

Geology of the Falu mine



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Geological Survey of Sweden

Cover picture: Oil painting of the Falu mine made at the end of the 1800th century by Pehr Hilleström. Photo: Tommy Johansson, STORA.©

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History

Historically the Falu mine is one of the most remarkable in the world. The mining of copper is thought to have started as early as before the 11th century, i.e. in the Viking era. According to popular myth it was not a viking who found the copper ore but a billy-goat called Kåre. The goat is said to have returned home one day with rust-coloured horns. The rust originated from where the copper ore came to the surface. Thus Kåre guided his master to the ore field.

The forerunner of Stora Kopparberget was founded in 1288, which

makes it the world's oldest running joint-stock company. The mine and the town of Falun prospered during the 17th century. Falun became Sweden's second-largest town. The substantial extraction of copper from the Falu mine was of fundamental economic importance for Sweden's aspirations to become a great power. As a result Sweden became one of the leading states in Europe and all the states surrounding the Baltic came into its sphere of interest.

Midsummer Eve 1687 was a disastrous day not only for Falun but for the whole country. The excavations had undermined the mountain and now a major collapse occurred. It resulted in the large depression known now as Stora Stöten (Fig. 1). The rubble interfered with mining for long afterwards. Mine expert Christopher Polhem tried with his exceptional mine machinery—models of which can be seen in the Falu Mine Museum—to set things right. However, the golden years of the mine were over and the Swedish era as a great power drew to a close (Fig. 2).

Falu mine today

During the 20th century Stora Stöten has been much enlarged through surface mining. Nowadays, however, all production comes from underground quarrying. Annual production is a ca. 200 000 tons of sulphide ore with an average content of 30 % sulphur, 6 % zinc, 2 % lead, and 0.5 % copper. Today zinc is the most important metal in the Falu mine, but silver (0.005 %) and gold (0.00004 %) are also important. The mine also yields pyrite, which is transported to a nearby factory for production of sulphuric acid. A unique product from the mining is the colour pigment, which not only led to the discovery of the ore through the billy-goat Kåre, but which also gives Swedish houses their characteristic red colour.

Fig. 1. Hans Ranie's map of the Falu mine was completed in 1683 and was the last map to be drawn before the great cave-in 1687. The map consists of 9 superimposed sheets with holes marking shafts, etc. cut in the paper—in a way characteristic for Swedish mine maps of that time. Photo: Tommy Johansson, STORA.©

Through the centuries the mining at Falun has caused many environmental problems. Today measures are taken to reduce these problems. However, environmental aspects should be seen against the fact that ore metals are the cornerstone of our civilisation.



Geology of the Falu area

The Falu mine is situated in the ore-field of Bergslagen. The ore deposit is surrounded by quartzites, mica schists and marble. The bedrock in the Falu area is dominated by metavolcanites ("leptites") metamorphosed acid to intermediary tuffs and lavas (see centrefold map). In connection with volcanic eruptions about 2 billion years ago the tuffs and lavas were deposited in seas bordering a continent. The originally horizontal layers are today almost vertical. This is due to subsequent strong regional metamorphism and deformation. The leptites were folded down into a structure with granites intruded around the flanks. A mountain chain, similar to that along South America's west coast today, was uplifted out of the seas. Through millions of years the mountain chain was weathered and eroded down to the relatively flat topography the bedrock shows now.

Ores

Fig. 2. Half Daler (= taler = dollar) copperplate coin from 1710. The crossed arrows indicate that the coin was minted in Falun. Photo: Bengt A. Lundberg, Statens Historiska Museum. ©

As can be seen from the geological map of the mine area (Fig. 3) the sulphide ore is composed of two

very different ore types, massive ore and impregnated ore. Traditionally, because of differences in hardness, the massive ore at the Falu mine has been called "wet ore" and the impregnated type "hard ore" (Figs. 5-6).

