Petrology and lithogeochemistry of the host rocks to the Nautanen Cu-Au deposit, Gällivare area, northern Sweden

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Master's Thesis

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Contents

Abstract

The Nautanen Cu-Au deposit is located 75 km north of the Arctic circle, and 10 km northeast of the town of Gällivare in northern Sweden. Nautanen is just 8 km west of the giant Malmberget apatite-iron ore deposit and 15 km north of one of Europe's largest copper producers, the Aitik Cu (Au) porphyry deposit. Nautanen is described as an Iron Oxide Copper Gold (IOCG) deposit or hybrid IOCG and contains a core of high grade resources of 0.63 Mt with 2.36% Cu, 1.3 ppm Au, 11 ppm Ag, or using a lower cut-off some 3 Mt with 0.75% Cu, 0.52 ppm Au, and 2 ppm Ag.

Nautanen is hosted in strongly altered and tectonically deformed Svecofennian volcanoclastic rocks on a major shear zone, the Nautanen Deformation Zone (NDZ). Alteration is dominated by scapolite, K-feldspar, epidote, sericite, and amphibole. Nautanen host rocks consist of steeply dipping, repeating layers of shoshonitic andesites, that were formed in a continental arc setting. The Nautanen rocks have lithogeochemical values characteristic of the low titanium, low zirconium Porphyrite Group of metavolcanics found in Norrbotten and are lithogeochemically similar to the volcanic host rocks to the Aitik deposit.

The high amount of magnetite and locally apatite at Nautanen, suggests a possible connection to the Malmberget apatite-iron ore. Titanite and allanite ages of c. 1.78 Ga at Nautanen correspond to the timing of IOCG overprinting noted at Aitik. Similar high salinity fluid inclusions as those noted as porphyry-related in the Aitik deposit have also been observed in Nautanen, indicating that porphyry type mineralization may have been present at the Nautanen locality as well. Multiple episodes of circulation of fluids and remobilization of ore minerals along the NDZ between Nautanen and Aitik have probably occurred.

Variations in tectonic processes, alteration, and magma fractionation have likely led to the small differences seen between the lithogeochemically indicated origins of the host rocks to the Nautanen and Aitik deposits.

Abstrakt

Koppar-guld fyndigheten Nautanen är belägen 75 km norr om polcirkeln, och 10 km nordost om Gällivare i norra Sverige. Fyndigheten ligger endast 8 km från den stora apatit-järnmalmen i Malmberget och 15 km norr om en av Europas största kopparproducenter, porfyrkoppar-(guld)malmen Aitik. Nautanen beskrivs som en järnoxid-koppar-guld (IOCG) fyndighet eller en hybrid IOCG med en kärna av höghaltiga reserver på 0.63 Mt med 2.36% Cu, 1.3 ppm Au, 11 ppm Ag, och med en lägre cut-off 3 Mt med 0.75% Cu, 0.52 ppm Au och 2 ppm Ag.

Nautanen sitter i kraftigt omvandlade och tektoniskt deformerade Svekofenniska vulkanoklastiska bergarter belägna på en större skjuvzon, Nautanen Deformation Zone (NDZ). Omvandlingen domineras av skapolit, kalifältspat, epidot, sericit och amfibol. Värdbergarterna utgörs av upprepade lager av brant stupande shoshonitiska andesiter, bildade i en kontinental öbåge-miljö. Bergarterna i Nautanen har en litogeokemisk signatur liknande den i de låg-Ti, låg-Zr metavulkaniska bergarter tillhörande porfyritgruppen i Norrbotten, och sammanfaller litogeokemiskt med Aitikmalmens vulkaniska värdbergarter.

Den stora mängden magnetit och ställvis apatit i Nautanen, antyder om ett möjligt samband mellan Nautanen-fyndigheten och Malmbergets apatit-järnmalm. Titanit- och allanit-åldrar på ca 1.78 Ga i Nautanen överensstämmer med tidpunkten för IOCG-överprägling observerad i Aitik. Liknande hög-salina vätskeinneslutningar som de som tolkats som porfyrkoppar-relaterade i Aitikmalmen, har också observerats i Nautanen, vilket tyder på att en mineraliseringshändelse av porfyrkoppar-typ även kan ha skett i Nautanen. Multipla episoder av cirkulerande fluider och remobilisering av malmmineral längst NDZ mellan Nautanen och Aitik har troligtvis ägt rum.

Variationer i tektoniska processer, omvandling och magmafraktionering har sannolikt lett till de små skillnader som observerats mellan det litogeokemiskt indikerade ursprunget hos värdbergarterna till Nautanenmineraliseringen och Aitikmalmen.

1. Introduction

The Nautanen Cu-Au (Ag, Mo) deposit is located 75 km north of the Arctic circle, and 10 km northeast of the town of Gällivare in northern Sweden. Mining in the area has been going on since the 18th century, with iron ore being taken from the ground at the Malmberget apatite iron ore deposit, just 8 km west of Nautanen (Martinsson et al. 2001). In 1898, ten years after the railway was built from Luleå to Gällivare, copper ore was discovered at Nautanen and mined from 1902 to 1907 (Geijer 1918). Sweden's largest sulphide mine, the Aitik deposit, was discovered in 1933 and went into production in 1968, it is located just 15 km south of Nautanen. The Nautanen deposit is much smaller than the two giant mines that it neighbours and has been estimated by the Swedish Geological Survey (SGU) to contain a core of high grade resources of 0.63 Mt with 2.36% Cu, 1.3 ppm Au, 11 ppm Ag, or using a lower cut-off some 3 Mt with 0.75% Cu, 0.52 ppm Au, and 2 ppm Ag (Danielsson 1985). The location of the Nautanen deposit close to two world class deposits offers a reasonably high potential for increasing the known reserves of the area, and this has encouraged mineral exploration by several companies throughout the past 50 years.

The Nautanen area has relatively well exposed bedrock and the original ore bodies were mostly found in outcrop. Between 1902 and 1907, some 71 835 tonnes of ore with grades of 1 to 1.5% copper and some gold were mined in the area by Nautanens Kopparfält AB (Geijer 1918). Arial geophysics were undertaken in the area in

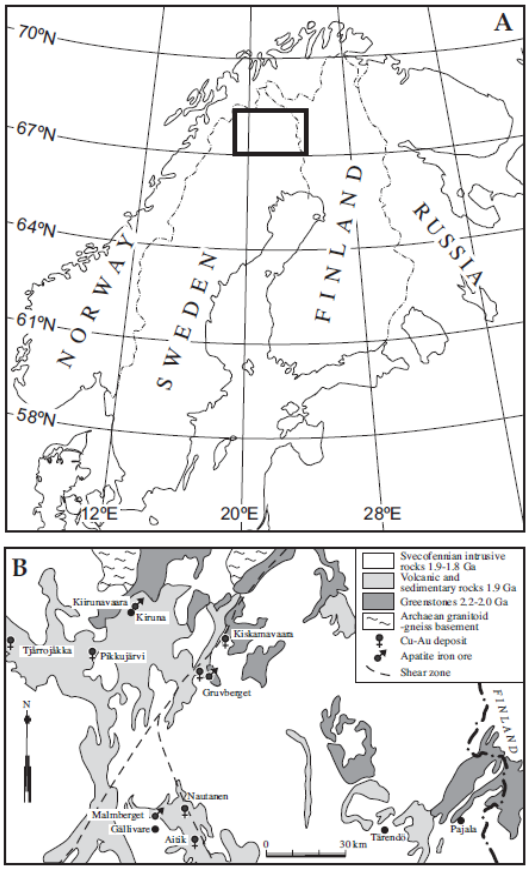


Figure 1. Geographical location of the Norrbotten mining district, northern Sweden (A), and a simplified geological map of the area including locations of significant Cu-Au and apatite iron ore deposits (B). (from Wanhainen 2005)

the 1960s and geological mapping was undertaken by the Swedish State Mining Property Commission (NSG) in the late 1960s, early 1970s. The largest drilling campaigns were also undertaken by NSG/Swedish Geological Co. (SGAB) in the late 1970s and from 1983 to 1985. In total over 100 drill holes were made by NSG/SGAB and the resulting 10 000+ meters of core most of which are housed at the SGU core warehouse in Malå. In 1997, 1998 the Nautanen area was investigated

and drilled by North Atlantic Natural Resources AB, whose core is also in Malå. In 2000-2008 Phelps Dodge drilled and investigated the area before optioning the area to an Australian Junior company, which subsequently dropped it. In 2009 the property was claimed by Boliden Mineral AB, who also owns the Aitik mine.

A limited amount of research has been done on the Nautanen deposit and its ore paragenesis, structural history, metamorphic events, age and relation to other deposits in the area are all poorly understood. Ore emplacement has been proposed to have taken place over various stages (Martinsson & Wanhainen 2004). The mineralization style has been described as an Iron Oxide Copper Gold (IOCG) deposit (Edfelt 2007, Gleeson & Smith 2009), IOCG hybrid-style deposit (Barton & Johnson 2004), and the possibility of a porphyry copper connection has been suggested (Martinsson & Wanhainen 2004).

The purpose of this work is to characterize the Nautanen host rocks lithologically and lithogeochemically in order to compare the deposit to other deposits in the area and begin to develop a better understanding of the geological history of the deposit and its relationship to other deposits in the area, noteably the Aitik deposit. To this end the methods undertaken have been the graphical logging of 1999 meters of drill core, descriptive analysis of 20 polished thin sections with plane polarized, reflective light and scanning electron microscopes, and the analysis of 35 high quality lithogeochemical samples.

2. Regional geology

The Northern Norrbotten area of Sweden is a major iron-copper-gold province and accounts for about 90% of the total tonnage of ore that is produced in Sweden (Wanhainen et al. 2005). It is an area that measures 200 by 100 km and is one of three important ore provinces in Sweden. The main ore bodies are hosted in Palaeoproterozoic rocks, mostly Karelian (2.5-2.0 Ga) and Svecofennian (1.9-1.88 Ga) in age.

The basement in the northern Norrbotten region is a 2.8 Ga Archaean granitoid gneiss which is unconformably overlain by Palaeoproterozoic successions of greenstone, porphyry and sedimentary successions (Martinsson et al. 2004). The 2.4-1.98 Ga Karelian units are rift related and lowest stratigraphically (Martinsson 1997) and are now preserved in deformed metamorphic belts intruded by granitoids (Smith et al. 2009). The Karelian units are overlain by the >1.9 Ga Greenstone Group which consists of tholeiitic to komatiitic volcanic rocks (Martinsson 1997).

Sveccofenian calc-alkaline andesites and related clastic sediments of the Porphyrite Group lie on top of the Greenstone Group and were formed in a continental arc setting (Martinsson 2004). The Porphyrite metavolcanics can be split into two groups, the low titanium, low zirconium Porphyrite andesites and the overlying high titanium, high zirconium basalts and thrachyandesitic Porphyry Group (Martinsson 2004). The Porphyry Group is overlain by the Kurravaara Conglomerate, the Kiirunavaara

Table 1. Main characteristics of Porphyry Cu-Au and IOCG deposits. (from Wanhainen 2005)

Main features	Porphyry Cu-Au	IOCG
Tectonic setting	Subduction-related island arc, continental margin	Intra-continental Extension along subduction-related continental margin
Age	Archaean to present, majority Mesozoic-Cenozoic	Archaean to present, majority Proterozoic
Main host rocks	1. Intermediate porphyritic intrusions 2. Intermediate volcanic and sedimentary rocks	1. Felsic-intermediate volcanic and sedimentary rocks 2. Felsic intrusions
Ore paragenesis	1. Magnetite 2. Chalcopyrite, pyrite ± pyrrhotite, chalcocite, molybdenite, bornite	1. Magnetite, hematite 2. Chalcopyrite, bornite, pyrite ± molybdenite, pyrrhotite
Alteration paragenesis	1. Biotite, K-feldspar, quartz (potassic) 2. Quartz, sericite, pyrite (phyllic) 3. Epidote, chlorite, calcite (propylithic) 4. Quartz, kaolinite, chlorite (argillic)	1. Albite, scapolite, amphibole 2. K-feldspar, magnetite, hematite, biotite quartz 3. Chlorite, muscovite (sericite), calcite, quartz
Mineralization style	Disseminated, vein, quartz stockwork	Disseminated, breccia infill, vein network, massive lenses, replacement
Ore fluid composition	Cation: Na ± K, Fe, Ca, Mn + CO_2 Solids: halite ± calcite 30-50 wt.%. NaCl T: 300-700°C	Cation: Na ± Ca, K, Fe, Mg + CO_2 Solids: halite ± calcite, FeP, hem 20-60 wt.%. NaCl T: 200-500°C
Structural control	Regional faults	Shear zones and faults
Assoc. with igneous activity	Temporal and spatial	Temporal
Parental magma	I-type	I-type, oxidized A-type
Other common minerals	Tourmaline, anhydrite	REE- and U-minerals, baryte, fluorite, tourmaline, apatite

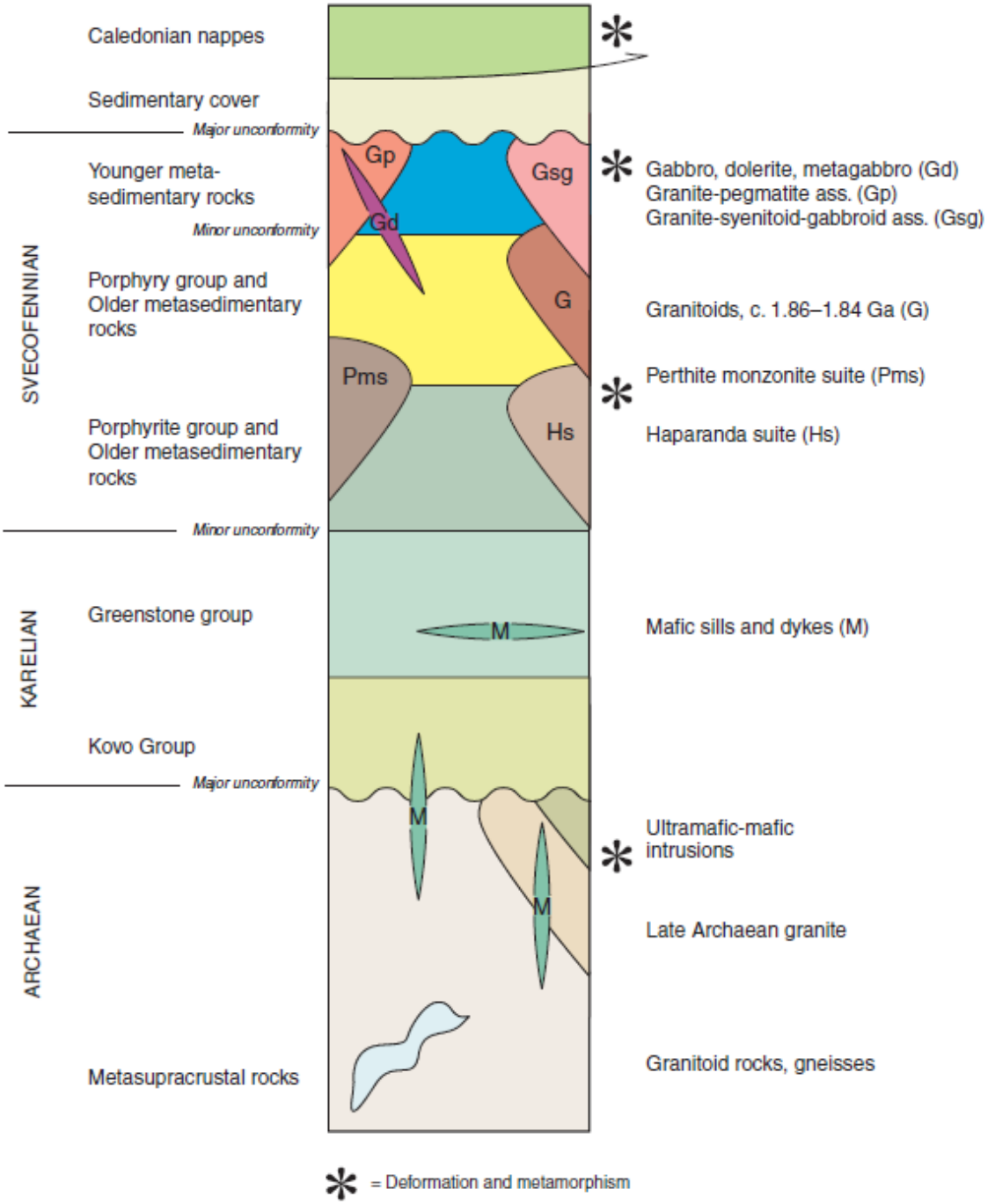


Figure 2. A schematic illustration of main rock units and events in Norrbotten. Not to scale. (from Martinsson et al. 2004)

Group, and the Hauki Quartzite. The Porphyrite Group is suggested to have formed in a subduction related event, while the Kiirunavaara Group has a geochemical signature suggesting within-plate volcanics (Martinsson 2004). The Hauki Quartzite is believed to have formed by uplift and erosion of the area (Martinsson 2004).

The Palaeoproterozoic sequence of volcanic and sedimentary rocks were deformed and metamorphosed ca. 1.88 Ga when the Haparanda suite of intrusions (1.89-1.87 Ga) were succeeded by the Perthite Monzonite suite (1.88-1.86) (Bergman et al. 2001). These plutonic intrusions have a calc-alkaline to alkali-calcic character and are believed to be comagmatic with the Porphyrite and Kiirunavaara Groups respectively (Bergman et al. 2001). The Lina suite of granitoids followed these intrusions ca. 1.79 Ga and they are related temporally to the Transscandinavian Igneous Belt (TIB) 1 intrusions in the Kiruna-Narvik area. Metamorphism of the supracrustal sequence during these intrusions peaked in the upper greenschist or lower amphibolites facies (Bergman et al. 2001). The youngest magmatic pulse to occur in the northern Norrbotten region was the intrusion of the ca. 1.71 Ga TIB 2 granitoids (Romer et al. 1992).

Northern Norrbotten is affected by regional scapolitization and albitization and at deposit scale in association with both iron oxide and copper-gold deposits (Smith et al. 2009). Apatite Iron Ores occur in the Porphyry and Kiirunavaara groups while IOCG and copper porphyry deposits occur in the Porphyrite Group (Martinsson 2004).

3. Local geology

3.1 Gällivare area

The Gällivare area of northern Norrbotten hosts both epigenetic Cu-Au ores and apatite iron ores. Most of the epigenetic Cu-Au deposits around Gällivare are located within or adjacent to the major shear zone known as the Nautanen Deformation Zone (NDZ) and are hosted in Svecofennian metavolcanics and metasediments. These rocks are known locally as the Muorjevaara Group and formed in an arc environment (Wanhainen & Martinsson 2004). Apatite iron ores are located in the Kiirunavaara Group which is restricted to the western part of the area (Fig. 3). These volcanics of intermediate to felsic composition have characteristics of an intraplate source (Wanhainen & Martinsson 2004). The NDZ is the most prominent tectonic structure in the area, and several parallel branches of schistose to mylonitic rocks occur within a zone up to 3 km wide that strikes north-northwest (Bergman et al. 2001).

A large-scale zoning pattern of metal association and alteration minerals is present along the NDZ. Deposits in the northwest contain magnetite and locally apatite as important minerals, which indicate a relationship to the nearby apatite iron ores in Malmberget. Alteration of the

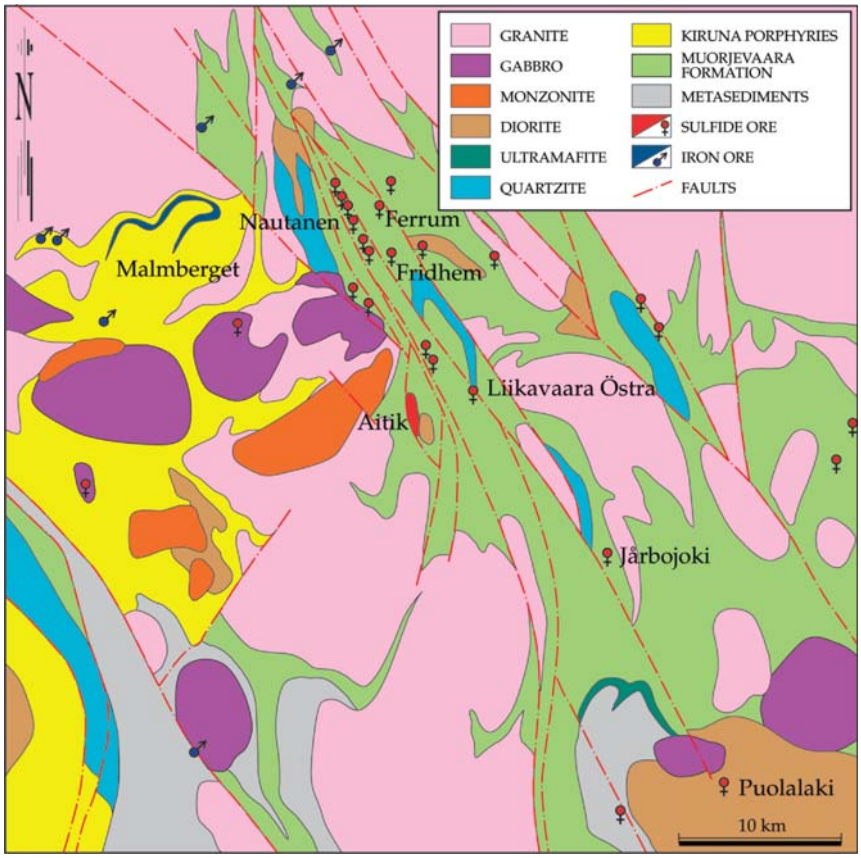


Figure 3. Geology of the Gällivare area (from Wanhainen & Martinsson 2004)

host rock in the northwest is dominated by strong scapolite and K feldspar alteration. In the southeast, pyrite increases in abundance while magnetite decreases, at the same time the Au/Cu ratio increases and alteration is dominated by biotite and sericite (Wanhainen & Martinsson 2004).

Mineralization in the NDZ occurs in both disseminated and vein style. Disseminated mineralization is interpreted as an early phase that is related to synorogenic 1.9 Ga intrusions, while vein style mineralization is a later phase related to remobilization and possibly addition from magmatic and hydrothermal processes active around 1.8 Ga (Wanhainen & Martinsson 2004). Several repeating hydrothermal events and remobilizations along the structures of the NDZ have led to the current distribution of mineralization in the area.

3.2 Nautanen

The rocks in the Nautanen area belong to the Muorjevaara Group of metavolcanics. The internal stratigraphy of the Muorjevaara Group is poorly understood, but is interpreted to consist of alternating layers of pelites and lithic arenites that are of mainly andesitic volcanoclastic origin

Table 2. Characteristics of Cu-Au mineralization in the Gällivare area (from Wanhainen & Martinsson 2004)

	Mineralization						Vein minerals
	Grades and tonnage	Occurrence	Main ore mineralogy	Metal association	Host rock	Alteration	
Aitik	0.4% Cu 0.2 ppm Au 4.2 ppm Ag 400 Mt [1]	Disseminated veins	Chalcopyrite Pyrite Magnetite Pyrrhotite	Cu-Au-Ag(-Fe)	Volcaniclastics Quartz-monzodiorite	Biotitization Sericitization K feldspar/ epidote Tourmalinization Scapolitization	Amphibole-biotite Quartz (zeolites) Tourmaline Barite Apatite
Nautanen	[2] 2.36% Cu 1.30 ppm Au 11 ppm Ag 0.63 Mt [3] [4] 0.34% Cu 0.3 ppm Au 2.3 Mt [5]	Veins disseminated	Chalcopyrite Magnetite Pyrite	Cu-Au-Ag-Fe	Volcaniclastics Mafic dykes	K feldspar/ epidote Scapolitization Tourmalinization Sericitization Garnets	Quartz (zeolites) Tourmaline Barite Carbonate Apatite
Ferrum	1.45% Cu	Veins	Chalcopyrite Bornite	Cu-Au(-W-Mo)	Volcaniclastics	Tourmalinization Scapolitization	Quartz Tourmaline Amphibole-pyroxene
Fridhem		Veins	Chalcocite Bornite Native gold (Hematite)	Au(-Cu)	Volcaniclastics	(Epidote)	Quartz Zeolites
Liikavaara	0.58% Cu 0.2 ppm Au 8 ppm Ag	Disseminated veins Pyrite	Chalcopyrite Pyrrhotite	Cu-Au-Ag(-W-Mo-Zn-Pb)	Volcaniclastics	Biotitization Chloritization	Quartz Carbonate (Tourmaline)
Järbojoki	0.2% Cu 0.4 ppm Au	Veins Disseminated	Pyrite Chalcopyrite (Magnetite) (Hematite)	Au-Cu(-Fe-W)	Volcaniclastics Diorite Mafic dykes	K feldspar Sericitization Epidotization Scapolitization	Quartz Carbonate (Tourmaline)
Puolalaki	7.61 ppm Au 3.36% As 0.18% Cu 0.15% W 0.11 Mt [3]	Veins Disseminated	Arsenopyrite Pyrrhotite (Chalcopyrite)	Au-As-Cu-W(-Co-Ni)	Paragneiss Granodiorite Aplite	Biotitization	

[1] Total production
[2] Mainly of vein-type
[3] Resources
[4] Mainly of disseminated character
[5] Indicated resources

(Martinsson & Wanhainen 2004). Amygdaloidal andesite lava and volcanogenic conglomerates are minor constituents (Ros 1980).

Intrusions from the Haparanda suite of diorite and granodioritic composition are common in the Muorjevaara Group and at Aitik have the character of a porphyritic high-level intrusion (Wanhainen & Martinsson 2001). A younger phase of intrusions known as the Lina Suite of granites is extensive in the area and pegmatites related to the Lina Suite can be found within the Muorjevaara Group (Martinsson & Wanhainen 2004).

The Nautanen deposit is hosted by strongly altered and deformed rocks set within the NDZ. Alteration and deformation are so pervasive that the original character of the rock is difficult to interpret, however less-deformed clastic metasedimentary rocks of the Muorjevaara Group are found on both sides of the shear zone adjacent to the Nautanen deposit (Bergman et al. 2001). The original rock is believed to consist of volcanoclastic sediments with an intermediate composition. Mafic dikes are also present, constituting a minor component mainly found in the eastern area. A more mafic component occurs in the ore zone,

which has been heavily scapolitized to the point where all primary textures and contact relations have been destroyed (Bergman et al. 2001).

Alteration minerals mainly include scapolite, microcline, epidote, biotite, sericite, amphibole, tourmaline and garnet. Scapolite dominates alteration in the east, garnet-biotite-microcline in the central area and sericite-garnet-tourmaline dominates to the west (Geijer 1918). Garnets show considerable variability. Barton and Johnson (2004) have identified distinct populations of garnets including REE-bearing grossular garnet, spessartine-rich garnet, and almandine-rich garnet. They interpret the spessartine-rich variety, which is found in sericite schists, to have formed early and the almandine-rich variety to have formed late at peak metamorphic conditions. All types of garnet are interpreted to have formed after the introduction of metals in the area and the increased abundance of garnet in mineralized zones is thought to have resulted from favourable bulk conditions (Barton & Johnson 2004). Danielsson (1985) observed garnet porphyroblasts that have been brecciated with quartz and sulphides indicating that some garnet may have formed previous to mineralization or at least before that latest episode of remobilization. Rotated garnet porphyroblasts and boudinaged tourmaline veins have been interpreted to indicate that alteration and mineralization are pretectonic to syntectonic (Ros 1980).

Magnetite is often the most common ore mineral, occurring in disseminated form throughout much of the deposit as well as in near massive pods, veins and lenses in association with garnet and amphibole-pyroxene-epidote skarn (Martinsson & Wanhainen 2004). Chalcopyrite is the main copper mineral and occurs in association with quartz-K-silicate rich assemblages, actinolite ± garnet-Ba-rich K feldspar, and in skarns composed of pyroxene-amphibole-quartz ± epidote ± Kfeldspar (Barton & Johnson 2004). Gold often occurs in association with copper and it is rare that high grades occur without significant copper mineralization. In disseminated mineralization the copper/gold ratio is about 1/1 (ppm/vol. %), but in rich copper mineralization the gold ratio is lower, approximately 0.1/1 (Martinsson & Wanhainen 2004). Pyrite is the next most common sulphide after chalcopyrite. An enrichment of cobalt has been observed in the pyrite and is related to the gold mineralization (Hålenius 1983). Other ore minerals that occur in accessory amounts include pyrrhotite, sphalerite, galena, carrolite, bismuthinite, molybdenite, and sheelite (Hålenius 1983).

Titanite and allanite dating from Nautanen has yielded an age of c. 1.78 Ga (Smith et al. 2009). This age is comparable to the timing of a late IOCG-type overprinting event identified in the Aitik deposit at c. 1.8 Ga (Wanhainen 2005). This suggests a relationship between IOCG-type deposition at Nautanen and IOCG overprinting at Aitik and indicates the remobilization of metals along the structures of the NDZ at this time. This age does not completely constrain the timing of mineralization in the Nautanen deposit however, as thermal metamorphic events near this time may have been responsible for resetting existing titanite and

allanite grains. There is evidence of multiple stages of mineralization which have occurred during pre-, early, ductile, and brittle stages of deformation (Barton & Johnson 2004).

4. Methodology

A total of 1999 meters of drill core were logged, 443 assay samples, 35 lithogeochemical samples, and 15 petrographic samples were taken. Polished thin sections were prepared from the petrographic samples by Vancouver Petrographics Ltd, Canada. The drill core consisted of 7 holes drilled by SGAB between 1977 and 1985 from the 5040 N profile of the Nautanen deposit. An additional 5 polished thin sections from SGU, taken from other drill holes, were also studied in order to describe mineralization typical of the deposit. The drill core was provided by SGU and logged at both the Malå SGU core logging facilities and the Boliden AB core logging facilities in Boliden.

Assay samples were taken roughly every 5m from the top of the hole to the bottom. Samples were prepared in Piteå by ALS Laboratory Group and analysed at their labs in Vancouver, Canada. Samples were analysed for trace level gold by fire assay and ICP-AES (inductively coupled plasma atomic emission spectrometry), and for ore grade gold by fire assay with gravimetric finish. Silver, molybdenum, and copper were analysed by aqua regia digestion and AAS (atomic absorption spectrometry). Total sulphur was analysed by Leco furnace.

Lithogeochemical samples were taken as representatives of the major rock and alteration types, 35 samples were taken in total. Samples for lithogeochemical analysis were analysed for major elements by ICP-AES (inductively coupled plasma atomic emission spectrometry), and for trace elements by ICP-MS (inductively coupled plasma mass spectrometry). Samples were prepared in Piteå and analysed in Vancouver by ALS Laboratory Group.

The thin sections and polished thin sections were examined microscopically in transmitted and reflected light. Polished thin sections were also analysed by energy dispersive X-ray (EDS) in a scanning electron microscope (SEM), using a backscatter detector (BSE) for sample images. Samples were analysed on a Hitachi S3400 N using INCA 4.06 software at the Department of Geology in Lund.

5. Petrological discription of the rocks

The host rock to the 5040 N profile consists of altered gneisses grading into schists in the heavier mineralized areas. The rocks are pophyritic with a very fine grained matrix and porphyroblasts of scapolite and garnet. Scapolite porphyroblast typically are around 2 mm in diameter (Fig. 4c), while garnets generally range from 2 mm up to 1 dm. Garnets increase in size and frequency with higher mineralization and it is uncommon to find Cu mineralization in rocks that do not contain garnet.

Alteration minerals are extensive and varied, with the least altered rock still showing strong scapolitization. The degree of alteration increases from scapolite ± garnet gneiss with the addition alteration minerals, to epidotized scapolite ± garnet gneiss, to a K-feldspar and epidotized scapolite ± garnet gneiss, to a completely skarnic heavily K-

feldspar and epidotized gneiss (Fig 4). As shown in table 3, it can be seen from point counts that the addition of epidote alteration is largely at the expense of biotite and amphibole which are also altered to chlorite. Along with the alteration of biotite to amphibole, plagioclase is at the same time breaking down to sericite. K-feldspar alteration occurs as matrix-sized secondary growth crystals. Alteration at the microscopic level is shown in figure 4. Magnetite is the most common ore mineral, both in the economically mineralized zones and throughout the host rock. It commonly makes up 3-4% of Nautanen rocks (Monro 1988). In profile 5040 N magnetite is found in disseminated grain form nearly everywhere and also in solid bands, sometimes with chalcopyrite. Magnetite bands are often accompanied by epidote. The disseminated magnetite is aligned to the same foliation as the biotite indicating early crystallisation, before shearing. Hematite is also found in trace amounts and has been observed locally as blebs in strongly K-feldspar altered rock. In places, pyrite has been partially oxidized to magnetite, leaving traces of concentric magnetite growth rings around a pyrite core (Monro 1988).

Chalcopyrite is the most common sulphide ore mineral followed by pyrite. Other ore minerals are native gold and silver, molybdenite, sphalerite, cuprite, pyrrhotite, scheelite, galena, carrolite, bismuthinite, tellurobismuthite, and bornite. These minerals are found in accessory amounts with the exception of bornite which can sporadically be found in more significant amounts.

Table 3. Main Nautanen host rock types of the 5040 N profile. Based on point counts from six thin sections.

