo. Late epidote-albite ± carbonate (?) overprint.
3. Amphibole-tourmaline ± albite ± quartz	c. 0.5–5 cm thick, quartz may be a late phase (vein re-opening). Often trend sub-parallel to bedding, laminae	Weak to moderate albite halo
4. Quartz-magnetite	c. 0.5–2 cm thick, planar to wavy, dilational. Disseminated magnetite preferentially along vein margins. Crosscut magnetite ± amphibole veinlets, cut by epidote veinlets	Weak K-feldspar halo
5. Quartz-tourmaline ± amphibole ± sulphide	c. 0.5–15 cm thick, planar. Rare sulphide disseminated along vein margins. Massive, anhedral blocky quartz in EVD	Weak amphibole halo
6. Epidote ± quartz ± albite	c. 0.1–2 cm thick, planar, laterally discontinuous in places. Grade into thicker (c. 5–8 cm) replacement zones. Local vuggy texture.	Weak to moderate epidote ± albite halo

1 = minerals listed in approximately decreasing relative abundance
± = sometimes present.

types occurring in the Eastern volcanosedimentary domain and Nautanen deformation zone are presented in Table 2.

Preliminary alteration paragenesis

Based on outcrop observations in the Eastern volcanosedimentary domain (EVD) and the Nautanen deformation zone (NDZ) domain, and a limited amount of thin section petrography, a preliminary alteration paragenesis is summarised as follows:

(1) In general, meta-volcanosedimentary rocks in the Eastern volcanosedimentary domain and Nautanen deformation zone domain display low to moderately intense, pervasive to selectively pervasive (i.e. patchy zones or bands, disseminations) sericite-scapolite±feldspar, amphibole-biotite-magnetite-tourmaline and K-feldspar alteration.

(2) In the Nautanen deformation zone domain, a moderate to intense potassic assemblage (biotite-amhpibole-garnet-magnetite-tourmaline±apatite±sulphide) forms linear, sub-parallel, seams, bands and zones that locally appear to overprint earlier (?) sericite-scapolite±feldspar alteration. Zones of relatively intense K-feldspar alteration, typically associated with later epidote, also occur.

(3) In the Nautanen deformation zone domain, potassic alteration locally grades into tourmaline-rich alteration zones associated with sulphide and quartz. In both the Eastern volcano-

sedimentary domain and the Nautanen deformation zone domain, quartz-tourmaline±sulphide veins occur, suggesting tourmaline may have been remobilised during a later phase of brittle deformation and fluid flow.

(4) Late-stage epidote±quartz±feldspar alteration (retrograde saussuritisation) forms selectively pervasive zones and epidote veinlets across the Eastern volcanosedimentary domain and the Nautanen deformation zone domain.

Future work aims to refine and better characterise the preliminary paragenesis and zonation patterns described above.

SUMMARY AND CONCLUSIONS

New field mapping, structural measurements, lithogeochemistry and geophysical data have been integrated to characterise a package of polydeformed and variably altered c. 1.9 Ga meta-volcanosedimentary rocks in the Nautanen area, northern Norrbotten. Preliminary conclusions are:

(1) The investigated sequence mainly consists of metamorphosed volcaniclastic and volcanogenic sedimentary rocks. Lesser intercalated and interbedded phyllite, schist and amphibolite units also occur, and gradational and layered compositional and textural variation is relatively common throughout the sequence. Locally, granitic and dioritic rocks intrude the meta-volcanosedimentary rocks.

(2) Lithogeochemical analysis of 'least altered' samples generally indicates an intermediate, calc-alkaline, basaltic andesitic to andesitic composition for the sequence. All units are broadly geochemically similar, suggesting a common source region and petrogenetic history. Combined lithological and lithogeochemical data suggest that the rocks in the eastern part of the study area are similar to those hosting the Nautanen Cu-Au deposit. The new data also confirm earlier proposals (e.g. Zweifel 1976, Monro 1988) that the supracrustal sequence in the Nautanen area is broadly equivalent to the host rocks at the Aitik Cu-Ag-Au deposit.

(3) The Nautanen area contains a variety of superimposed ductile and brittle structures formed during multiple deformation events. The dominant structures in the area are large-amplitude folds and the composite, north-north-west striking Nautanen deformation zone (NDZ). Locally, the Nautanen deformation zone transects and truncates the limbs of the large-amplitude, moderate to tight folds. Brittle structures including sulphide-bearing quartz veins also occur.