The central part of the mine consists of massive ore. Horizontally it forms a Z-shaped fold, 130 m wide and 500 m long. The ore body, which has a steep dip SSE, splits at depth into three separate lenses (Fig. 4). Those are known as Storgruvekisen, Källortskisen and the Queen's ore body (Drottningkisen), and are 330, 360 and 500 m deep, respectively. West of the main ore is the small Lovisa ore, at only 180 m depth.

Pyrite is the dominant ore mineral in the massive ore. Some parts comprise almost pure pyrite, while in other parts the economically important minerals sphalerite, galena and chalcopyrite are more abundant. Pyrrhotite and magnetite are unimportant, as are gold and silver-bearing tennantite and tetrahedrite. Vein minerals are mainly quartz or more locally carbonates. In addition there is anthophyllite, cordierite, andalusite, and chlorite in the quartz-rich ores and actinolite, diopside and garnet in the calcareous ores. Because of

intensive weathering in the crushing chambers several new-formed minerals can be found there (Figs. 7–8, 10–12).

The massive ore usually has a coarse-grained homogeneous texture but there are also parts with a more or less evident banding (Fig. 5). The ore tonnage for the extracted portion of the massive ore is estimated as more than 30 million tons, while the remainder is considerably less.

Somewhat southwest of the main ore body (Storgruvekisen) lies a smaller massive ore body called Lorichs. This is richer in zinc and lead than the main ore.

The impregnated ore, the other important ore type, is concentrated in two areas surrounding the main ore. These are called the Eastern and Western hard ore areas (Fig. 3). Impregnated ore refers to those parts of the quartzite which contain sufficient sulphide ore, primarily chalcopryite, to make possible its extraction. As seen on the mine map (Fig. 3) the impregnated ore zones often show an irregular and diffuse boundary against the country rock. However, many are thought to have an elongation towards NE, and like the

massive ore they dip steeply. Below 150 m depth impregnation mineralization decreases progressively.

Chalcopryite is the most important ore mineral, but small amounts of pyrrhotite, sphalerite, galena, and magnetite are found in the quartzitic host rock (Fig. 6). Much of the chalcopryite is bound in later quartz veins in the quartzite. The copper content of the extracted impregnated ore is estimated as 5–6 %.

Found only in the Eastern hard ore area is a notable mineral association comprising solid gold and several rare bismuth-selenium minerals (Fig. 19). It had long been known that the copper ore in the Falu mine contained a little gold, but it was not until 1881 that gold visible to the naked eye was found (Fig. 17). The interest which this discovery aroused in the Eastern hard ore area brought with it an increased knowledge of the geological occurrences of gold and its relationship to other minerals. Investigations have shown that although gold is associated with