Mineral (vol %)	Scap-Bt Gniess (low alt.)	Scap-Bt Gniess (Epidote alt.)	Scap-Bt Gniess (K-spar/epi alt.)	Gt-Ser Gniess	Banded Gniess	Skarn
K-feldspar	4	5	13	8	4	
Quartz	15	10	6	5	21	
Plagioclase	15	17	29	15	16	
Sericitic Plag	2	12	21	31	11	
Biotite	29	2	2	15	11	
Amphibole	7	3			3	
Chlorite		18	14	8	7	18
Scapolite	17	8		2	9	
Epidote	8	19	13	1	1	70
Calcite		1				11
Garnet	2			1		
Tourmaline		2				
Apatite	1	1				
Titanite		1				1
Opaques	1	2	3	8	17	

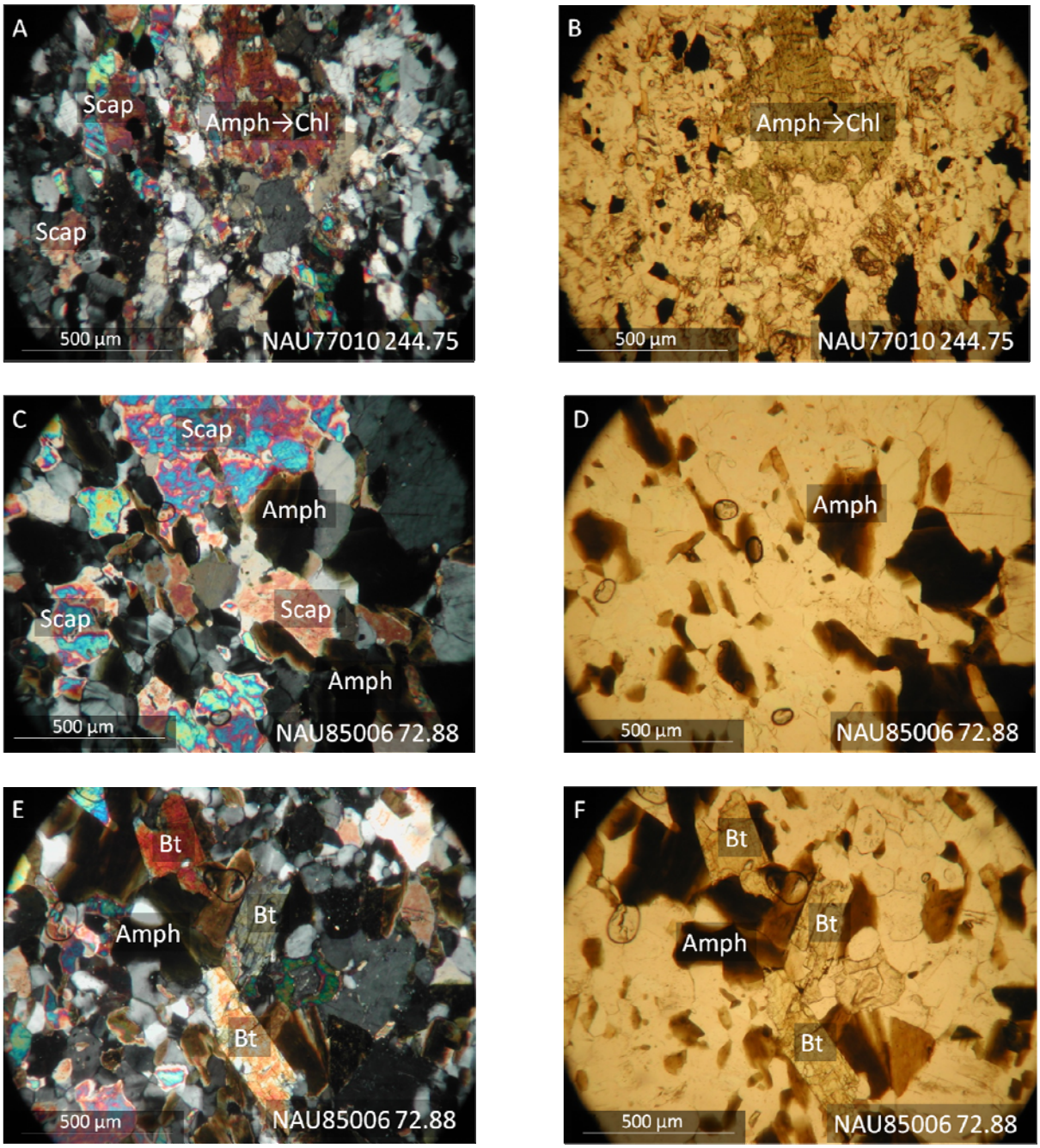
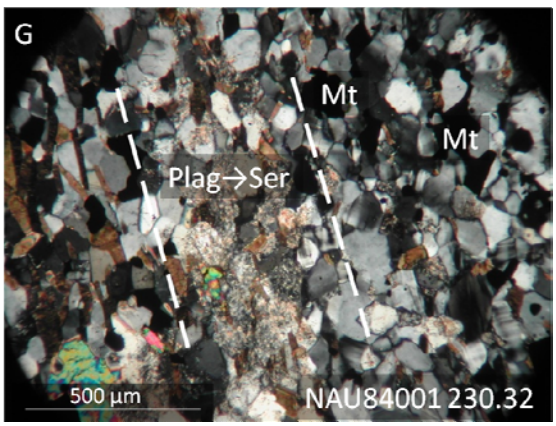
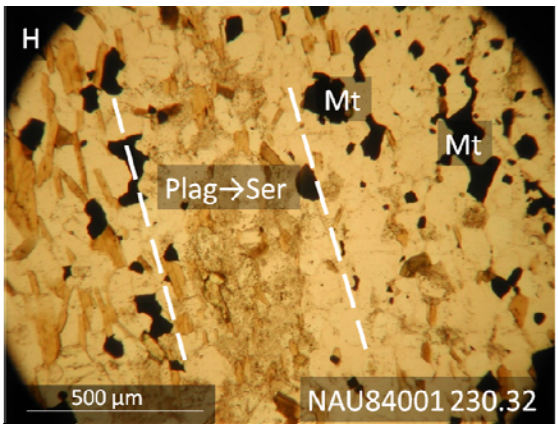
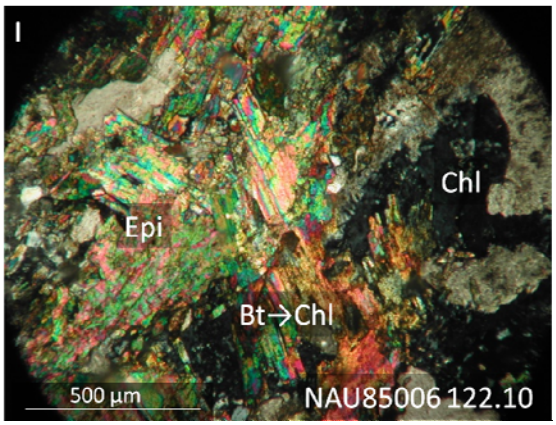


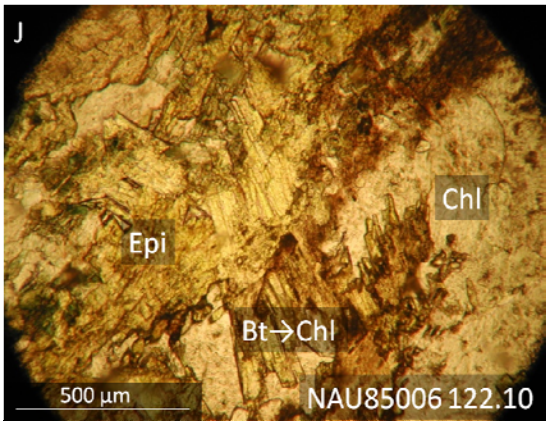
Figure 4. Nautanen alteration in thin section. Images are taken in cross polarized (left) and plane polarized (right) transmitted light. Image K (next page) was taken in plane polarized reflective light. A,B, Amphibole-biotite banded gneiss. Chloritization of amphibole, early stages of sericitization of plagioclase, scapolite porphyroblasts. C, D, E, F, Garnet-scapolite-biotite-amphibole gneiss. Large scapolite porphyroblasts are shown in C. In E and F, light coloured biotite is being altered to epidote, Dark brown minerals are former biotite grains altered to amphibole.

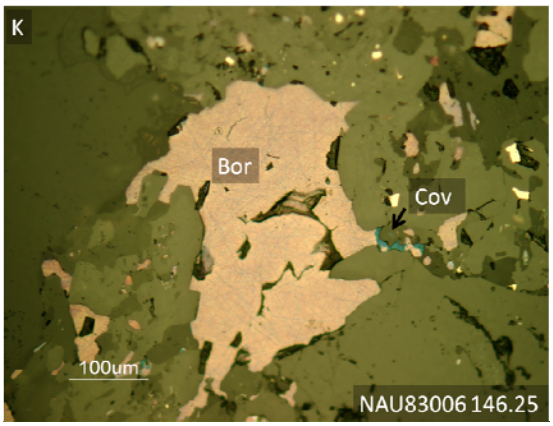
Figure 4 continued:

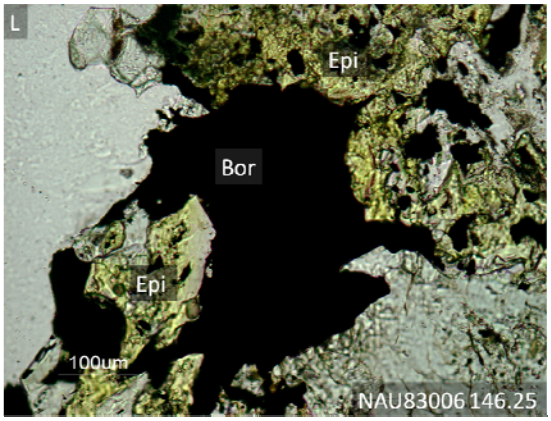












G, H, Garnet-sericite gneiss. Very fine grained, strongly foliated. Sericite occurs in bands parallel to foliation, high amounts of magnetite, and usually low grade disseminated chalcopyrite.
I, J, K-feldspar/epidote skarnic gneiss. Primary textures mostly destroyed, biotite altered to epidote, extensive chloritization, calcite also common. K, L, Mineralization, in this case bornite with blue covellite, is accompanied by epidote, light yellow/green on right.

Chalcopyrite is found as disseminated grains in the rock and as well as in veins of fairly large grains greater than 100 µm. Chalcopyrite is also commonly found filling microscopic fractures in pyrite and magnetite (Fig. 5). The accessory ore minerals are usually found with chalcopyrite and most filling fractures. Chalcopyrite and to some extent bornite, have been oxidized to malachite and chrysocolla as evidenced by boulders at the Nautanen site. Covellite, observed in thinsection, is also a result of oxidation of the copper minerals. Gold is found mainly as individual grains in association to chalcopyrite, and it is rare to find high values of gold that are not associated with high copper values. The gold grains vary in composition. Silver is typically a major component, usually making up more than 50wt% of the grain, and mercury is often a minor component, <10wt% (Table 4). Silver also occurs separate from gold in aggregates with telluride. The Au/Ag ratio is highly variable and most of the gold grains occur in small fractures in pyrite and magnetite grains indicating that gold precipitation occurred late and might be the product of remobilization of earlier gold mineralization that occurred associated with the chalcopyrite (Fig. 5).

Enrichment of cobalt has been noted in the pyrite grains by Hålenius (1983), and these Co-rich pyrite grains occur with gold grains, as does bismuthinite (Table 4). Future assaying for cobalt and bismuth could allow for better evaluation of this relationship and its potential for use in future exploration. Barite occurs as veins in the mineralized area and an enrichment of barium in microcline near gold rich zones has been noted. Barium has similar chemical properties to potassium, and seems to substitute for K in feldspars. Enrichment in barium is seen at a larger scale as well for both the Nautanen and Aitik deposits, making it a potential tool for exploration in the Gällivare area.

Table 4. SEM point analysis. Samples carbon coated, acceleration voltage 17.5, standardized with pure cobalt. INCA standards were used and this introduced a high degree of error in the results. Ideally total weight percent values should be between 97% and 103% so the values obtained here should only be used for a general idea of the wt% of identified elements

		Wt%								
Sample	Point	Au	Ag	Hg	Bi	Pb	Co	Fe	S	Total
NAU83006 146.25	1	21.67	70.53	11.83						104.03
	2	19.94	69.75	12.53						102.22
	3	22.52	67.98	13.65						104.16
NAU83002 114.4	1	86.9	27.47							114.37
	2	2.48	24.04		49.74	10.73			15.76	102.76
	3 (Py)						1.48	45.51	54.4	101.39
NAU83002 144.40	1	32.11	79.75							111.86
	2	71.59	45.65							117.24
	3	53.94	58.2							112.14

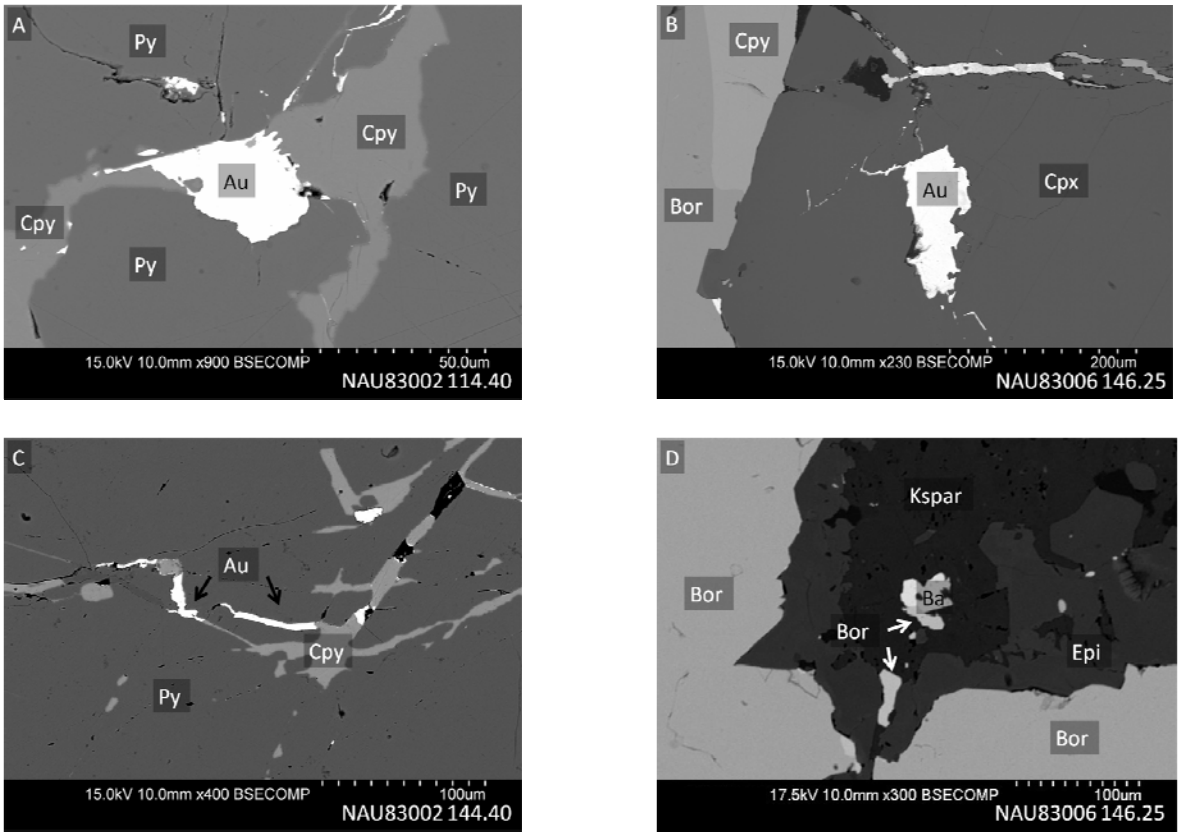


Figure 5. SEM images of gold (Au) found as grains and in microscopic veins in association with chalcopyrite (Cpy) filling fractures of pyrite (Py) and pyroxene (Cpx). Figure D shows barite (Ba) occurring with bornite (Bor) in feldspar (Kspar). The bornite is being rimmed by epidote (Epi).

6. Geochemistry

Analytical results for the major and trace elements of representative samples of the Nautanen host rock are presented in Table 5. Since the host rocks to the Nautanen deposit have undergone heavy alteration, geochemical data records a compound of primary signatures with secondary alteration and metamorphic mass changes (Fig. 6 and Fig. 7). Geochemistry diagrams in this section use elements that are believed to be immobile, but interpretations as the origin of the rocks must be taken with care since it is not clear if traditionally immobile elements really have been immobile in this area. The absence of fresh samples and the degree of tectonic deformation in the area makes it difficult to interpret the evolution of the magmas.

Samples taken from profile 5040 N can be broken into three groups by using the Nb/Y – Zr/Ti discrimination plot (Pearce 1996). The discrimination plot shows one group of andesites or basaltic andesites, another group of trachyandesites, and a final third group is made up of three samples that plot as rhyolite/dacite (Fig. 8). When compared to the observed rock types only the

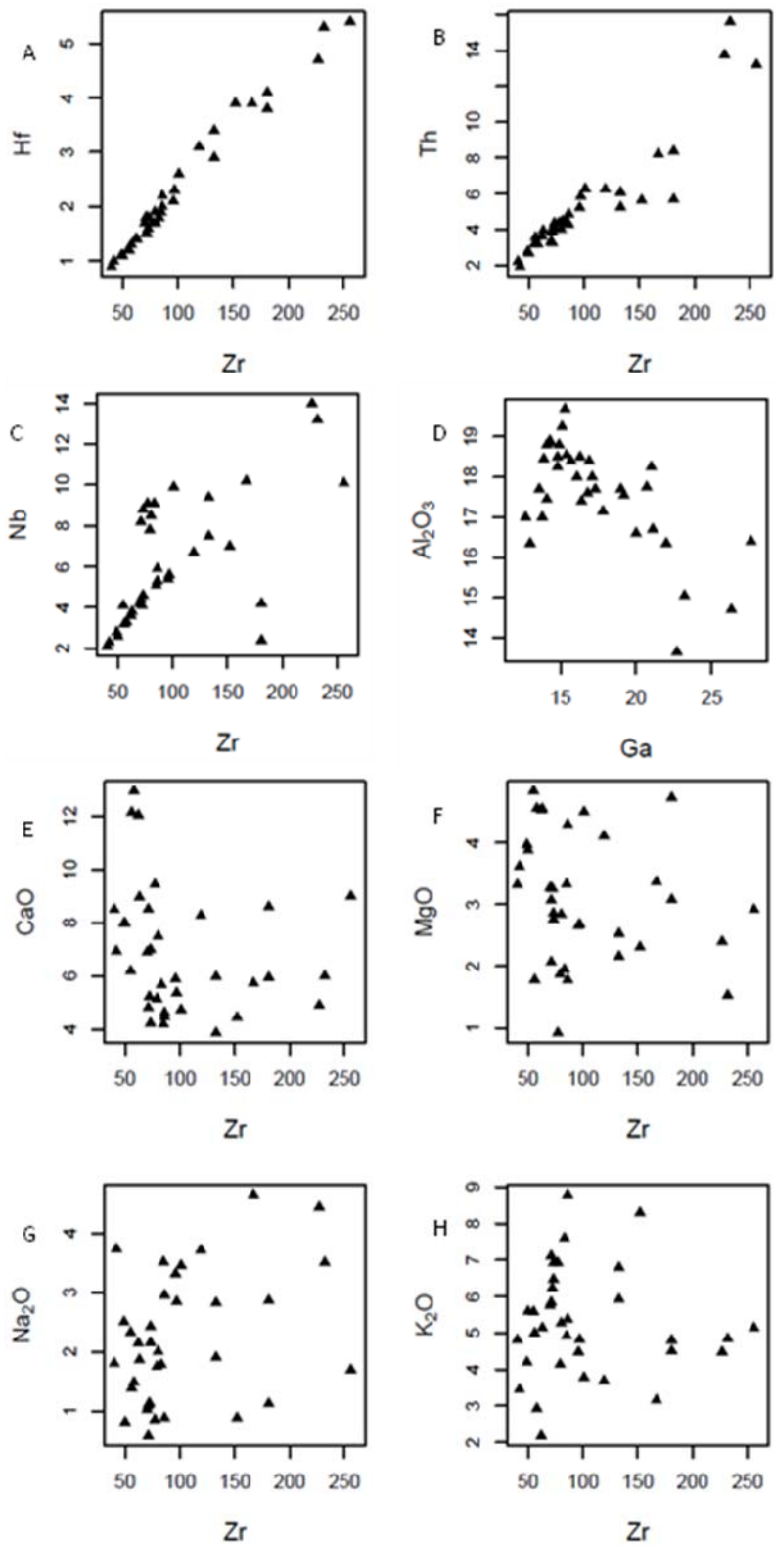


Figure. 6 Trace element lithogeochemistry.
Immobile elements Zr-Hf-Th-Nb (a, b, c) show a strong correlation suggesting rocks derived from a single suite. The non-correlated Ga- Al_2O_3 plot (d) and the Zr vs Alkali elements plots (e, f, g, h) show that mobile elements have have been strongly effected due to alteration and mass changes

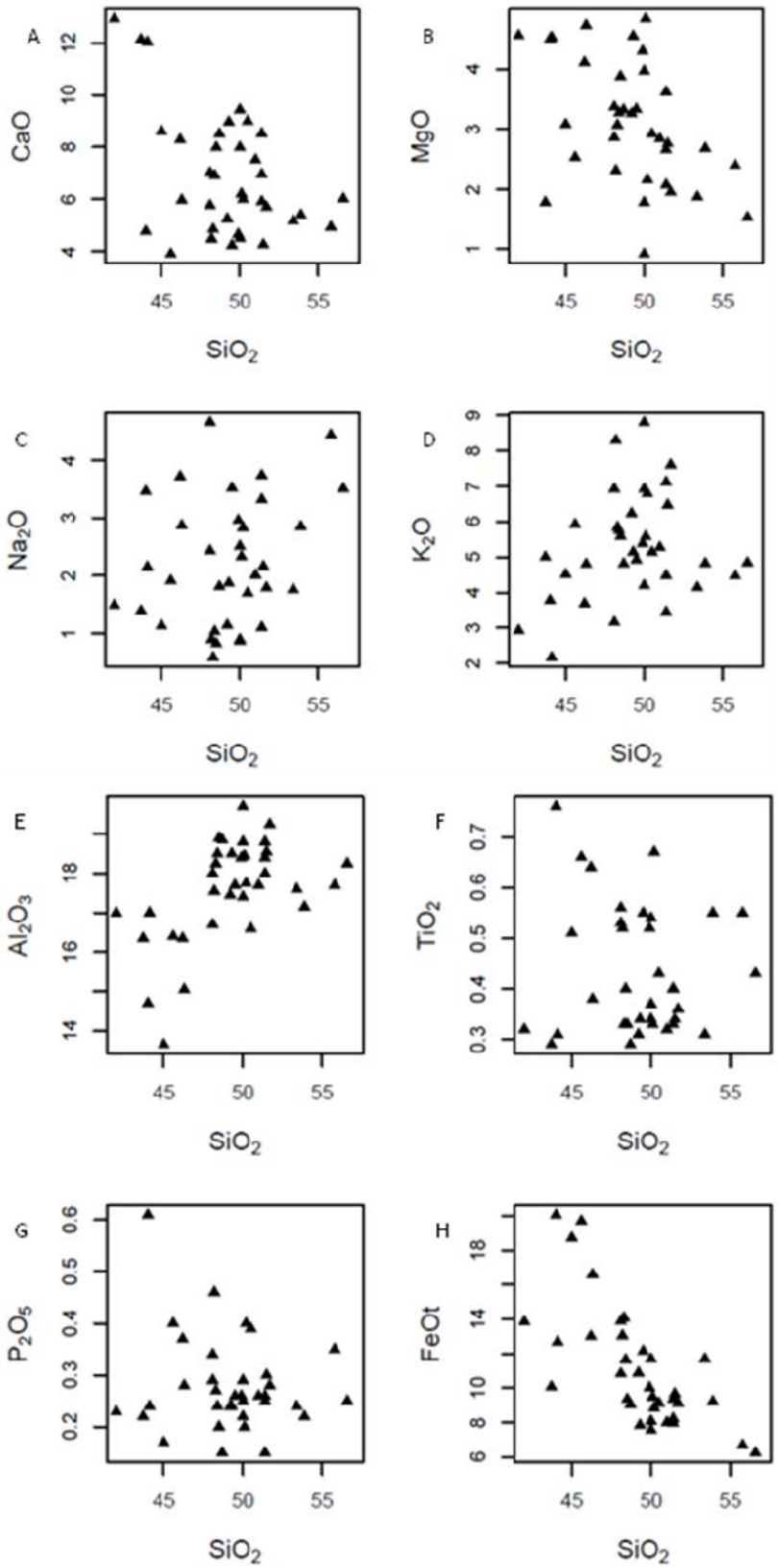


Figure. 7 The major elements plotted against SiO_2 show that there has been strong movement of mobile elements, making them unreliable for identifying rock types

Table 5. Major and trace element analyses of representative samples from the Nautanen host rock. Major element and S data are shown in wt%. Trace element data are shown in ppm. LOI= Loss on ignition.

Sample	03020 10	03020 20	03020 23	03020 36	03020 49	04001 3	05006 7	77011 60	77011 5	03020 43
Rock Type	Bt-Ot Gneiss	Bt Gneiss	Hbl-Bt-Ot Gneiss	Skarnoic Bt-Ot Gneiss	Banded Gneiss	Bt-Amph. Gneiss	Sar-Bt-Ot Gneiss	Bt Gneiss	Bt-Ot Gneiss	Bt-Ot Gneiss
SiO2	48.5	50.1	49.2	43.7	51	53.9	48.2	44	53.4	48.3
Al2O3	18.9	18.45	17.45	16.35	17.7	17.15	17.55	14.7	17.6	18.25
Fe2O3	10.4	10.55	12.1	11.2	8.9	10.25	14.5	22.3	13	15.65
CaO	7.99	6.2	5.24	12.15	7.51	5.38	4.46	4.75	5.16	4.83
MgO	3.88	4.84	3.26	1.78	2.84	2.68	2.31	4.5	1.87	3.07
Na2O	0.82	2.33	1.14	1.39	2.01	2.85	0.89	3.46	1.76	0.58
K2O	5.59	5.58	6.23	5	5.27	4.82	8.29	3.78	4.14	5.84
Cr2O3	0.01	0.01	0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
TiO2	0.33	0.33	0.31	0.29	0.32	0.55	0.52	0.76	0.31	0.33
MnO	0.79	0.55	0.61	0.71	0.56	0.42	0.72	0.45	0.83	0.89
P2O5	0.2	0.2	0.24	0.22	0.26	0.22	0.46	0.61	0.24	0.27
SrO	0.02	0.03	0.02	0.05	0.03	0.02	0.03	0.06	0.03	0.02
BaO	0.34	0.15	0.26	0.18	0.21	0.14	0.41	0.1	0.2	0.34
LOI	2.19	1.39	2.4	5.36	1.88	0.8	1.28	0.4	0.96	1.7
Total	100	100.5	98.5	98.4	98.5	99.2	99.6	99.9	99.5	100
Ba	2650	1215	2120	140.5	1670	1210	3310	809	1610	2630
Co	23.4	43.1	35.9	26.4	38.1	21.2	51.5	44.9	20.5	37.2
Cr	60	90	60	60	10	30	30	10	10	10
Cs	2.91	15.95	6.14	2.69	4.06	11.7	4.85	17.35	6.13	11
Cu	5	<5	28	18	28	17	132	<5	91	22
Ga	14.3	13.9	14.1	13	17.3	17.8	19.2	26.3	16.8	14.8
Hf	1.1	1.2	1.5	1.2	1.7	2.3	3.9	2.6	1.9	1.5
Mo	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Nb	2.6	4.1	4.1	3.2	8.5	5.6	7	9.9	7.8	8.2
Ni	19	33	28	17	14	19	18	21	12	21
Pb	<5	5	5	5	6	7	10	6	6	<5
Rb	175	210	265	193	171	208	200	170	165	255
Sn	<1	<1	<1	<1	1	1	1	2	<1	1
Sr	177	232	173.5	391	247	186	246	425	199.5	193.5
Ta	0.1	0.2	0.2	0.1	0.4	0.3	0.3	0.3	0.3	0.3
Th	2.67	3.17	4.13	3.56	4.46	5.85	5.63	6.28	4.02	3.86
Tl	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
U	1.75	2.67	1.66	1.07	0.95	1.37	1.85	1.62	1.68	0.96
V	121	109	113	75	92	165	128	318	91	76
W	3	4	12	7	13	2	13	<1	6	11
Y	7.7	8.1	9.9	9.5	13.4	12.2	10.6	13.9	10.2	9.8
Zn	72	65	54	50	70	50	86	127	64	137
Zr	50	55	72	56	80	97	152	101	79	71
La	18.2	21.8	31.5	32.8	40	26.1	26.4	43.4	25.5	17.1
Ce	38	45.4	61.2	63.4	79.3	52.2	50.1	82.3	49.1	34.9
Pr	4.78	5.77	7.49	7.95	9.96	6.51	6.46	9.05	5.71	4.39
Nd	17.2	21	26.1	27.4	34.6	22.2	24.4	33.2	22.1	15.7
Sm	3.14	3.64	4.51	4.61	5.67	3.96	4.03	5.32	3.79	2.77
Eu	1.08	1.19	1.65	1.53	1.66	1.18	0.89	1	1.23	0.8
Gd	2.67	3.04	4.04	3.85	4.81	3.56	3.49	4.82	3.42	2.54
Tb	0.34	0.37	0.48	0.46	0.59	0.47	0.4	0.59	0.44	0.34
Dy	1.61	1.69	2.1	1.98	2.65	2.43	1.9	2.59	2	1.76
Ho	0.3	0.31	0.37	0.35	0.49	0.48	0.36	0.49	0.37	0.35
Er	0.82	0.85	0.97	0.94	1.4	1.36	1.07	1.43	1.03	1.01
Tm	0.08	0.09	0.08	0.09	0.16	0.16	0.15	0.18	0.14	0.11
Yb	0.7	0.72	0.73	0.74	1.16	1.26	1.1	1.25	0.9	0.89
Lu	0.11	0.11	0.11	0.11	0.18	0.19	0.16	0.21	0.13	0.14

Table 5 continued:

Sample	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Rock Type	Hr.-Amph. Gneiss	Biotite Hr.-Amph. Gneiss	Hr.-Amph. Gneiss	Hr.-Qz. Gneiss	Hr.-Amph. Gneiss	Banded Gneiss	Banded-Qz. Gneiss	Hr.-Amph. Gneiss	Hr.-Amph.-Qz. Gneiss	Bpt-Hr.-Amph. Gneiss
SiO2	51.3	50	51.7	43.6	48.1	53.0	50.6	45	50.3	44.5
Al2O3	10.55	10.7	10.25	16.4	16.7	17.7	10.25	13.65	16.6	15.05
Fe2O3	10.75	9.41	10.15	21.9	15.45	7.43	6.94	20.0	10.15	10.45
CaO	4.34	4.44	5.69	5.66	5.73	4.93	4.61	6.61	4	5.64
MgO	2.76	0.92	2.85	2.55	3.37	2.4	1.55	3.09	2.92	4.75
Na2O	2.16	0.86	2.79	1.91	4.05	4.14	3.51	1.13	1.7	2.07
K2O	4.97	4.93	7.4	3.93	3.16	4.90	4.04	4.31	5.14	4.8
Cr2O3	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
TiO2	0.34	0.37	0.36	0.66	0.56	0.55	0.43	0.51	0.43	0.39
MnO	0.25	0.22	0.21	0.54	0.61	0.26	0.50	0.02	0.30	0.44
P2O5	0.3	0.29	0.28	0.4	0.34	0.33	0.23	0.17	0.39	0.28
SrO	0.04	0.04	0.03	0.07	0.05	0.12	0.07	0.08	0.09	0.07
BaO	0.26	0.14	0.39	0.46	0.26	0.10	0.27	0.51	0.21	0.15
LOI	1.9	2	1.1	0.1	1.08	0.2	0.96	1.09	1.4	0.39
Total	99.4	99.7	100.3	100.3	100	99.8	100.3	100.3	99.2	100
Ba	2020	3370	3010	3490	2050	1970	2200	4150	1070	1225
Co	28	17.8	23	30.1	29.9	20.7	16.3	32.9	23	41.3
Cr	10	10	10	<10	<10	<10	10	10	10	10
Cs	7.11	2.01	6.00	14.9	5.4	7.27	7.4	4.37	0.35	20.9
Cu	17	23	16	450	131	<5	43	415	445	41
Ga	13.4	13.3	23.1	27.4	21.1	19	21	22.7	20	25.2
Hf	1.6	1.7	1.8	2.8	2.8	4.7	3.3	2.8	3.4	4.1
Mo	<2	2	4	3	<2	<2	2	<2	<2	<2
Nb	8.8	9.1	9.1	9.4	10.2	16	13.2	9.4	10.1	4.2
Ni	15	11	11	10	7	<5	10	12	9	16
Pb	7	5	5	7	7	5	7	7	8	6
Rb	200	203	239	210	413.9	109	120	133	177	170.3
Sn	1	1	<1	2	1	1	1	2	1	2
Sr	341	343	401	556	200	651	499	300	401	403
Th	0.3	0.3	0.4	0.8	0.5	0.8	0.7	0.1	0.4	0.8
Th	4.03	4.30	4.46	3.26	0.23	13.73	13.6	3.08	13.2	0.37
Tl	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
U	0.96	3.38	2.31	1.94	2.06	4.5	3.99	2.28	2.05	3.13
V	70	91	111	306	120	109	60	230	103	210
W	0	22	0	3	<1	<1	3	1	1	<1
Y	0.1	11.0	10	0	13	16.2	14.7	14.5	17.2	12.3
Zn	77	51	50	141	70	51	99	161	130	150
Zr	73	77	63	133	107	207	230	101	230	101
La	31.7	30.3	30.1	32.7	11.0	55.0	51.3	36.5	35.4	30.3
Ce	61	39.3	55.4	61.1	25.1	110	100.5	51.9	72.7	32.9
Pr	7.97	7.46	4.92	4.95	3.47	13	11.9	4.77	9.25	3.81
Nd	27.6	25.6	36.1	22.7	16.6	41.7	44.1	23.2	31.6	21.7
Sm	4.33	4.34	4.06	3.46	3.90	6.35	6.74	4.17	5.54	3.91
Eu	1.07	1.44	1.23	0.90	0.93	1.69	1.30	1.10	1.43	0.91
Gd	3.5	3.30	3.30	3.00	3.13	5.00	5.06	3.71	4.03	3.02
Tb	0.4	0.40	0.44	0.36	0.46	0.67	0.65	0.53	0.65	0.45
Dy	1.7	2.20	2.00	1.60	2.49	3.10	2.77	2.07	3.23	2.2
Ho	0.31	0.43	0.39	0.32	0.49	0.61	0.56	0.33	0.63	0.43
Er	0.93	1.22	1.06	0.84	1.41	1.8	1.69	1.54	1.06	1.31
Tm	0.11	0.15	0.12	0.1	0.21	0.23	0.23	0.21	0.25	0.10
Yb	0.68	1.07	0.93	0.83	1.33	1.63	1.66	1.38	1.63	1.23
Lu	0.15	0.17	0.15	0.16	0.2	0.27	0.26	0.20	0.31	0.22

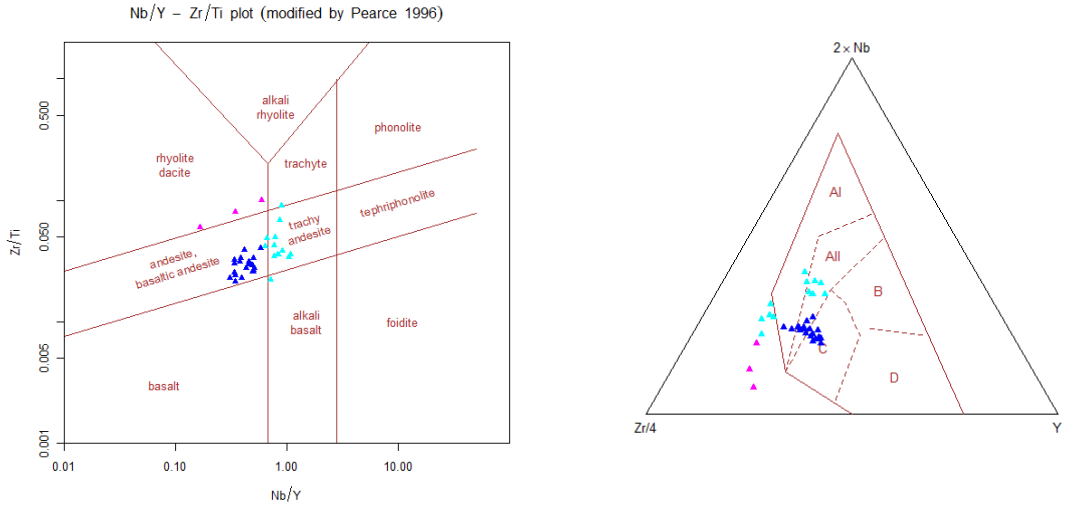


Figure 8. Left, Nautanen profile 5040 N lithogeochemical samples plotted on Nb/Y – Zr/Ti discrimination diagram for volcanites (modified by Pearce 1996). Right, Andesites 2 plot separately, and similar to rhyodacites (Meschede 1986, geotectonic for basaltoids). Samples are colour coded based on classification, dark blue = basaltic andesite, light blue = trachyandesite, pink = rhyodacite.

three banded gneiss samples can be constrained to one geochemically interpreted rock type, which is the trachyandesites. The trachyandesites and basaltic andesites are expected in this area while the rhyodacites are not. The three samples that fall into the rhyodacite category do not consistently plot in a tight group when compared for various trace elements and a possible explanation for this is that this rock is sourced from sediments thus providing a greater amount of variables to the chemical make up of the rock, another possibility is strong alteration, and a third possibility is that they show the effects of a fractioning magma. Within the trachyandesite group a further subdivision can be made with the use of the Meschede geotectonic plot for basaltoids (1986) (Fig. 8). A larger degree of alteration or a sedimentary source vs an igneous one could be responsible for the difference within this group. The presence of similar but compositionally slightly different andesites probably indicates that the host rocks are derived from several different magmas, or that the magma(s) are showing signs of weak fractionation.