(4) Metasomatic-hydrothermal alteration affects the study area and is most intensely developed within the Nautanen deformation zone domain, spatially coincident with relatively high-strain deformation and local IOCG-style mineralisation. For rocks in the Nautanen deformation zone, alteration is dominated by generally pervasive sericite-scapolite±feldspar and banded biotite-amphibole-magnetite-garnet-tourmaline assemblages, associated with disseminated sulphide (pyrite, chalcopyrite and bornite). Magnetite, amphibole, quartz and epidote veins occur throughout the study area and locally display weak to moderately developed alteration haloes. Deformed and altered bedrock transected by the Nautanen deformation zone is generally enriched in Cu, Au, Ag and Fe compared to analogous units outside the high-strain zone. Likewise, Cu concentrations have a generally positive correlation with higher Ag, Au and Fe abundances.

(5) The meta-volcanosedimentary rocks in the Nautanen area belong to the Muorjevaara group, one of several c. 1.9 Ga, orogenic supracrustal successions occurring across Norrbotten (collectively equivalent to the regional Porphyrite group of Bergman et al. 2001).

Our ongoing work in the Nautanen area hopes to further characterise and refine the preliminary findings presented here. Paleoproterozoic supracrustal rocks transected by major deformation zones represent an important target for detailed, integrated geological investigations in Norrbotten, given their association with metasomatic-hydrothermal base and precious metal mineralisation.

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APPENDIX
2014 field observations, sampling and geophysical measurements

Geological mapping, structural measurements, rock sampling (lithogeochemistry, geochronology, petrophysics) and ground geophysical measurements (magnetometry, magnetic susceptibility, VLF-resistivity, gamma-ray spectrometry) were performed over 20 field days in June and August 2014. This appendix contains details about the practical aspects of the field work, along with some additional geophysical data.

Grid coordinates quoted in this section correspond to the Sweref99 coordinate system (northing and easting values, respectively) and were measured using a hand-held GPS with c. ±5 m horizontal precision.

Outcrop observations, measurements and sampling

Figure 20 shows the location of the 2014 outcrop observations and sampling points. In total, 207 outcrop observations were made. As part of these, 279 structural measurements, 80 lithogeochemistry samples, 54 reference and thin section samples and four geochronology samples were acquired. Additionally, outcrop geophysical measurements and sampling were also conducted (see below).Within the Nautanen deformation zone, the majority of observations and sampling were made along two east–west profiles close to the Nautanen and Liikavaara Cu-Au prospects.

For comparison, Figure 20 also shows the location of SGU field observations made in 1995 and 1997 during a regional mapping campaign (e.g. Bergman & Kübler 1997). Information about additional SGU field mapping, sampling and drilling in the Nautanen area is available in historical exploration reports (e.g. see Lynch & Jönberger 2014, and references therein).

Ground geophysical measurements

Geophysical fieldwork during 2014 consisted of three magnetometer profile measurements, two grid-based magnetometer surveys, five VLF-resistivity profiles, 28 gamma-ray spectrometer measurements at 13 localities, 621 magnetic susceptibility measurements on 72 outcrops, and the collection of 23 petrophysical samples.

Figure 21 shows the location and orientation of the three magnetometer and five VLF-resistivity profiles (white and black profiles, respectively). The highlighted VLF profiles (red rectangles) correspond to the Liikavaara (northern) and Sakakoski (southern) models shown in Figure 14. In addition, Figure 21 shows the location and extent of the two ground magnetometer surveys at the Nautanen and Snolkokk Cu-Au prospects (see Figs. 22 and 23, respectively). Here, ground magnetic measurements were conducted to better resolve geological structures identified in aeromagnetic data and to trace the extent of magnetite banding and alteration. Figure 21 also shows the outline of the 3D susceptibility model shown in Figure 25 (yellow square, discussed below), and the locations of gamma-ray measurements and petrophysical sampling (yellow circles, discussed below).

Preliminary gamma-ray spectrometry data

At 13 localities (Fig. 21), the concentrations of potassium, uranium and thorium were measured using a hand-held gamma-ray spectrometer on outcrop surfaces. Average elemental concentrations for several units are presented below (number of measurements in parentheses).

Massive, alkali feldspar granite (c. 1.8 Ga Lina-type, granite-pegmatite suite)

In the northern Eastern volcanosedimentary domain (7466303/757447), a massive granite contains 3.4% K, 14.0 ppm U and 26.0 ppm Th (n = 3). In the WVD (7462478/751381 and 7462477/751119), a massive granite contains 4.9% K, 11.0 ppm U and 67.0 ppm Th (n = 5).

