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160 Ma of magmatic/hydrothermal and metamorphic activity in the Gällivare area: Re–Os dating of molybdenite and U–Pb dating of titanite from the Aitik Cu–Au–Ag deposit, northern Sweden

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Abstract Host rocks to the Aitik Cu–Au–Ag deposit in northern Sweden are strongly altered and deformed Early Proterozoic mica(-amphibole) schists and gneisses. The deposit is characterised by numerous mineralisation styles, vein and alteration types. Four samples were selected for Re–Os molybdenite dating and 12 samples for U–Pb titanite dating in order to elucidate the magmatic/hydrothermal and metamorphic history following primary ore deposition in the Aitik Cu–Au–Ag deposit. Samples represent dyke, vein and alteration assemblages from the ore zone, hanging wall and footwall to the deposit. Re–Os dating of molybdenite from deformed barite and quartz veins yielded ages of $1,876 \pm 10$ Ma and $1,848 \pm 8$ Ma, respectively. A deformed pegmatite dyke yielded a Re–Os age of $1,848 \pm 6$ Ma, and an undeformed pegmatite dyke an age of $1,728 \pm 7$ Ma. U–Pb dating of titanite from a diversity of alteration mineral associations defines a range in ages between 1,750 and 1,805 Ma with a peak at ca. 1,780 Ma. The ages obtained, together with previous data, bracket a 160-Ma (1,890–1,730 Ma) time span encompassing several

generations of magmatism, prograde to peak metamorphism, and post-peak cooling; events resulting in the redistribution and addition of metals to the deposit. This multi-stage evolution of the Aitik ore body suggests that the deposit was affected by several thermal events that ultimately produced a complex ore body. The Re–Os and U–Pb ages correlate well with published regional Re–Os and U–Pb age clusters, which have been tied to major magmatic, hydrothermal, and metamorphic events. Primary ore deposition at ca. 1,890 Ma in connection with intrusion of Haparanda granitoids was followed by at least four subsequent episodes of metamorphism and magmatism. Early metamorphism at 1,888–1,872 Ma overlapping with Haparanda (1,890–1,880 Ma) and Perthite-monzonite (1,880–1,870 Ma) magmatism clearly affected the Aitik area, as well as late metamorphism and Lina magmatism at 1,810–1,774 Ma and TIB1 magmatism at 1,800 Ma. The 1,848 Ma Re–Os ages obtained from molybdenite in a quartz vein and pegmatite dyke suggests that the 1,850 Ma magmatism recorded in parts of northern Norrbotten also affected the Aitik area.

Keywords Aitik Cu–Au–Ag deposit · Titanite · Molybdenite · Re–Os and U–Pb dating · Northern Norrbotten ore province · Sweden

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Introduction

The northern Norrbotten Fe–Cu–Au province (Fig. 1) is one of the most important mining districts in Europe. It contains numerous epigenetic copper–gold ores, stratiform copper ores and apatite iron ores (e.g. the Aitik Cu–Au–Ag deposit, the Viscaria Cu deposit, the Kiirunavaara and Malmberget apatite iron deposits, respectively). It is responsible for about 90 percent of the total ore produced in Sweden at present.

The Aitik mine is situated 60 km north of the Arctic Circle, and 15 km southeast of Gällivare in northernmost

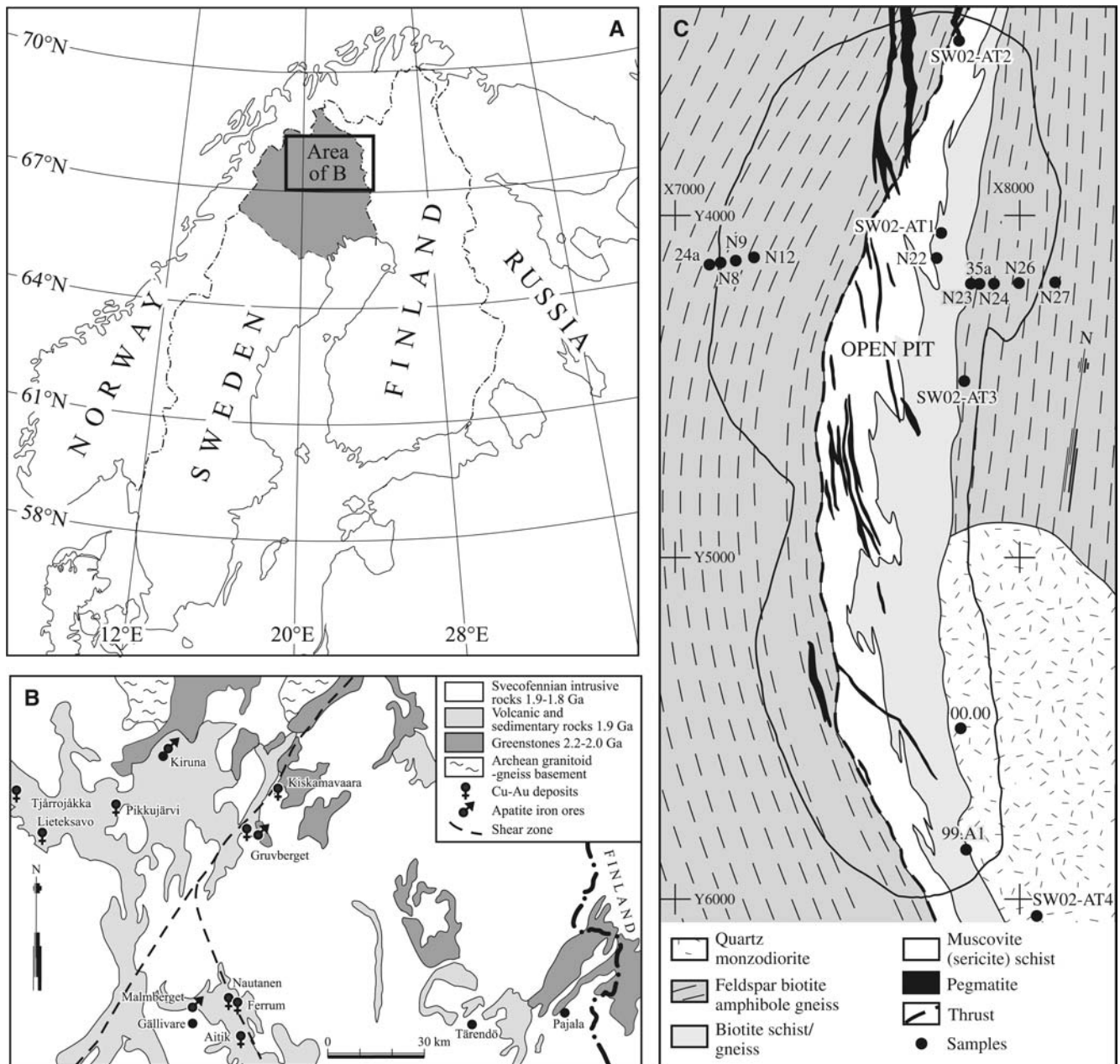


Fig. 1 Geology of the northern Norrbotten ore province and the Aitik Cu–Au–Ag deposit. **a** The location of the northern Norrbotten ore province in Scandinavia. *Shaded area* represents the Norrbotten County. **b** Simplified geological map of the northern Norrbotten ore province. **c** Plan view of the Aitik Cu–Au–Ag deposit

Sweden (Fig. 1). It is of major economic importance with an annual production of 18 Mt at 0.4% Cu, 0.2 ppm Au and 4.2 ppm Ag. About 400 Mt of ore have been produced from an open pit since mining began in 1968, with ore reserves totalling 244 Mt and additional mineral resources of 970 Mt (Boliden Annual Report 2003).