When the interpreted protoliths are plotted on the cross section a series of steeply dipping repeating lithologies is apparent. This is consistent with what would be expected in the Nautanen area, where strong isoclinical folding and a strong penetrative NNW-SSE trending tectonic fabric has been documented (Monro 1988). Mineralization cuts across theses layers while still steeply dipping and following the general structural controls of the host rock. Alteration of all types can also be found in all the lithologies.

Appendix A shows the steeply dipping and repeating nature of the geochemically defined layers, Appendix B shows the strongest zones of mineralization.

When compared to volcaniclastic rocks from the Aitik deposit, Nautanen rocks appear to be very similar. By the Nb/Y – Zr/Ti discrimination diagram (Pearce 1996) Aitik rocks fall primarily into the andesite, basaltic andesite category, with some samples also indicating trachyandesites (Fig. 9). In a Th/Yb – Ta/Yb binary diagram Nautanen rocks plot values determined to be characteristic of shoshonites by Pearce (1982) (Fig. 9). Some of the lower values overlap calc-alkaline rocks and the general pattern is characteristic of rocks of the Porphyrite group, it is also very similar to the values of volcaniclastic rocks in the Aitik deposit. The rocks from both deposits are indicated to have formed in a continental arc setting (Fig. 9) from the Woods Zr/117 - Nb/16 – Th geotectonic classification diagram (1980). There is a positive correlation to TiO_2 and V values for both deposits and it is possible to distinguish between Aitik rocks and Nautanen rocks through these values since TiO_2 values are lower in Nautanen rocks (Fig. 9).

7. Discussion

A petrological and geochemical examination of the host rocks in the 5040 N profile shows them to fit with what has previously been described in the area, they appear to be highly altered andesites that formed in a continental arc environment. The host rocks to the Nautanen deposit are very similar to the volcaniclastic host rocks of the Aitik deposit. The type of alteration identified fits best with what is typically associated with an IOCG type deposit (Hitzman et al. 1992). What remains poorly known is the degree of influence other ore forming processes and the remobilization of earlier deposited metals had on the deposit and the timing and duration of these events.

Titanite and allanite have been dated by U–Pb analysis and have been determined to have formed c. 1.78 Ga. in the Nautanen area (Smith et al. 2009). This likely determines the age of the last major hydrothermal event, which at around 1.78 Ga is a fit with what is thought to be widespread regional IOCG mineralization and associated alteration described throughout the Gällivare area (Broman & Martinsson 2000). The nature of the extreme alteration that occurred during this event at the Nautanen locality makes it difficult to study previous influences on the deposit but some hypothesis can be made. The proximity to the Malmberget apatite-iron ores combined with the abundance of magnetite and presence of apatite in Nautanen suggests a connection between the two. However, apatite is also found in Aitik, weakening this argument. The apparent early emplacement of magnetite seen in mineralized thin sections from Nautanen supports the idea of an early connection to Malmberget, and it is thus possible that mineralization at the Nautanen deposit began around 1.92 Ga (Smith et al. 2009) during the formation of the Malmberget apatite-iron ores. Porphyry style mineralization related to the Haparanda suite of intrusions began c. 1.89 Ga at the Aitik deposit (Wanhainen 2005) and it is possible that similar mineralization

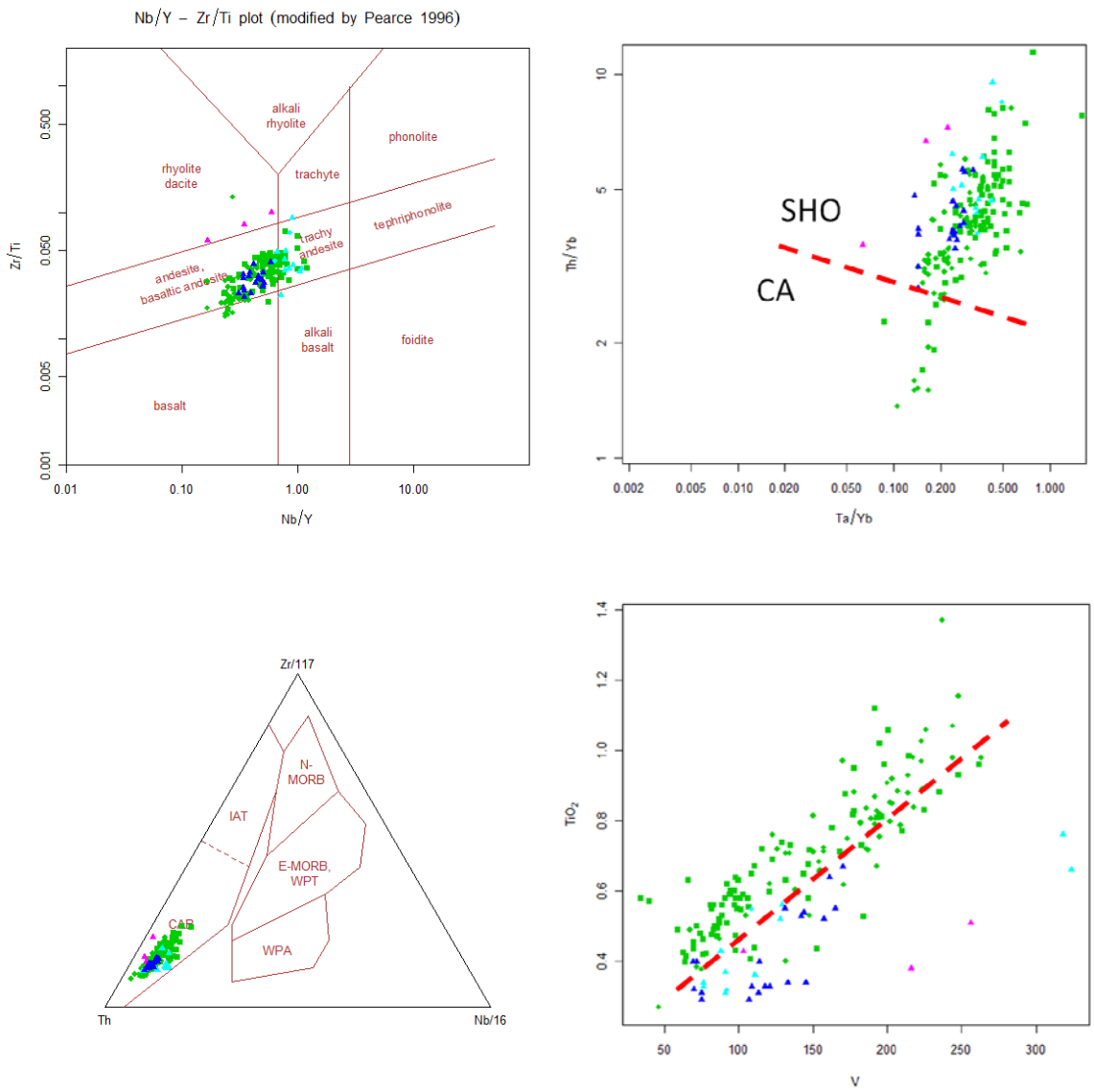


Figure 9. Top left, Nb/Y – Zr/Ti discrimination diagram (Pearce 1996). Top right, Th/Yb versus Ta/Yb binary diagram. Red dotted line indicates location of fields for shoshonite and calc-alkaline magmatic origin. Based on the Th/Yb – Ta/Yb discrimination diagram for volcanic arc basalts (Pearce 1982). Bottom left, Th - Zr/117 – Nb/16 geotectonic classification diagram (Wood 1980). All Nautanen and and Aitik samples plot together in the continental arc field. Bottom right, TiO_2 vs V binary diagram shows a slight difference between the Aitik volcanics and the Nautanen host rocks. Blue and Pink points represent Nautanen samples, Aitik volcanics are in green for comparison.

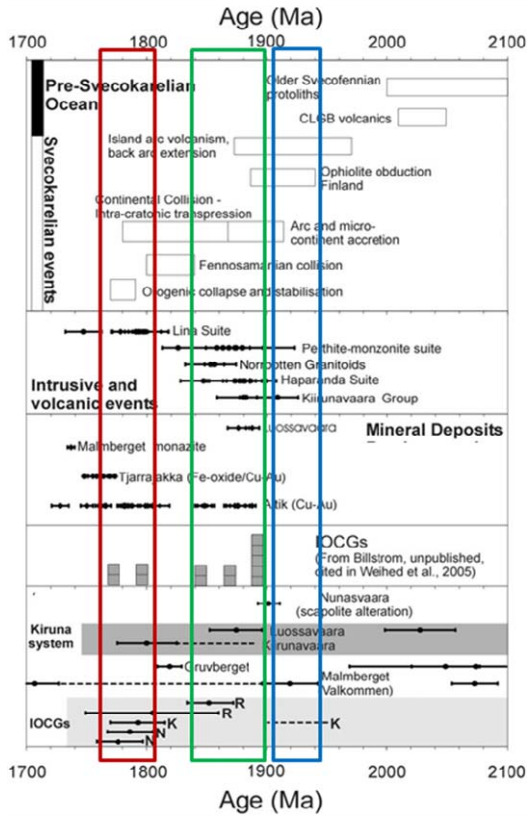


Figure 10. (modified from Smith et al. 2009). N= Nautanen, K= Kallosalmi, R= Rakkurijärvi. Blue rectangle= possible introduction of magnetite at Nautanen corresponding to early mineralization at Malmberget. Green rectangle= porphyry mineralization at Aitik, period of Haparada suite intrusions and possible porphyry mineralization at Nautanen. Red rectangle= IOCG event at Nautanen, corresponding to timing of Lina suite intrusions and IOCG overprinting at Aitik.

events were taking place during this period at Nautanen from local Haparanda suite intrusions there (Martinsson et al. 2001). Extensive tectonic remobilization along the NDZ is likely to have taken place, possibly several times between the first and last major mineralization events in the region. Early mineralization in the Nautanen deposit is believed to be responsible for the disseminated distribution of ore whereas the veining is believed to be related to the later mineralization and possibly to significant remobilization of the disseminated ore at that time (Martinsson & Wanhainen 2004). The late mineralization, which is IOCG in nature, is believed to be connected to the granite intrusions of the Lina Suite due to the presence of tourmaline, scheelite, and molybdenite (Martinsson & Wanhainen 2004), and occurred during the same time that widespread IOCG mineralization is believed to have occurred throughout northern Norrbotten.

There has clearly been a late IOCG event at circa 1.78 Ga that has had a strong influence on the deposits current attributes. There is also the possibility that early disseminated mineralization of Cu-Au is sourced from intermediate intrusions, similar to the porphyry type mineralization described at Aitik (Martinsson & Wanhainen 2004). Due to the large size and economic importance of Cu porphyry deposits, understanding the possible presence and degree of influence of this type of mineralization at Nautanen is of high significance for exploration companies. It has been noted by Wanhainen (2005), that statistically speaking there is a possibility of another major porphyry deposit in the northern Norrbotten region when taking the size of favourable terrain into account and comparing it to the frequency and spacing of other major Cu porphyry districts in the world.

Similar high salinity fluid inclusions as those noted as porphyry-related in the Aitik

deposit have also been observed in Nautanen (Broman & Martinsson, 2000), indicating that porphyry type mineralization may have been present at the Nautanen locality as well. Investigation of Haparanda suite granodiorites in the Nautanen area, and high salinity NaCl-$CaCl_2$ fluid inclusions in the Nautanen area could further indicate Aitik type porphyry mineralization (Wanhainen 2005). Due to glacial deposits covering much of the surrounding area geophysics is crucial for better understanding the geology and structures in the area. It is also possible that investigating through drilling to the outer edges of the area where the SGU/SGAB focused may increase the current level of knowledge as well as drilling deeper than the approximately 200 m depth that has previously been explored.

8. Conclusion

The extensive alteration and deformation of the Nautanen deposit makes it difficult to reconstruct the deposit's early history. Lithogeochemical analysis of immobile elements shows Nautanen host rocks consist of steeply dipping, repeating layers of shoshonitic andesites, that were formed in a continental arc setting. The Nautanen rocks have lithogeochemical values characteristic of the low titanium, low zirconium Porphyrite Group of metavolcanics found in Norrbotten and are lithogeochemically similar to the volcanic host rocks to the Aitik deposit. Variations in tectonic processes, alteration, and magma fractionation have likely led to the small differences seen between the host rocks of the Nautanen and Aitik deposits.

9. Acknowledgements

This work was financed by Boliden Mineral AB, and thanks are due to Boliden Mineral AB and the many employees there who offered their help to me during the completion of this project. This work was also made possible through materials made available by the Geological Survey of Sweden, special thanks goes out to the staff at the survey's Malå office for their help. I would like to express my gratitude to my supervisors who helped guide me through the writing of this thesis, from Lund University, Anders Scherstén, Ulf Söderlund, and Leif Johansson, from the Luleå University of Technology, Christina Wanhainen, and from Boliden Mineral AB, Roger Nordin.

I would also like to thank the many students I met and made friends with throughout my years of studying, they made the years I spent completing this degree some of the most enjoyable. Last, but certainly not least, I would like to thank family for endless support along the long path of my education. I could not have made it to where I am today without the positive thoughts they sent me from a world away.

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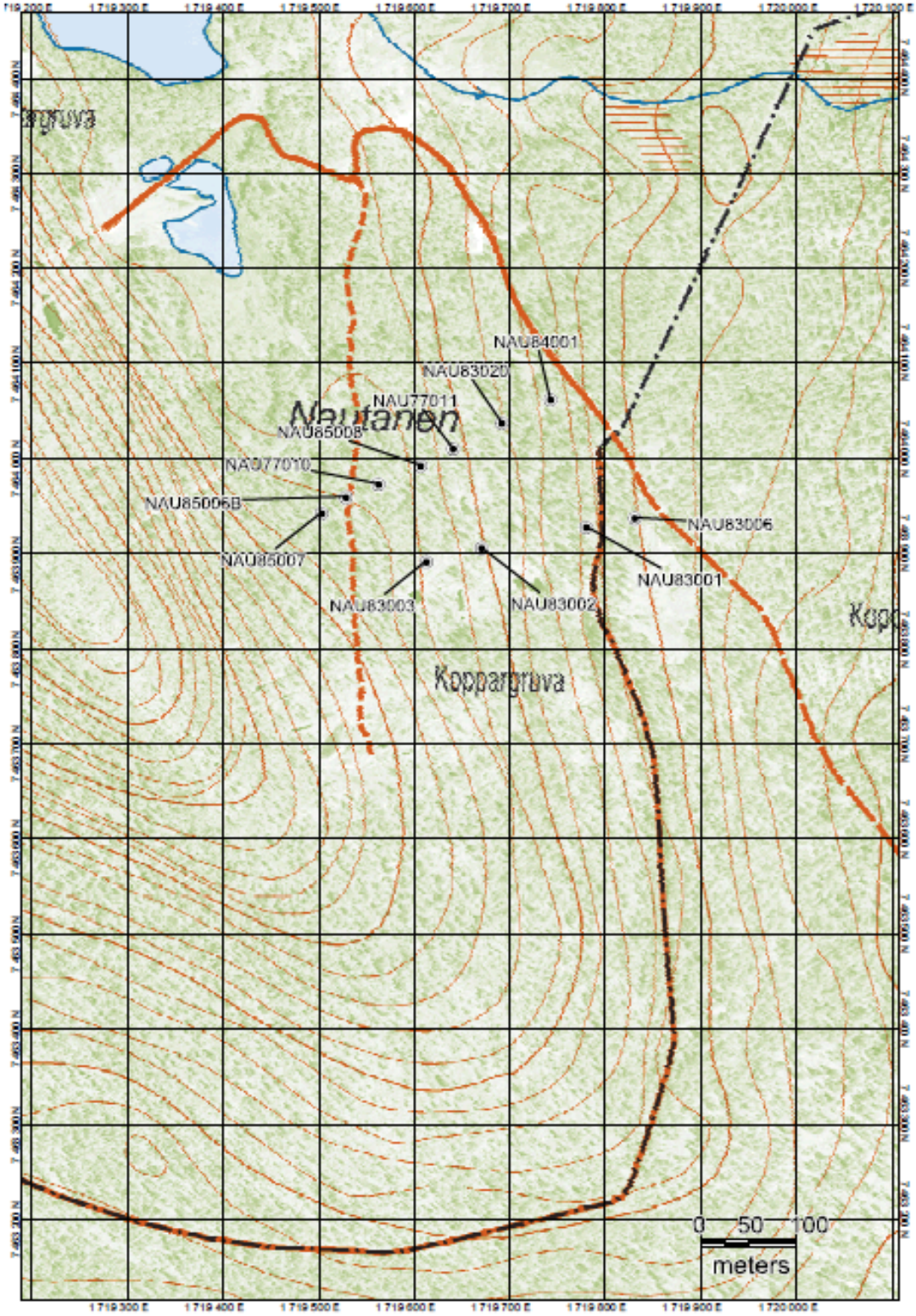
Appendix A. Location of drill holes studied in this thesis



Appendix B. Thinsection locations and discriptions

Profile 5040N

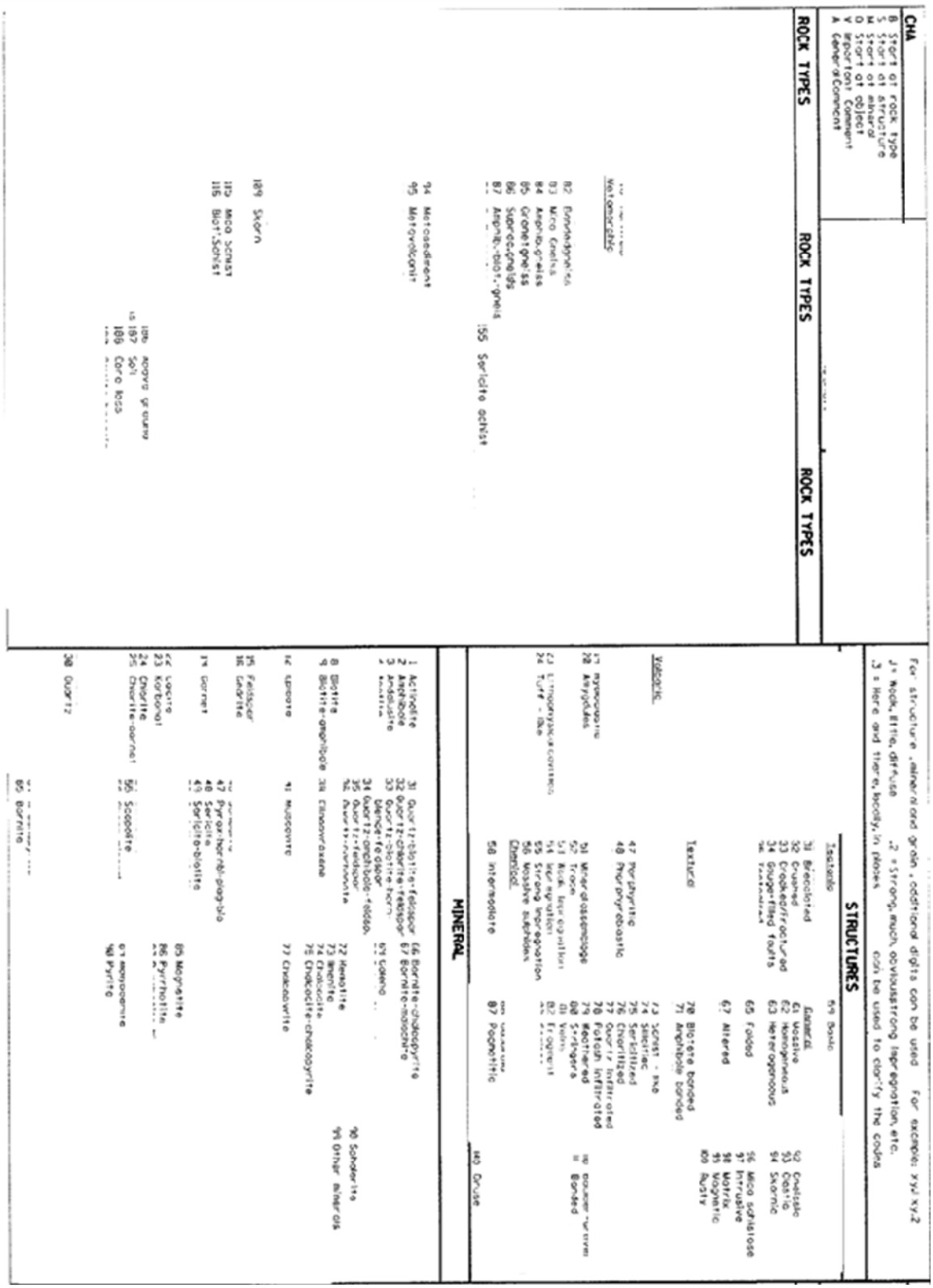
Sample	Depth (m)	Rock Type	Comment
NAU77010 1	214.50	Scap-Bt-Amph Gniess	Magnetite band, with epidote
NAU77010 2	233.75	Scap-Gt-Bt-Amph Gniess	Amphibole bands with epidote
NAU77010 3	244.50	Banded Gniess	
NAU77011	269.05	Epi-Gt-Bt Gniess	Magnetite impregnation
NAU83020 1	9.74	Scap-Bt Gniess	
NAU83020 2	45.55	Epi-Scap-Bt Gniess	
NAU83020 3	60.69	Scap-Gt-Bt Gniess	
NAU83020 4	196.55	Scap-Gt-Bt Gniess	Calcite veined, epi/K altered
NAU84001	230.32	Gt-Ser Gniess	Metasedimentary(?)
NAU85006 1	33.75	Epi-Scap-Gt-Bt-Amph Gniess	
NAU85006 2	72.88	Scap-Gt-Bt-Amph Gniess	
NAU85006 3	122.10	Skarnic Bt-Amph Gniess	K, epidote altered
NAU85007 1	108.30	Scap-Bt Gniess	Albite haloed amphibole bands
NAU85007 2	124.57	Hem-Skarnic Gniess	Hematite, K alteration
NAU85007 3	215.40	Scap-Bt Gniess	Calcite veined

Supplementary thin sections prepared by the SGU

Relative frequency of ore minerals in selected thinsections as described by Hålenius (1983)

DDH	Depth (m)	Mag	Cpy	Py	Po	Au	Bor	Sph	Mo	Bis	Bis Tell	Car	Gal
NAU83001	270,50	3	5	4		1		1		1	1		
NAU83002	114,08	5	4	3		1				1			1
NAU83002	144,40	5	5	3		1		1	2				1
NAU83003	197,68	5	3	3	1	1		2	1				
NAU83006	146,25	4	5	1		1	3		1	1	1	1	1

Appendix C. Profile 5040N logs- code answer key

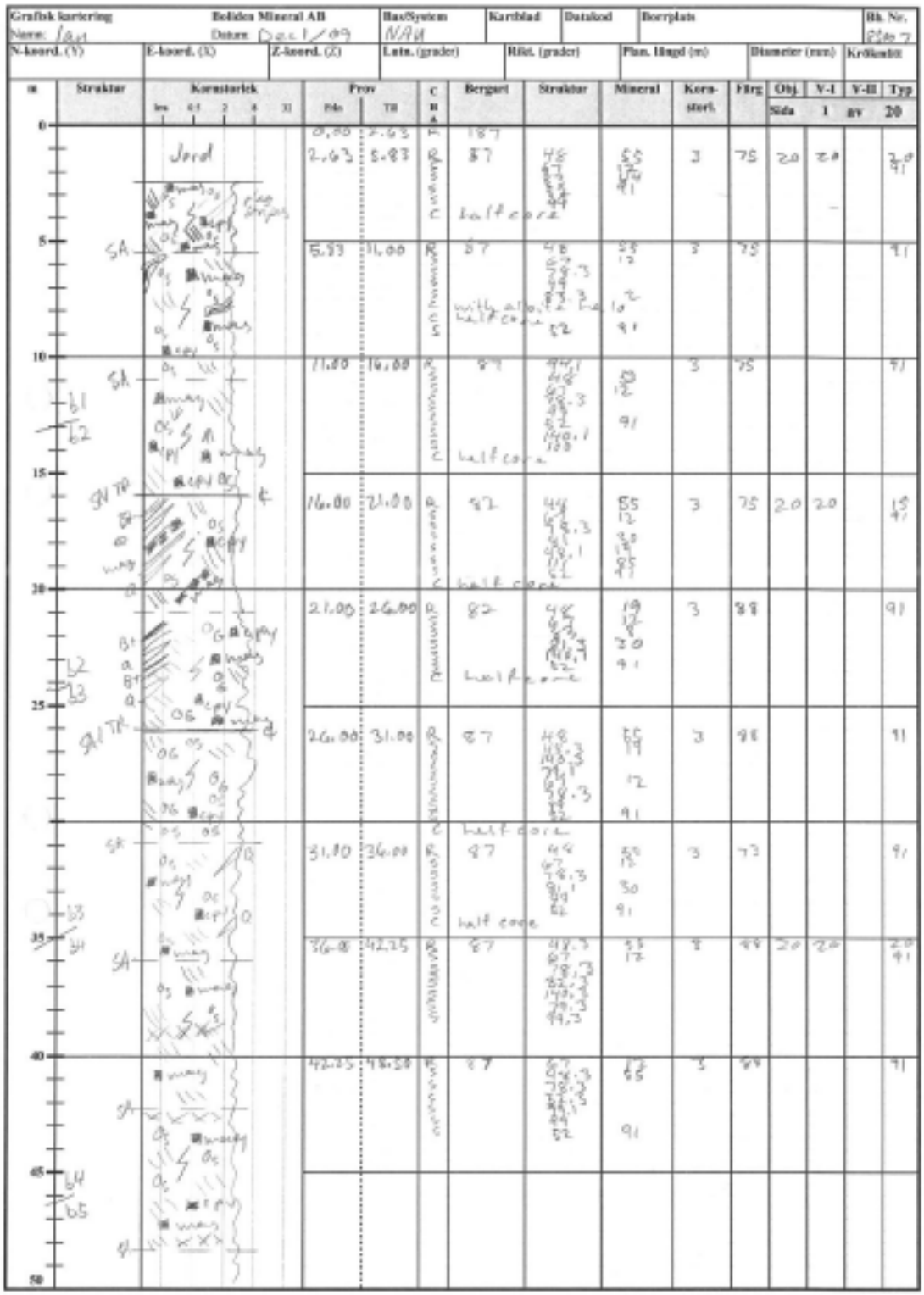


Appendix C. Profile 5040N logs- code answer key (cont.)

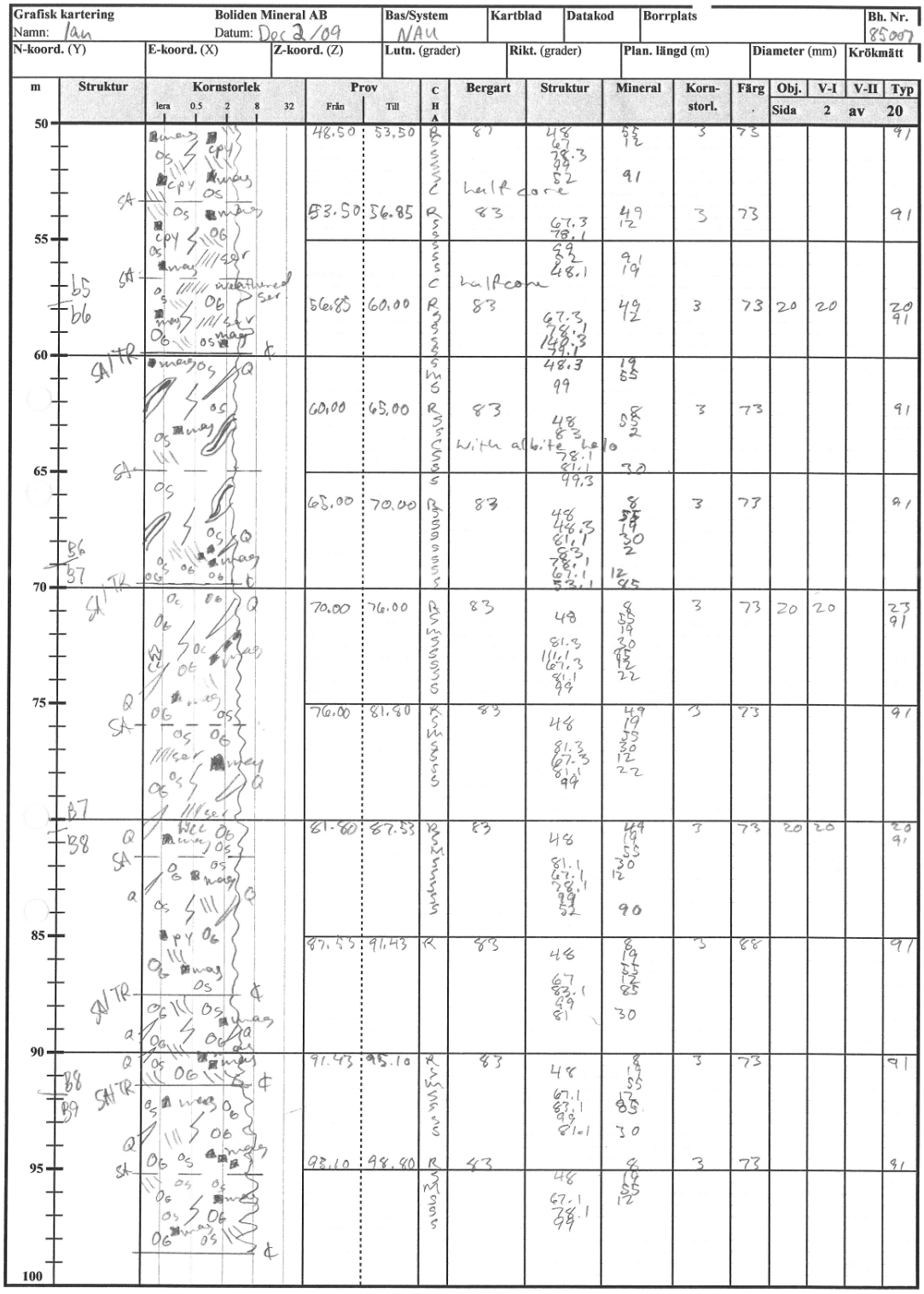
GRAIN SIZE	COLOUR		COLOUR
1 Aphanitic 2 Fine-grained 3 Medium grained 4 Coarse grained 5 Very coarse-grained 6 Uneven grained	1 Reddish white 5 Pale red 7 Red 11 Reddish brown 20 Light brown 26 Brown	71 Black 73 Dark grey 75 Grey 77 Light grey 79 White	87 Greenish grey 88 Dark greenish grey (For other colours, see International rock colour chart)

OBJECT	TYPE	OBJECT	TYPE
20 Secondary S S_{21}-S_{27}			
	20 Secondary mineral layer		
			91 Chemical analysis

Appendix C. Profile 5040N logs- NAU85007



Appendix C. Profile 5040N logs- NAU85007 (cont)



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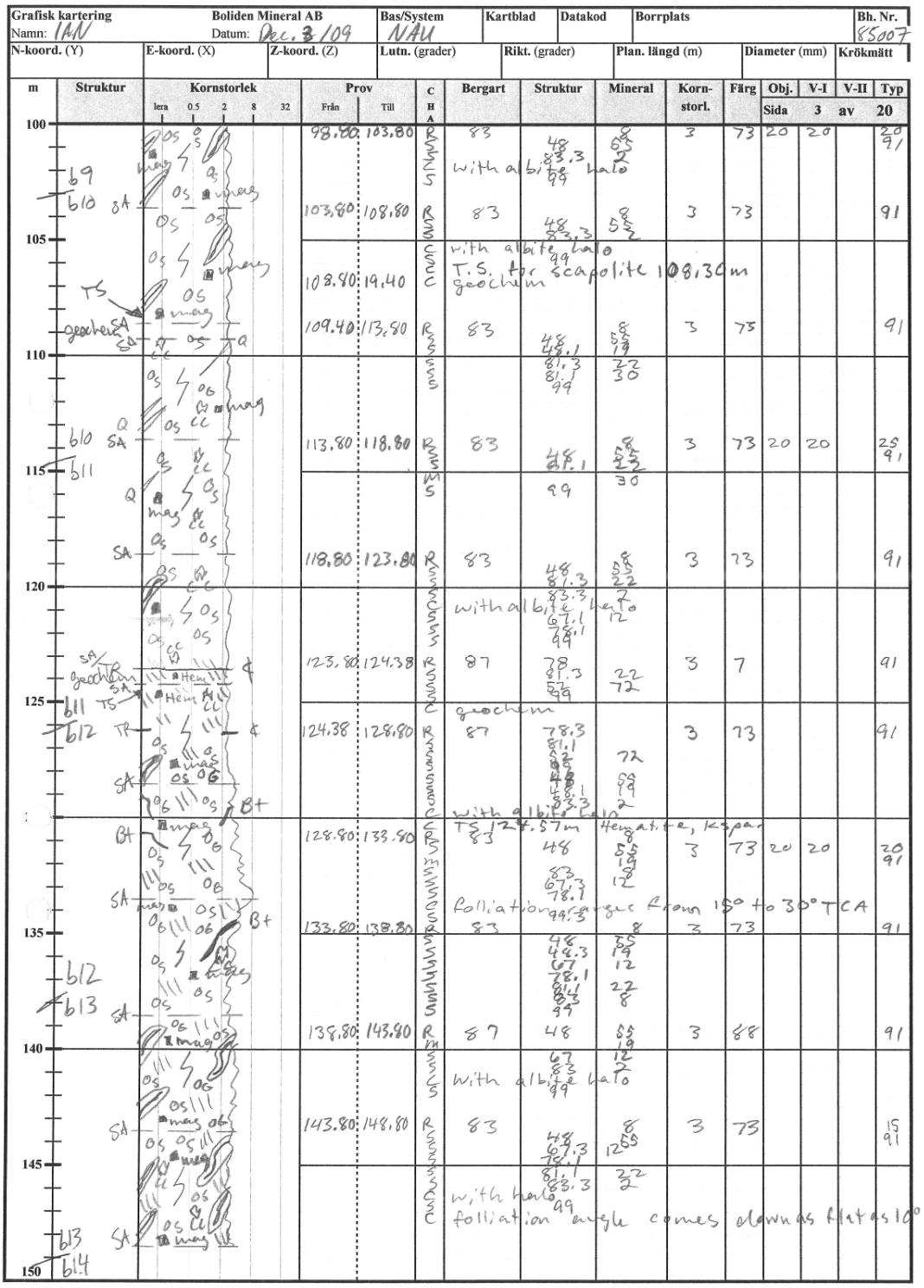
Namn: Ian	Datum: Dec 2/09	NAU				85007