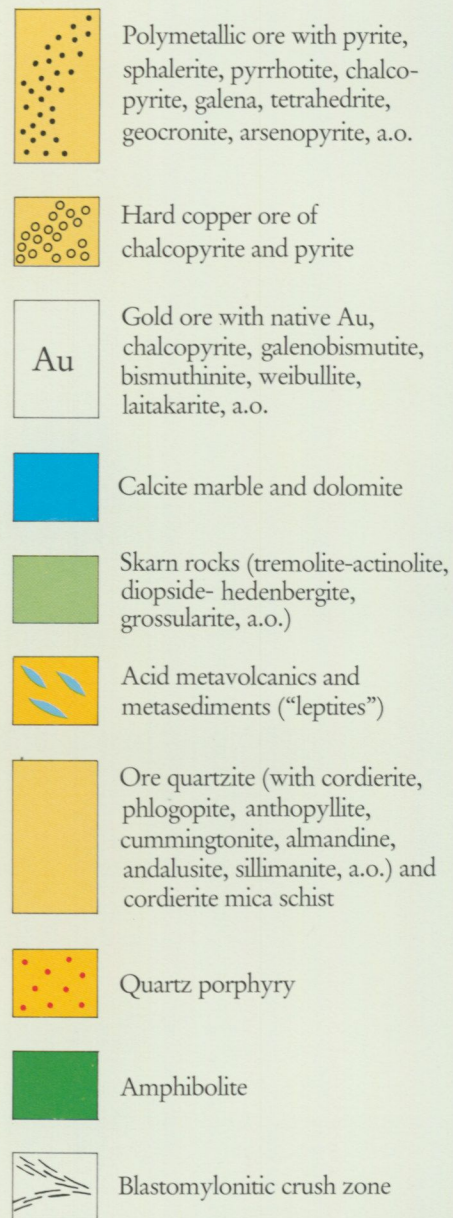
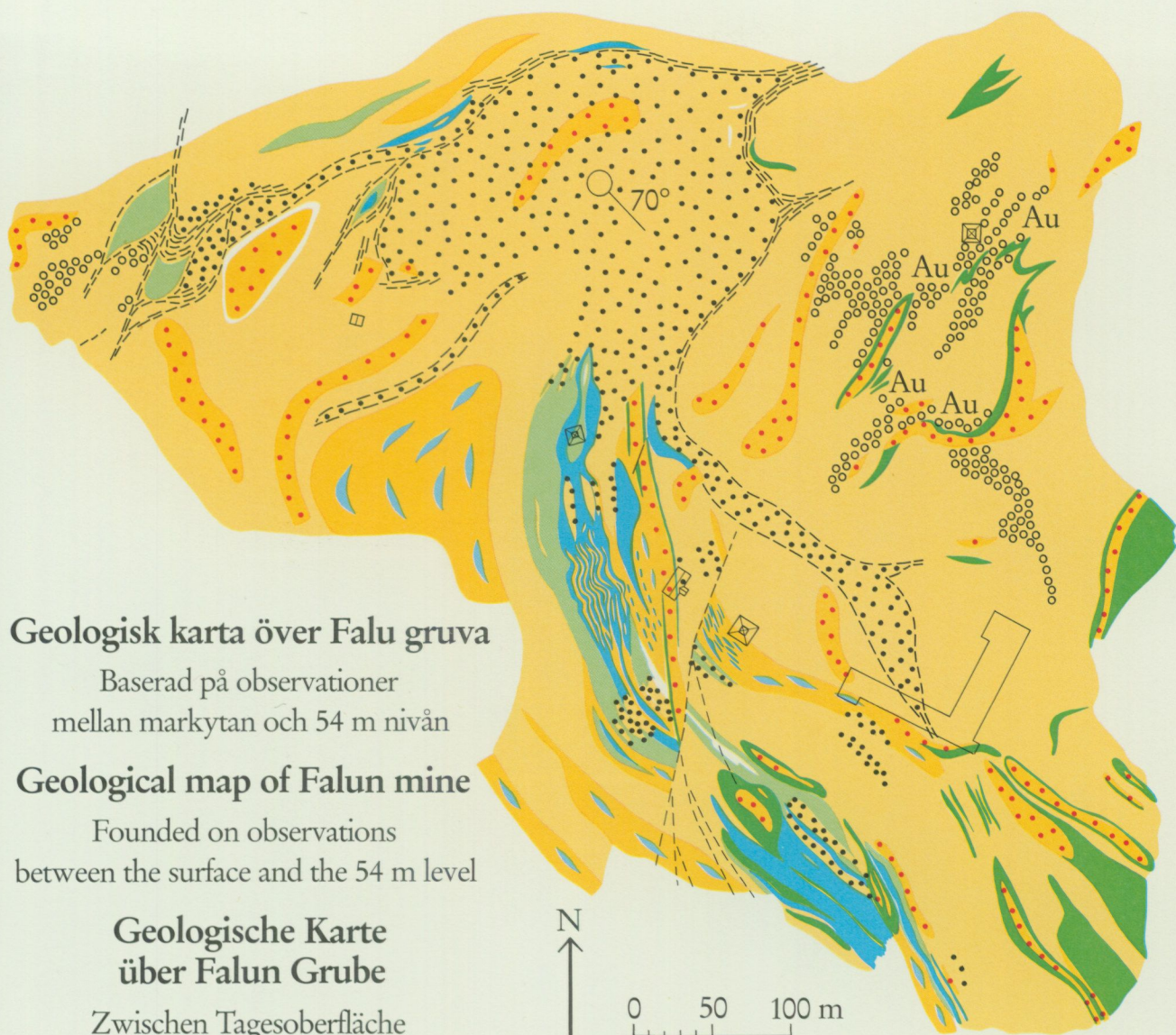