Among the genetic models proposed for the Aitik deposit are those suggesting a syngenetic sedimentary origin (Zweifel 1976), and those consistent with a magmatic-hydrothermal origin (Yngström et al. 1986;

Monro 1988; Drake 1992, Wanhainen and Martinsson 1999). A genetic relationship between the Aitik deposit and a mineralised intrusion in its footwall was first suggested by Monro (1988), who interpreted Aitik as a deformed and metamorphosed porphyry copper deposit.

The present paper focuses on the multi-stage evolution of the Aitik Cu–Au–Ag deposit. The chronology of rocks and alteration types within the deposit are presented based on Re–Os dating of molybdenite and U–Pb dating of titanite. The relationship of these ages to regional geological events, such as magmatism and metamorphism, is outlined and discussed, as well as the influence these events apparently had on the deposit. Results from this study, together with previous data, define a 160 million years history of magmatism and metamorphism in the Aitik area. This prolonged evo-

lution is temporally associated with IOCG-style mineralisation in the Norrbotten ore province and demonstrates the complex metallogeny of the area. Cu–Au mineralisation of both porphyry- and IOCG-affinity has formed close in time (Weiher 2003) which suggests the possibility to generate hybrid deposits with unusual characteristics.

Regional and local geology

The Precambrian bedrock in northern Sweden includes a ca. 2.8–2.6 Ga Archean granitoid-gneiss basement, which is unconformably overlain by Palaeoproterozoic volcanic and sedimentary successions. Rift-related 2.5–2.0 Ga Karelian units occur at the lowest stratigraphic level, and are overlain by terrestrial to shallow water Svecofennian successions formed at ca. 1.9 Ga. These Palaeoproterozoic volcanic and sedimentary rocks are intruded by the 1.89–1.87 Ga Haparanda and Perthite-monzonite suites, which have a calcalkaline to alkalic character and are considered to be comagmatic with the Svecofennian volcanic rocks (Witschard 1984; Bergman et al. 2001). An early Svecofennian deformation and metamorphic event affected Haparanda suite intrusions, but seems to mainly pre-date Perthite-monzonite suite intrusions (Bergman et al. 2001). 1.86–1.84 Ga granitoids of two types occur in the eastern part of northern Norrbotten. One type (Pingisvaara-type) has granitic-granodioritic compositions and is penetratively deformed. The other type (Jyryjoki-type) has a calcalkaline character with monzogranite and granodiorite as major components. It is weakly foliated and associated with pegmatite (Bergman et al. 2001). The younger Lina suite comprises ca. 1.79 Ga minimum melt granites and pegmatites (Skiöld et al. 1988), which are temporally related to TIB 1 (Transcandinavian Igneous Belt) intrusions in the Kiruna-Narvik area (Romer et al. 1992, 1994). A second tectonothermal event occurred at least locally at this time (Bergman et al. 2001). The youngest plutonic rocks are represented by ca. 1.71 Ga TIB 2 granitoids close to the Swedish-Norwegian border (Romer et al. 1992).

On a more local scale, the bedrock in the Gällivare area consists of metamorphosed Svecofennian (ca. 1.9 Ga) intermediate volcanic rocks and clastic sediments that were intruded by 1.9–1.8 Ga plutonic rocks of granitic, gabbroic and dioritic composition (Witschard 1996). The 1.79 Ga Lina granite is most widespread and surrounds the Aitik deposit at distances of 2–8 km. In the Aitik region the supracrustal rocks and the ca. 1.9 Ga intrusive rocks are at amphibolite facies (Zweifel 1976).

The Aitik Cu–Au–Ag deposit

The main ore minerals at Aitik are chalcopyrite, pyrite and magnetite, with pyrrhotite, bornite and molybdenite as minor components. High copper grades occur in the

central part of the ore body in the form of finely disseminated chalcopyrite. Ore minerals also occur as pure sulphide veinlets, and as poly-mineralic veinlets with quartz, amphibole, and biotite. Towards the hanging wall side of the ore, the copper grade decreases and pyrite becomes the dominant sulphide. Towards the footwall, disseminated sulphides are accompanied by clots and patches of chalcopyrite, which increase the copper grades (Wanhainen et al. 2003c).

Subeconomic mineralisation of magmatic/hydrothermal origin occurs within a porphyritic quartz monzodiorite in the footwall (Monro 1988). It is a grey and fine-grained (0.3–0.6 mm) rock with plagioclase phenocrysts in a matrix dominated by plagioclase and biotite. This intrusion belongs to the Haparanda suite of granitoids (Wanhainen and Martinsson 2001) and has been dated at 1887 ± 8 Ma (Wanhainen et al. submitted). The main ore may have a similar magmatic/hydrothermal origin, but the present irregular distribution of sulphides in the ore zone, the diversity of mineralisation styles, and the different degrees of deformation of these styles, suggest considerable reworking of mineralisation and/or an addition of metals by later events (Wanhainen et al. 2003c). The hanging wall contact of the ore body is sharp and structurally controlled (Drake 1992).

The host rocks of the ore are mainly garnet-bearing biotite gneiss and schist, and quartz-muscovite (sericite) schist of interpreted Svecofennian volcanoclastic origin (Wanhainen and Martinsson 1999). Biotite, garnet, sericite, K feldspar, epidote, amphibole, pyroxene, tourmaline and scapolite are characteristic components of strongly altered host rock. The metamorphosed volcano-sedimentary rocks situated outside the ore zone are feldspar–biotite–amphibole gneisses.

Deformed barite veins containing varying amounts of pyrite, chalcopyrite, magnetite and actinolite are locally abundant. They are white or light pink, and vary in width from 1 to 50 cm. Pegmatite dykes contain quartz, K feldspar, and plagioclase, minor biotite and muscovite, and accessory tourmaline. Those striking along the main foliation of the rocks may or may not display deformation features, while all those crosscutting the foliation are undeformed. Pegmatite dykes of both types within the ore zone are often mineralised while those in the hanging wall are barren, consistent with mobilization of sulphides during dyke emplacement.

Zeolites (stilbite and chabazite) together with sulphides occur as crystals in drusy vugs in some of the pegmatite dykes and quartz veins. These vugs also often contain quartz, K feldspar, scapolite, amphibole, tourmaline, epidote, chlorite, calcite, and magnetite, with zeolites representing the latest phase within the vugs.