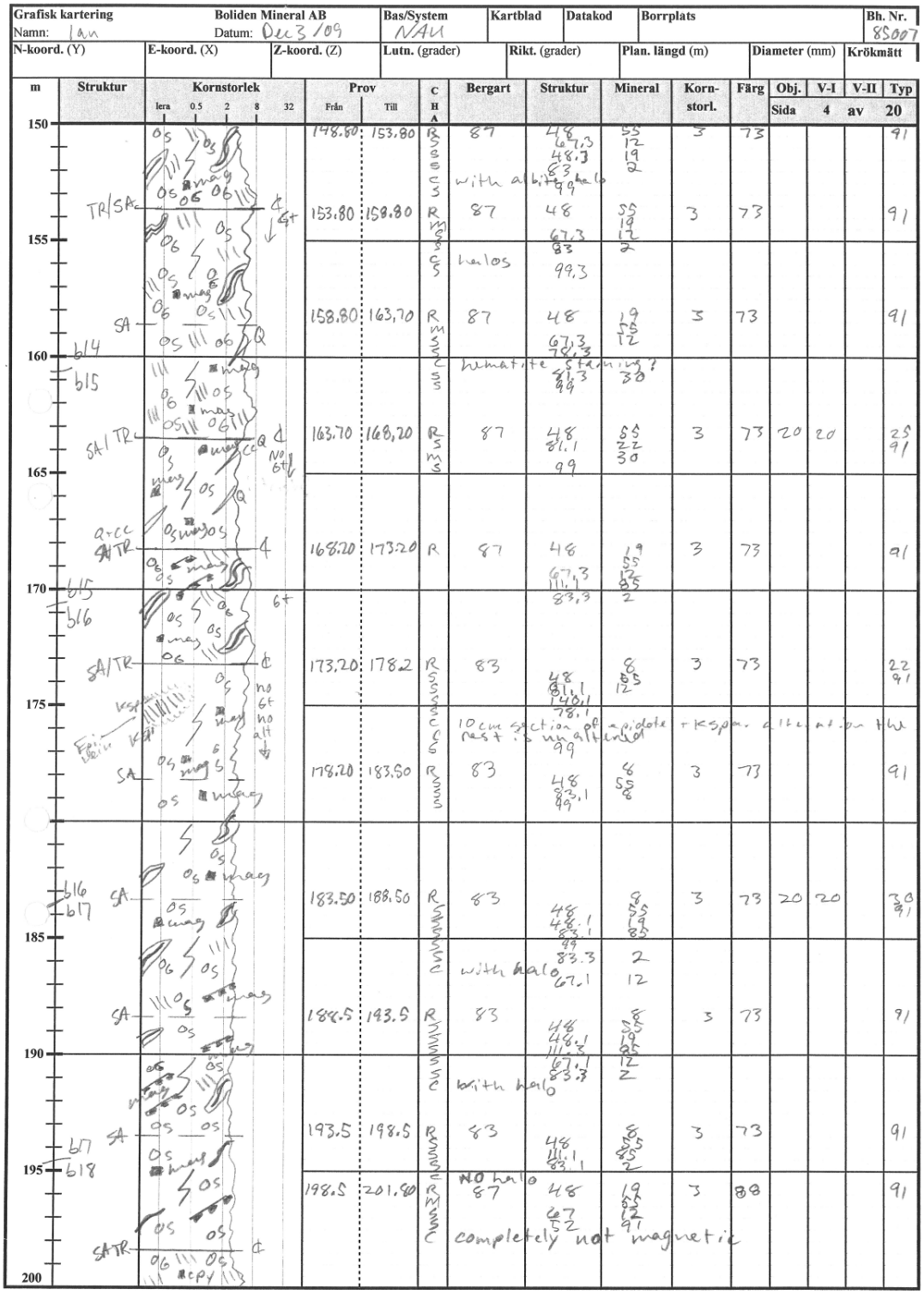
N-koord. (Y)	E-koord. (X)	Z-koord. (Z)	Lutn. (grader)	Rikt. (grader)	Plan. längd (m)	Diameter (mm)	Krökmätt

m	Struktur	Kornstorlek (lera 0.5 2 8 32)	Prov Från	Prov Till	CHA	Bergart	Struktur	Mineral	Korn-storl.	Färg	Obj. Sida	V-I 2	V-II av	Typ 20
50			48.50	53.50	R S S S S C	83	48 61 78.3 99 52	55 12 91	3	73				91
			53.50	56.85	R S S S S C	83	67.3 78.1	49 12	3	73				91
55			56.85	60.00	R S S S S C	83	99 52 48.1 67.3 78.1 48.3 48.1	91 19 49 12	3	73	20	20		20 91
60			60.00	65.00	S M S R S S S S	83	48.3 99 48 83 78.1 81.1 99.3	19 55 55 2 30	3	73				91
65			65.00	70.00	S R S S S S S S	83	48 46.3 81.1 83 78.1 67.1 53.1	8 55 19 30 2 12 95	3	73				91
70			70.00	76.00	R S S S S S S	83	48 81.3 111.1 67.3 81.1 99	8 55 19 30 12 22	3	73	20	20		23 91
75			76.00	81.80	R S M S S S S	83	48 81.3 67.3 81.1 99	49 19 55 30 12 22	3	73				91
			81.80	87.53	R S M S S S S	83	48 81.1 67.1 78.1 99 52	49 19 55 30 12 90	3	73	20	20		20 91
85			87.53	91.43	R	83	48 67 83.1 99 81	8 19 55 12 85 30	3	88				91
90			91.43	95.10	R S S S S S S	83	48 67.1 87.1 99 81.1	8 19 55 12 85 30	3	73				91
95			95.10	98.40	R S M S S S	83	48 67.1 78.1 99	8 19 55 12	3	73				91
100														

Appendix C. Profile 5040N logs- NAU85007 (cont)



Appendix C. Profile 5040N logs- NAU85007 (cont)



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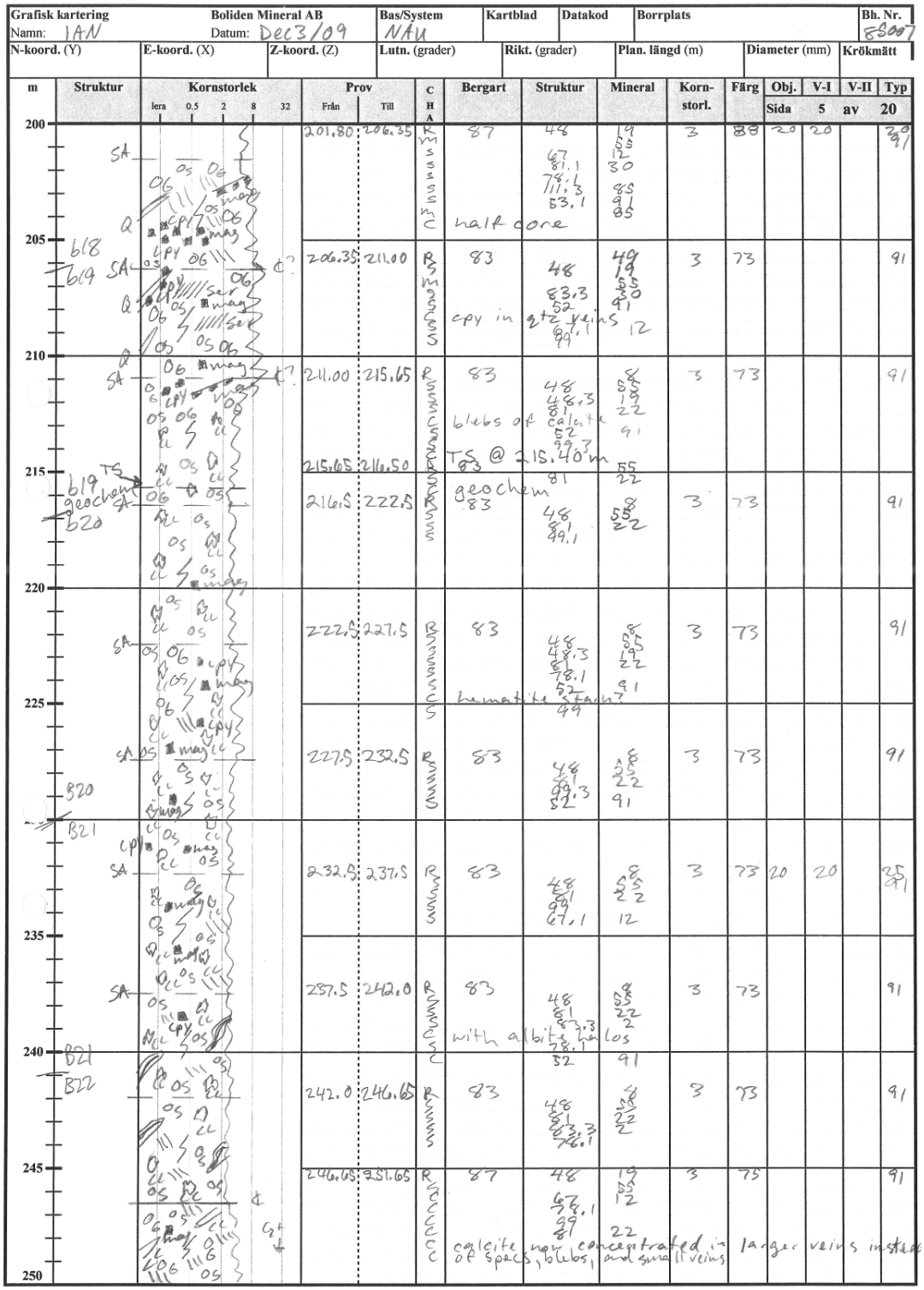
Namn: Ian	Datum: Dec 3 /09	NAU				85007

N-koord. (Y)	E-koord. (X)	Z-koord. (Z)	Lutn. (grader)	Rikt. (grader)	Plan. längd (m)	Diameter (mm)	Krökmätt

m	Struktur	Kornstorlek (lera 0.5 2 8 32)	Prov Från	Prov Till	C H A	Bergart	Struktur	Mineral	Korn-storl.	Färg	Obj. Sida	V-I 4	V-II av	Typ 20
150			148.80	153.80	R S S S S	87 with albite halo	48 67.3 48.3 83 99	55 12 19 2	3	73				91
	TR/SA		153.80	158.80	R M S S	87	48 67.3 83	55 19 12 2	3	73				91
155					C S	halos	99.3							
	SA		158.80	163.70	R M S S	87	48 67.3 78.3	19 55 12	3	73				91
160	b14 b15				C S S	hematite staining?	81.3 99	30						
	SA/TR		163.70	168.20	R S M S	87	48 81.1 99	55 22 30	3	73	20	20		25 91
165														
	a+cc SA/TR		168.20	173.20	R	87	48 67.3 111.3	19 55 12 85	3	73				91
170	b15 b16						83.3	2						
	SA/TR		173.20	178.2	R S S S S	83	48 81.1 148.1 78.1	8 85 12	3	73				22 91
175					C S	10 cm section of epidote + Kspar. alteration the rest is unaltered	99							
	SA		178.20	183.50	R S M S	83	48 83.1 99	8 55 8	3	73				91
	b16 b17 SA		183.50	188.50	R S S S S	83	48 48.1 83.1 99	8 55 19 85	3	73	20	20		38 91
185					S S C	with halo	83.3 67.1	2 12						
	SA		188.5	193.5	R S S S S	83	48 48.1 111.3 67.1	8 55 19 85 12	3	73				91
190					S S C	with halo	83.3	2						
	SA		193.5	198.5	R S S S S	83	48 111.1 83.1	8 55 85 2	3	73				91
195	b17 b18		198.5	201.50	R M S S C	NO halo 87 completely not magnetic	48 27 52	19 85 12 91	3	88				91
	SA/TR													
200														

Appendix C. Profile 5040N logs- NAU85007 (cont)



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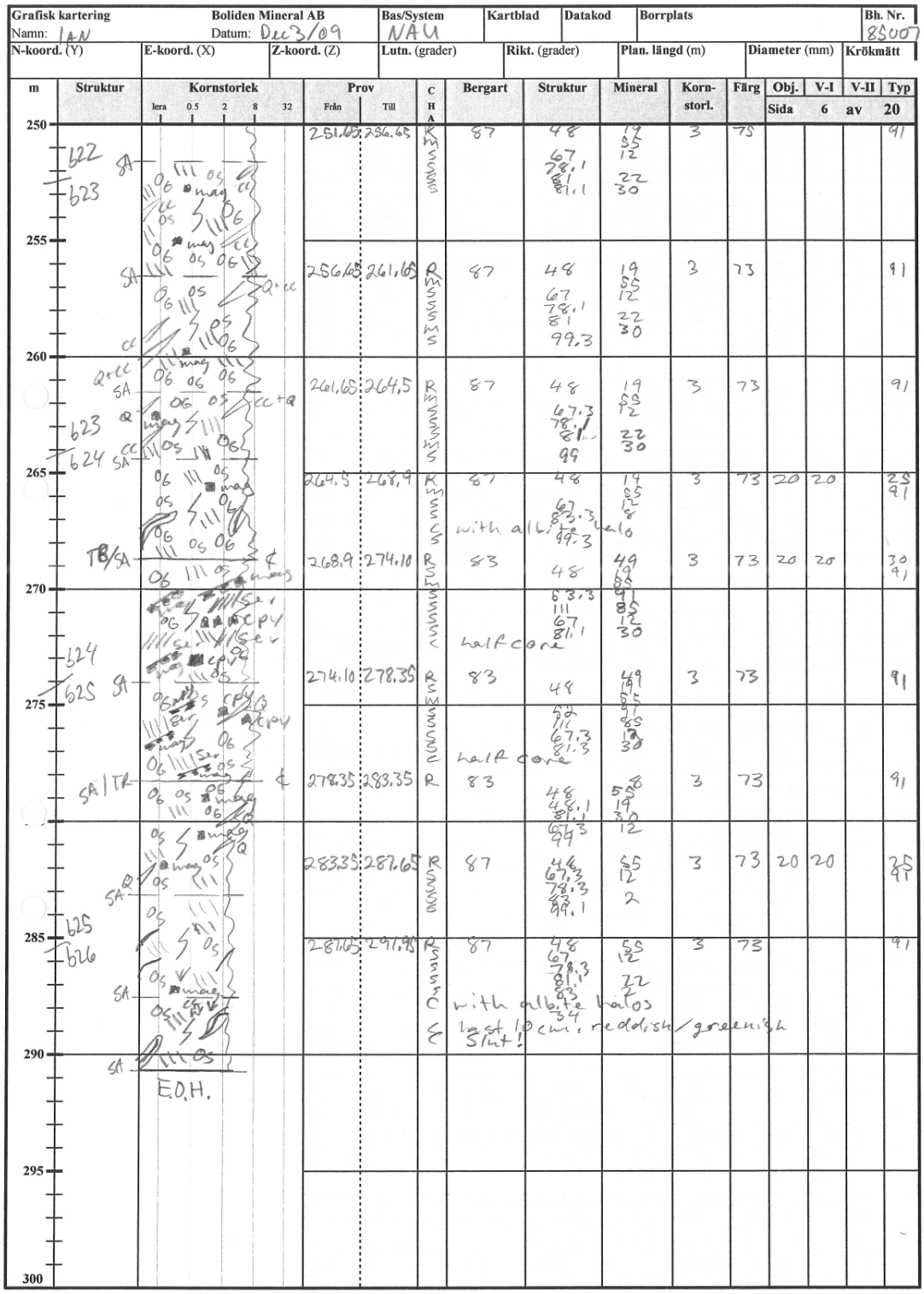
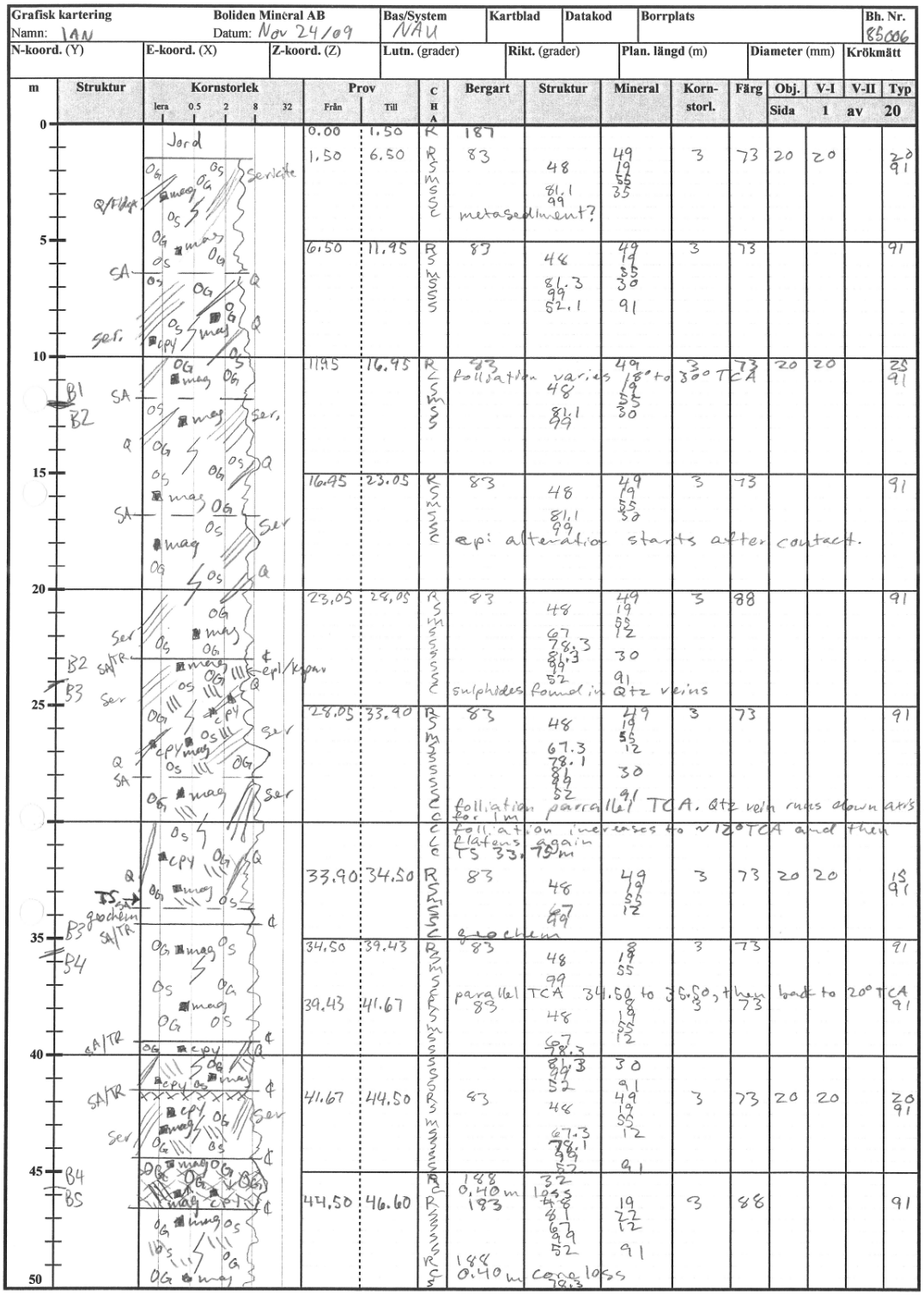
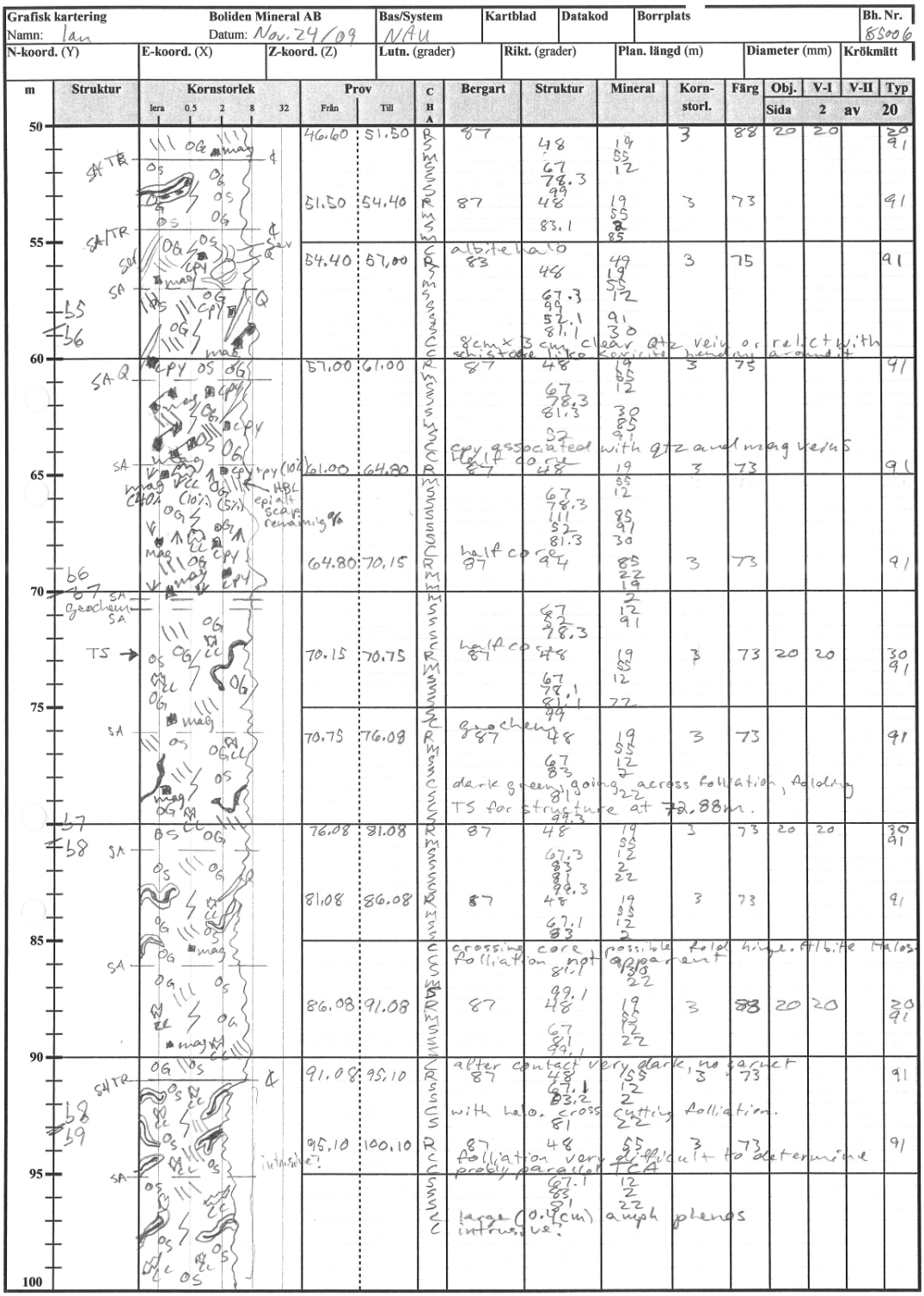


Appendix C. Profile 5040N logs- NAU85006



Appendix C. Profile 5040N logs- NAU85006 (cont.)

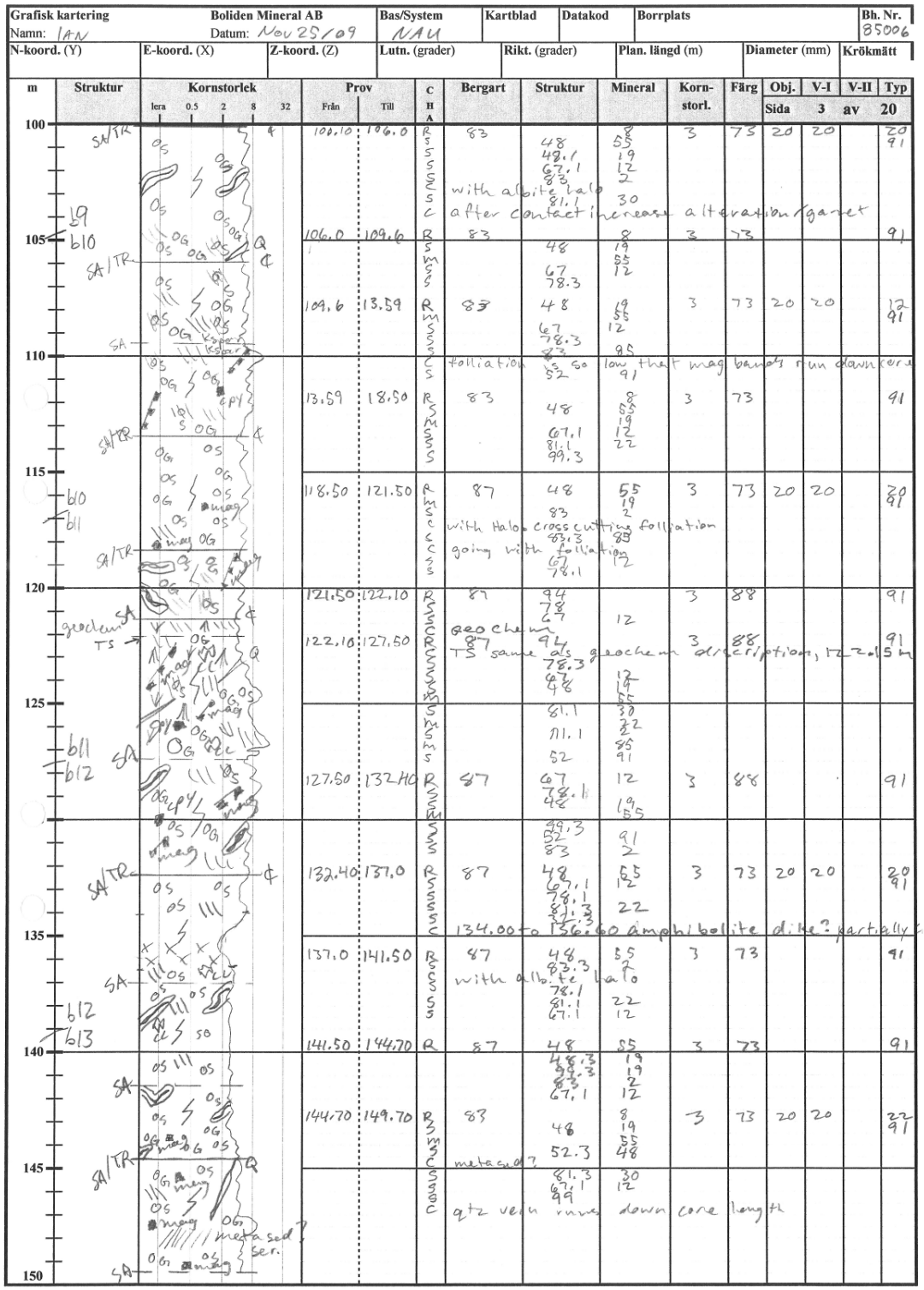


Grafisk kartering	Boliden Mineral AB	Bas/System	Kartblad	Datakod	Borrplats	Bh. Nr.
Namn: Ian	Datum: Nov. 24/09	NAU				85006

N-koord. (Y)	E-koord. (X)	Z-koord. (Z)	Lutn. (grader)	Rikt. (grader)	Plan. längd (m)	Diameter (mm)	Krökmätt

m	Struktur	Kornstorlek (lera, 0.5, 2, 8, 32)	Prov Från	Prov Till	CHA	Bergart	Struktur	Mineral	Korn-storl.	Färg	Obj. Sida	V-I 2	V-II av	Typ 20
50			46.60	51.50		87	48, 67, 78.3	19, 85, 12	3	88	20	20		30, 91
			51.50	54.40		87	48, 99, 83.1	19, 85, 85	3	73				91
55			54.40	57.00		83	albite halo, 46, 67.3, 99, 57.1, 81.1	49, 19, 85, 12, 91, 30	3	75				91
							8cm x 3 cm clear qtz vein or relict with schistose inco[illegible] sericite around it							
60			57.00	61.00		87	48, 67, 78.3, 81.3, 57	19, 85, 12, 30, 85, 91	3	75				91
							cpy associated with qtz and mag veins							
			61.00	64.80		87	half core 48, 67, 78.3, 111, 57, 81.3	19, 85, 12, 85, 91, 30	3	73				91
65														
			64.80	70.15		87	half core 94	85, 22, 19	3	73				91
70			70.15	70.75		87	half core 48, 67, 78.1, 81.1, 99	19, 85, 12, 22	3	73	20	20		30, 91
75			70.75	76.08		87	geochem 48, 67, 83, 81, 99.3	19, 85, 12, 2, 22	3	73				91
							dark green, going across foliation, folding TS for structure at 72.88m.							
			76.08	81.08		87	48, 67.3, 83, 81, 99.3	19, 85, 12, 2, 22	3	73	20	20		30, 91
			81.08	86.08		87	48, 67.1, 83	19, 85, 12, 2	3	73				91
85							crossing core foliation not apparent, 81.1, 99.1	possible fold hinge. Albite halos, 22						
			86.08	91.08		87	48, 67, 81	19, 85, 12, 22	3	88	20	20		30, 91
90			91.08	95.10		87	after contact very dark, no garnet, 48, 67.1, 83.2, 81	55, 12, 2, 22	3	73				91
							with halo, cross cutting foliation.							
			95.10	100.10		87	48, 67.1, 83, 81	55, 12, 2, 22	3	73				91
95							foliation very difficult to determine prob. parallel TCA							
							large (0.4 cm) amph phenos intrusive?							
100														

Appendix C. Profile 5040N logs- NAU85006 (cont.)

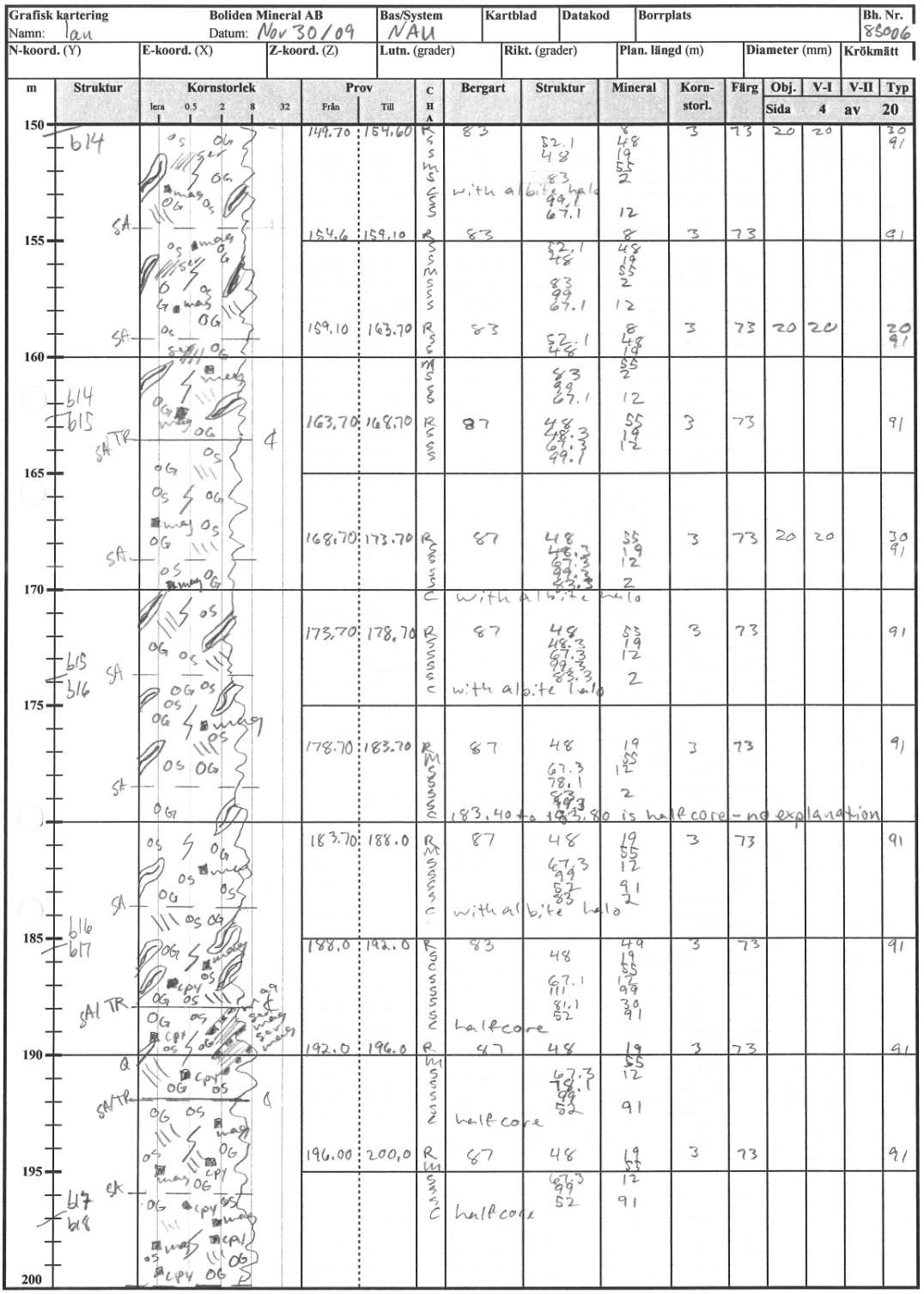


Grafisk kartering	Boliden Mineral AB	Bas/System	Kartblad	Datakod	Borrplats	Bh. Nr.
Namn: IAN	Datum: Nov 25/09	NAU				85006

N-koord. (Y)	E-koord. (X)	Z-koord. (Z)	Lutn. (grader)	Rikt. (grader)	Plan. längd (m)	Diameter (mm)	Krökmätt

m	Struktur	Kornstorlek (lera, 0.5, 2, 8, 32)	Prov Från	Prov Till	CHA	Bergart	Struktur	Mineral	Korn-storl.	Färg	Obj. Sida	V-I 3	V-II av	Typ 20
100	SA/TR		100.10	106.0	R S S S S S C	83 with albite halo after contact increase alteration/garnet	48 48.1 67.1 83 81.1	8 55 19 12 2 30	3	73	20	20		20 91
105	b10 SA/TR		106.0	109.6	R S M S S	83	48 67 78.3	8 19 55 12	3	73				91
			109.6	13.59	R S M S S C	83	48 67 78.3	19 55 12 85	3	73	20	20		12 91
110	SA				C S	foliation so low that mag bands run downcore	52	91						
	SA/TR		13.59	18.50	R S M S S S	83	48 67.1 81.1 99.3	8 55 19 12 22	3	73				91
115	b10 b11 SA/TR		118.50	121.50	R M S C C S S	87 with Halo cross cutting foliation going with foliation	48 83 83.3 67 78.1	55 19 2 85 12	3	73	20	20		20 91
120	geochem SA TS		121.50	122.10	R S S C R S S S	87 geochem	94 78 67	12	3	88				91
			122.10	127.50	87 TS same als geochem description, 12.20-15 m		94 78.3 67 48	12 14 55	3	88				91
125	b11 b12 SA				S S S S		81.1 81.1 52	30 72 85 91						
			127.50	132.40	R S S S	87	67 78.1 48	12 19 55	3	88				91
					S S S		49.3 52 83	91 2						
	SA/TR		132.40	137.0	R S S S S S C	87	48 67.1 78.1 81.3 83.3	55 12 22	3	73	20	20		20 91
135						134.00 to 136.60 amphibolite dike? partially								
	SA b12 b13		137.0	141.50	R S S S S S	87 with albite halo	48 83.3 78.1 81.1 67.1	55 2 22 12	3	73				91
140			141.50	144.70	R	87	48 48.3 99.3 83 67.1	55 19 19 2 12	3	73				91
	SA		144.70	149.70	R S M S C	83 metased?	48 52.3	8 19 55 48	3	73	20	20		22 91
145	SA/TR				S S S C	qtz vein runs down core length	81.3 67.1 99	30 12						
150	SA	metased? ser.												

Appendix C. Profile 5040N logs- NAU85006 (cont.)