Fig. 3.



Geologisk karta över Falu gruva

Baserad på observationer
mellan markytan och 54 m nivån

Geological map of Falun mine

Founded on observations
between the surface and the 54 m level

**Geologische Karte
über Falun Grube**

Zwischen Tagesoberfläche
und 54 m Niveau

0 50 100 m

Hans J. Koark 1986

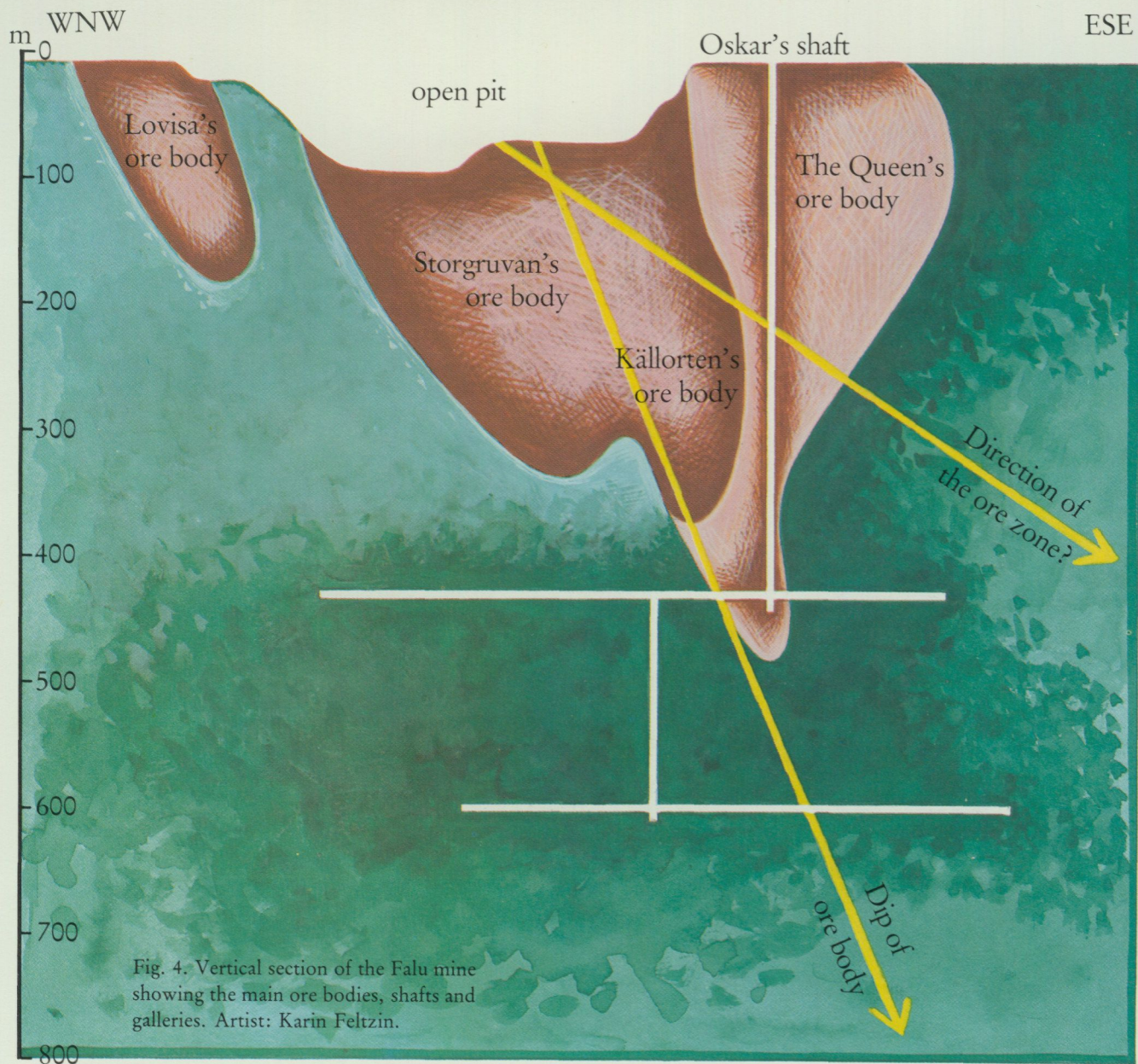


Fig. 4. Vertical section of the Falu mine showing the main ore bodies, shafts and galleries. Artist: Karin Feltzin.