Re–Os dating of molybdenite and U–Pb dating of titanite

This study utilizes two widely recognised minerals for radiometric dating, molybdenite and titanite, using dif-

Table 1 Sample location and description

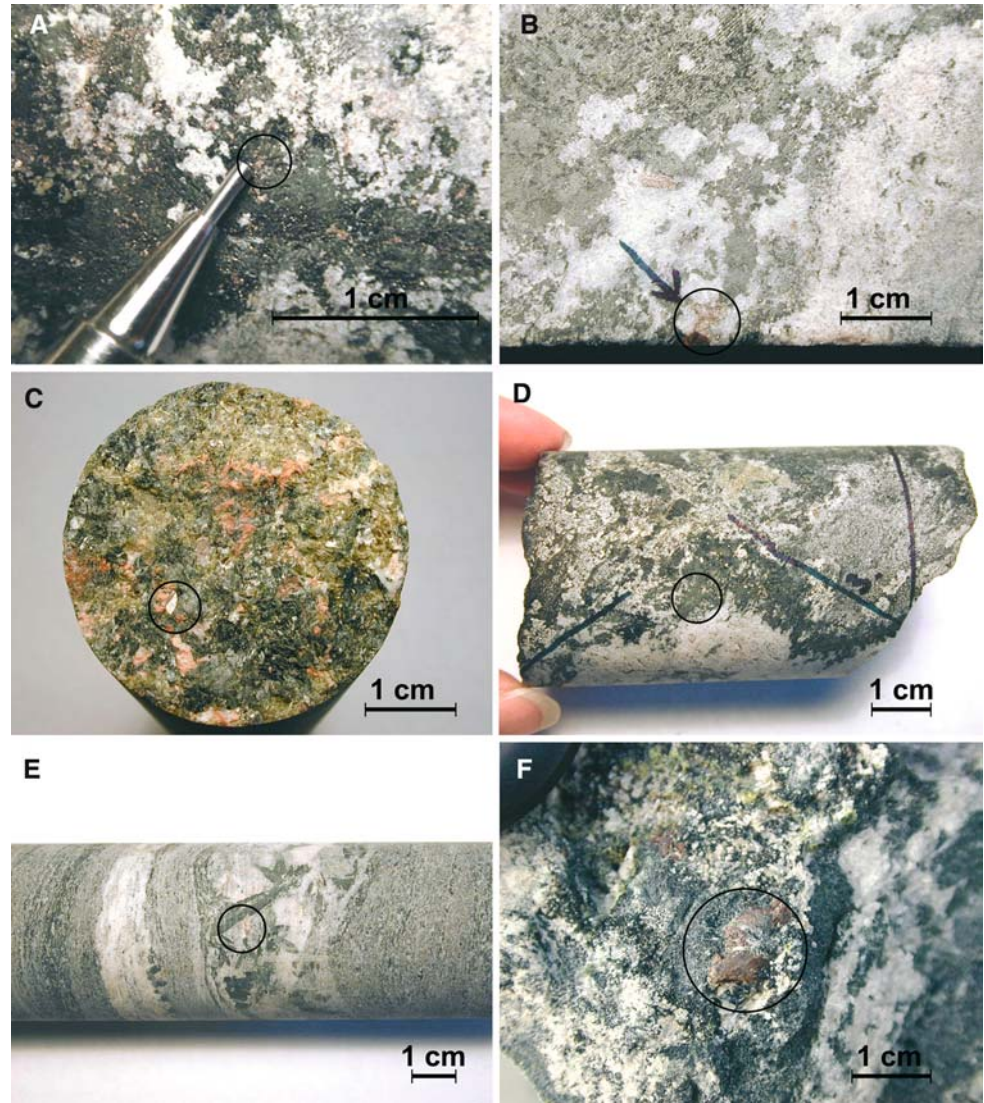
Sample no.	Location (dh/m or local x, y, z coord)	Description
N22	659/127.8	Titanite in amphibole–feldspar–scapolite–epidote–magnetite alteration envelope around 7-cm wide, folded feldspar-vein. Amphibole contains minor pyrite and chalcopyrite. Vein is hosted by biotite-(amphibole) gneiss within the ore zone
N12	879/277.2	Titanite in amphibole–feldspar band within the hangingwall amphibole-banded feldspar–biotite gneiss. Amphibole band is 5-mm wide and bordered by feldspar
00.00	7,850X5,500Y120Z	Titanite in scapolite altered quartz monzodiorite within the footwall. Alteration minerals also include amphibole–feldspar–quartz–epidote
24a	879/59.5	Titanite in amphibole–feldspar–pyroxene–quartz–epidote–magnetite alteration. Titanite grains are 0.5–1 mm. Alteration patches of amphibole–pyroxene–magnetite are deformed, bordered by quartz–feldspar, and hosted by feldspar–biotite–amphibole gneiss within the hanging wall
N26	855/220.9	Titanite in K-feldspar–epidote–amphibole–pyrite–magnetite altered amphibole–feldspar banded biotite gneiss within the footwall
N24	855/114.3	Titanite in amphibole–feldspar border around quartz vein. Titanite grains are 0.5–1 mm. Quartz + amphibole–feldspar vein is strongly folded, pyrite-bearing, and hosted by feldspar–biotite–amphibole gneiss within the footwall
N8	879/75.4	Titanite in amphibole–feldspar–pyroxene–quartz–epidote–magnetite alteration. Alteration vein is boudinaged and hosted by feldspar–biotite–amphibole gneiss within the hanging wall
N9	879/143.1	Titanite in amphibole–feldspar–magnetite alteration. Titanite grain is 4 mm. Alteration vein is boudinaged and hosted by feldspar–biotite–amphibole gneiss within the hanging wall
N23	855/64.4	Titanite in amphibole–scapolite altered feldspar–biotite gneiss within the footwall. Titanite grains are 0.5 mm. Amphibole contains pyrite. Scapolite is cloudy, bluish (weakly deformed appearance), and cuts foliation in feldspar–biotite gneiss
N27	855/347.0	Titanite in pyroxene altered feldspar–biotite–amphibole gneiss within the footwall. Thauasite and zeolite (chabazite) have filled cavities within the pyroxene, which is bordered by feldspar
99A1	7,850X5,5850Y130Z	Titanite in coarsegrained, undeformed pegmatite dyke containing feldspar, quartz and accessory biotite, tourmaline and chalcopyrite. Pegmatite dyke is N–S trending (parallel to main foliation), dips 79°W, and is located at the footwall-ore zone contact
35a	855/81.0	Titanite in quartz–scapolite–amphibole alteration within feldspar–biotite–amphibole gneiss in the footwall. Titanite aggregate is 3 mm. Scapolite and amphibole are partly altered to zeolite–calcite–epidote–chlorite
SW02-AT1	659/83.2	Molybdenite in folded, 3–6 cm wide barite vein with rich dissemination of magnetite and chalcopyrite, and minor pyrite. Barite vein is pale pink and hosted by biotite-(amphibole) gneiss within the ore zone
SW02-AT2	7,800X3,500Y135Z	Molybdenite in folded, medium to coarsegrained pegmatite dyke containing feldspar, quartz, muscovite and accessory tourmaline and chalcopyrite. Molybdenite grains are intergrown with coarsegrained muscovite and K-feldspar. Pegmatite dyke is N–S trending (parallel to main foliation) and located in the muscovite schist alteration zone at the hangingwall-ore zone contact
SW02-AT3	7,850X4,500Y120Z	Molybdenite in 6-cm wide, undeformed, medium-grained pegmatite dyke containing quartz, feldspar, and accessory biotite, magnetite, chalcopyrite and pyrrhotite. Pegmatite dyke is E–W trending (cutting main foliation), dips 90°, and is hosted by biotite–feldspar–amphibole gneiss within the ore zone
SW02-AT4	970/102.3	Molybdenite in 1-cm wide quartz vein containing 1–4 mm chalcopyrite crystals. The quartz monzodioritic host rock is weakly potassically altered and also exhibits trace-weak impregnation of epidote. The quartz vein itself does not show an alteration envelope

ferent dating methods. This has been successfully done in earlier studies (e.g. Torrealday et al. 1999; Skirrow et al. 2000; Stein et al. 2001) in order to elucidate the often complex evolution of mineralisations in regionally altered and metamorphosed terranes.