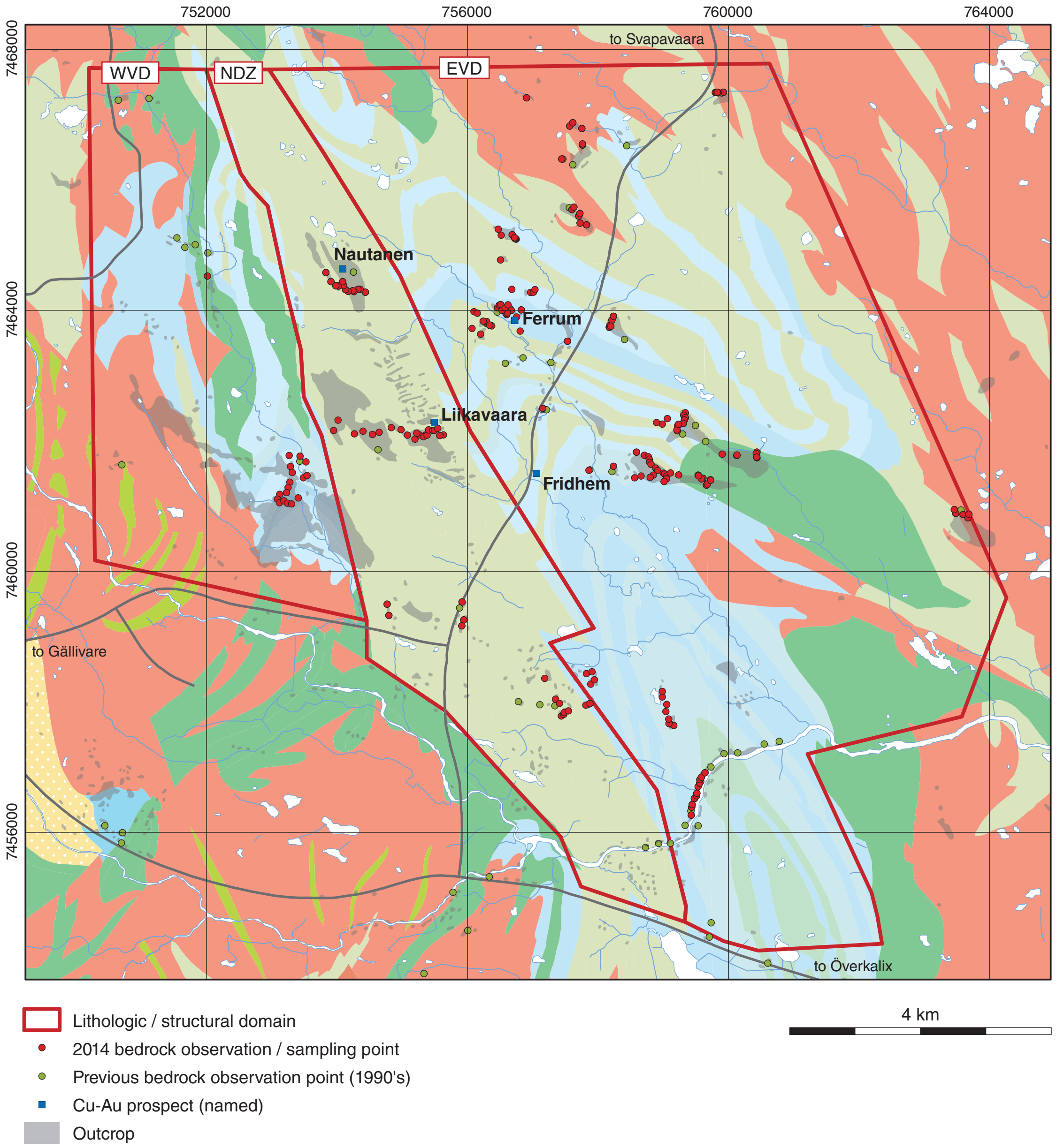

Figure 20. Location of outcrop observations and sampling points made during summer 2014. Historical observation points (1995 and 1997) are also shown. EVD = Eastern volcanosedimentary domain, NDZ = Nautanen deformation zone, WVD = Western volcanosedimentary domain.