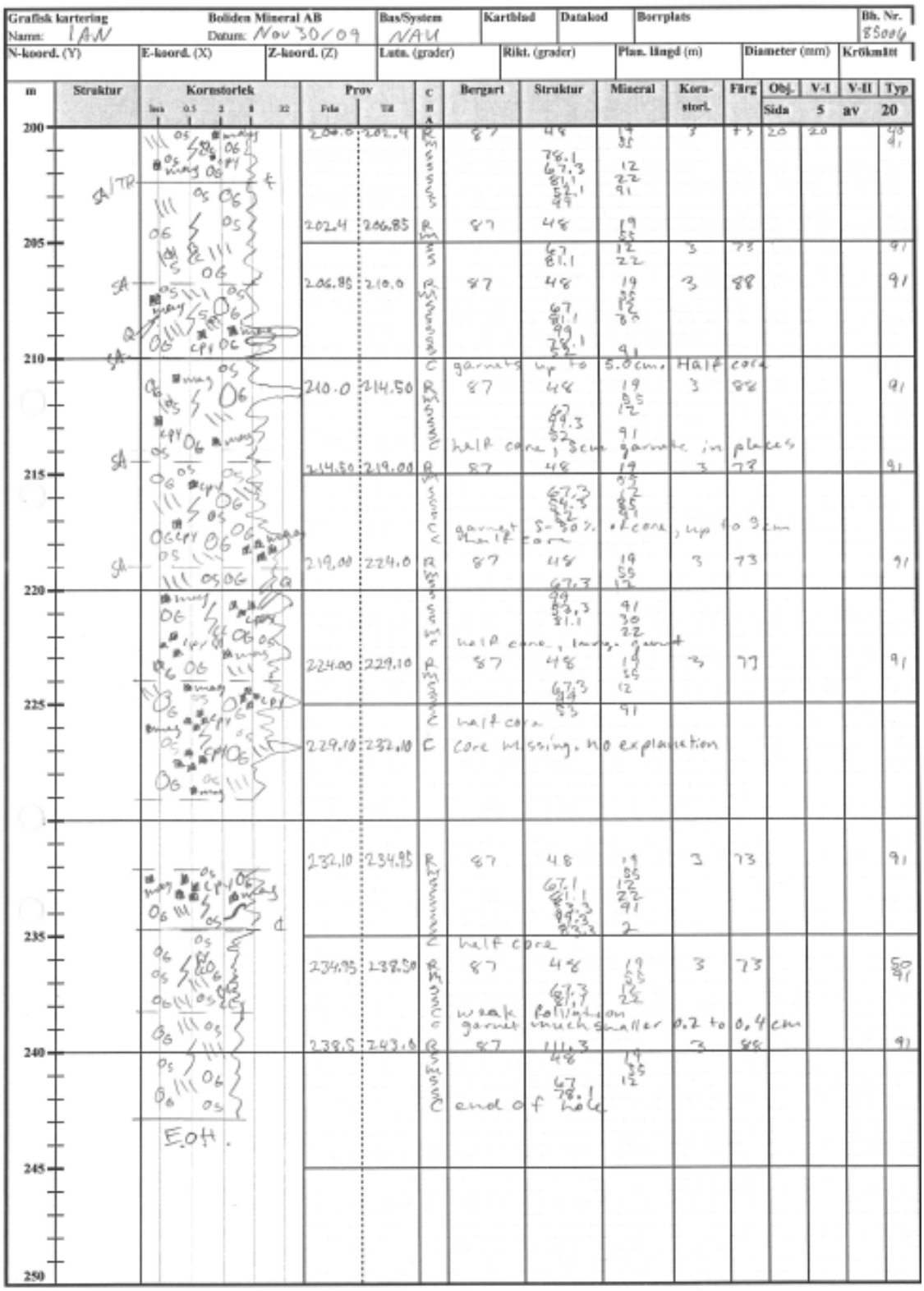


Grafisk kartering	Boliden Mineral AB	Bas/System	Kartblad	Datakod	Borrplats	Bh. Nr.
Namn: lau	Datum: Nov 30/09	NAU				85006

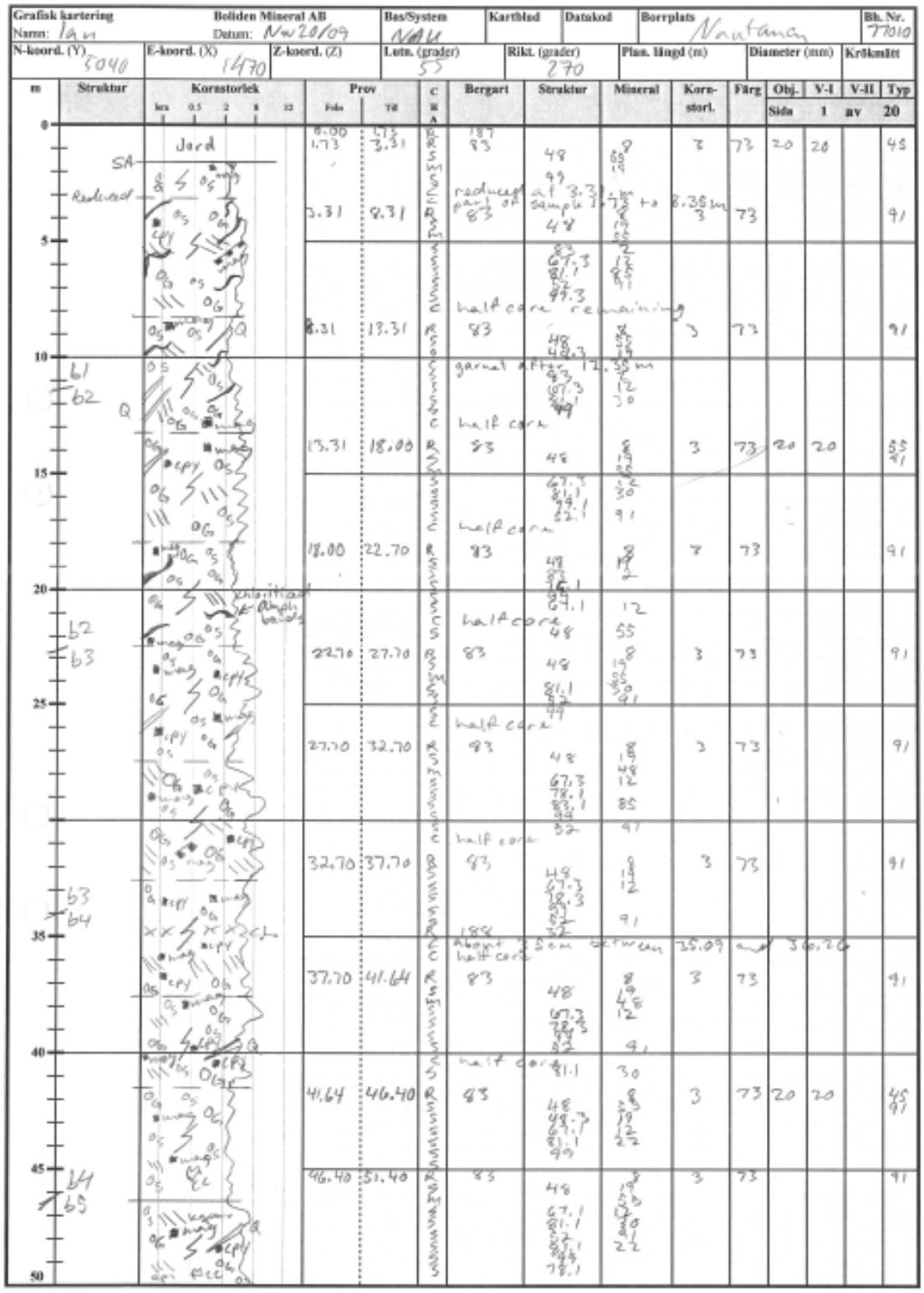
N-koord. (Y)	E-koord. (X)	Z-koord. (Z)	Lutn. (grader)	Rikt. (grader)	Plan. längd (m)	Diameter (mm)	Krökmätt

m	Struktur	Kornstorlek (lera, 0.5, 2, 8, 32)	Prov Från	Prov Till	CHA	Bergart	Struktur	Mineral	Korn-storl.	Färg	Obj. Sida	V-I 4	V-II av	Typ 20
150	b14		149.70	154.60	R S S M S S S	83 with albite halo	52.1 48 83 99 67.1	8 48 19 55 2 12	3	73	20	20		30 91
155	SA		154.6	159.10	R S S M S S S	83	52.1 48 83 99 67.1	8 48 19 55 2 12	3	73				91
	SA		159.10	163.70	R S S	83	52.1 48	8 48 19	3	73	20	20		20 91
160	b14 b15 SA TR	4	163.70	168.70	M S S R S S S	87	83 99 67.1 48 48.3 67.3 99.1	55 2 12 55 19 12	3	73				91
165	SA		168.70	173.70	R S S S S C	87 with albite halo	48 48.3 67.3 99.1 83.3	55 19 12 2	3	73	20	20		30 91
170	b15 b16 SA		173.70	178.70	R S S S S C	87 with albite halo	48 48.3 67.3 99.1 83.3	55 19 12 2	3	73				91
175	SA		178.70	183.70	R M S S S S C	87 183.40 to 183.80 is half core - no explanation	48 67.3 78.1 83 99.3	19 55 12 2	3	73				91
185	b16 b17 SA TR		183.70	188.0	R M S S S S C	87 with albite halo	48 67.3 99 57 83	19 55 12 91 2	3	73				91
			188.0	192.0	R S S S S S C	83 halfcore	48 67.1 111 81.1 52	49 19 55 19 99 30 91	3	73				91
190	SA TR		192.0	196.0	R M S S S S C	87 halfcore	48 67.3 78.1 99 52	19 55 12 91	3	73				91
195	b17 b18		196.00	200.0	R M S S C	87 halfcore	48 67.3 99 52	19 55 12 91	3	73				91
200														

Appendix C. Profile 5040N logs- NAU85006 (cont.)



Appendix C. Profile 5040 logs- NAU77010



Grafisk kartering — Boliden Mineral AB

Namn: Ian	Datum: Nov 20/09	Bas/System NAU	Kartblad	Datakod	Borrplats Nautanen	Bh. Nr. 77010
N-koord. (Y) 5040	E-koord. (X) 1470	Z-koord. (Z)	Lutn. (grader) 55	Rikt. (grader) 270	Plan. längd (m)	Diameter (mm) / Krökmätt

Sida 1 av 20

Prov Från	Prov Till	CRA	Bergart	Struktur	Mineral	Korn-storl.	Färg	Obj.	V-I	V-II	Typ
0.00 1.73	1.73 3.31	R	187 83	48 49	8 65 19	3	73	20	20		45
3.31	8.31	R	83	48 83 67.3 81.1 82 99.3	8 19 55 12 85 91	3	73				91
8.31	13.31	R	83	48 49.3 83 67.3 81.1 99	8 55 19 12 30	3	73				91
13.31	18.00	R	83	48 67.3 81.1 99.1 82.1	8 19 55 30 91	3	73	20	20		55 91
18.00	22.70	R	83	48 83 76.1 99 67.1	8 19 12	3	73				91
22.70	27.70	R	83	48 48 81.1 82 99	12 55 8 19 55 30 91	3	73				91
27.70	32.70	R	83	48 67.3 78.1 83.1 99 52	8 19 48 12 85 91	3	73				91
32.70	37.70	R	83 188	48 67.3 78.3 83 82 52	8 19 12 91	3	73				91
37.70	41.64	R	83	48 67.3 78.3 83 82	8 19 48 12 91	3	73				91
41.64	46.40	R	83	81.1 48 49.7 67.1 81.1 99	30 8 55 19 12 22	3	73	20	20		45 97
46.40	51.40	R	83	48 67.1 81.1 82 83.1 99 78.1	8 19 55 30 19 12 22	3	73				91

reduced part of sample at 3.31 to 8.36 m

half core remaining

garnet after 12.35 m

half core

half core

half core

half core

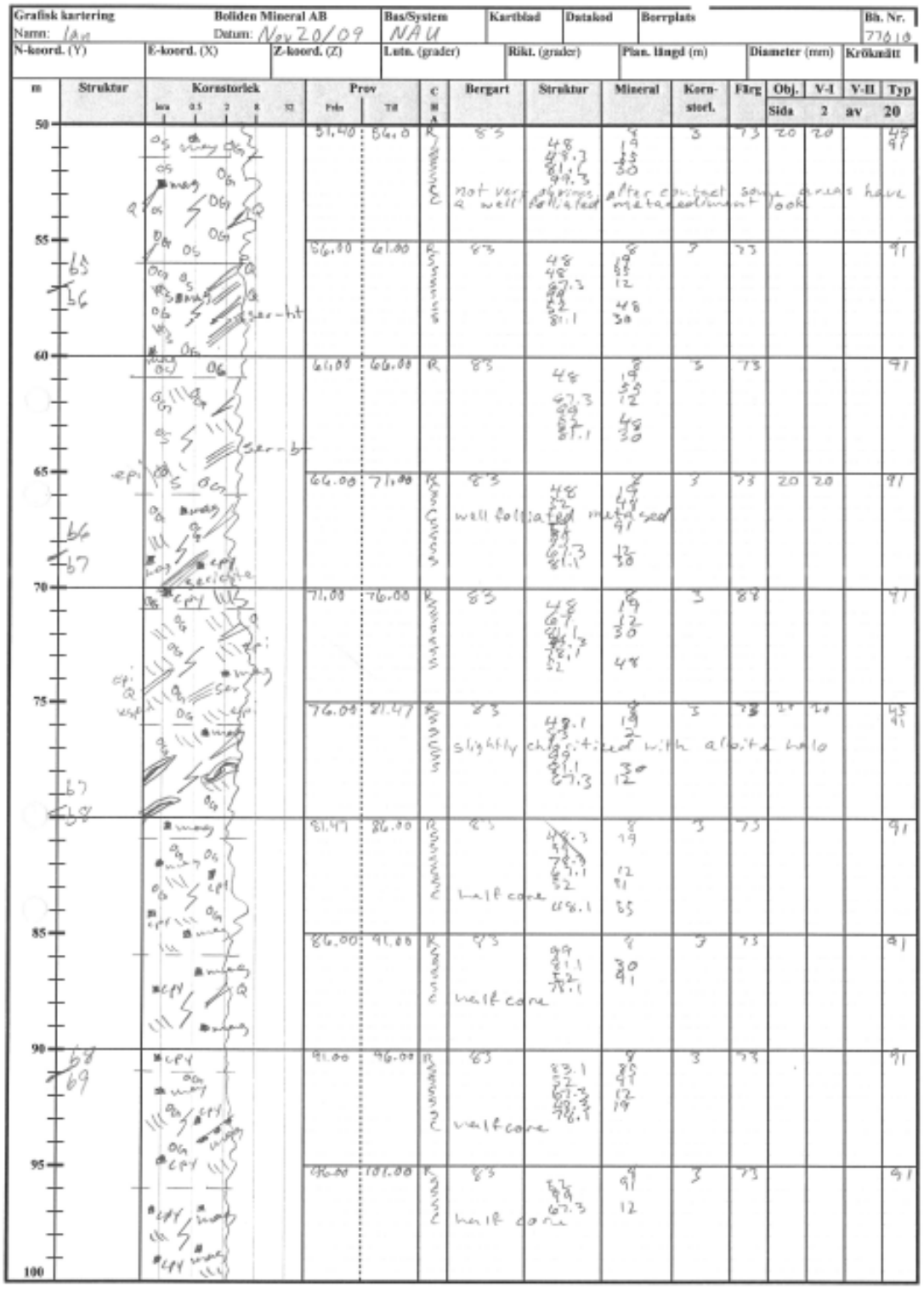
half core

About 35 cm between 35.09 and 36.20

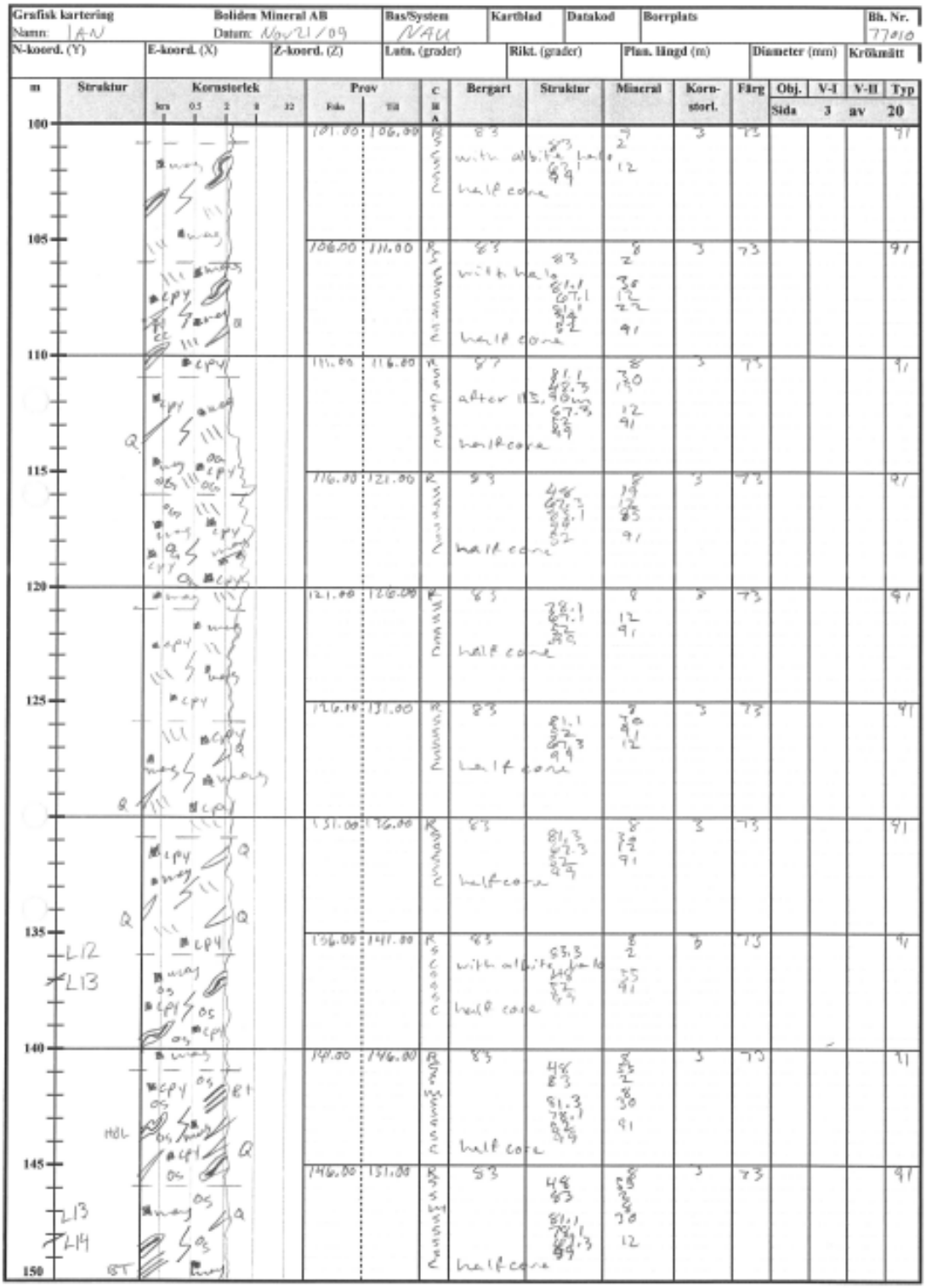
half core

half core

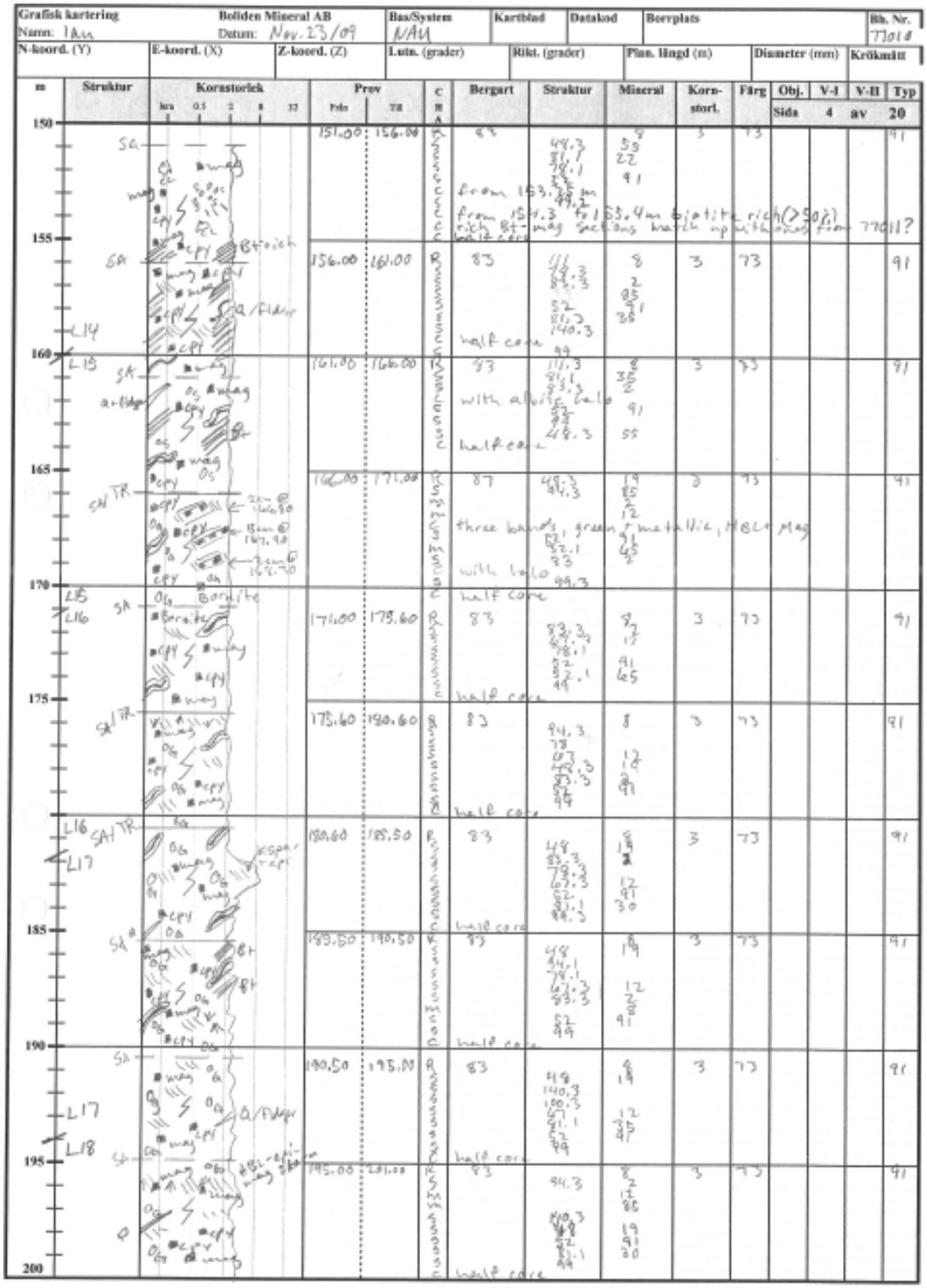
Appendix C. Profile 5040 logs- NAU77010 (cont.)



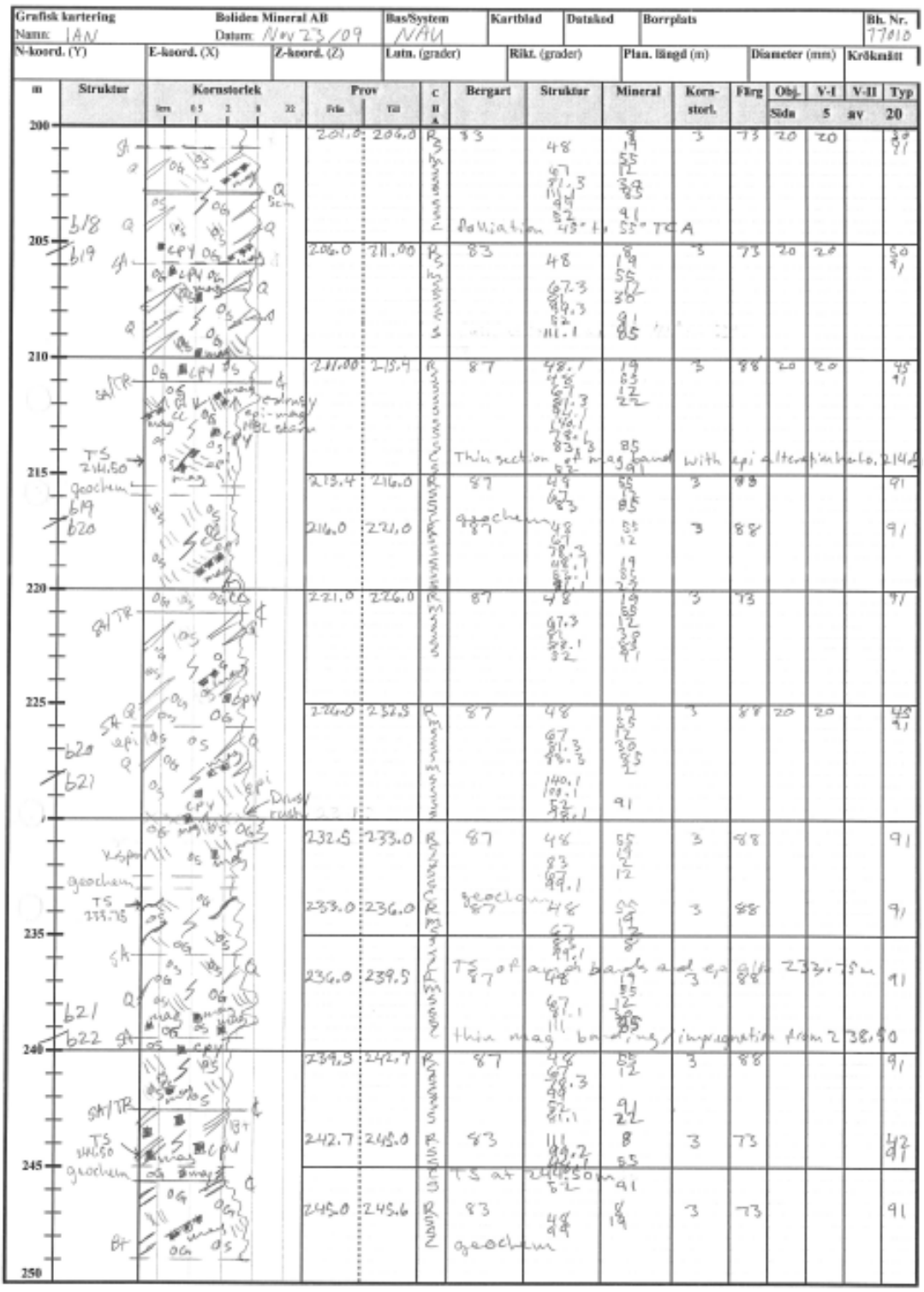
Appendix C. Profile 5040 logs- NAU77010 (cont.)



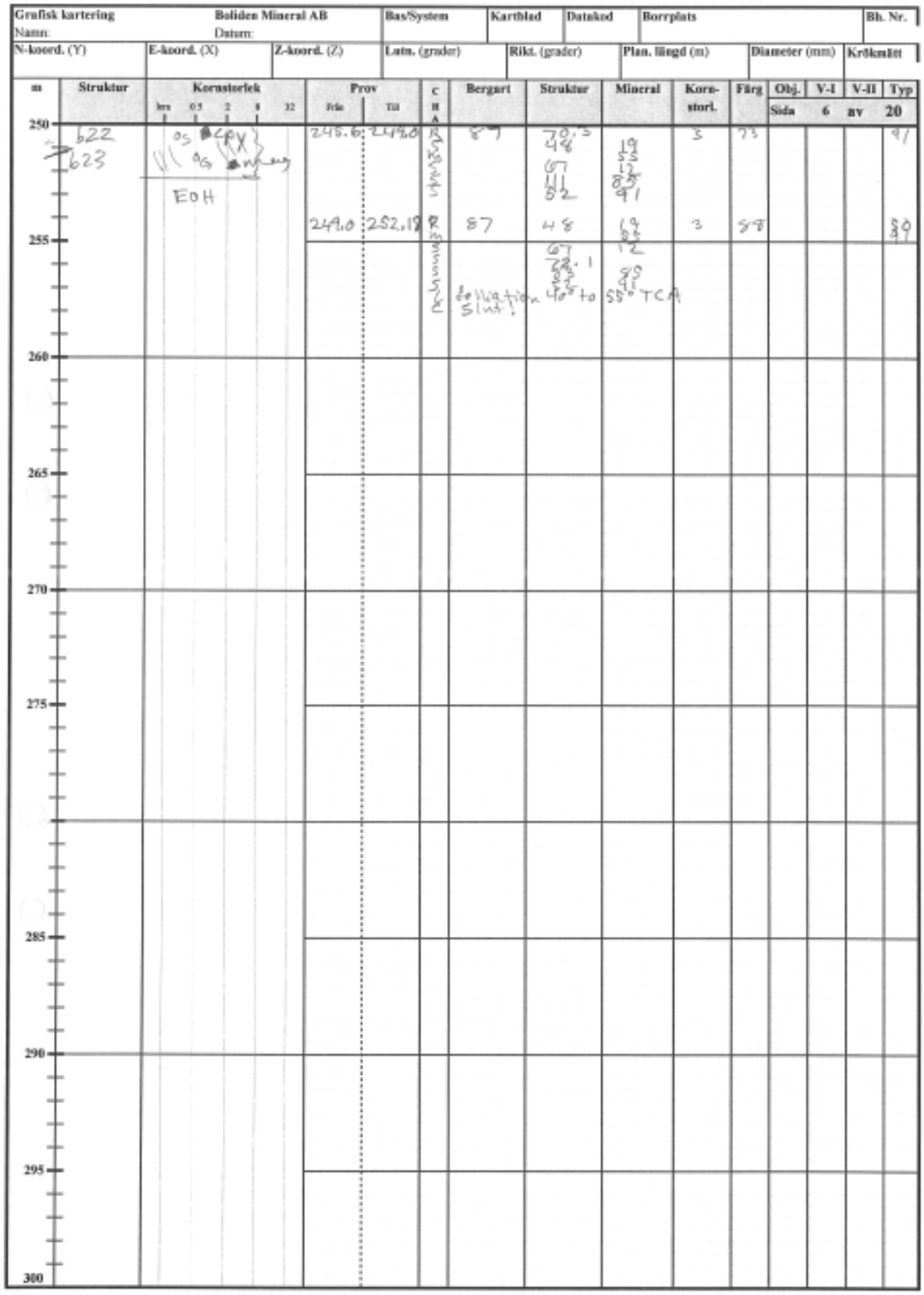
Appendix C. Profile 5040 logs- NAU77010 (cont.)



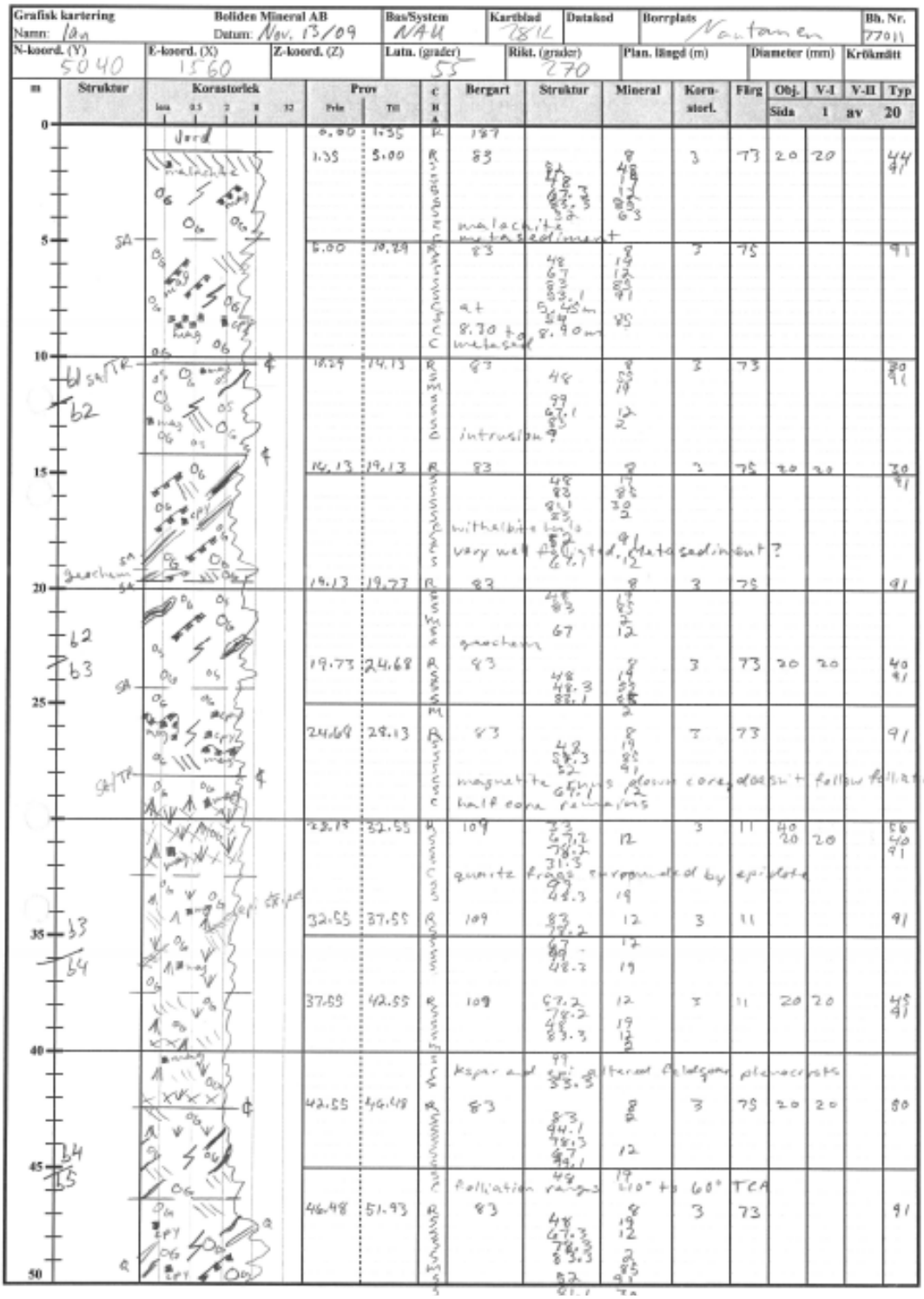
Appendix C. Profile 5040 logs- NAU77010 (cont.)