Molybdenite presents a unique situation for Re–Os dating in that it usually contains ppm level Re and essentially no initial Os, making it a single mineral

chronometer. General principles and methodology for molybdenite dating are outlined in Stein et al. (2001). Elemental decoupling of parent-daughter (^{187}Re – ^{187}Os), a feature endemic to molybdenite and particularly recognized in multiply deformed terranes (Stein et al. 2001, 2003b) is overcome by a protocol for preparation of mineral separates at applied isotope research for industry and the environment (AIRIE) using tar-

Fig. 2 Photographs showing alteration and vein mineral assemblages of some of the U–Pb titanite dated samples. Analysed titanite grains are encircled. **a** Sample 24a: titanite–amphibole–pyroxene–magnetite–quartz–feldspar–epidote. **b** Sample N22: titanite–amphibole–feldspar–scapolite–epidote–magnetite–chalcopyrite–pyrite. **c** Sample N26: titanite–K feldspar–epidote–amphibole–magnetite–pyrite. **d** Sample N24: titanite–amphibole–feldspar–quartz–pyrite. **e** Sample N9: titanite–amphibole–feldspar–magnetite. **f** Sample 00.00: titanite–scapolite–amphibole–feldspar–quartz–epidote



geted drilling to capture complete grains for specific parageneses. Sample-to-sample and within sample reproducibility of molybdenite ages in the porphyry environment have been amply documented (e.g., Watanabe and Stein 2000; Selby and Creaser 2001). Re–Os dating of molybdenite can be used to directly determine the age of mineralisation related to magmatic events, but equally important is the utility of this mineral in recording metamorphic events throughout an orogenic history, as has been demonstrated for northern Sweden (Stein et al. 2003a, accepted). The Re–Os chronometer can be effective despite ductile deformation (Stein and Bingen 2002; Stein et al. 2004) and metamorphism up to granulite facies conditions (Bingen and Stein 2003).

U–Pb dating is a well-established method for dating various events, such as magmatism, metamorphism, deformation, and hydrothermal processes, during which titanite may form (Heaman and Parrish 1991). Since the U–Pb titanite system is more susceptible to postcrystallization disturbances relative to the behaviour of molybdenite, the possibility that certain titanite ages

may reflect post-peak metamorphic cooling ages must be considered. Most authors believe that the closure temperature for titanite is well above 600°C and probably closer to 700°C (Möller et al. 2000). The temperatures and the duration of the thermal event near the Aitik ore zone are not tightly constrained, but based on the temperature for upper amphibolite facies metamorphism (Zweifel 1976), we suggest peak temperatures were 600–675°C. This is close to suggested U–Pb closure temperatures for titanites and one cannot rule out the possibility that the U–Pb system in potential premetamorphic titanites was disturbed during peak-metamorphism.

Samples dated

Many dyke, vein and alteration assemblages associated with the Aitik Cu–Au–Ag deposit contain accessory titanite or molybdenite, and this provides a means for precisely dating metamorphic and magmatic/hydro-

Table 2 Re–Os data for the Aitik Cu–Au–Ag deposit, Norrbotten County, northern Sweden

AIRIE run#	Sample	Total Re (ppm)	¹⁸⁷ Os (ppb)	Common Os (ppb)	Age (Ma)
MDID-95	SW02-AT1	1,484 (6)	29,622 (13)	< 0.1	1,876 ± 10
MDID-120	SW02-AT1	1,474 (1)	29,400 (11)	< 0.1	1,875 ± 6
MDID-66	SW02-AT2	54.04 (4)	1,061.7 (5)	1 ± 7	1,848 ± 6
MDID-96	SW02-AT3	215.7 (3)	3,959 (9)	1 ± 6	1,728 ± 7
MDID-92	SW02-AT4	75.90 (7)	1,492 (5)	3 ± 12	1,848 ± 8

Assumed initial ¹⁸⁷Os/¹⁸⁸Os for age calculation = 0.2 ± 0.1

Absolute uncertainties shown, all at 2-sigma level, for last digit indicated

Decay constant used for ¹⁸⁷Re is 1.666 × 10⁻¹¹ year⁻¹ (Smoliar et al. 1996)

Ages calculated using ¹⁸⁷Os = ¹⁸⁷Re (e^{-λt}-1) include analytical and ¹⁸⁷Re decay constant uncertainties

thermal events that have affected the Aitik rocks. No dateable minerals were found in settings believed to represent the primary ore deposition. Independent geological information, however, indicates that primary ore deposition may be related to ca. 1,890 Ma magmatism represented by the nearby footwall intrusion (Wanhainen et al. submitted).

The 16 samples selected for geochronological work represent some of the dyke, vein and alteration types that are present in the deposit. They were taken either from drill core or from the open pit at the Aitik mine. Four molybdenite samples were selected for Re–Os dating (see Fig. 1, Table 1 for location and detailed description of samples). Molybdenite SW02-AT1 is from a deformed barite vein that also contains magnetite and minor chalcopyrite and pyrite. Sample SW02-AT2 consists of molybdenite intergrown with coarse-grained muscovite and K-feldspar from a N–S trending, deformed, and mineralized pegmatite. Sample SW02-AT3 consists of molybdenite from an undeformed, mineralized, and E–W trending pegmatite. Molybdenite SW02-AT4 occurs as sparse millimetre grains in a 1-cm wide chalcopyrite-bearing quartz vein within the footwall intrusion. The sample weights were 25 mg and 11 mg (replicate) for SW02-AT1, 22 mg for SW02-AT2, 25 mg for SW02-AT3, and 1.5 mg for SW02-AT4. For SW02-AT4, all of the visible molybdenite grains were removed in their entirety in order to ensure a robust age result (Stein 2005 in press).

Twelve titanite samples were selected for U–Pb dating (see Fig. 1, Table 1 for location and detailed description of samples). Titanites are typically reddish-brown, rather coarse-grained with mm-sized crystals making up larger aggregates (Fig. 2). Both deformed and undeformed mineral textures are represented among the alteration types. Samples N22, N12, 24a, N26, N24, N8 and N9 represent deformed amphibole + feldspar ± quartz ± pyroxene ± scapolite ± epidote ± magnetite ± sulphide alteration (Fig. 2a–e). They were sampled along a profile of drill cores extending from the hanging wall to the footwall in the northern part of the mine (Fig. 1). Sample 00.00 is an example of scapolite alteration of the footwall quartz monzodiorite (Fig. 2f). Sample N23 represents amphibole-scapolite alteration of

a rock that is less deformed than the samples mentioned above. Sample N27 is titanite from undeformed pyroxene alteration containing cavities filled with zeolite and thaumasite (Ca₃Si(CO₃)(SO₄)(OH)₆·12H₂O). Sample 99A1 is from the open pit, and consists of titanite from a N–S trending, undeformed, and mineralized pegmatite, and sample 35a represents quartz–scapolite–amphibole alteration, which in turn is partly altered to chlorite, epidote, calcite, and zeolite.