Muorjevaara Group meta-volcanosedimentary rocks (c. 1.9 Ga; variably altered and weathered)
In the WVD (7461818/752026), a metavolcaniclastic rock contains 4.3% K, 3.4 ppm U and 11.0 ppm Th (n = 2). In the northern Nautanen deformation zone, close to the Nautanen Cu-Au deposit (7464467/754134), a magnetite-altered intermediate metavolcaniclastic rock contains 6.3% K, 2.9 ppm U and 20.0 ppm Th. In the west-central Nautanen deformation zone, c. 1.7 km west of the Liikavaara Cu-Au prospect (7462606/753814), an intermediate to felsic metavolcaniclastic rock contains 2.4% K, 2.0 ppm U and 4.3 ppm Th. In the east-central Nautanen deformation zone at the Liikavaara prospect (7462159/755389), a magnetite-altered felsic metavolcaniclastic rock contains 5.3% K, 2.7 ppm U and 13.0 ppm Th. In the southern Nautanen deformation zone near the Lina River (7455749/758178), a metavolcaniclastic rock

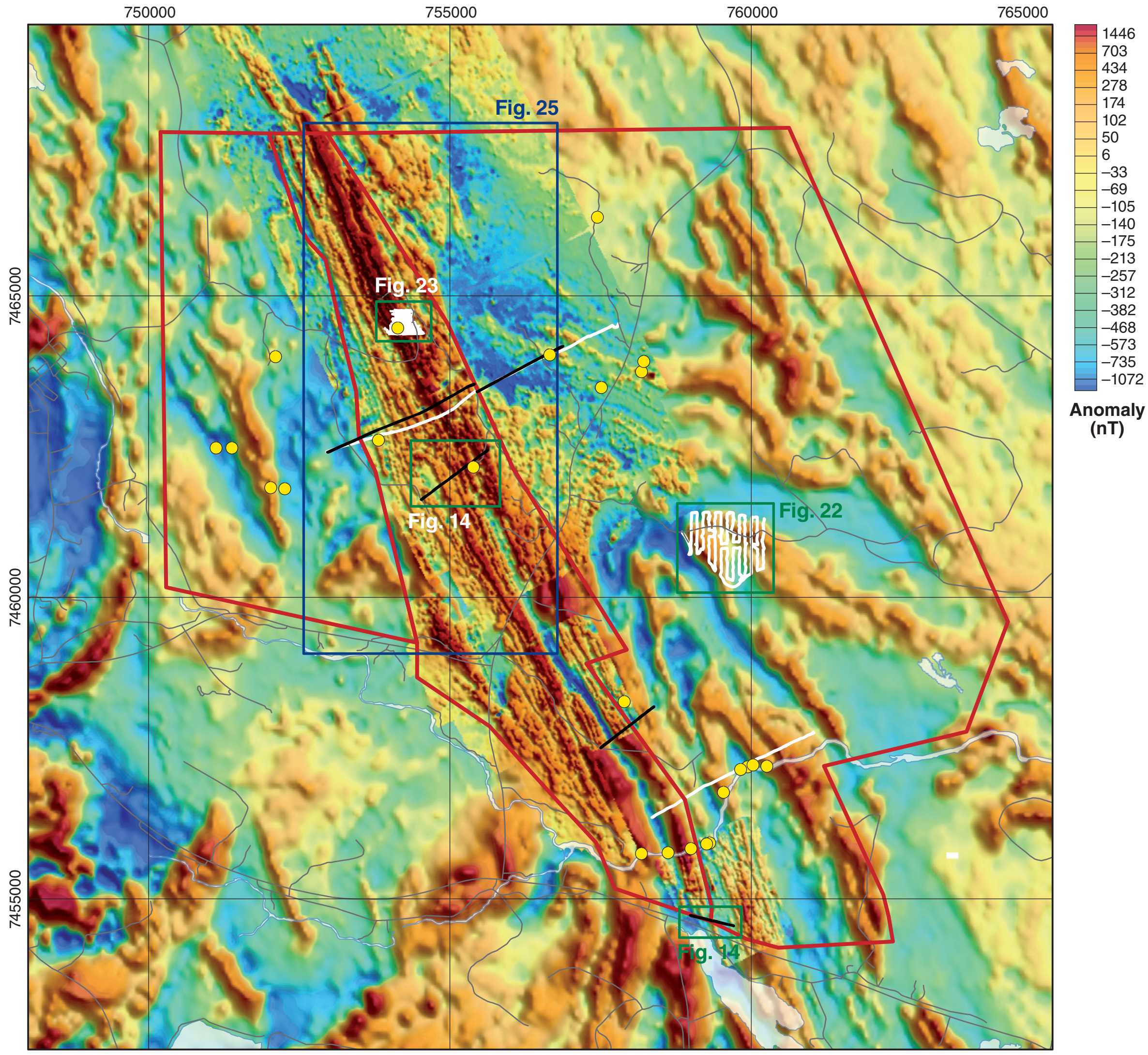

Figure 21. Combined airborne and ground magnetic anomaly map over the Nautanen area. White lines are ground magnetometer measurements. Thicker black lines show VLF-resistivity measurements, with the highlighted profiles (red rectangles) corresponding to the Liikavaara (northern) and Sakakoski (southern) profiles shown in Fig. 14. Yellow circles represent the locations of gamma-ray spectrometry measurements and petrophysical sampling.

that coincides with a moderately high, north-north-west striking magnetic anomaly, contains 2.3% K, 1.5 ppm U and 5.3 ppm Th (n = 2).