the impregnated ore area it occurs not in the ordinary quartzite but is concentrated in the light and thin (<0.15 m) quartz veins which cut the quartzite. In these quartz veins chalcopyrite and pyrite are also found, as well as the interesting bismuth-selenium minerals (Fig. 19).

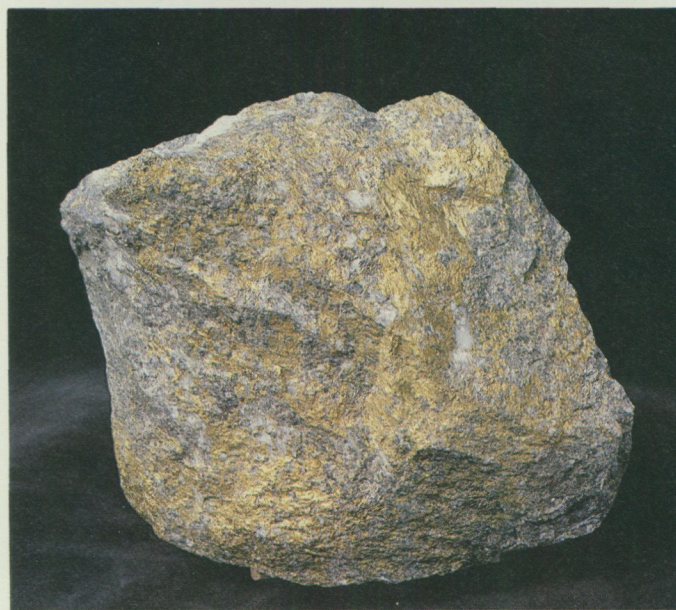


Fig. 4. Vertical section of the Falu mine showing the main ore bodies, shafts and galleries. Artist: Karin Feltzin.