Analytical methods

Molybdenite Re–Os

For this study, a Carius-tube digestion was used for molybdenites. Molybdenite is dissolved and equilibrated with a mixed Re–double Os spike (185Re–188Os–190Os) in HNO₃–HCl (inverse *aqua regia*) by heating for 12 h at 230°C in a sealed, thick-walled glass ampoule (Markey et al. 2003). The double Os spike permits a dual check for common Os and a mass fractionation correction, leading to high precision results. The Os is recovered by distilling directly from the Carius tube *aqua regia* into HBr, and is subsequently purified by microdistillation. The Re is recovered by anion exchange. The Re and Os are loaded onto Pt filaments and isotopic compositions are determined using NTIMS on NBS 12-inch radius, 68° and 90° sector mass spectrometers at Colorado State University. Two in-house molybdenite standards, calibrated at AIRIE, are run routinely as an internal check. Blanks are routinely monitored at AIRIE, and data are always reported as blank-corrected values.

Titanite U–Pb

Titanites were hand-picked from drill cores, but also separated from hand-specimens taken in the open pit. The final separation was carried out under a binocular microscope, and in some cases a Frantz magnetic separator was used for pre-concentration. The chemical procedures and mass spectrometry was carried out

Table 3 TIMS U–Pb data for titanites from the Aitik Cu–Au–Ag deposit, Norrbotten County, northern Sweden. Also shown are calculated $^{207}\text{Pb}/^{206}\text{Pb}$ regression ages using a fixed lower intercept age of 300 ± 150 Ma

Sample	Weight (μg)	U (ppm)	Pb tot (ppm)	Comm Pb (ppm)	$^{206}\text{Pb}/^{204}\text{Pb}^a$ (meas.)	$^{206}\text{Pb} - ^{207}\text{Pb} - ^{208}\text{Pb}$ radiog. Pb (at%) ^b	$^{206}\text{Pb}/^{238}\text{U}^b$	$^{207}\text{Pb}/^{235}\text{U}^b$	$^{207}\text{Pb}/^{206}\text{Pb}$ age (Ma)	Regression age (Ma)	Th/U
N22	128	51.2	24.7	8.4	129	87.0 – 9.6 – 3.4	0.3224 ± 05	4.905 ± 17	1,805 ± 6	1,805 ± 6	0.149
N12a	125	696	202	2.5	4,458	82.8 – 9.0 – 8.2	0.2764 ± 20	4.132 ± 31	1,773 ± 2	1,781 ± 6	0.330
N12b	55.3	240	76.1	1.0	4,341	82.6 – 9.2 – 8.2	0.3031 ± 20	4.530 ± 31	1,773 ± 2	1,801 ± 18	0.306
00.00a	194	72.9	23.6	1.3	1,046	86.8 – 9.5 – 3.7	0.3093 ± 19	4.672 ± 30	1,792 ± 2	1,799 ± 4	0.146
00.00b	261	78.8	24.8	0.95	1,487	87.2 – 9.5 – 3.3	0.3067 ± 12	4.605 ± 20	1,781 ± 3	1,788 ± 5	0.127
N8	170	52.4	17.9	1.6	588	84.3 – 9.2 – 6.5	0.3114 ± 08	4.674 ± 14	1,781 ± 3	1,785 ± 4	0.263
24a	113	88.5	34.2	4.1	407	78.4 – 8.5 – 13.1	0.3106 ± 12	4.657 ± 19	1,778 ± 3	1,783 ± 4	0.582
N24	199	93.9	29.8	1.7	981	87.7 – 9.5 – 2.8	0.3053 ± 08	4.566 ± 13	1,774 ± 3	1,781 ± 5	0.108
N26	224	72.7	23.1	1.1	1,178	87.0 – 9.4 – 3.6	0.3057 ± 08	4.576 ± 14	1,775 ± 2	1,782 ± 4	0.137
N9	178	116	37.6	1.1	1,932	84.2 – 9.2 – 6.6	0.3092 ± 20	4.634 ± 30	1,778 ± 2	1,783 ± 3	0.265
N23	120	164	49.4	0.80	3,590	87.4 – 9.4 – 3.2	0.3017 ± 07	4.472 ± 11	1,758 ± 2	1,765 ± 5	0.122
N27	148	131	38.3	0.38	6,011	89.7 – 9.7 – 0.6	0.3032 ± 09	4.499 ± 12	1,759 ± 2	1,766 ± 4	0.024
99A1	125	75.8	25.8	0.81	1,742	82.8 – 8.9 – 8.3	0.3168 ± 07	4.704 ± 15	1,761 ± 2	1,760 ± 3	0.339
35a	158	51.8	16.0	0.90	1,032	90.0 – 9.6 – 0.4	0.3052 ± 26	4.496 ± 39	1,747 ± 4	1,750 ± 5	0.013

^aCorrected for mass fractionation (0.10 ‰ per amu)

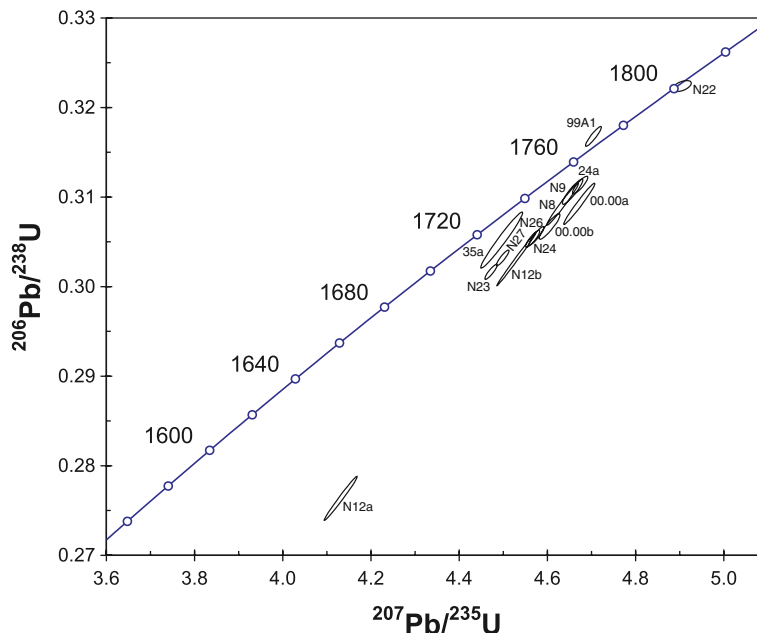
^bCorrected for mass fractionation, blank and common Pb – according to the Stacey–Kramers two-stage model (1975)
Errors in the isotope ratios are given at the 95 % confidence level

at the Laboratory for Isotope Geology at the Swedish Museum of Natural History in Stockholm. Treatment of titanite fractions selected for age determinations was as follows; an initial wash in acetone, then cleaning with weak HNO_3 , and finally a rinse in distilled water. Isotope dilution analysis was performed with a $^{233}\text{U}/^{205}\text{Pb}$ spike solution and the samples were subsequently dissolved in a mixture of concentrated HF and HNO_3 in teflon bombs at ca. 200°C for 3–5 days following the method developed by Krogh (1973). Concentrated HCl was subsequently added to complete the dissolution. After evaporation and uptake in HBr an initial ion exchange step was carried out to create purified Pb aliquots. The uranium fractions went through a second ion exchange procedure in HCl with removal of remaining Fe. Finally, Pb samples were loaded on single filaments, whereas the uranium samples were loaded using a double-filament arrangement, and the appropriate isotopic ratios were measured on a Finnigan MAT 261 thermal ionisation mass spectrometer. The software package of Ludwig (1991, 2000) was used to calculate and plot relevant ages and associated errors.