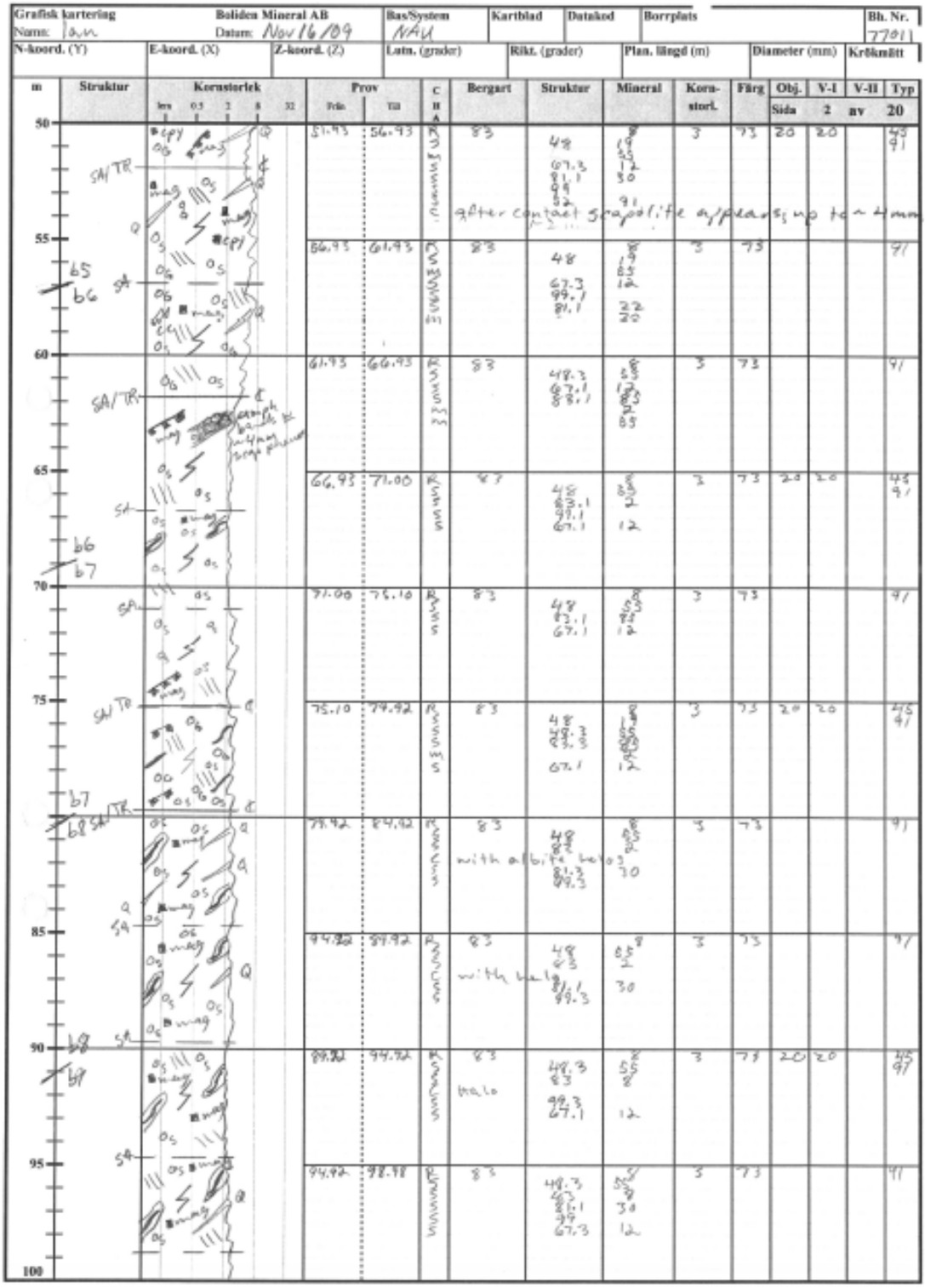
Appendix C. Profile 5040 logs- NAU77010 (cont.)



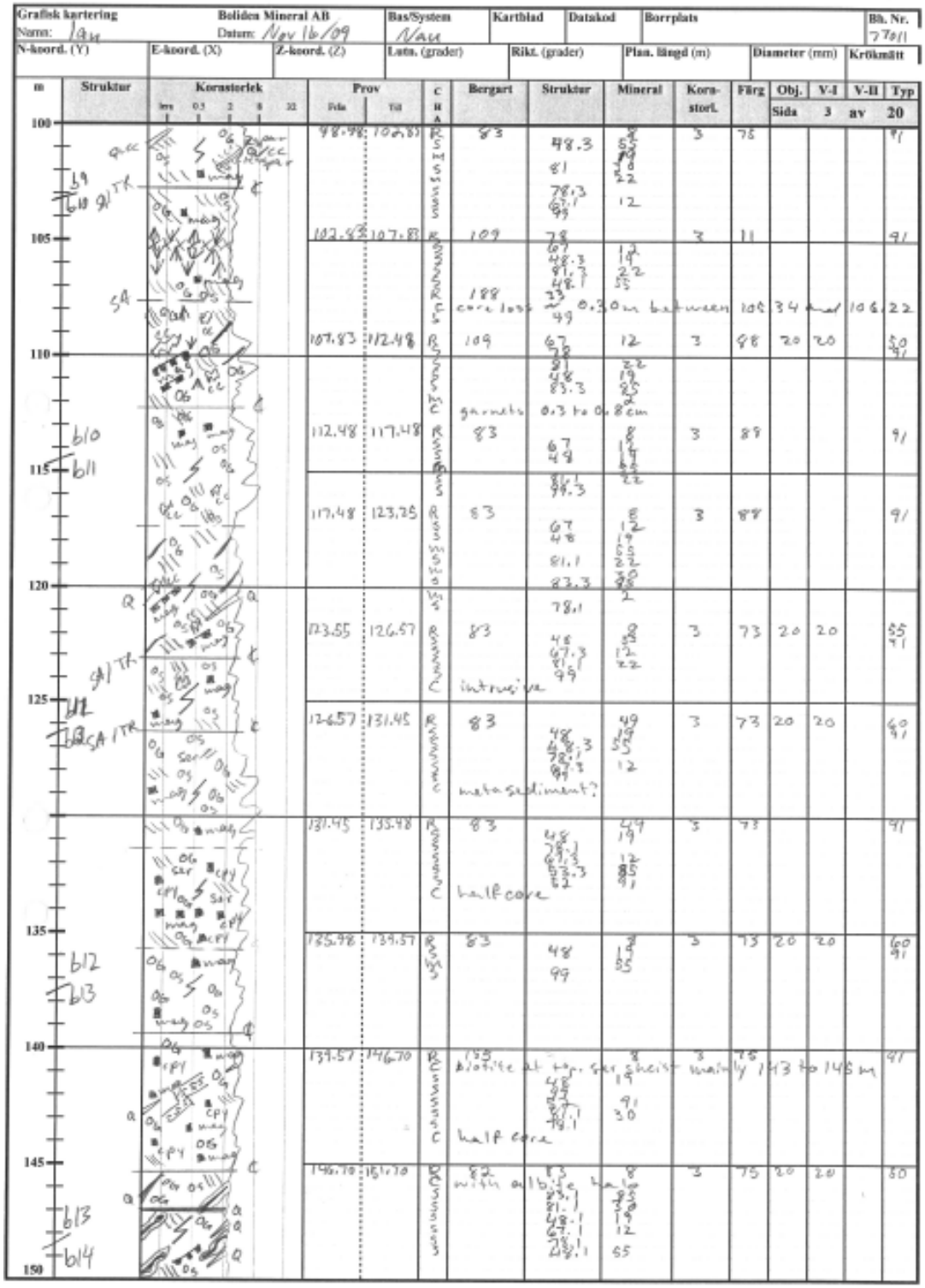
Appendix C. Profile 5040 logs- NAU77011



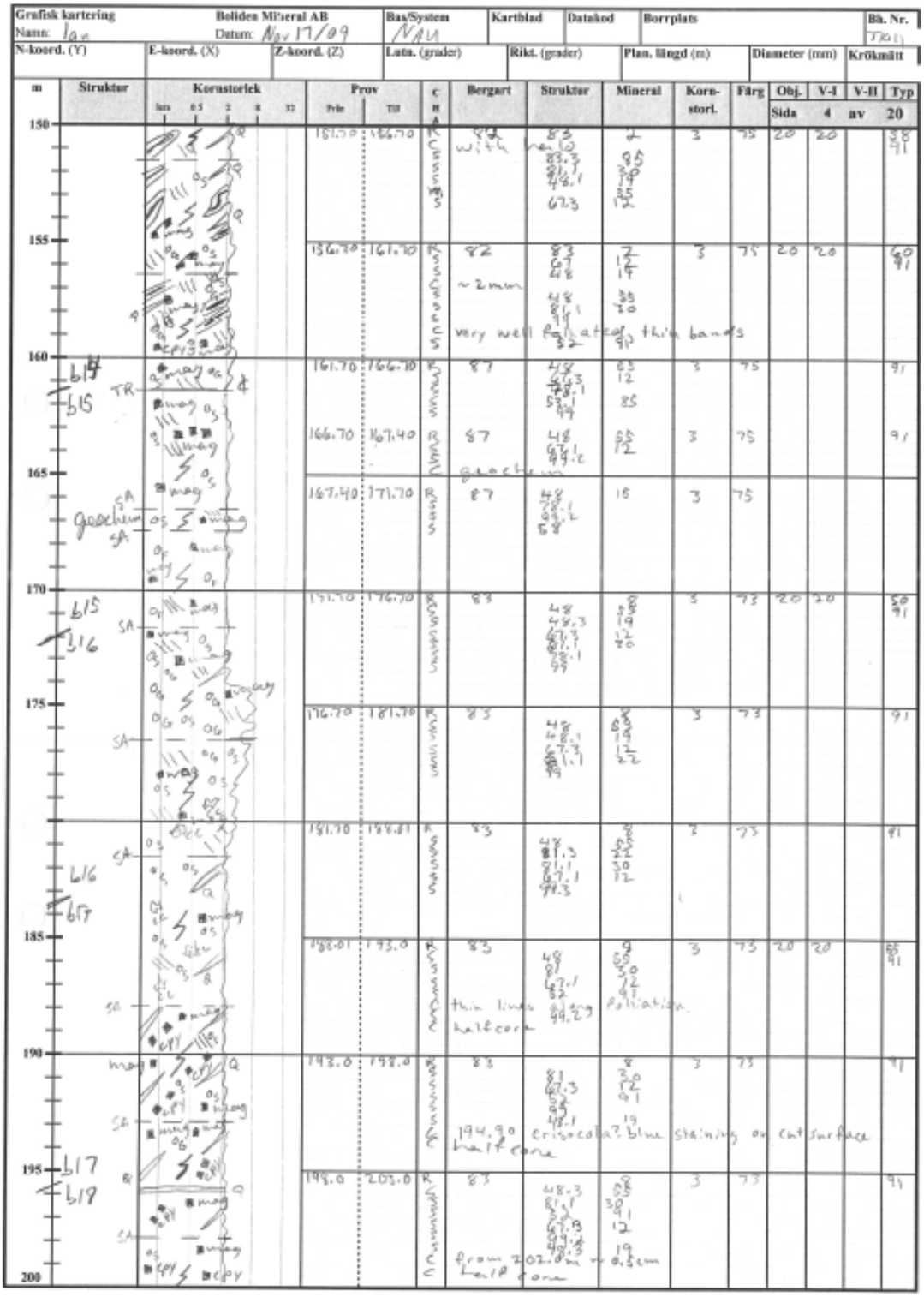
Appendix C. Profile 5040 logs- NAU77011 (cont.)



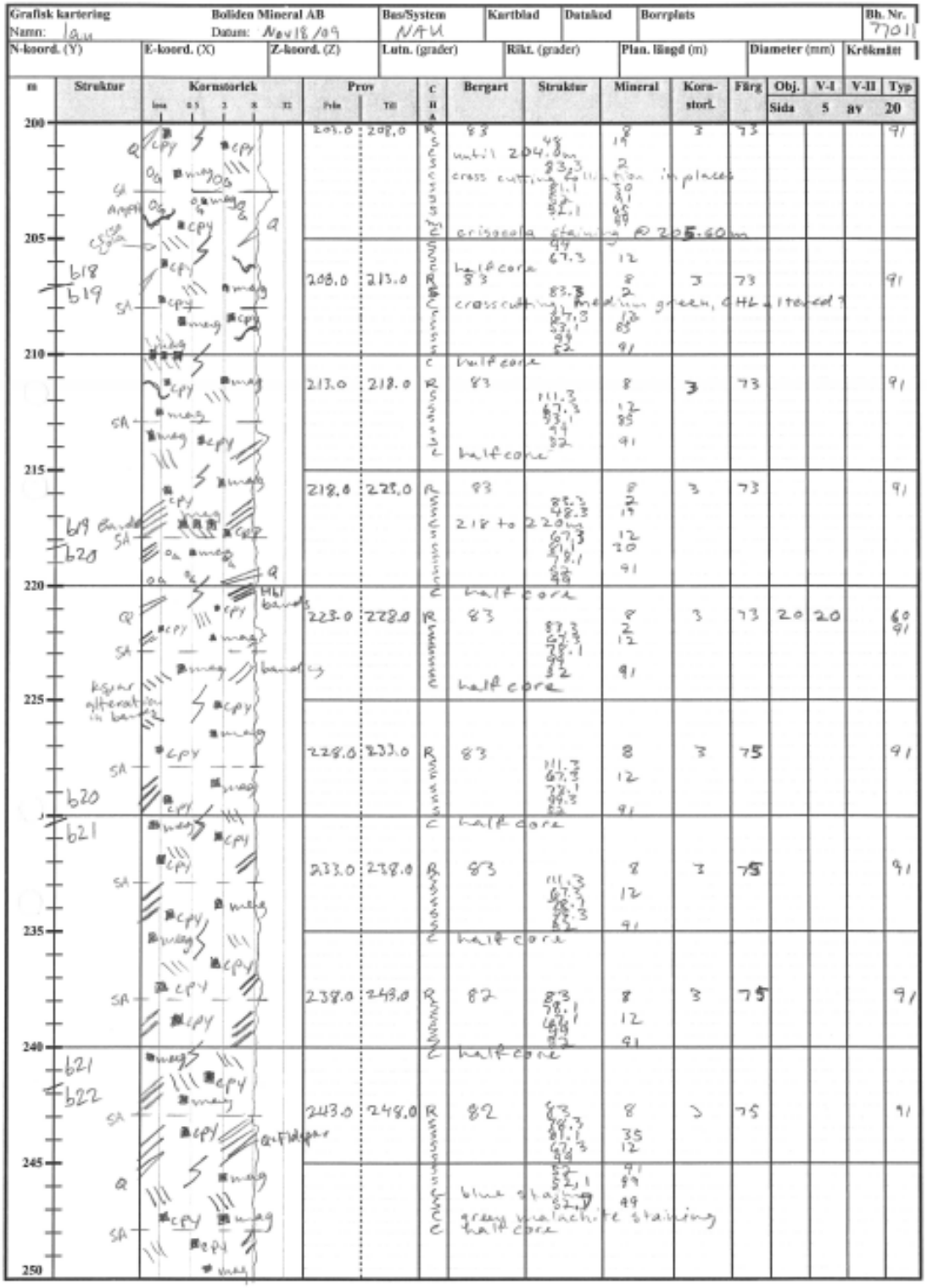
Appendix C. Profile 5040 logs- NAU77011 (cont.)



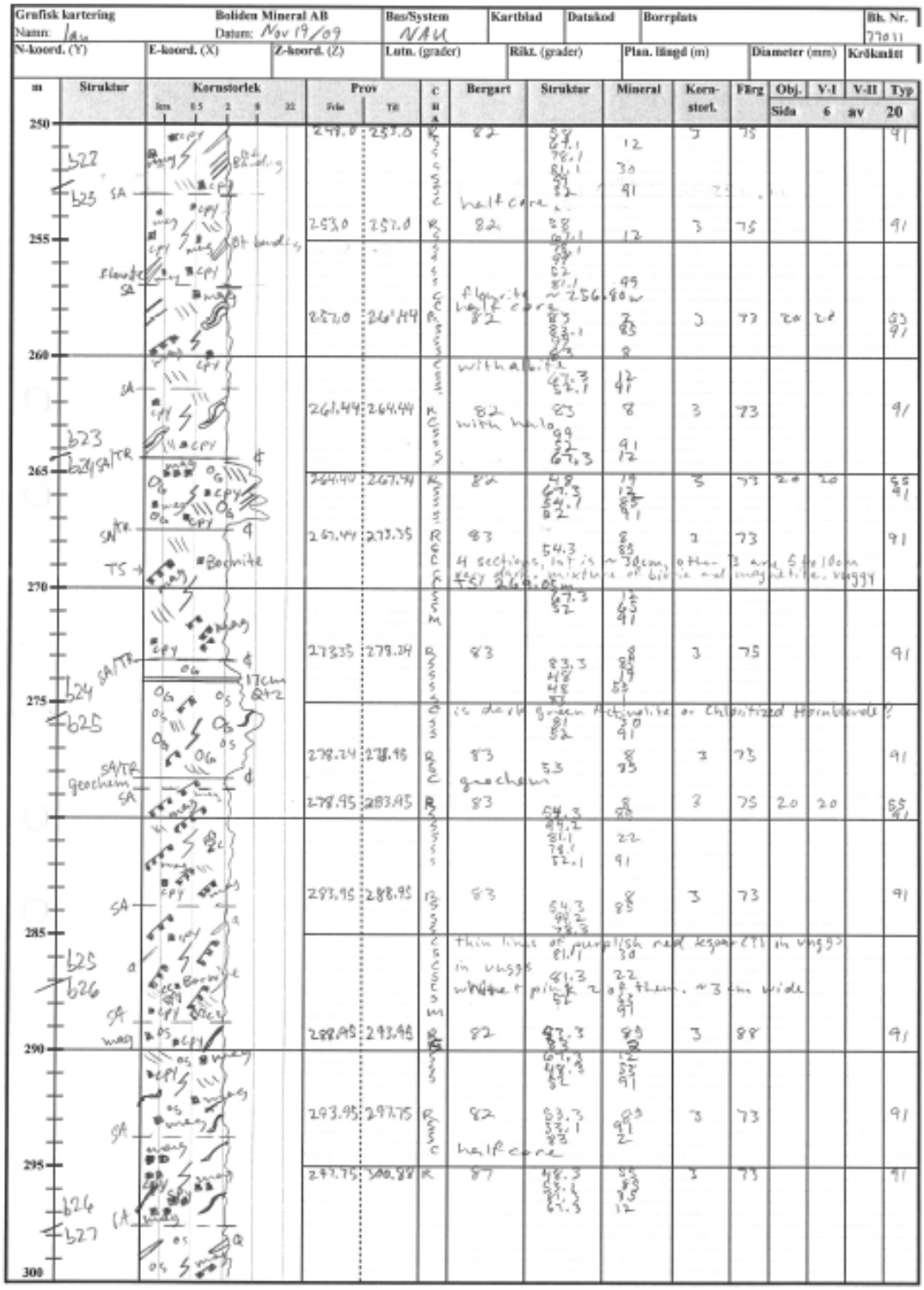
Appendix C. Profile 5040 logs- NAU77011 (cont.)



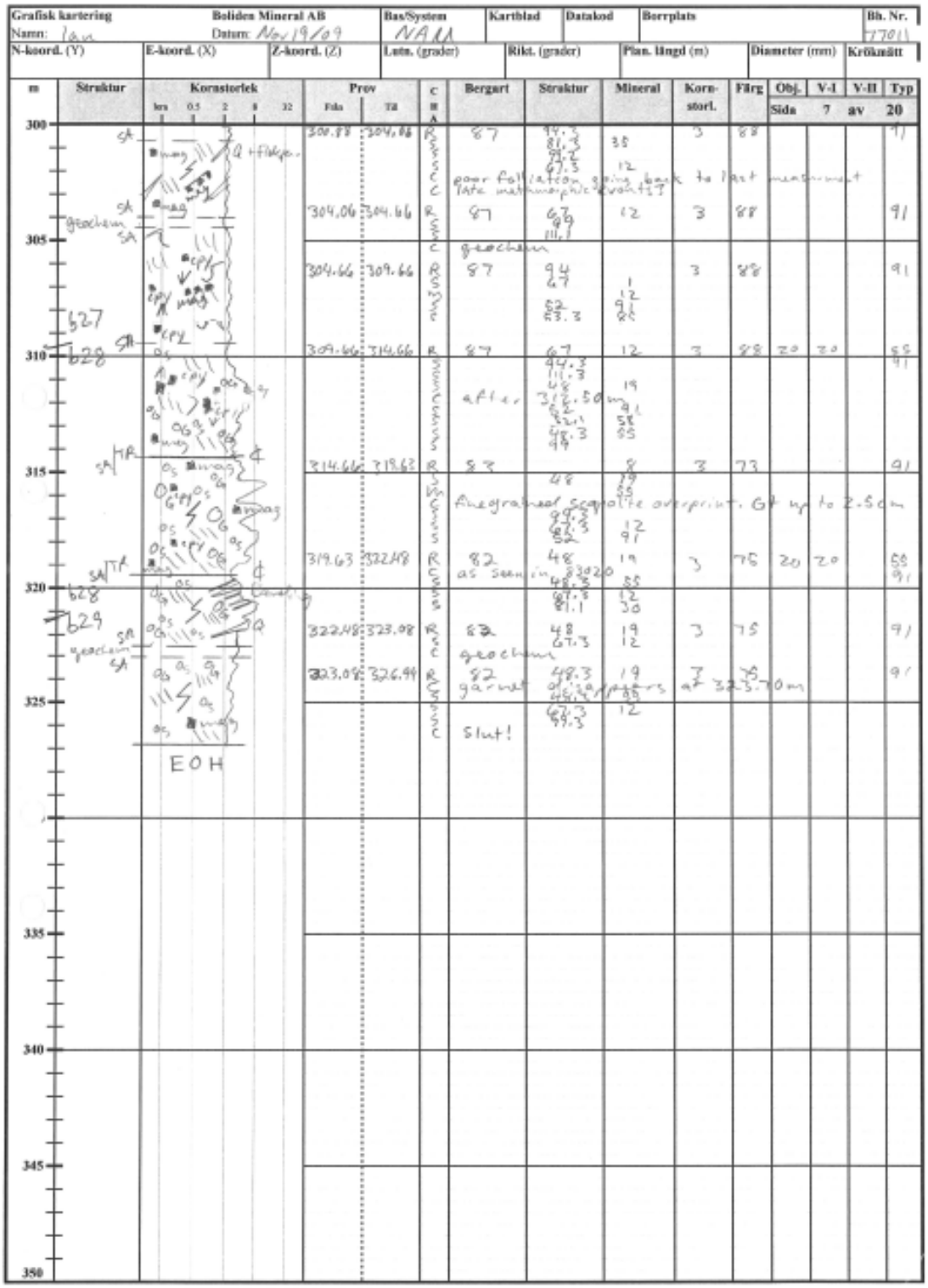
Appendix C. Profile 5040 logs- NAU77011 (cont.)



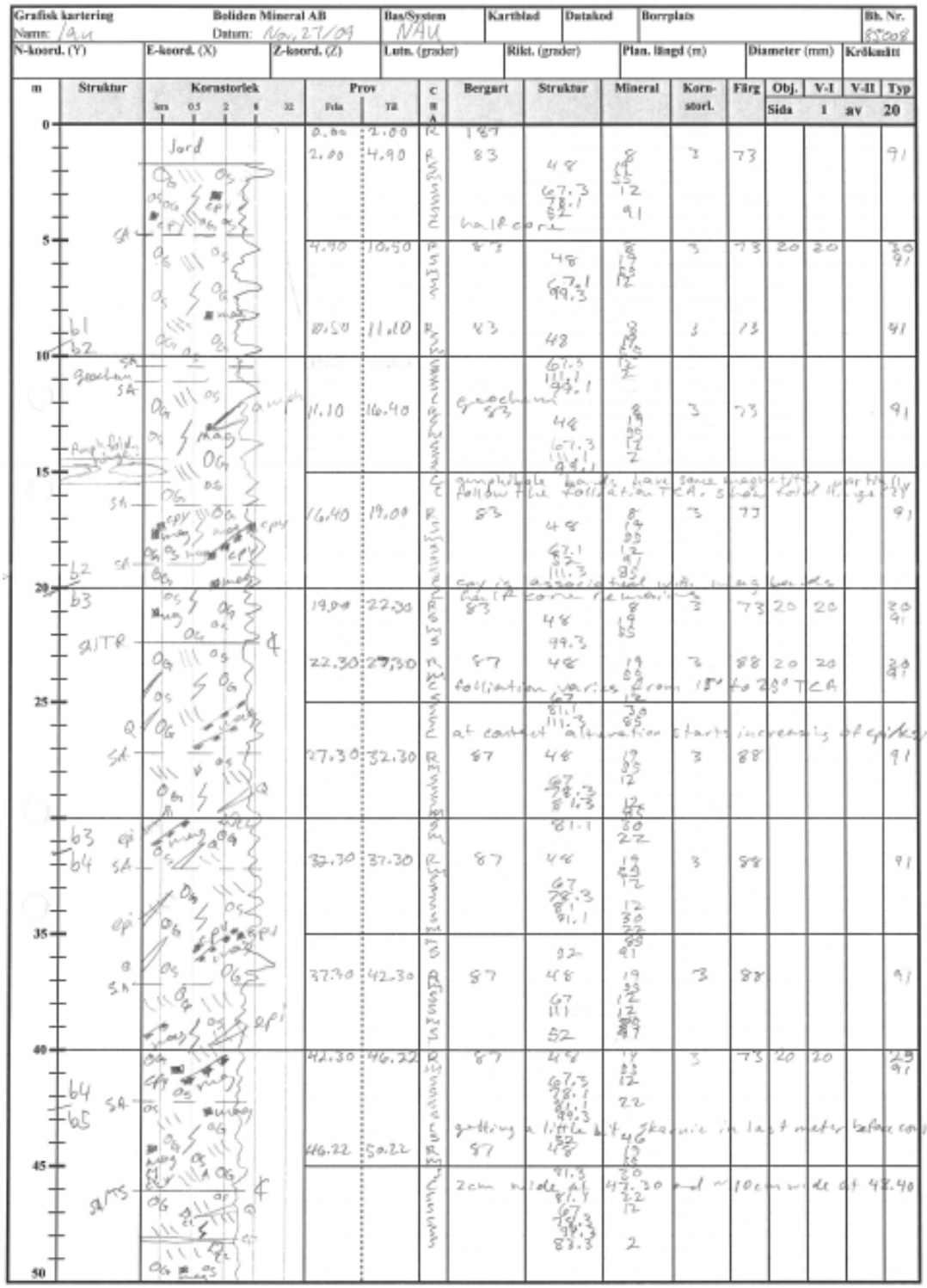
Appendix C. Profile 5040 logs- NAU77011 (cont.)



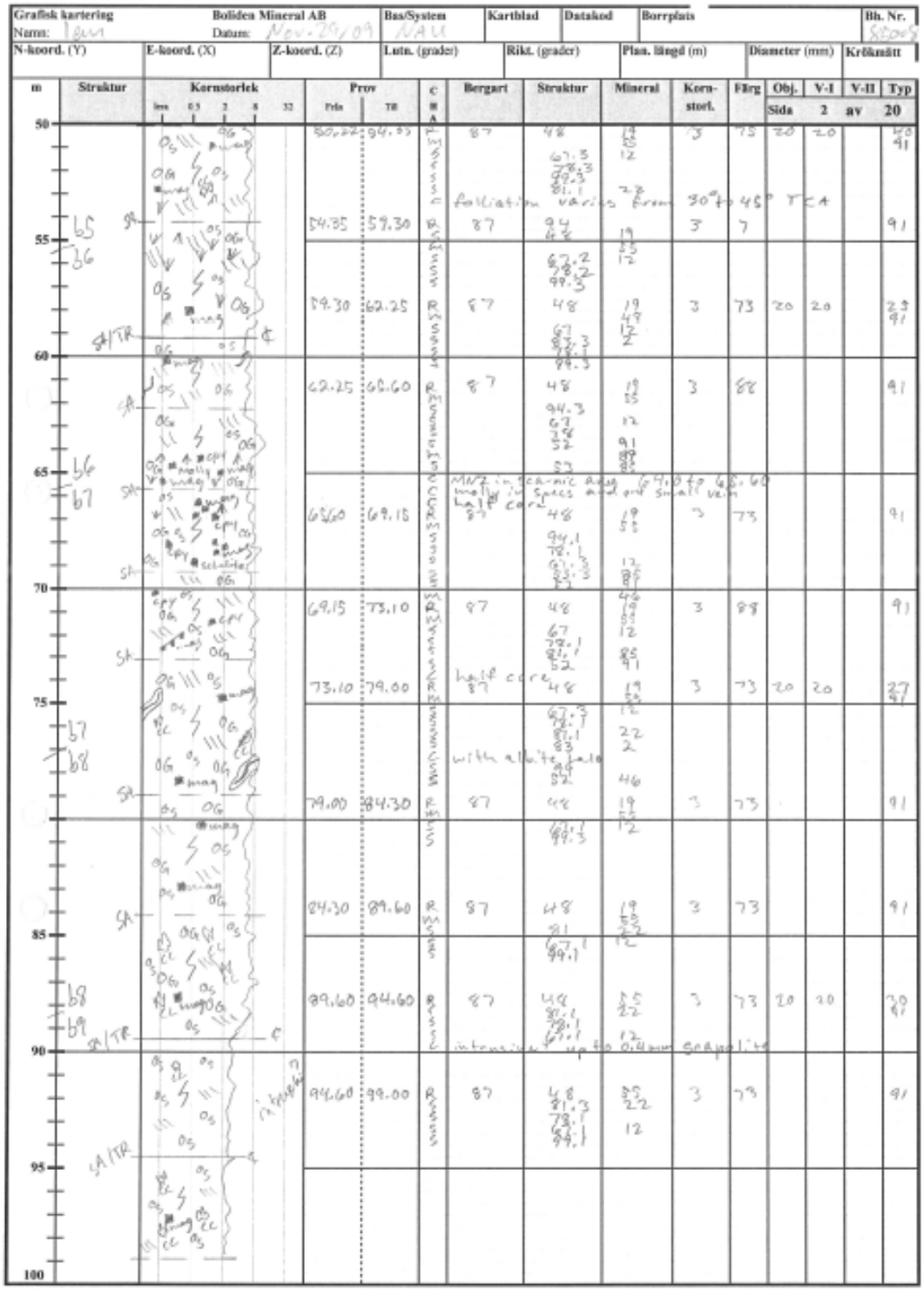
Appendix C. Profile 5040 logs- NAU77011 (cont.)



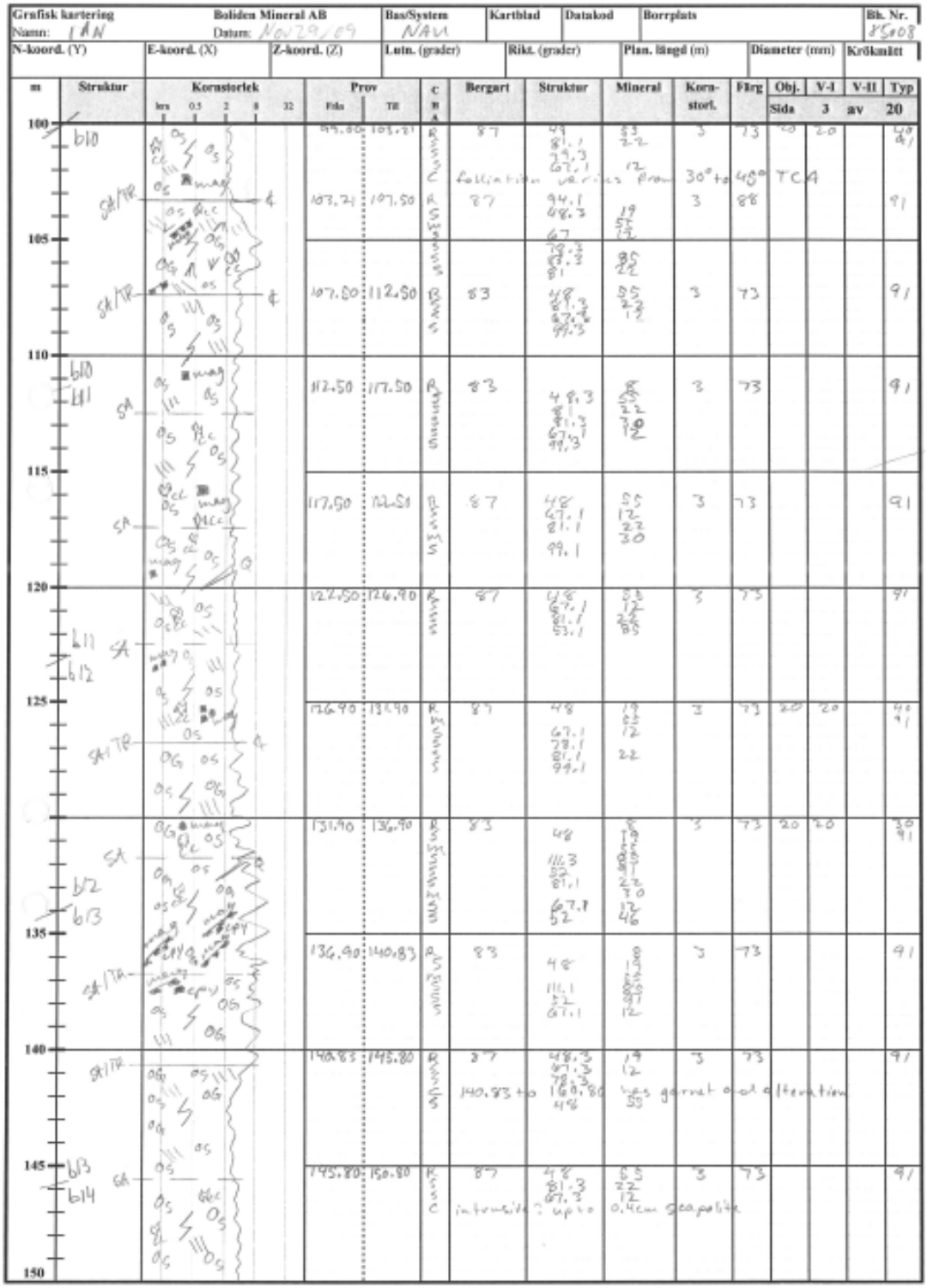
Appendix C. Profile 5040 logs- NAU85008



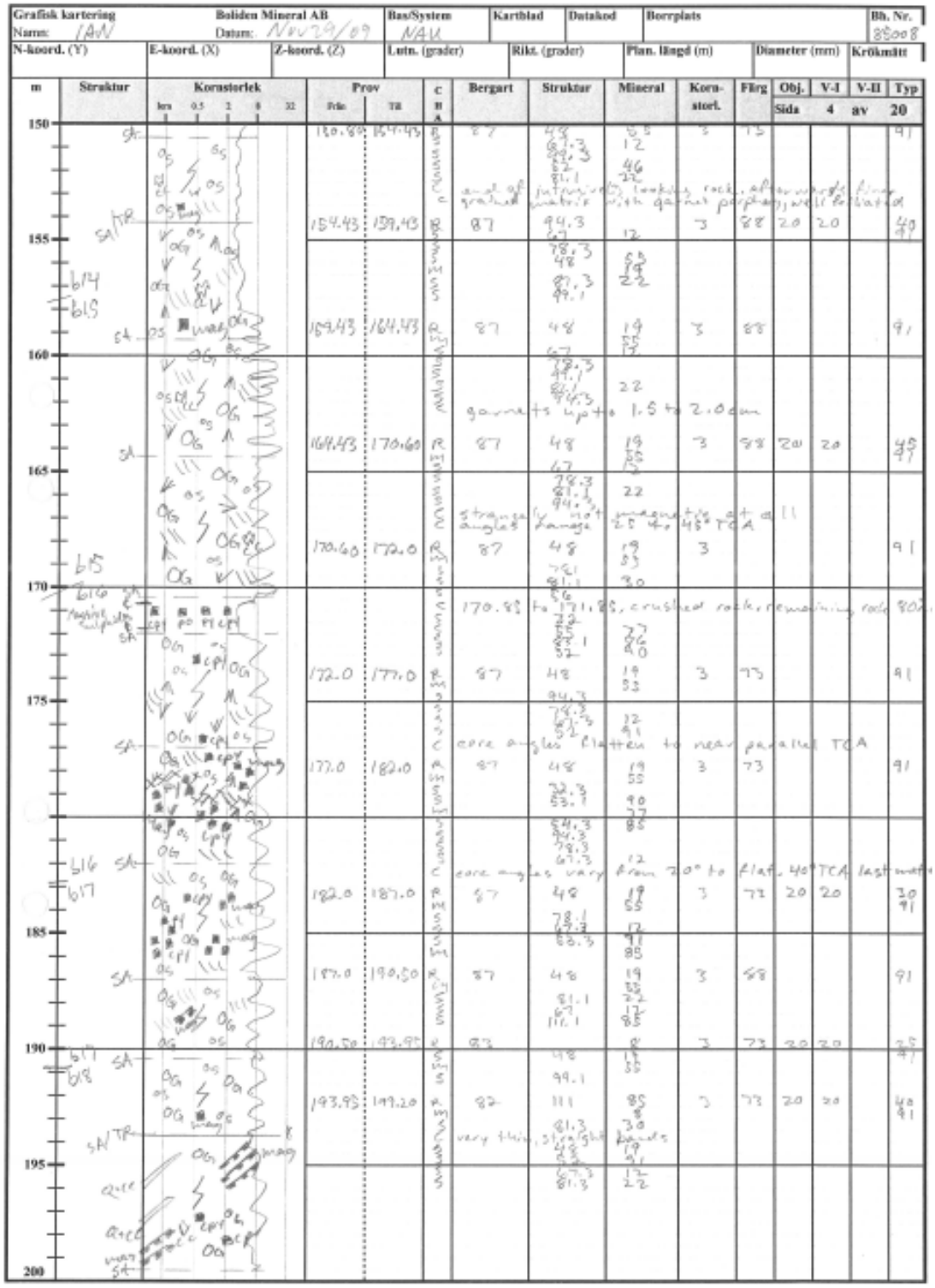
Appendix C. Profile 5040 logs- NAU85008 (cont.)