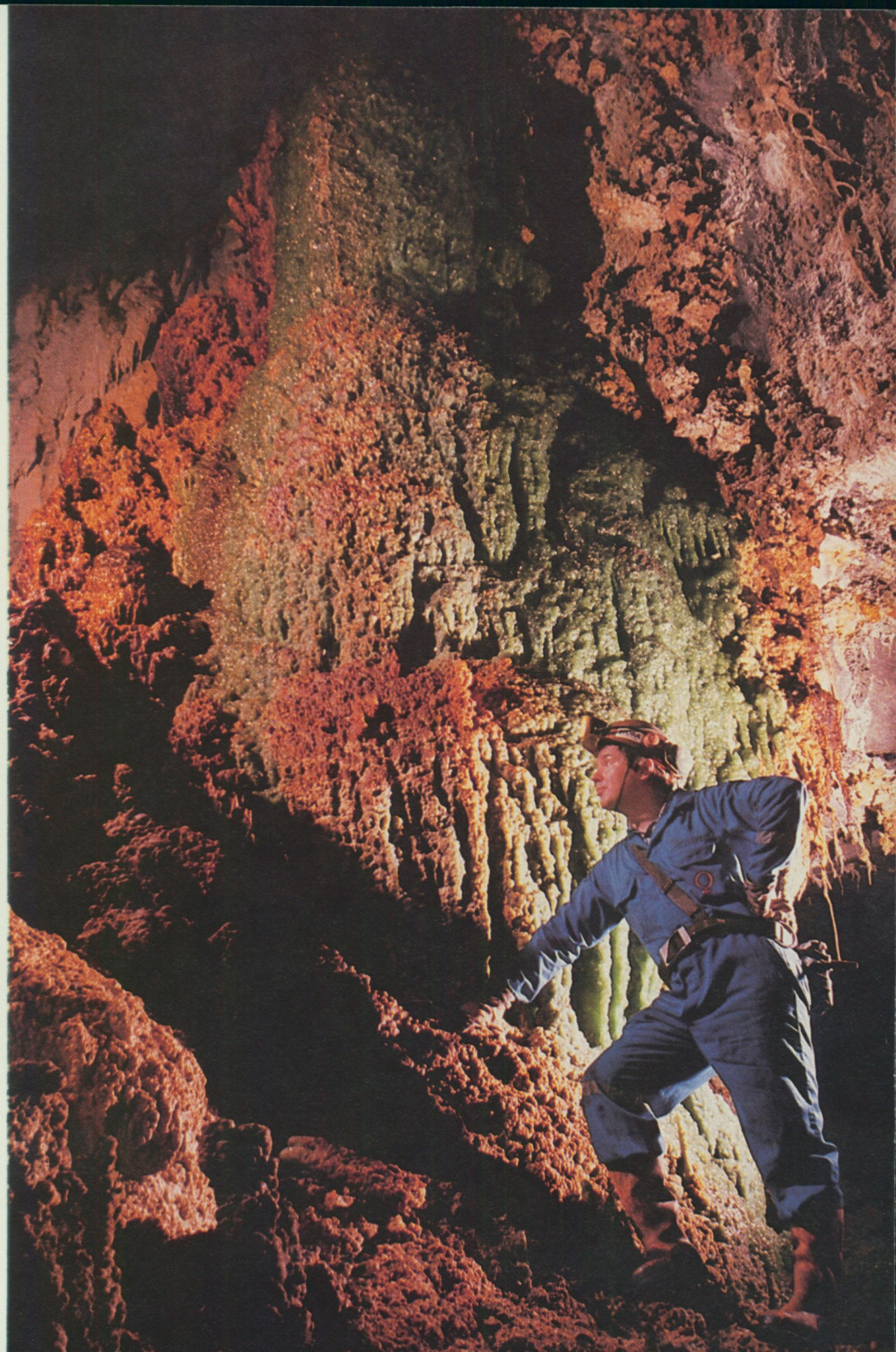
Fig. 5. Massive sulphide ore ("wet ore") of yellowish chalcopyrite and sphalerite. Photo: Anders Damberg, SGU.©

Fig. 6. Impregnated sulphide ore ("hard ore") of chalcopyrite with quartz veins in quartzite. Photo: Anders Damberg, SGU.©



Fig. 7. Tooth-like dripstone of limonite (iron hydroxide) from the Falu mine. Photo: Anders Damberg, SGU.©

Fig. 8. Dripstone of iron sulphate in the Falu mine. Due to the extreme temperature of 60°C in this hall the growth rate can reach 5 m per year. Photo: Tommy Johansson, STORA.©



Rocks

The impregnated ore and to a large extent the massive ore are enclosed in and surrounded by a notably quartz-rich rock, in Fig. 3 and the centre-fold map called quartzite. The quartzite is dominated by quartz and a variable content of biotite, cordierite and anthophyllite. The rock is massive, light to dark grey in colour and often glassy in appearance. The darker colour comes from a higher content of biotite. Nearest to the ores the quartzite is often light-coloured, but becomes darker away from the ore. Anthophyllite, often as small fan-shaped clusters, is usually found in the immediate vicinity of the ore but also occurs in other parts of the quartzite.