Results

The Re–Os data for the molybdenite samples at Aitik are presented in Table 2 along with a footnote explanation of uncertainties in measurements and calculations. The data reported in Table 2 are blank-corrected for $\text{Re} = 1.16 \pm 0.024$ pg, total $\text{Os} = 1.9 \pm 0.1$ pg, and $^{187}\text{Os}/^{188}\text{Os} = 0.24 \pm 0.01$. Although the double Os spike is now routinely used at AIRIE, this particular data set does not require the double spike since Re levels are moderate to high, and the samples are old (Palaeoproterozoic). One replicate to improve spiking is reported for SW02-AT1, and is based on a second mineral separate from the drill core. This replicate (MDID-120) is in excellent agreement with the first Re–Os result (MDID-95), providing ages of $1,875 \pm 6$ and $1,876 \pm 10$ Ma, respectively. Other age results are $1,848 \pm 6$ and $1,848 \pm 8$ for molybdenites SW02-AT2 and SW02-AT4, respectively, and a much younger $1,728 \pm 7$ Ma age for molybdenite SW02-AT3 from the late E–W crosscutting and undeformed pegmatites. There is notably high Re in sample SW02-AT1. However, the Re concentration in SW02-AT4 may be somewhat underrepresented because, as described earlier, the millimetre molybdenite grains in this chalcopyrite-bearing quartz vein were rare, and the drilled mineral separate contained perhaps 10–20% quartz. Concentrations of Re and Os in silicate are negligible, so silicate contamination in the molybdenite separate does not affect the age, but reduces the reported Re and ^{187}Os concentration data. Common Os (Table 2) is wholly insignificant as they are less than the analytical uncertainty on the ^{187}Os measurement and the ^{187}Os com-

Fig. 3 U–Pb concordia diagram for the investigated titanite samples from the Aitik Cu–Au–Ag deposit. Data points are shown with 2σ error ellipse



ponent in the reported common Os is at best a few percent. If molybdenite exchanged Os with any other sulphide in sufficient quantity to affect the age, the molybdenite would contain measurable common Os (Stein et al. 2003a, 2003b).

Most of the U–Pb titanite data are slightly to moderately discordant and sample N12a displays a strong discordance (Table 3 and Fig. 3), whereas sample 99A1 shows a weak reverse discordance. $^{207}\text{Pb}/^{206}\text{Pb}$ ages vary considerably, and even duplicate analyses performed on samples 00.00 and N12 indicate certain variability, and related regression ages (Table 2) are not fully within error of each other. However, even though the availability of uranium seems to have varied during titanite growth (cf. Table 3), the very similar ratios of radiogenic ^{206}Pb , ^{207}Pb and ^{208}Pb , and Th/U ratios in the duplicate pairs suggests that duplicate samples represent a single event. Variable $^{207}\text{Pb}/^{206}\text{Pb}$ ages could either signal a complex post-crystallization history affecting a single age population, or be due to discrete crystallization events. These two main options are further discussed below.

Discussion and conclusions

Aitik is a magmatic-hydrothermal deposit, in which primary copper mineralisation is interpreted to have been connected with intrusion of a ca. 1.89 Ga Haparanda-type quartz monzodiorite (Wanhainen 2001; Wanhainen et al. 2003b; Wanhainen et al. submitted). However, the distribution pattern of sulphides within the ore body indicates that the configuration of any such primary mineralisation has been disturbed (Wanhainen et al. 2003c), and that younger mineralisation events might have taken place.

Geochronological background

The broad geochronology of magmatic events in northern Sweden is fairly well known, but only a few studies have addressed the metamorphic history of this area (Billström et al. 2002; Stein et al. 2003a, Stein 2005 in press). According to Bergman et al. (2001), an early regional metamorphic event occurred in the Aitik area between 1,888 and 1,872 Ma, contemporaneously with early magmatism represented by the 1.89–1.87 Ga Haparanda and Perthite-monzonite suites (Bergman et al. 2001) and widespread 1.88–1.86 Ga hydrothermal activity recorded by alteration and IOCG (Iron oxide–copper–gold) mineralisation (Billström and Martinsson 2000). A second regional metamorphic event occurred between 1,810 and 1,774 Ma (Bergman et al. 2001), and was associated with emplacement of the Lina and TIB 1 intrusive suites (Skiöld et al. 1988; Romer et al. 1992; 1994), and 1.80–1.75 Ga hydrothermal alteration and IOCG mineralisation (Billström and Martinsson 2000). The Lina granite is of crustal origin, is widespread in northern Norrbotten, and is constrained by the U–Pb method to have been emplaced from 1.81–1.77 Ga (Bergman et al. 2001, 2002). Post-orogenic microcline granites and pegmatitic granites in Finland, comparable with the Lina granites, have been U–Pb zircon dated at 1.80–1.78 Ga (Väänänen and Lehtonen 2001; Lehtonen 1984). Lina magmatism, from early intrusion of granite massifs to later injection of pegmatite dykes, was clearly extended in time. Altogether, this implies that host rocks at the Aitik Cu–Au–Ag deposit were affected by two major episodes.

The radiometric analyses which form part of this study clearly show that molybdenites were formed at different times. U–Pb titanite data are mainly discordant and more difficult to interpret. In the simplest case,

individual sample points represent a number of discrete growth events and the discordance is due to a single episodic lead-loss event. Thus, the indicated normal discordance evidenced by most of the samples, implies that the $^{207}\text{Pb}/^{206}\text{Pb}$ ages are minimum ages of formation. This would suggest that by forcing data for individual analysis through a fixed, reasonable lower intercept, one would be able to calculate ages that better approximate the “true” crystallization ages. Larsson and Tullborg (1998) have studied published U–Pb zircon data from the Swedish Proterozoic bedrock and found that a Phanerozoic Pb loss at ca. 300 Ma is a common phenomenon. The relatively large degree of discordance for certain Aitik titanites requires a young Pb loss, and it is reasonable to assume that all fractions, to a variable extent, suffered from a common Phanerozoic event. Accordingly, by anchoring regressions of titanite at an age of 300 ± 150 Ma, a new set of $^{207}\text{Pb}/^{206}\text{Pb}$ ages for the individual Aitik samples can be calculated (Table 3). Although error overlap makes any clear distinction between different samples questionable, it seems that there is a distinct age population at ca. 1,780 Ma. With the assumptions made above, it is also obvious that ages, both younger and older than 1,780 Ma, exist.