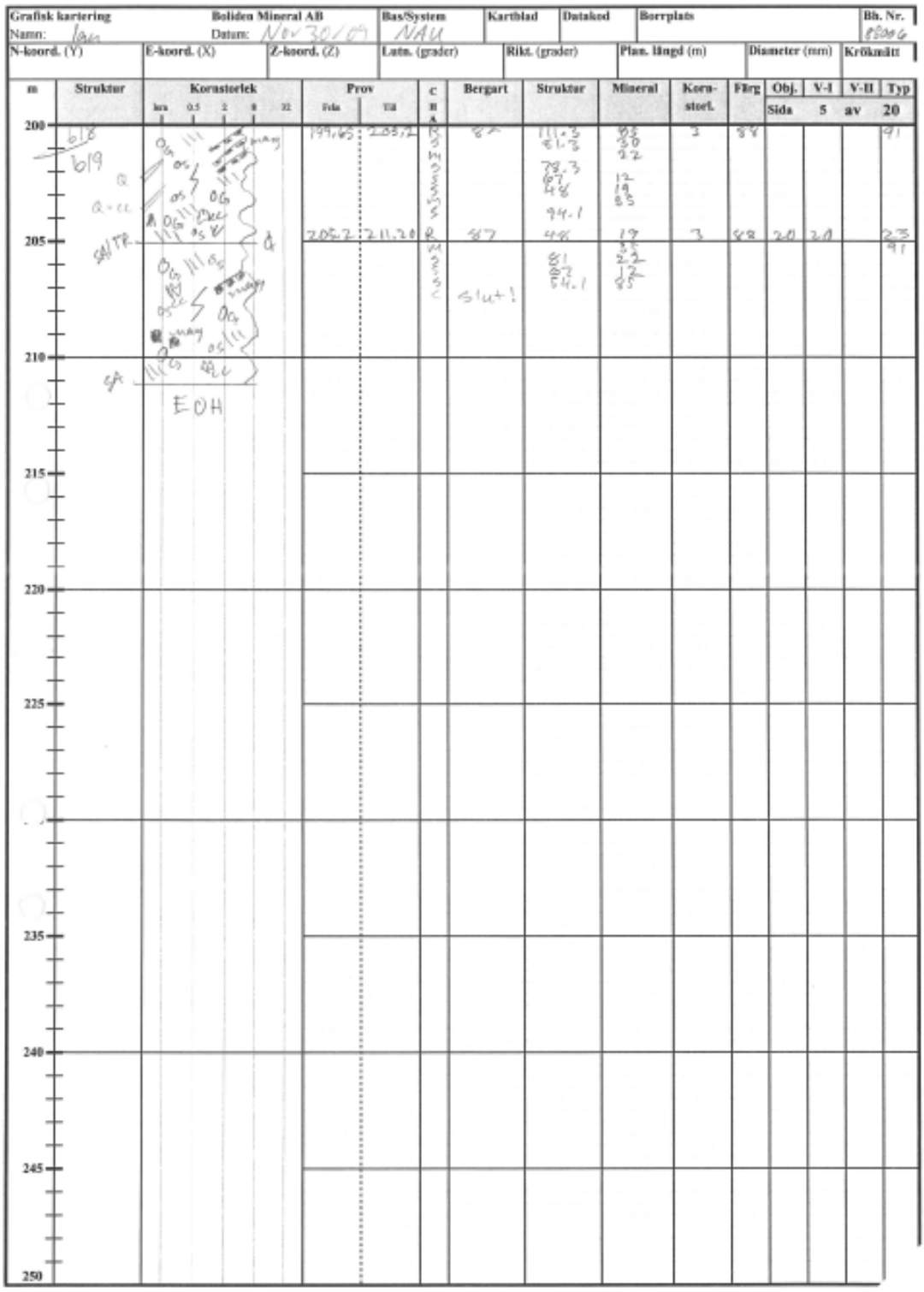
Appendix C. Profile 5040 logs- NAU85008 (cont.)



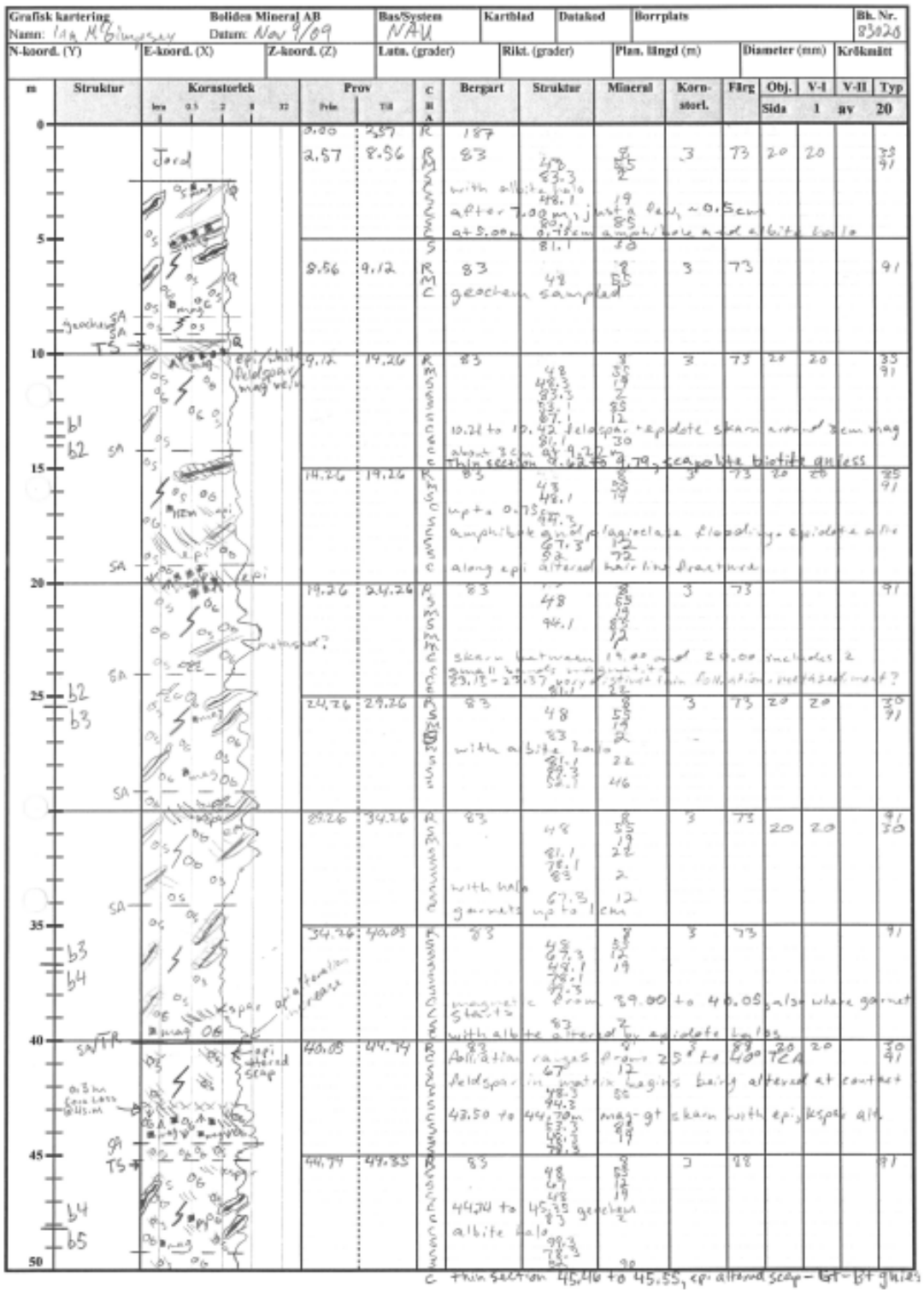
Appendix C. Profile 5040 logs- NAU85008 (cont.)



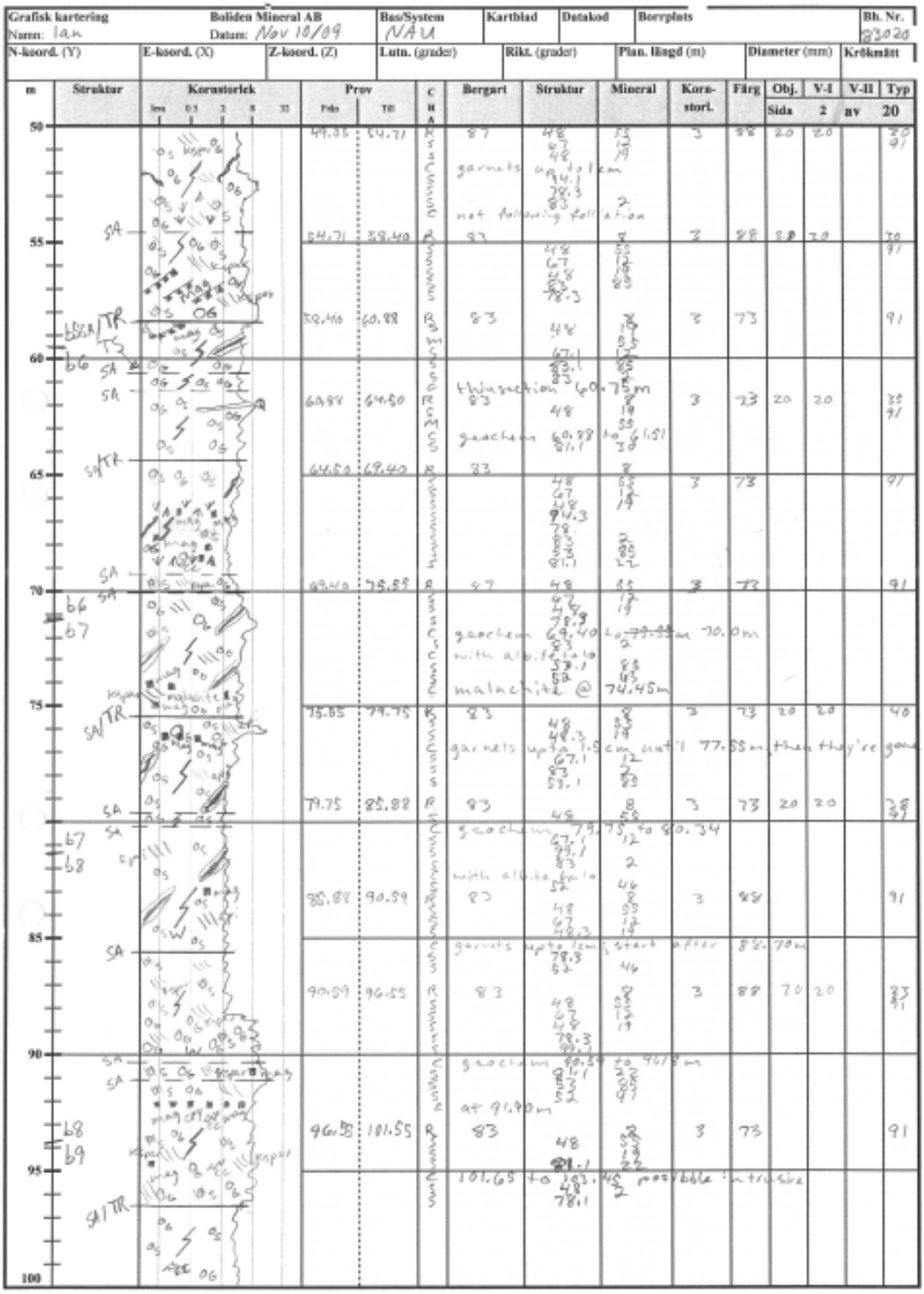
Appendix C. Profile 5040 logs- NAU85008 (cont.)



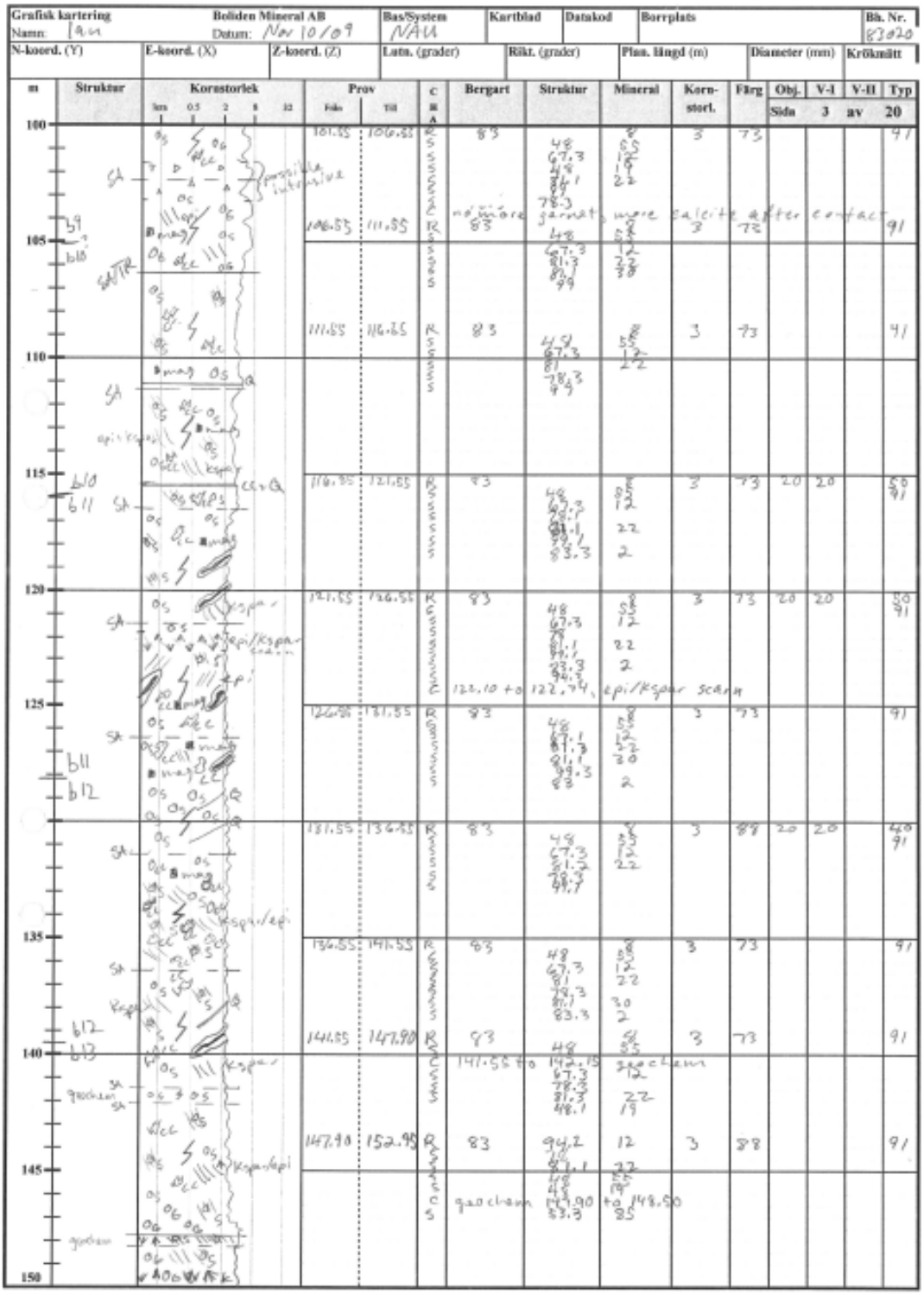
Appendix C. Profile 5040 logs- NAU83020



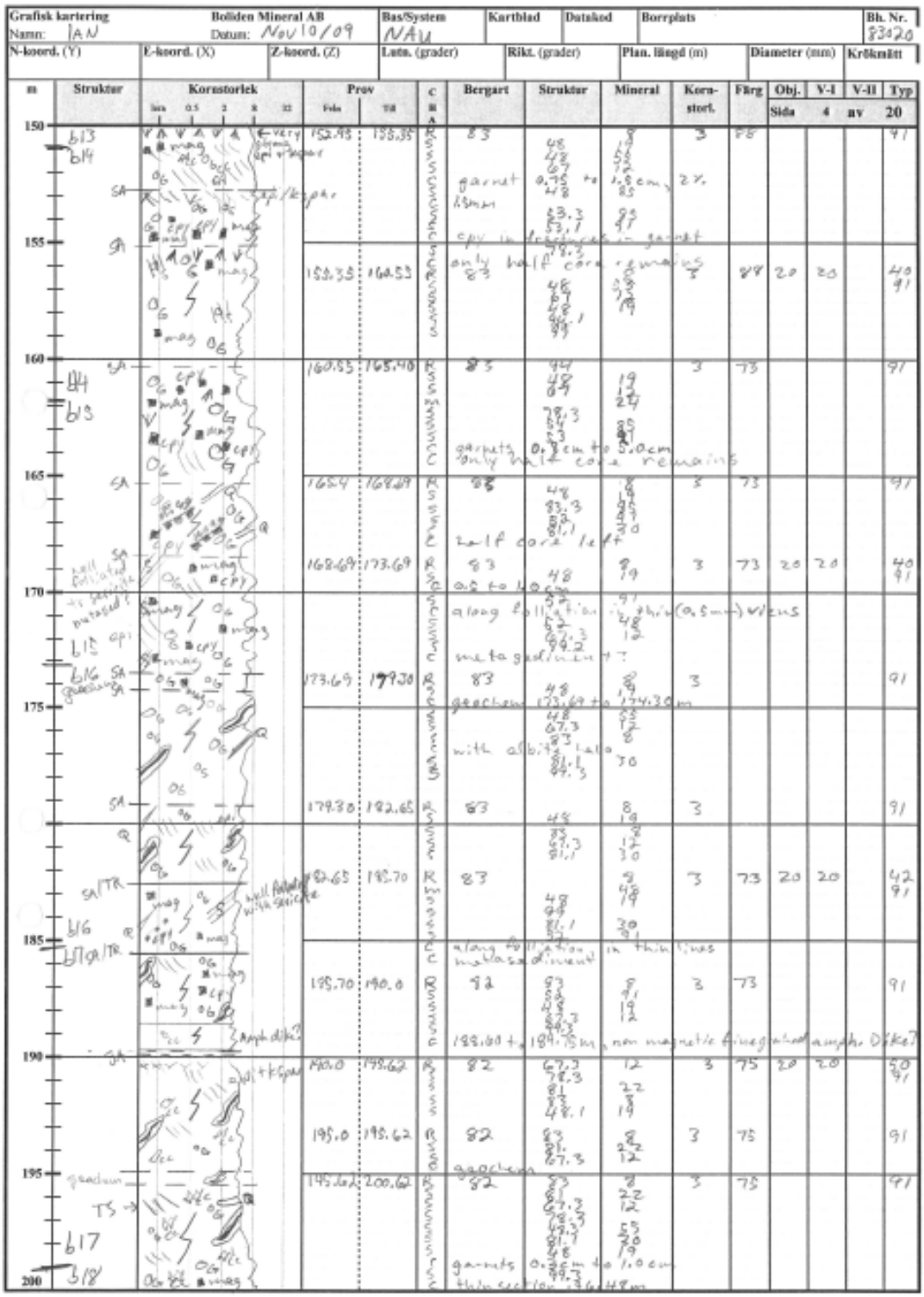
Appendix C. Profile 5040 logs- NAU83020 (cont.)



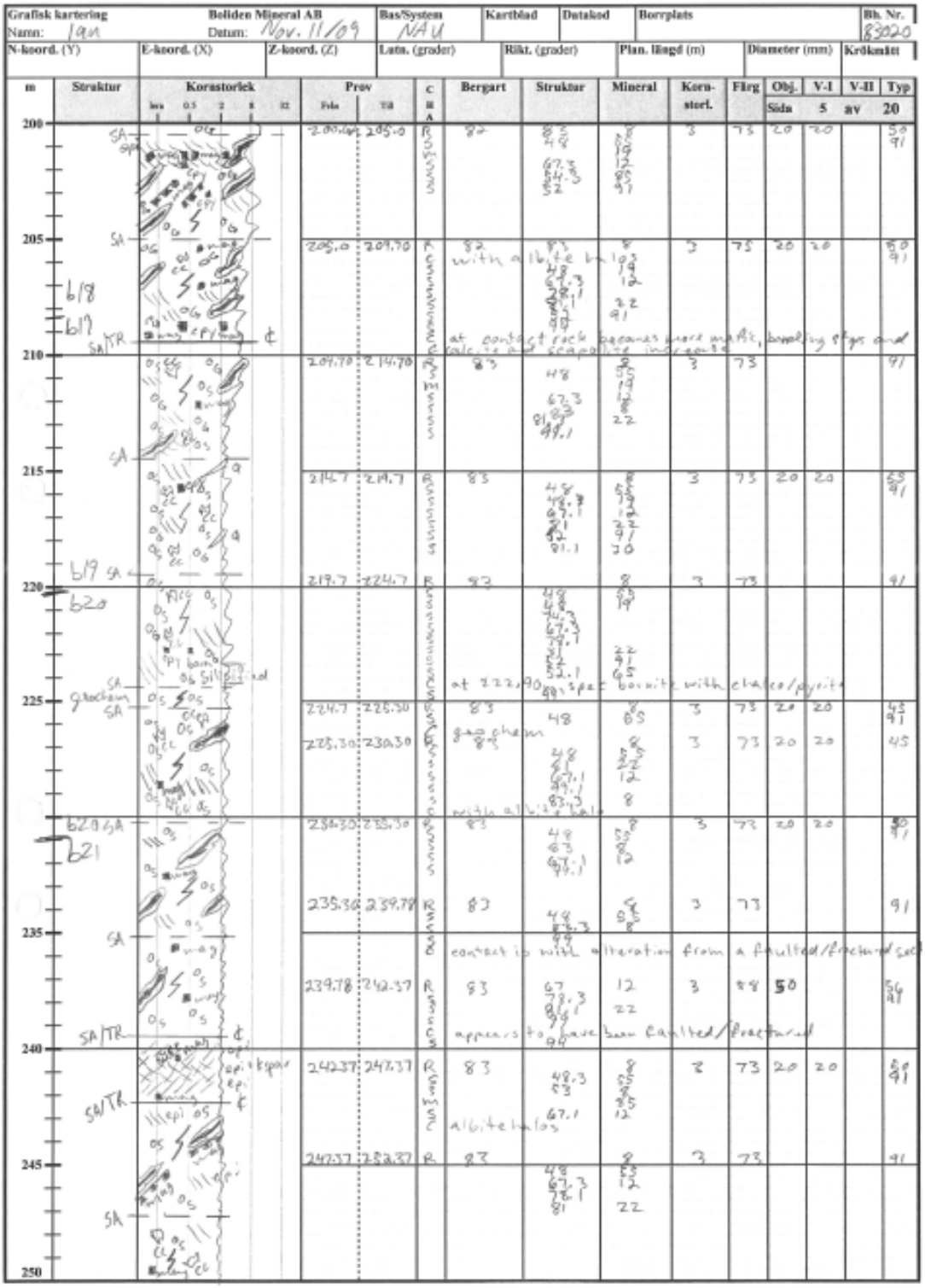
Appendix C. Profile 5040 logs- NAU83020 (cont.)



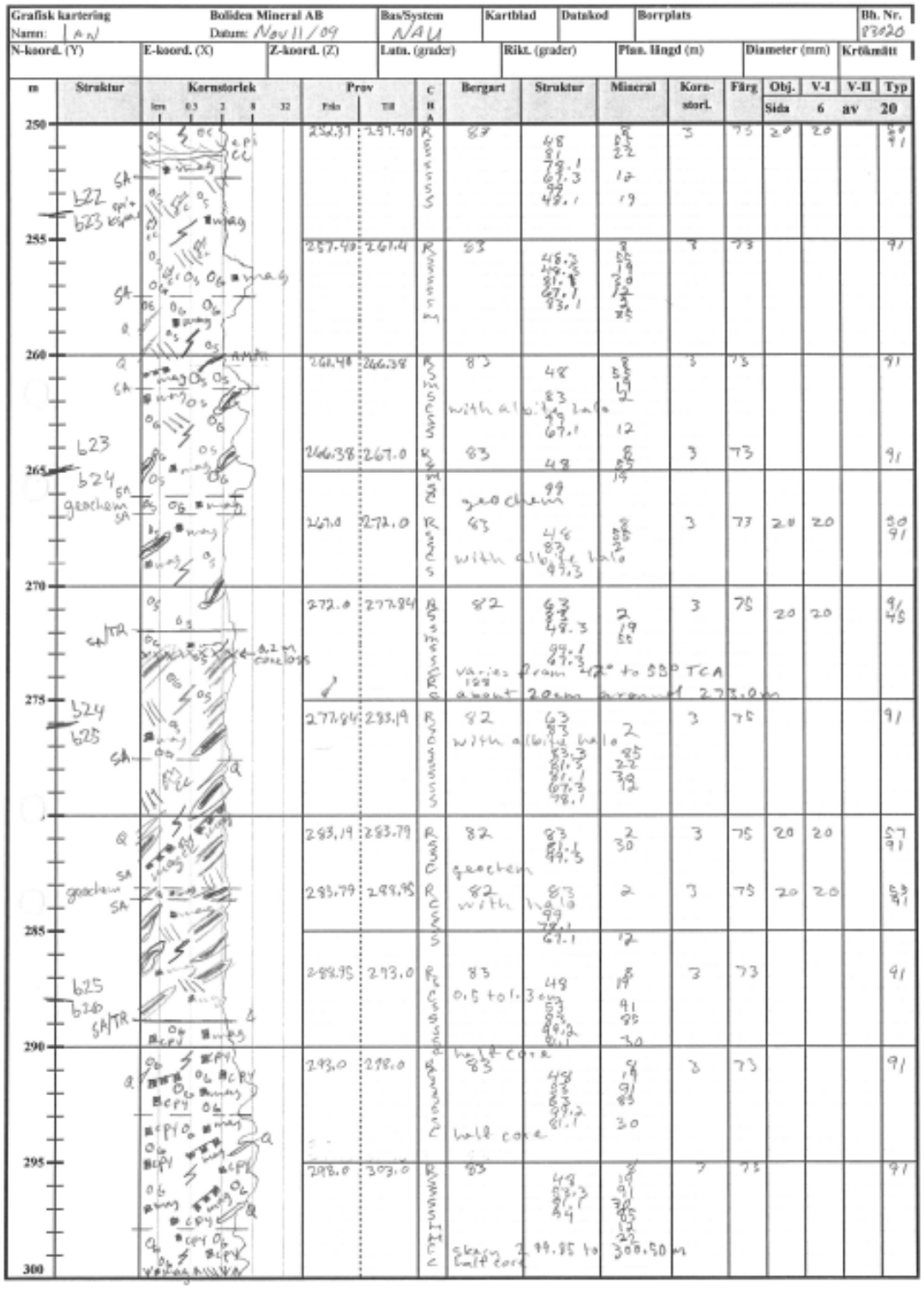
Appendix C. Profile 5040 logs- NAU83020 (cont.)



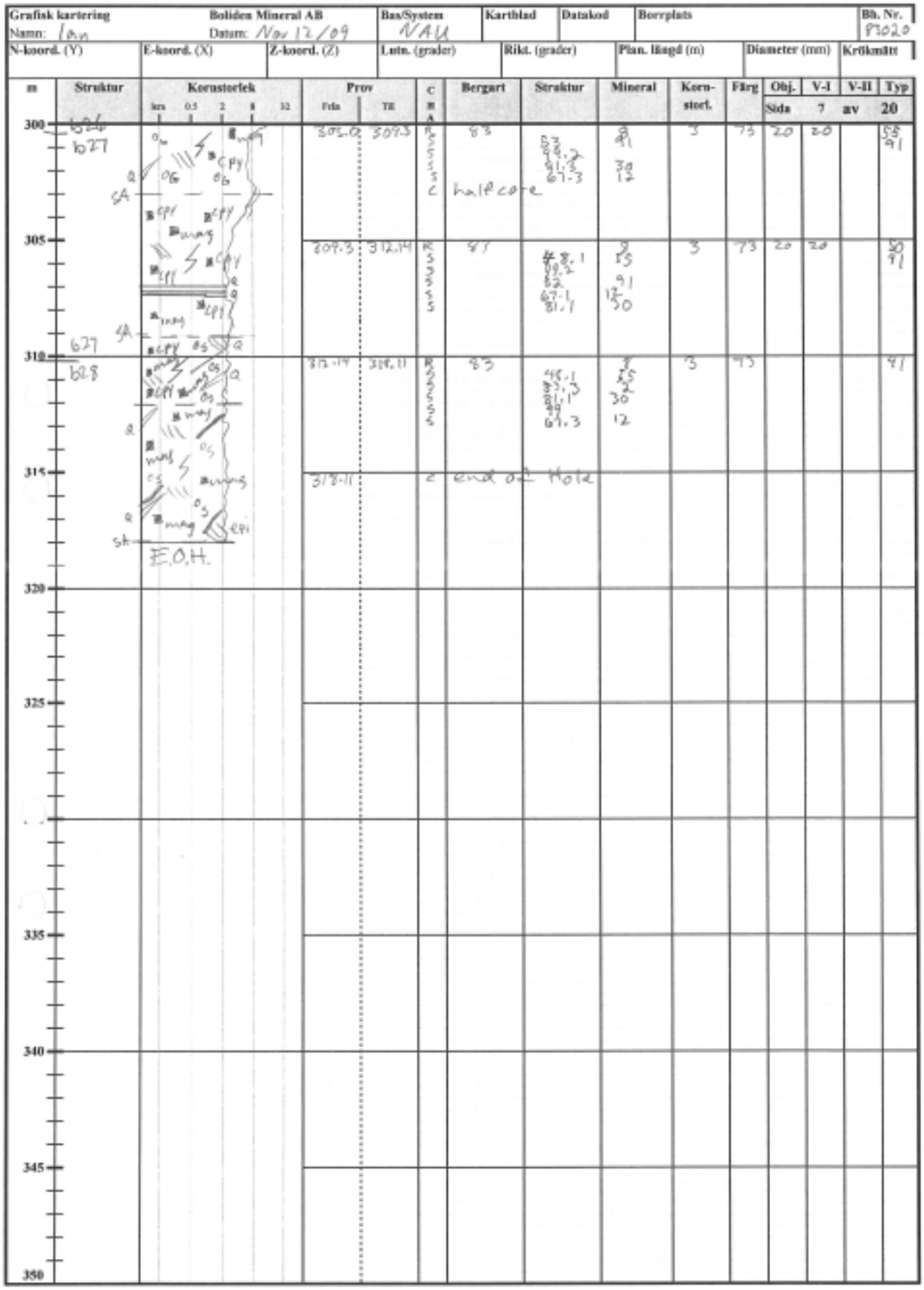
Appendix C. Profile 5040 logs- NAU83020 (cont.)



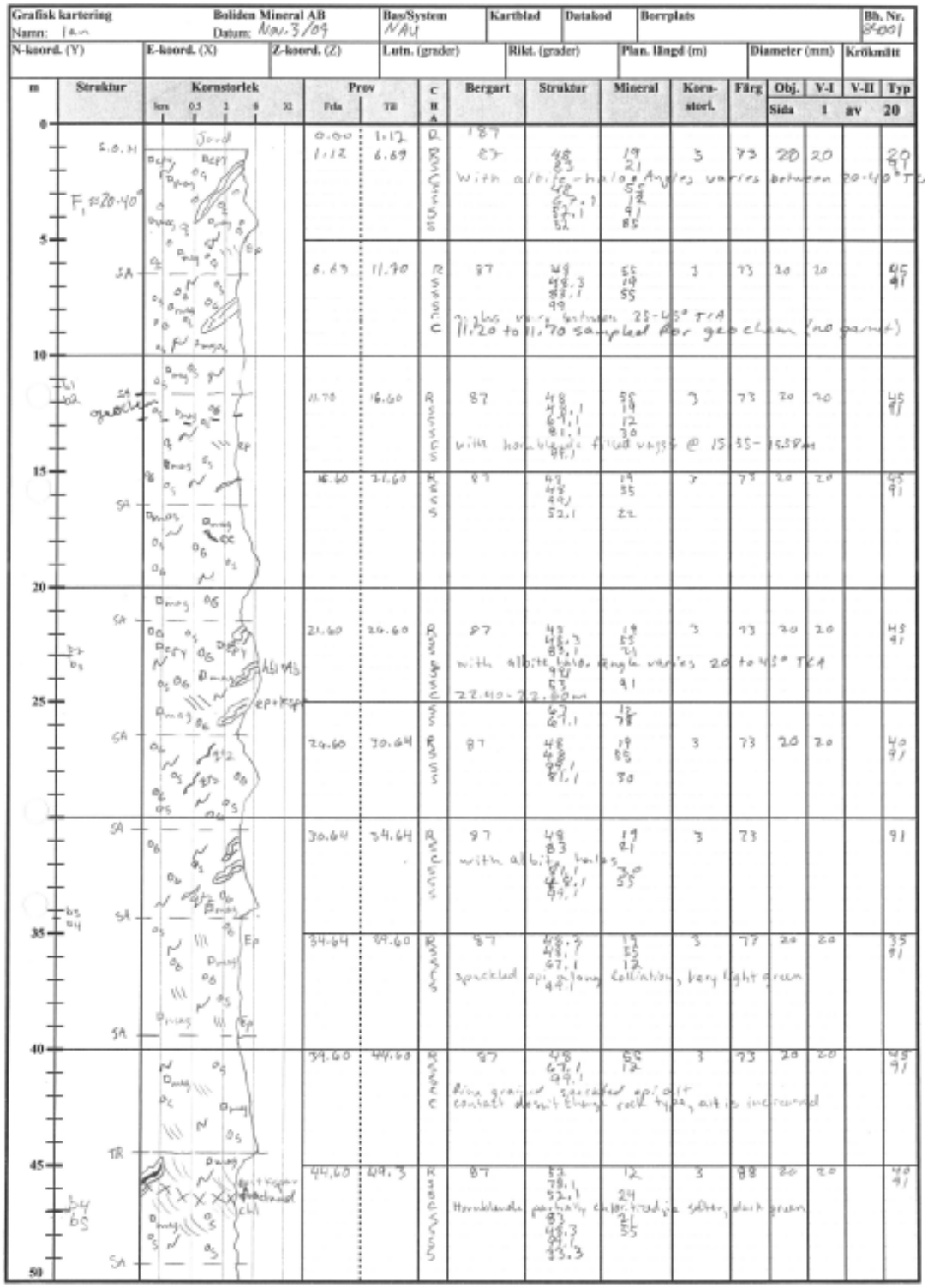
Appendix C. Profile 5040 logs- NAU83020 (cont.)