Micaceous rocks—mica schists and quartz-biotite gneisses—are found chiefly in the central parts of the synform (blue on the centre fold map). Gradual transitions between these rocks and the metavolcanites are common. Parts of the schist might have been formed by further alteration of metavolcanites. Most rock types designated as metasediments on the centre fold map were sedimentary rocks primarily.

The massive ore is partly associated with lenses of calcite and dolomite marble and skarn rocks. According to the geological map (Fig. 3) those occur mainly south of Källortskisen and in the area between the Lovisa ore and just north of Storgruvekisen. These rock types are also found as scattered inclusions and spots within the massive ore, but never in the impregnated ores. Both kinds of rock can be sulphide-bearing but entirely sulphide-free varieties do occur.

The massive ore and country rock are to a large extent separated by a narrow zone (1–20 m) of a poorly defined rock type, known by an old quarryman's term as "sköl". The "sköl" zones also occur within the massive ore and in the country rocks. They generally decrease in importance with depth. From the dominant minerals a distinction can be made between chlorite and talc "sköls". Large amounts of chalcopyrite were extracted previously from the "sköls", so called "sköl" ores, but because of their fragility they cause problems in present day mining. There are many aspects to their formation, but the most important point is that the "sköl" zones were

formed by differential movements between the relatively soft massive ore and the hard country rock.

The rocks in the mine area, are penetrated by a large number of veins of quartz porphyry and amphibolite. The quartz porphyry is massive, often with some larger quartz scattered in the fine-grained, light-coloured matrix. The quartz porphyry has al-



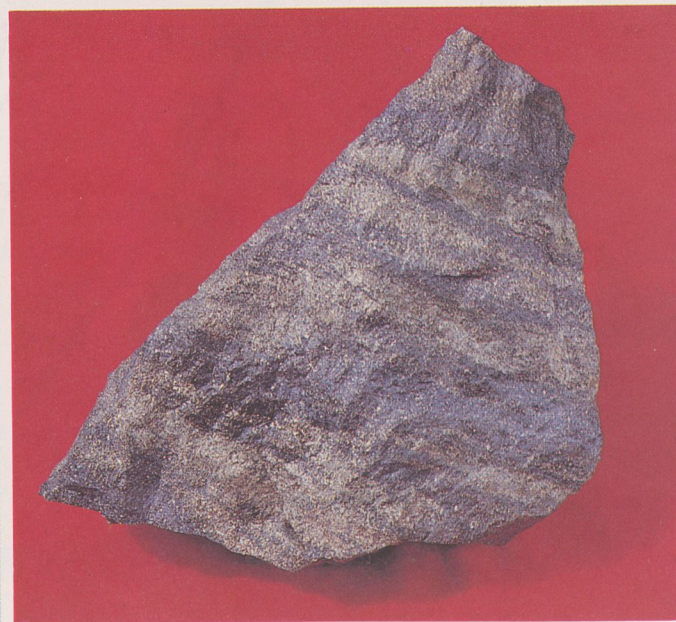
Figs. 9–12. Minerals from the Falu mine. Photo: Anders Damberg, SGU.®