Preliminary petrophysical data

At 23 localities (Fig. 21), outcrop samples were collected for petrophysical analysis (rock density, magnetic susceptibility). Preliminary densities for Muorjevaara group rocks are as follows.

In the northern Nautanen deformation zone, close to the Nautanen Cu-Au deposit (7464467/754134), a magnetite-altered, intermediate metavolcaniclastic rock has a density of 2 782 kg/m^3. In the west-central Nautanen deformation zone, c. 1.7 km west of the Liikavaara Cu-Au prospect (7462606/753814), an intermediate to felsic metavolcaniclastic rock has a density of 2 704 kg/m^3. In the east-central Nautanen deformation zone at the Liikavaara prospect

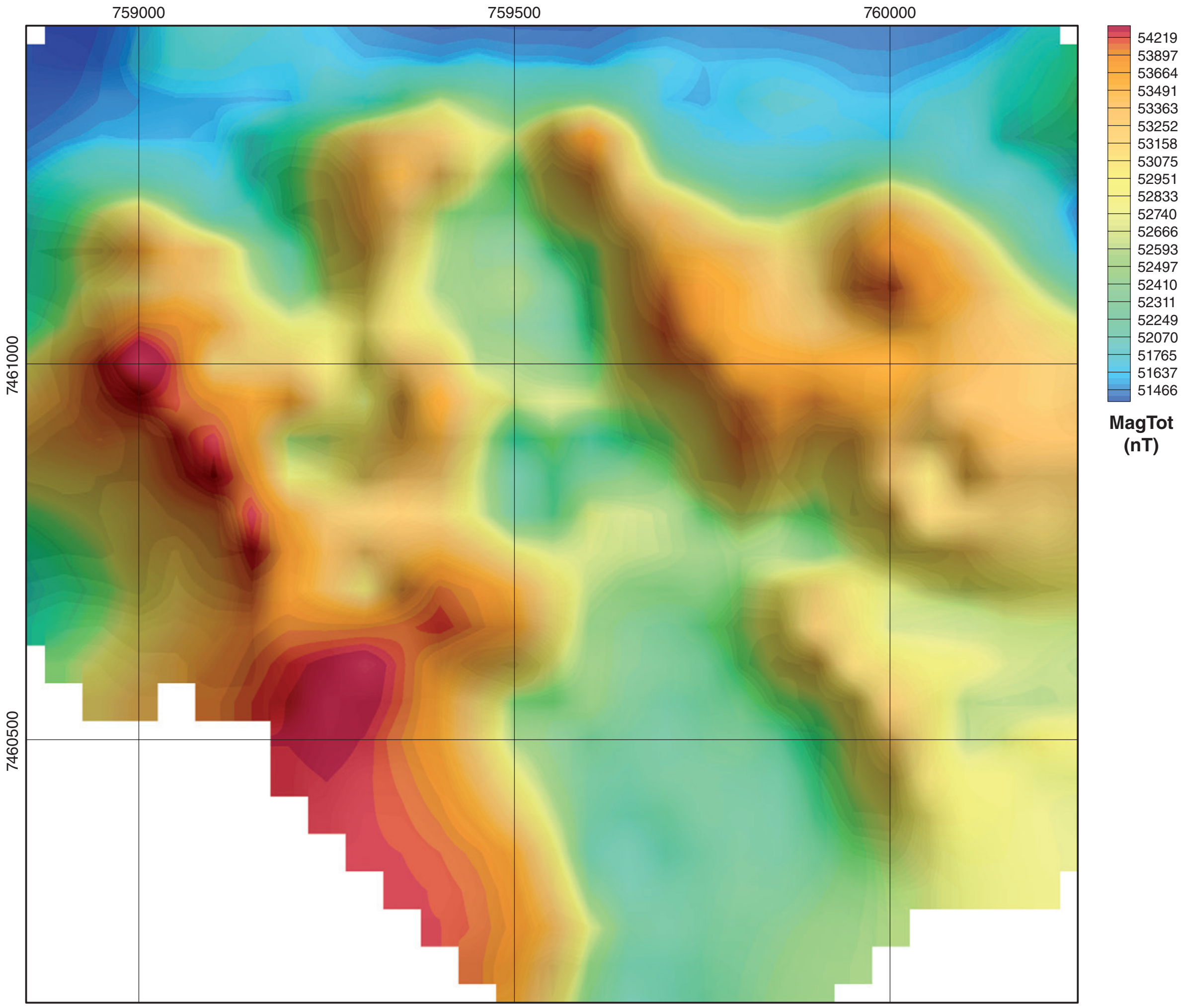

Figure 22. Magnetic map near Snolkokk , eastern Nautanen area (see Fig. 21 for location). The map is based on ground magnetic measurements conducted along north–south profiles with a line spacing of 100 m.