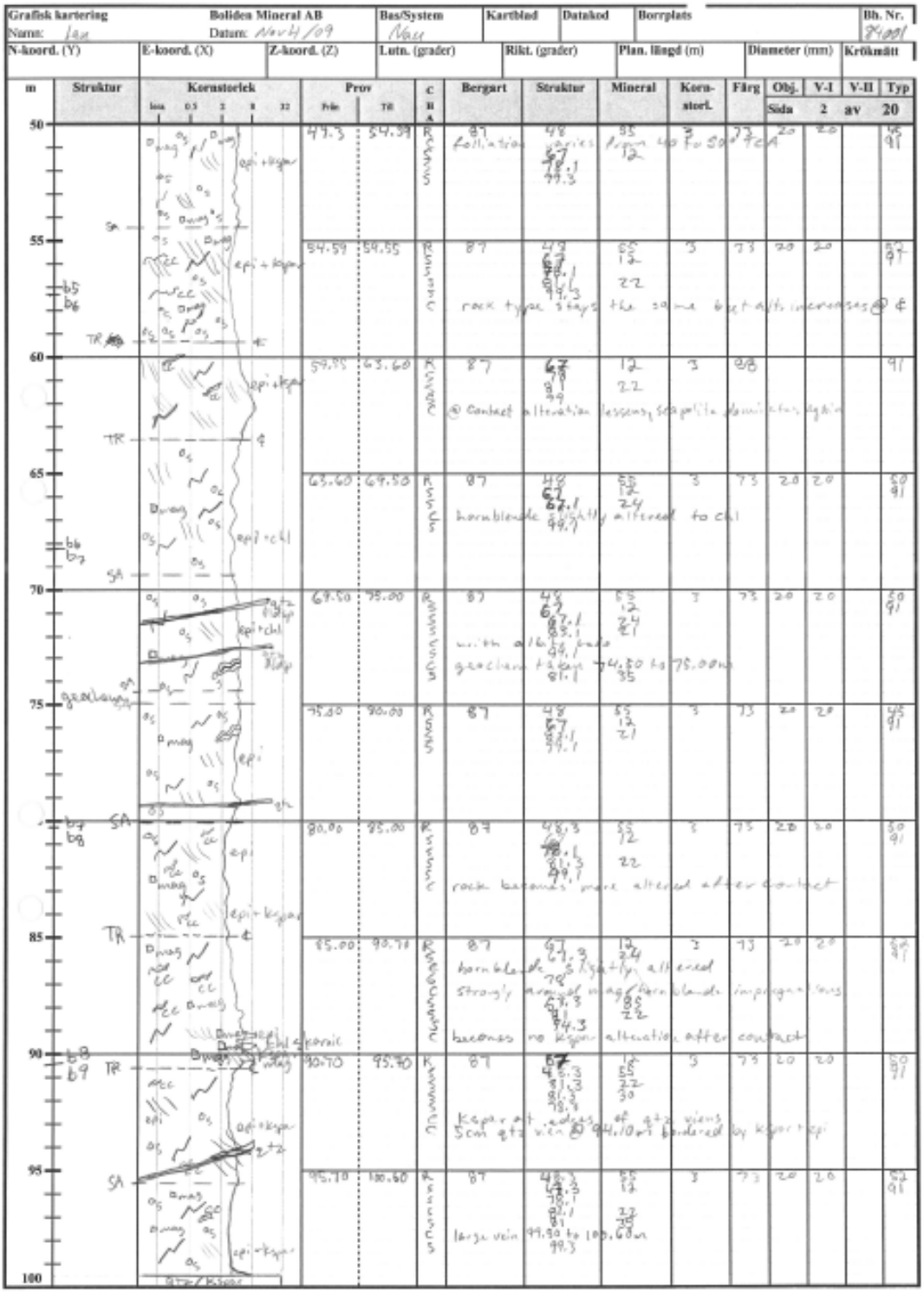
Appendix C. Profile 5040 logs- NAU83020 (cont.)



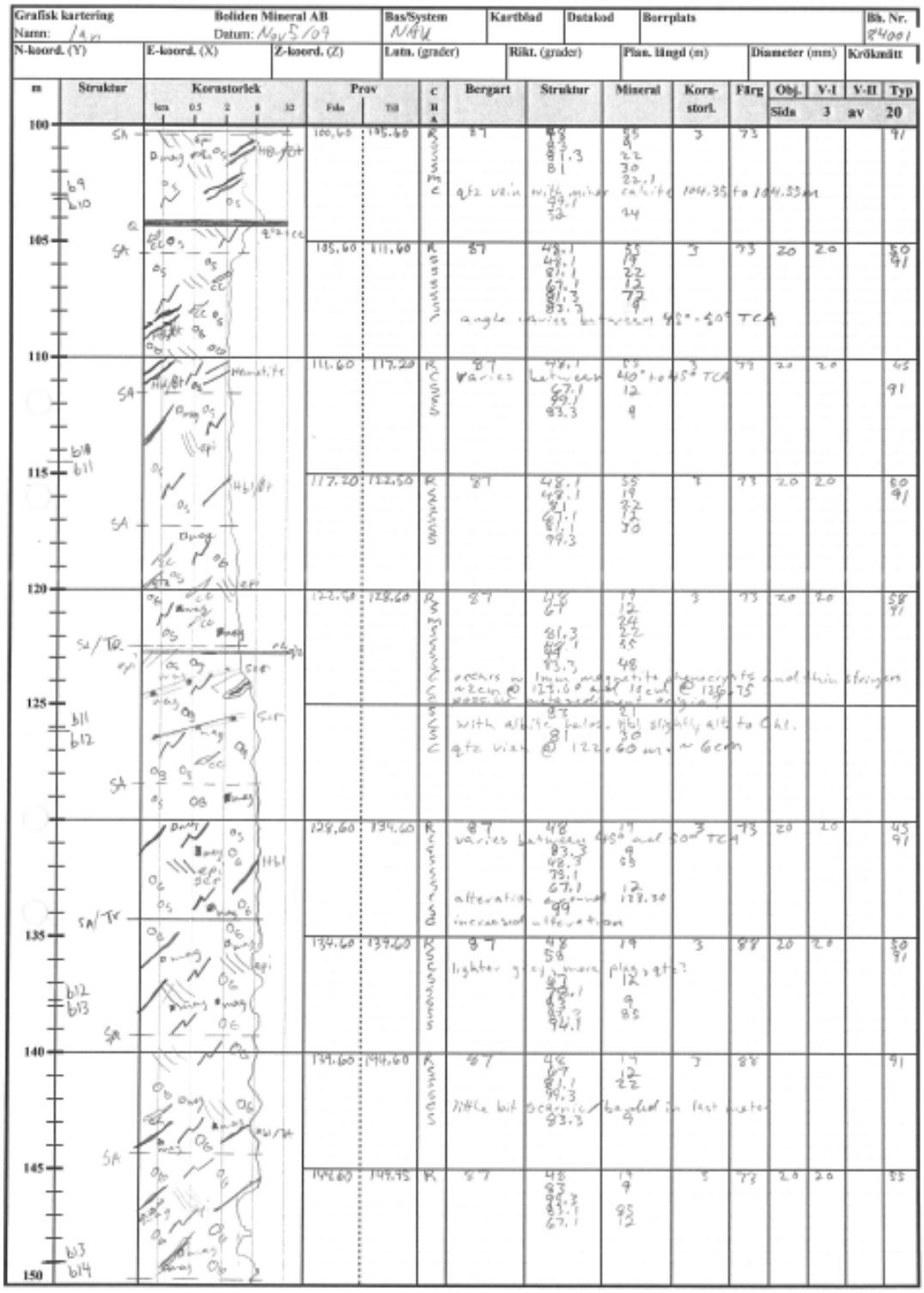
Appendix C. Profile 5040 logs- NAU84001



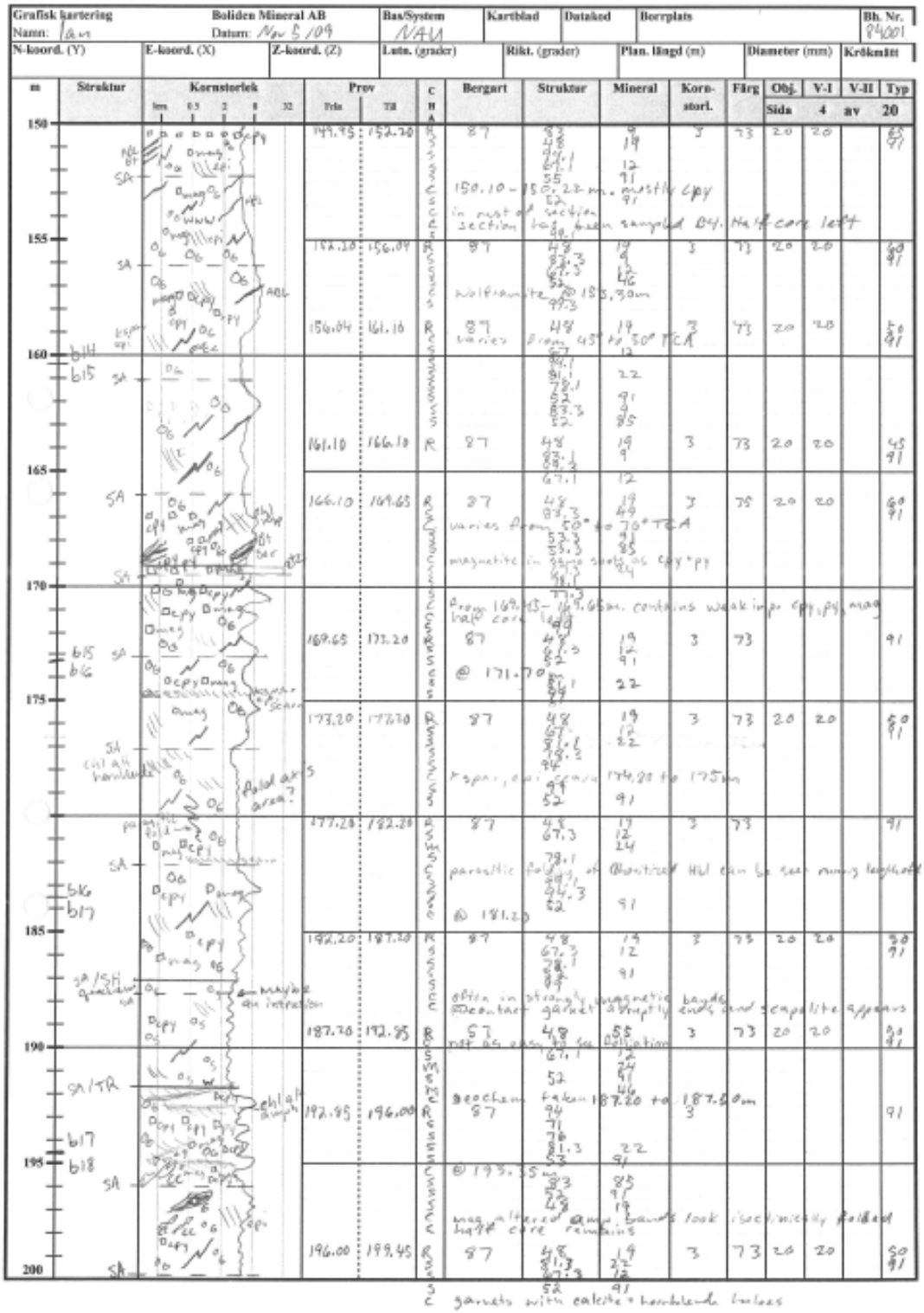
Appendix C. Profile 5040 logs- NAU84001 (cont.)



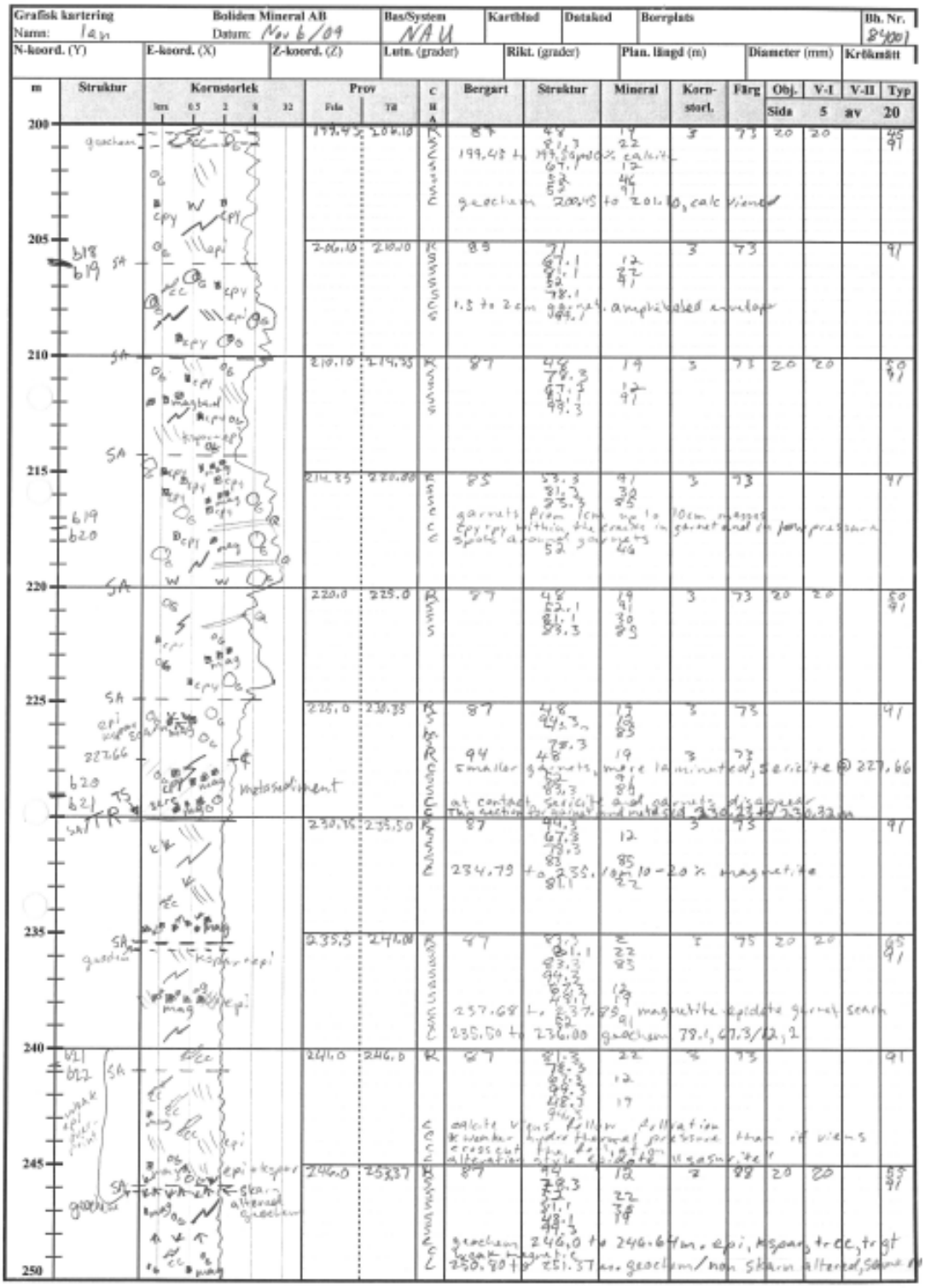
Appendix C. Profile 5040 logs- NAU84001 (cont.)



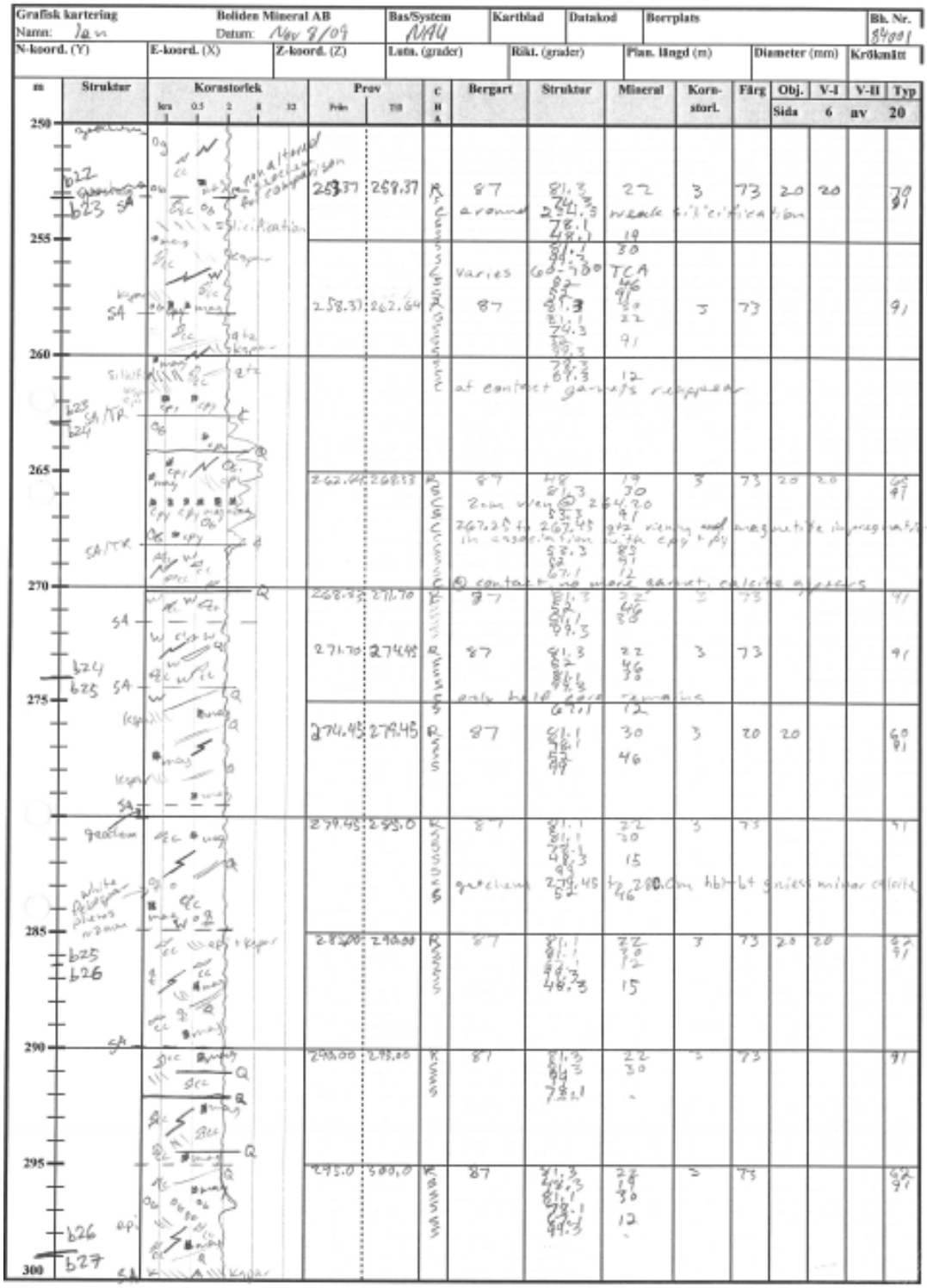
Appendix C. Profile 5040 logs- NAU84001 (cont.)



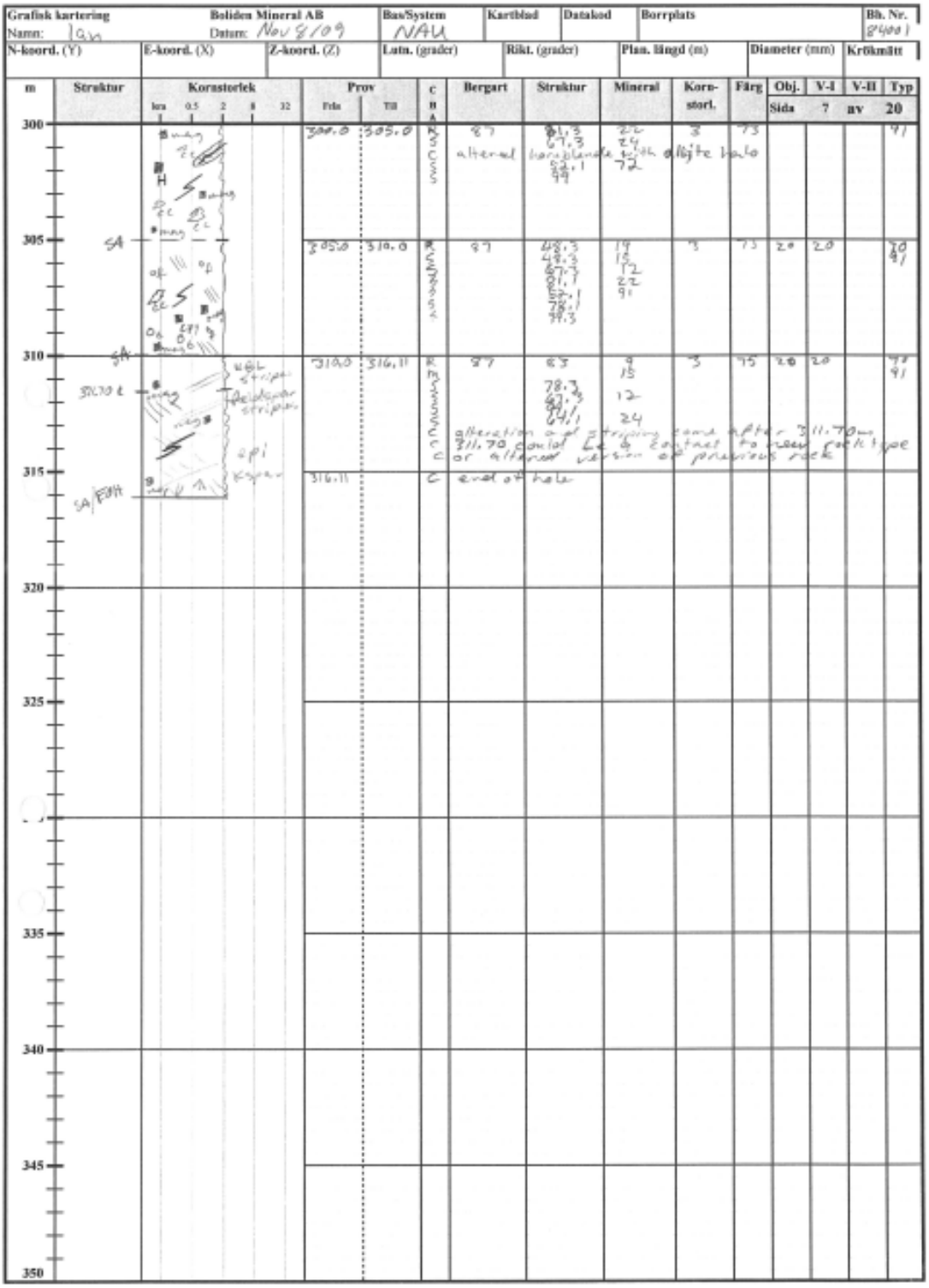
Appendix C. Profile 5040 logs- NAU84001 (cont.)



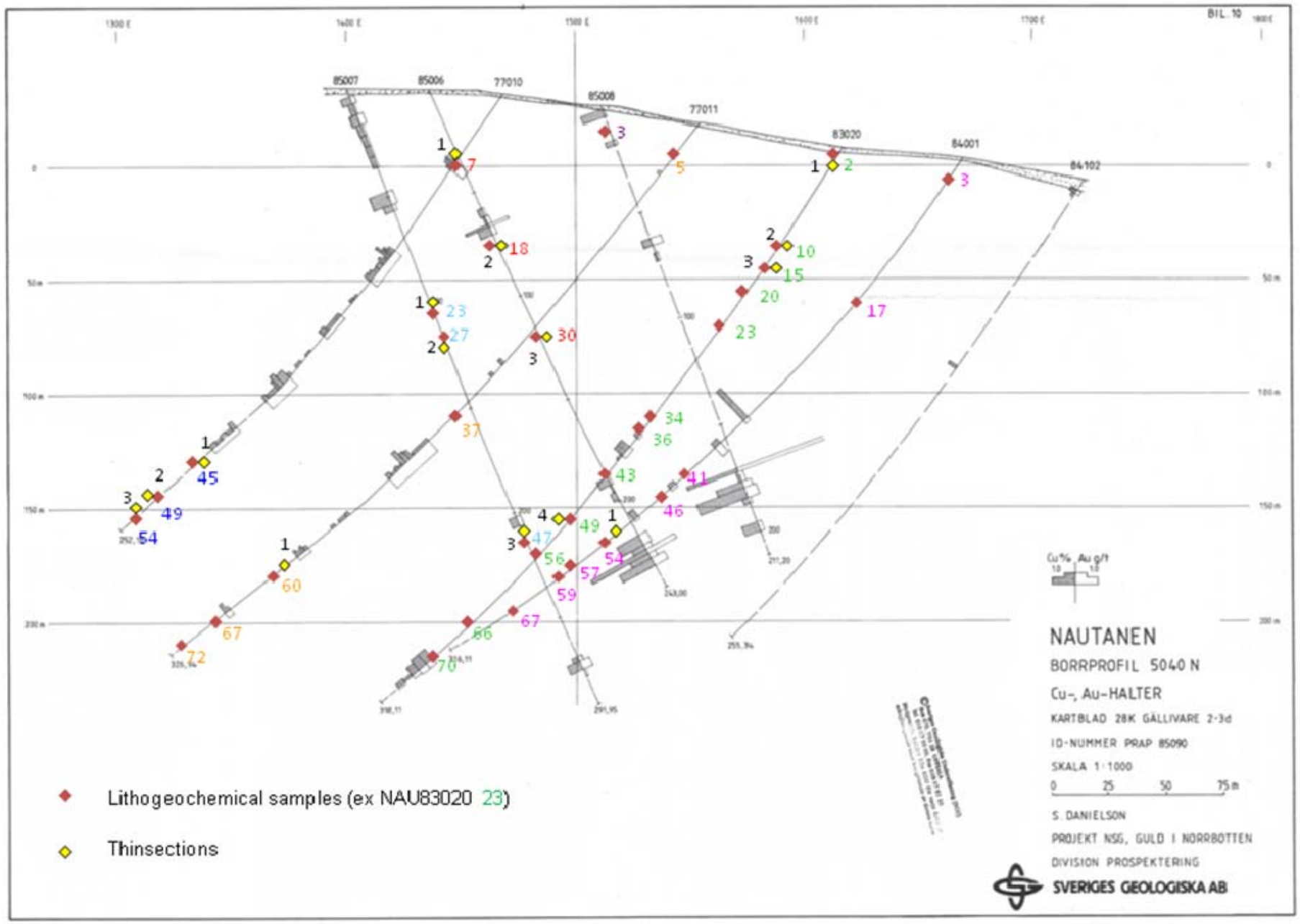
Appendix C. Profile 5040 logs- NAU84001 (cont.)



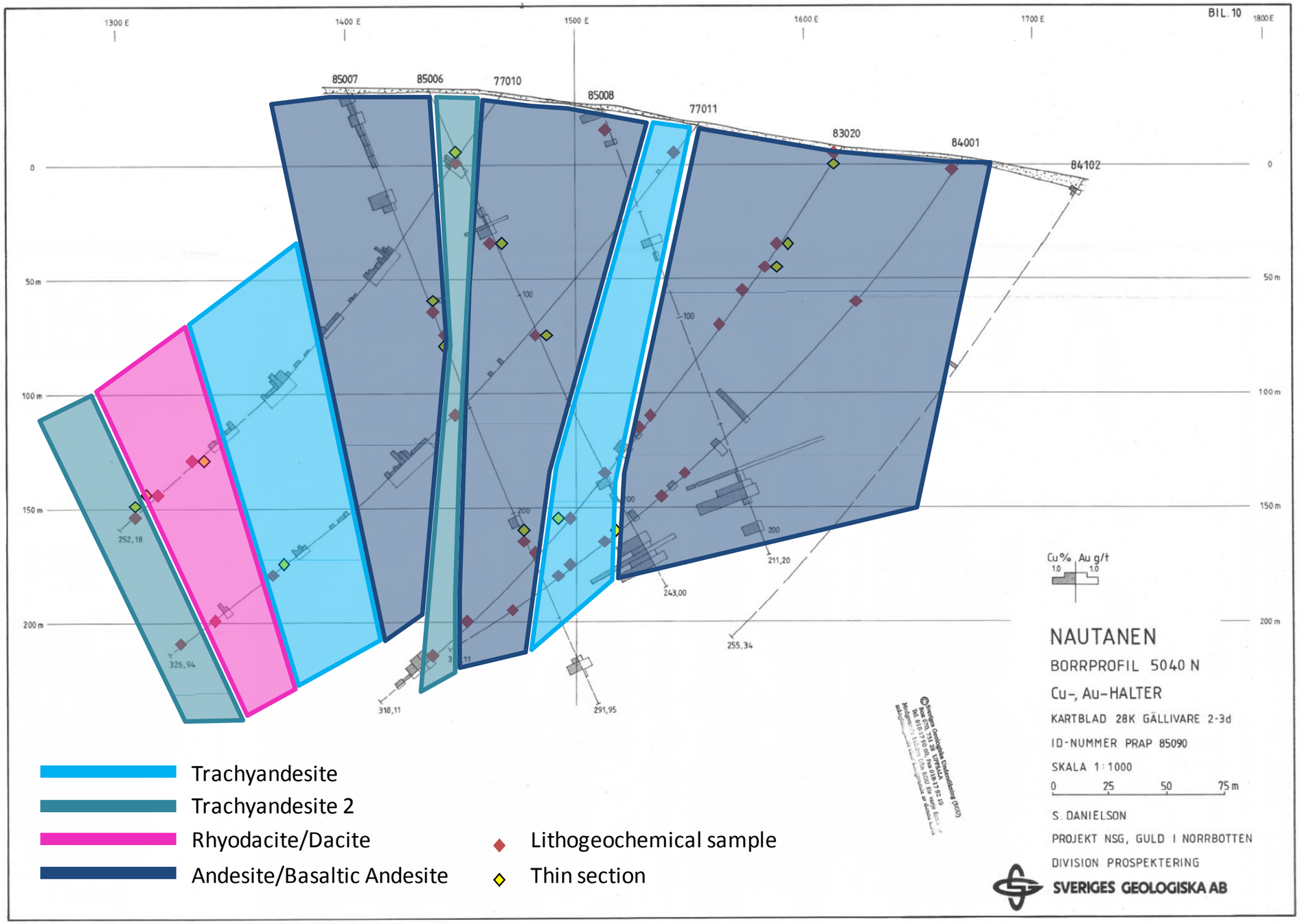
Appendix C. Profile 5040 logs- NAU84001 (cont.)



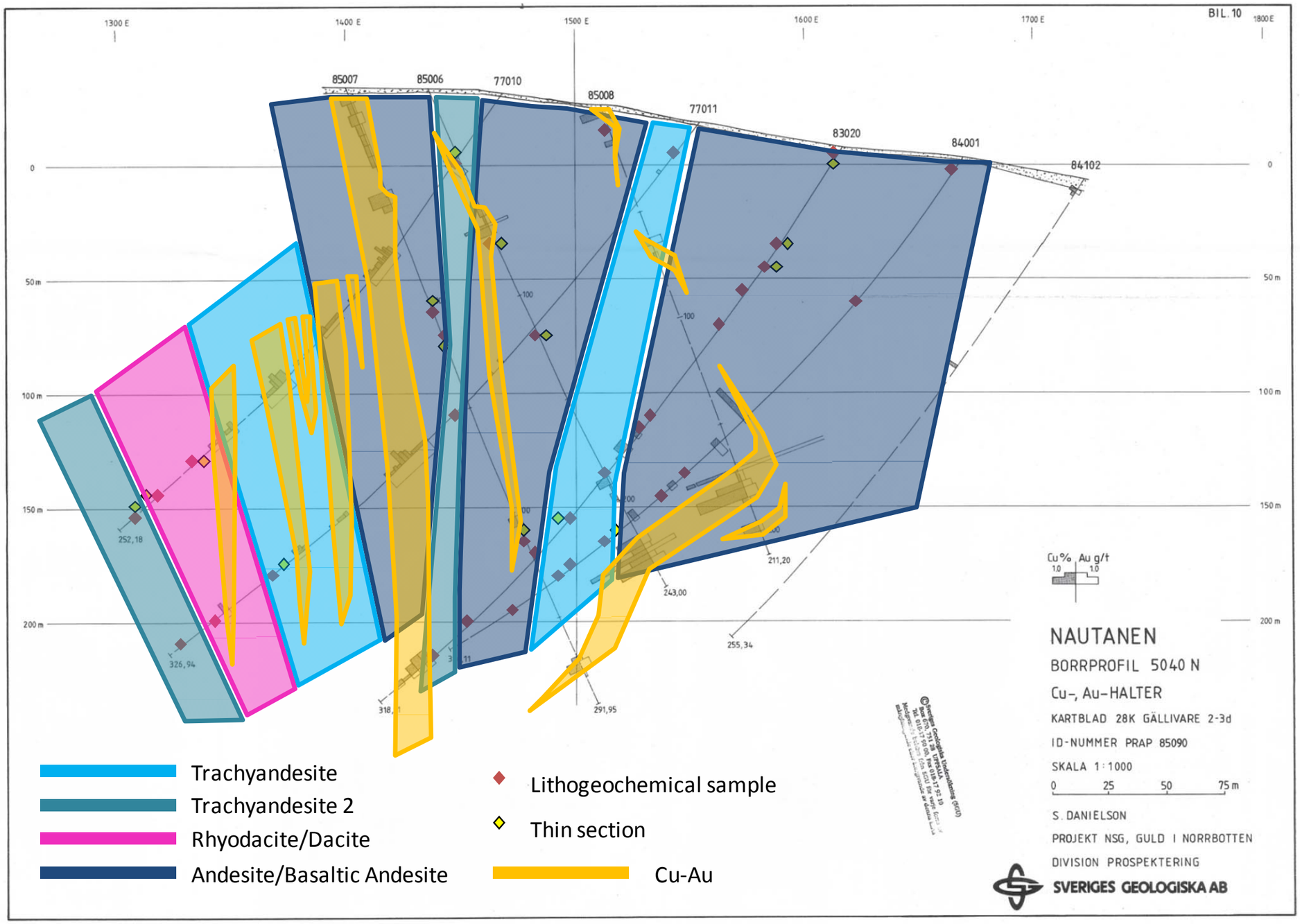
Appendix D. Location of lithogeochemical samples and thin sections from profile 5040 N (modified from Danielsson 1985)



Appendix E. Lithogeochemical based cross section of profile 5040 N (modified from Danielson 1985)



Appendix F. Lithogeochemical based cross section of profile 5040 N with areas of strong mineralization added (modified from Danielson 1985).



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