The discordance of the U–Pb titanite data is not unexpected in an ore environment where repeated fracturing and reactivation may provide easy access for infiltrating fluids with the ability to leach loosely bound radiogenic Pb from the titanite lattice. However, there are certain features that enable some broad distinctions to be made between dated titanites, and suggest that titanites must have grown during different events. For instance, it is known that several mineral associations exist, and these were most likely developed during different stages. Different mineral associations are also variably deformed, which give indications of a relative order between mineral-forming stages. Titanite belonging to a deformed mineral assemblage must be earlier, and represent a separate growth event, than in a completely undeformed assemblage. It is also reasonable to assume that titanites in similar parageneses were formed during roughly the same time period. Even if titanites are characterized by overgrowths, at least two titanite-forming episodes are required. If overgrowths exist, this should be reflected by a minimum age of ca. 1,800 Ma for an early core-forming episode and a maximum age of 1,765 Ma for a later overgrowth as most $^{207}\text{Pb}/^{206}\text{Pb}$ ages fall in this interval. We can also assume that the tendency for $^{207}\text{Pb}/^{206}\text{Pb}$ ages to cluster around 1,780 Ma is not a coincidence. If mixed ages are common, then it is highly unlikely that the mixing proportions should be similar and yield basically identical ages for seven of the twelve analysed samples. Therefore, we propose that 1,780 Ma marks a real titanite-forming event. It is also noteworthy that sample N27 and 35a is the only samples related (spatially) to a zeolite-bearing assemblage. These titanites yield the youngest ages of those anal-

ysed, and have probably formed in the beginning of a declining metamorphic stage which ultimately led to zeolite formation.

By inference, the isotopic, mineralogical and geological constraints mentioned above suggest that at least four different growth events should be distinguished, at ca. 1,800 Ma (possibly a minimum age), ca. 1,780, 1,765 Ma (possibly a maximum age) and at 1750 Ma. These ages are obviously approximate and cannot be given strict error limits or further constrained. Still, they indicate that titanite grew during different events. Moreover, these periods correlate well with major thermal pulses suggested by Stein et al. (2003a) and Stein (accepted) based on a regional Re–Os study of molybdenites from northern Sweden. It may also be mentioned that two samples (N27 and 35a), which we believe exemplify late-stage hydrothermal titanites, have distinctly low Th/U ratios compared to the other titanites (Table 3).

The Aitik ore zone is a complex system that has experienced metamorphism, deformation and repeated hydrothermal overprinting. In order to unravel individual growth histories for titanite one would require the usage of high-resolution techniques, such as SIMS and LA-ICP-MS, and this is beyond the scope of this study. It is clear though from the spread in $^{207}\text{Pb}/^{206}\text{Pb}$ ages, that peak metamorphism has not reset the U–Pb systematics for all dated titanites since this would have resulted in fairly homogeneous post-peak ages, assuming a common cooling history. It is subsequently shown that it is possible to put temporal constraints on titanite growth at Aitik by combining geological information and TIMS U–Pb titanite ages.

1,875 Ma deformed barite vein

The Re–Os age of the sulphide-bearing, deformed barite vein in the Aitik ore zone is 1875 ± 6 Ma similar to the magmatism generating the 1.89–1.88 Ga Haparanda suite and 1.88–1.87 Ga Perthite-monzonite suite, and the early Svecofennian (1.89–1.87 Ga) metamorphic event. It is not clear if this magmatic/metamorphic event only caused remobilisation of previously formed sulphides (cf. Marshall et al. 2000), or if it represents a slightly later mineralisation event. However, the difference in sulphur isotope composition of barite compared to the main mineralisation (Wanhainen and Martinsson 2003a) indicates at least minor addition of sulphides at this time. The majority of the Aitik ore is believed to be genetically related to the spatially associated 1.89 Ga Haparanda suite quartz monzodiorite intrusion on basis of its style, metal assemblage, and the presence of a stockwork zone (Wanhainen et al., submitted). This inferred later mineralisation may have been related to the intrusion of perthite-monzonite granitoids, or to early-stage (1,888–1,872 Ma) metamorphism. The former explanation is preferred since vein-like hydrothermal barite genetically related to intrusive rocks is a known

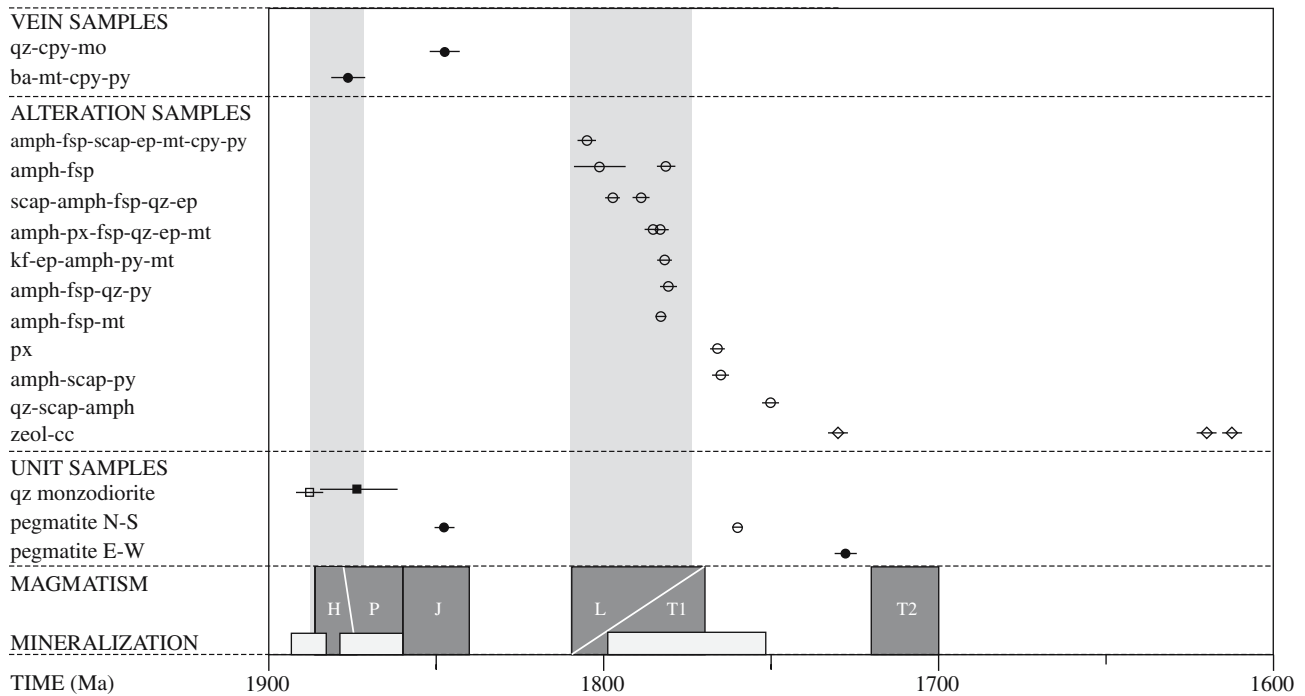


Fig. 4 Evolution of the Aitik Cu–Au–Ag deposit in comparison with regional magmatic/hydrothermal and metamorphic events. The time table is based on U–Pb titanite dates (*open circles*) and Re–Os molybdenite dates (*filled circles*) from this study, U–Pb zircon dates from Wanhainen et al. (submitted) (*open box*) and Witschard (1996) (*filled box*), and U–Pb stilbite dates (*diamond*) from Romer et al. (1994). Age data on magmatic (*dark grey boxes*) and metamorphic (*shaded areas*) events are from Bergman et al. (2001). Age data on mineralizing events (*light grey boxes*) are from Billström and Martinsson (2000) and Wanhainen et al. (submitted). *H* Haparanda suite, *P* Perthite–monzonite suite, *J* Jyryjoki granite, *L* Lina suite, *T* Transcandinavian igneous belt granites. Mineral abbreviations: *qz* quartz, *ba* barite, *px* pyroxene, *fsp* feldspar, *kf* K feldspar, *amph* amphibole, *ep* epidote, *scap* scapolite, *cc* calcite, *zeol* zeolite, *cpy* chalcopyrite, *py* pyrite, *mo* molybdenite, *mt* magnetite