(7462159/755389), a magnetite-altered felsic metavolcaniclastic rock has a density of 2 702 kg/m^3. In the southern Nautanen deformation zone close to the Lina River (7455749/758178), a metavolcaniclastic rock has a density of 2 727 kg/m^3.

These preliminary rock densities fall within the range (c. 2 700–3 000 kg/m^3) for metavolcanosedimentary rocks in the Nautanen area (Fig. 24). Based on the residual gravity anomaly map (Fig. 24), an approximately north-north-west aligned, curvilinear to irregular positive anomaly ('Sorvanen anomaly' of Carlson 1989) approximately coincides with the position and orientation of the Nautanen deformation zone. This association indicates that the zone of high-strain deformation and preferential biotite-amphibole-magnetite±tourmaline alteration has relatively higher densities compared to areas to the east and west of the Nautanen deformation zone. For example, a somewhat linear cluster of higher density rocks (>2 900 kg/m^3) in the northern Nautanen deformation zone overlaps with a positive gravity anomaly (Fig. 24) and north-north-west aligned high magnetic susceptibility zones (Fig. 21). The bedrock in this area consists of sheared and altered metavolcaniclastic rocks that host Cu-Au±Fe mineralisation at the Nautanen and Liikavaara prospects. In general, dioritic to granitic intrusions, and less altered and sheared Muorjevaara group units correspond to local minima in the gravity anomaly map (Fig. 24).

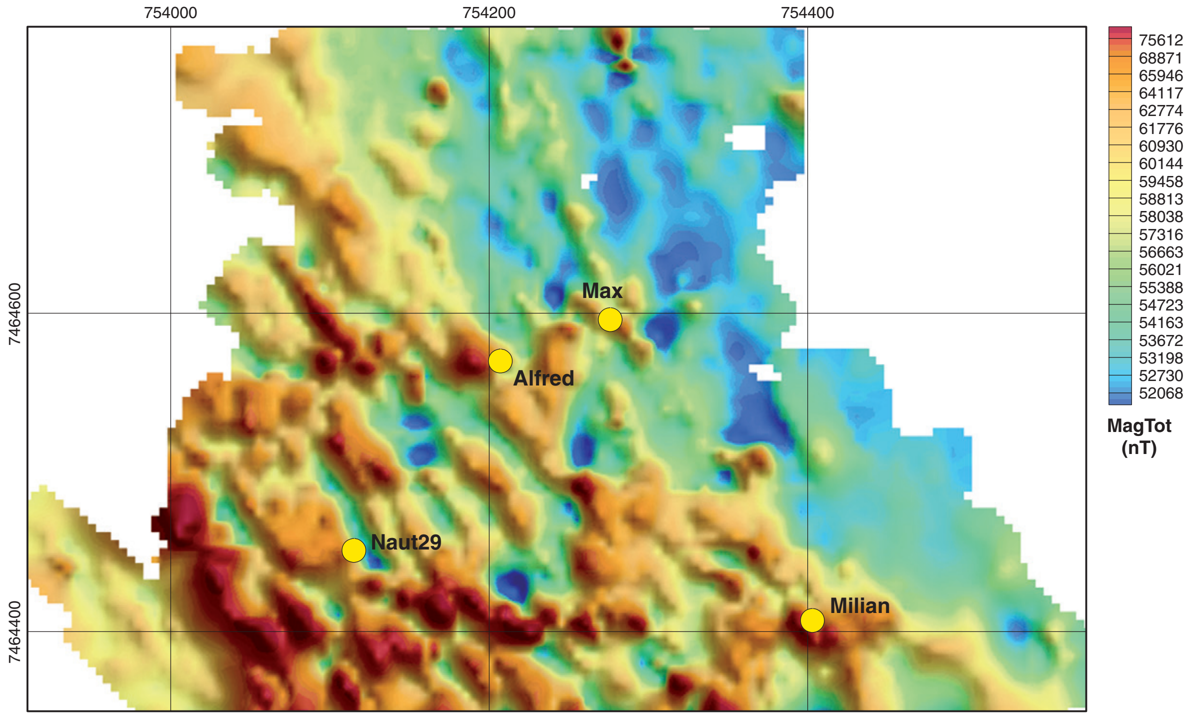

Figure 23. Ground magnetic map over the Nautanen Cu-Au deposit (see Fig. 21 for location). Ground magnetic measurements were conducted along east–west profiles with a line separation of 10 m. The locations and names of historical open pits are also shown.

Preliminary 3D geophysical modelling of magnetite-banded rocksin the Nautanen deformation zone

Figure 25 shows a preliminary 3D inversion model for deformed and altered bedrock in the Nautanen deformation zone. The outline approximately corresponds to the yellow square in Figure 21 (c. 5 × 5 km). The model was generated in Geosoft using the 'VOXI' module, and is based on airborne magnetic susceptibility data. It consists of volume pixels (voxels) which have a resolution of 250 × 250 m in the horizontal direction and 50 m in the vertical direction (at the surface). The voxels successively increase in size in the vertical direction by a factor of 1.08.

The model visualises two magnetic susceptibility isosurfaces connecting voxels with the same susceptibility values and highlights their general 3D form and orientation. From a geologic perspective, the isosurfaces can be viewed as proxies for magnetite-alteration and effects of deformation enhanced fluid flow within the Nautanen deformation zone.

In the southern Nautanen deformation zone, the lower susceptibility isosurface ($18\,000 \times 10^{-5}$ SI units, cyan colour) dips to the west-south-west. North of northing grid line 7464000, both the lower and higher ($30\,000 \times 10^{-5}$ SI units, grey colour) isosurfaces tend to have an opposing east-north-east dip. In the aeromagnetic data (Fig. 21), a possible deformation zone striking north-west transects the 7464000 northing grid line. Thus, the lateral change in isosurface dip may reflect the primary structural character of the Nautanen deformation zone or later deformational effects that caused a degree of structural reorientation. Ongoing modelling aims to better resolve this issue.