feature (e.g. Lowell and Guilbert 1970; Margolis and Britten 1995), and also because Cu–Au mineralization is known to be associated to perthite–monzonite granitoids in northern Norrbotten (Martinsson et al. 2001; Bergman et al. 2002).

Approximately 1,850 Ma deformed pegmatite dykes and quartz veins

Molybdenite ages of $1,848 \pm 6$ Ma and $1,848 \pm 8$ Ma were obtained for a N–S trending, chalcopyrite-bearing pegmatite dyke, and a chalcopyrite-bearing quartz vein hosted by the quartz monzodiorite, respectively. No mineralisation of this age is known in the area. However, the age of ca. 1.85 Ga for molybdenite SW02-AT2 and SW02-AT4 is similar to the 1.86–1.84 Ga U–Pb age for the Jyryjoki granite obtained by Bergman et al. (2001). We therefore suggest that the pegmatite dyke and quartz vein at Aitik are temporally related to ca. 1.85 Ga magmatic activity in parts of northern Norrbotten.

Approximately 1,800–1,780 Ma deformed alteration- and vein-assemblages

Several different types of veins and alteration styles appear to have formed within the approximate time span 1,800–1,780 Ma at the Aitik deposit. This coincides with, and was probably caused by, a second major regional metamorphic/deformational event that commenced at around 1,810 Ma, associated with the onset of Lina and TIB 1 magmatism (Bergman et al. 2001). U–Pb ages at Aitik around 1,800 Ma for samples N22 and 00.00 indicate that formation of amphibole–feldspar–quartz–epidote–magnetite alteration and scapolite alteration were contemporaneous with Lina and TIB 1 magmatism and associated metamorphism. As Lina magmatism declined, regional metamorphism continued with repeated pegmatite injections.

A $1,776 \pm 8$ Ma old titanite from a meta-andesite at Nunasvaara, 8 km west of the Aitik deposit, is suggested to have formed close to peak metamorphic conditions in the Gällivare area (O. Martinsson, unpublished data). This age is similar to the titanite ages of deformed K feldspar + epidote + amphibole + pyrite + magnetite alteration (sample N26), amphibole + feldspar ± quartz ± pyrite alteration (sample N12, N24), and amphibole + feldspar ± pyroxene ± quartz ± epidote ± magnetite alteration (sample 24a, N8, N9) developed within the Aitik deposit.

Approximately 1,765–1,750 Ma alteration, undeformed pegmatite dykes, and deformed-undeformed veins

A later event in the deposit area is marked by amphibole–scapolite alteration which defines a slightly de-

formed alteration type crosscutting the main, N–S foliation in the biotite gneiss. Titanite sample N23 typifies such an assemblage and yields an age of ca. 1,765 Ma. A similar age is obtained for pyroxene alteration (sample N27) of the footwall feldspar–biotite–amphibole gneiss. Cavities within the pyroxene are filled with zeolite and thaumasite, which points to a crystallisation age younger than 1,765 Ma for these minerals.

Lina granite is usually associated with pegmatite, and pegmatite dykes belonging to this suite are common at Aitik. The titanite age of around 1,760 Ma for the undeformed, N–S trending pegmatite dyke (sample 99A1) dates its emplacement, and extends the age range of small granitoid intrusions of Lina type and probably marks the final stages of Lina magmatism in the Gällivare area.

The age of titanite sample 35a indicates a quartz–scapolite–amphibole alteration event occurred around 1,750 Ma. Zeolite together with calcite, epidote and chlorite, being alteration products of scapolite and amphibole, probably formed soon after 1,750 Ma. Also, the almost undeformed appearance (crosscutting veins, minerals crosscutting foliation) of samples N23, N27, 99A1 and 35a suggests that deformation was waning by ca. 1,765 Ma.

1,728 Ma undeformed pegmatite dyke

The intrusion of E–W trending, undeformed pegmatites at $1,728 \pm 7$ Ma (sample SW02-AT3) was the last igneous event in the Aitik area, and probably the last period to cause remobilisation of ore sulphides. These pegmatites probably correspond to the 1,700–1,720 Ma TIB 2 granites in northern Norrbotten, and the latter are not known to be mineralised. Further input of sulphides contemporaneous with this magmatic event is therefore not considered likely. This is corroborated by the fact that these undeformed pegmatites are mineralised within the ore zone, but barren outside, which suggests a local assimilation of metals rather than an addition. Zeolite-veins in the Gällivare area also yield stilbite U–Pb ages of $1,730 \pm 6$ Ma (Romer 1996), indicating low-temperature ($< 220^\circ\text{C}$, Gottardi and Galli 1985, Chipera and Apps 2001) conditions at the end of this magmatic/hydrothermal event. $1,613 \pm 2$ Ma and $1,620 \pm 2$ Ma (titanite U–Pb ages) zeolite-bearing veins have also been reported from this area (Romer 1996), suggesting that even younger events may have affected parts of the Gällivare area.

Concluding remarks

The objective of this study was to determine the timing of events affecting the Aitik ore body. Two widely recognized minerals for radiometric dating, molybdenite and titanite, reveal a complex age pattern with distinct episodes expressed by the different chronometers.

Molybdenum could largely have been introduced by magmas, a view consistent with the appearance of molybdenite in pegmatites, whereas titanite growth mainly was promoted by hydrothermal events.

The Re–Os and U–Pb ages presented here, together with previous data, indicate that the present character of the Aitik deposit is the result of a multi-episodic evolution that lasted for roughly 160 Ma. This evolution includes interpreted primary, major ca. 1.89 Ga copper mineralisation, followed by at least four episodes of magmatism and metamorphism (Fig. 4), resulting in remobilisation and addition of sulphides. Such repeated reworking and addition of metals produced the copper distribution pattern and concentrations found in the Aitik deposit today.

The evolution of the Aitik deposit can be correlated with regional magmatic/hydrothermal and metamorphic events (Fig. 4). The interplay between regional metamorphism, magmatism, and local deformation is not understood in detail although it seems that the time span 1,800–1,750 Ma was significant for remobilisation of the primary ore body.

To some extent radiometric evidence also constrains the duration of deformation styles. For example, it appears that the ductile deformation, coinciding with the regional metamorphism that started at ca. 1,810 Ma, ended at around 1,765 Ma and was followed by a more brittle-style of deformation.

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