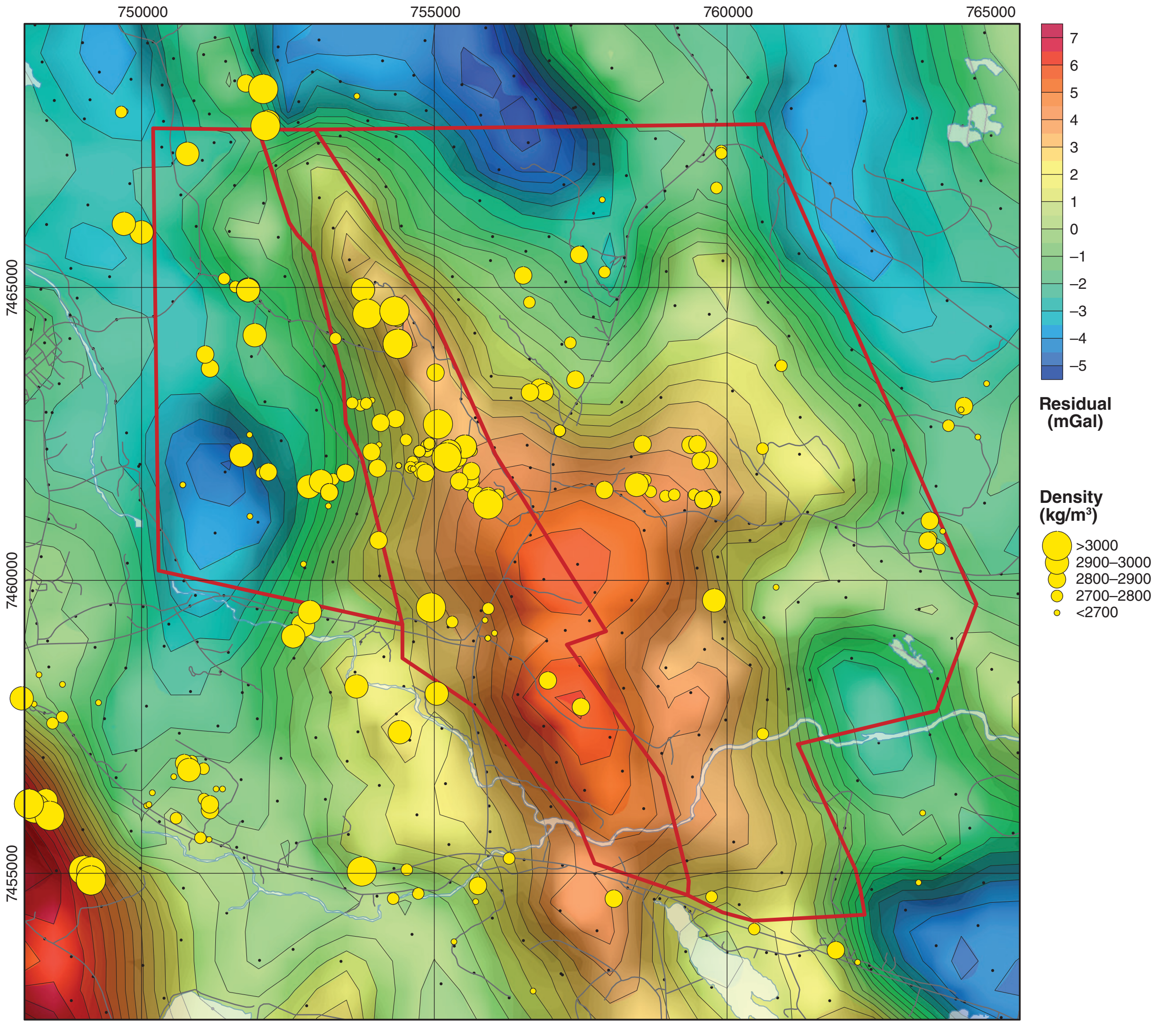

Figure 24. Residual gravity anomaly map over the Nautanen area. Rock densities are shown with proportional point sizes. White points are gravity measurement locations.

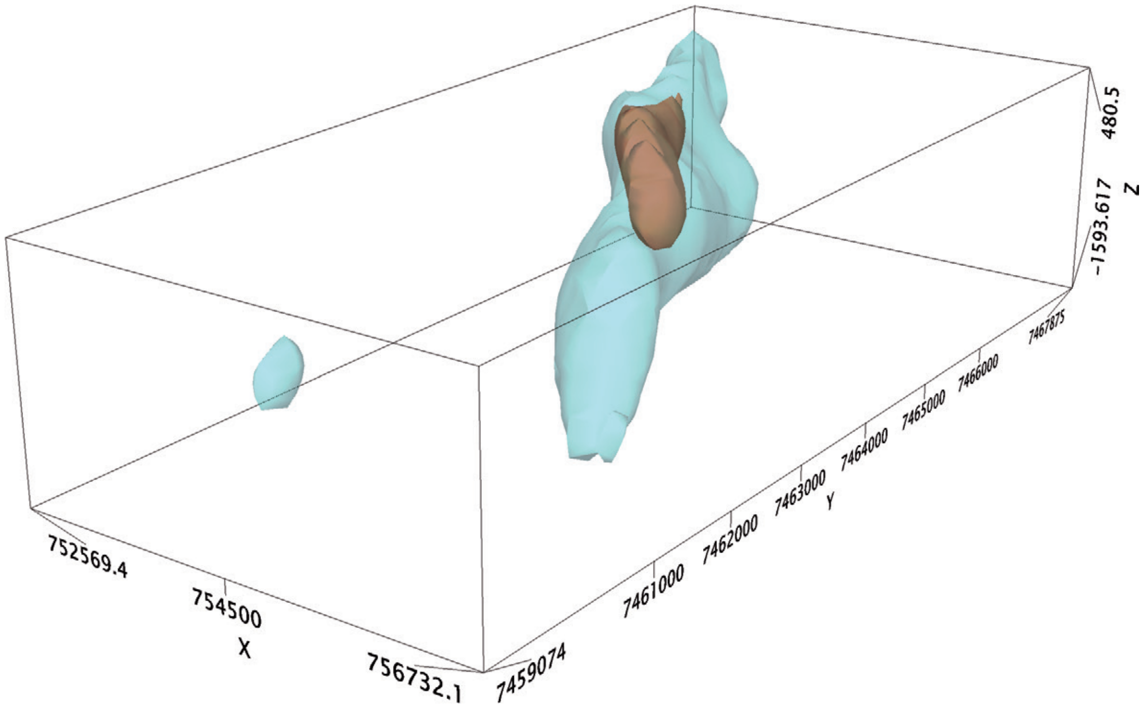

Figure 25. Three-dimensional magnetic susceptibility model for the Nautanen deformation zone (outline is yellow rectangle in Fig. 21). The cyan isosurface represents voxels with susceptibilities of 18 000 × 10^{-5} SI units. The smaller, grey isosurface corresponds to voxels with higher susceptibilities of 30 000 × 10^{-5} SI units. View is from south-east to north-west