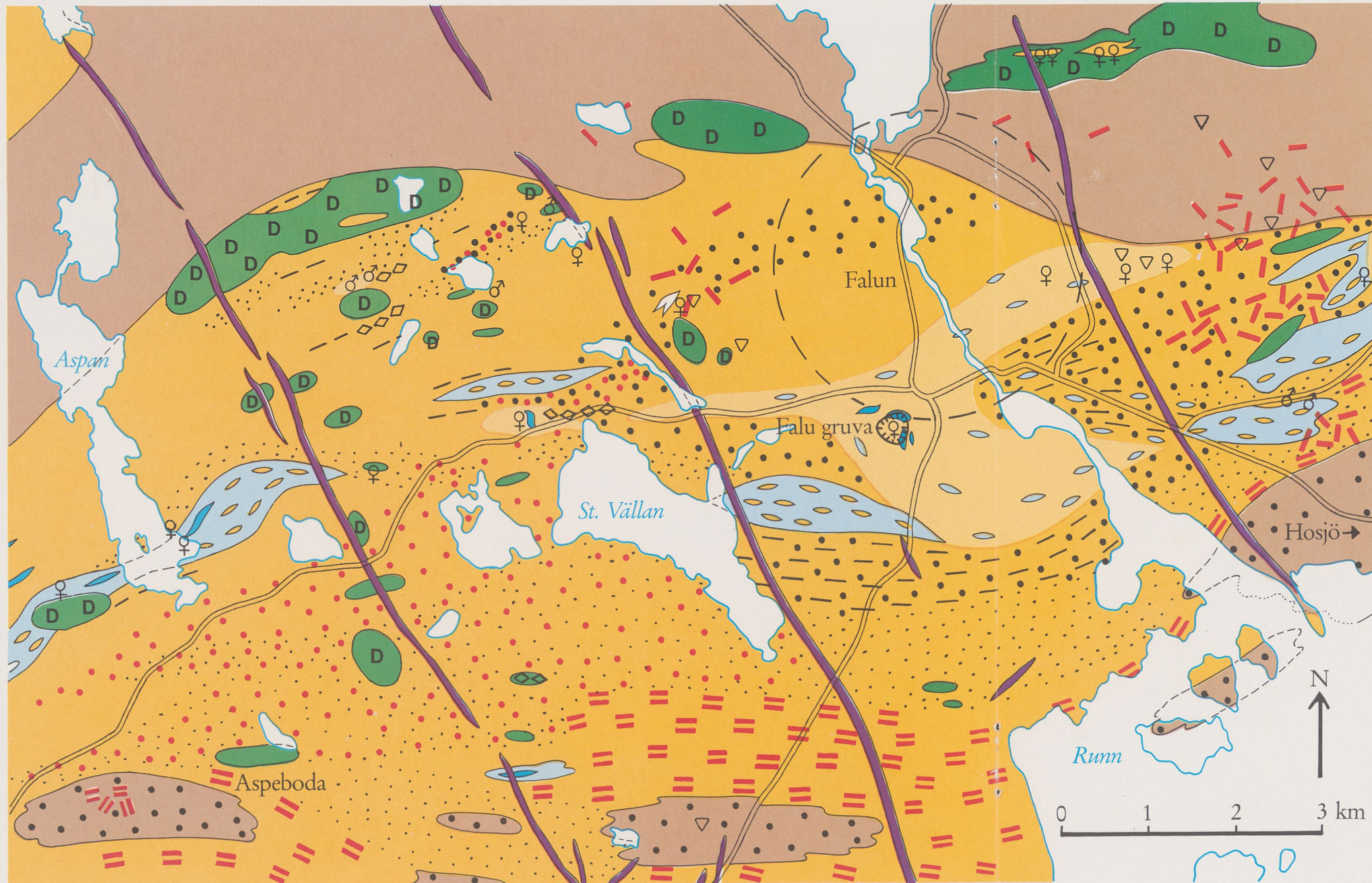
Upper left: De Witt's specimen from 1878. Geocronite in upper left, tennantite in lower right, and galena in the middle part.

Upper right: Sphalerite and yellowish chalcopyrite.

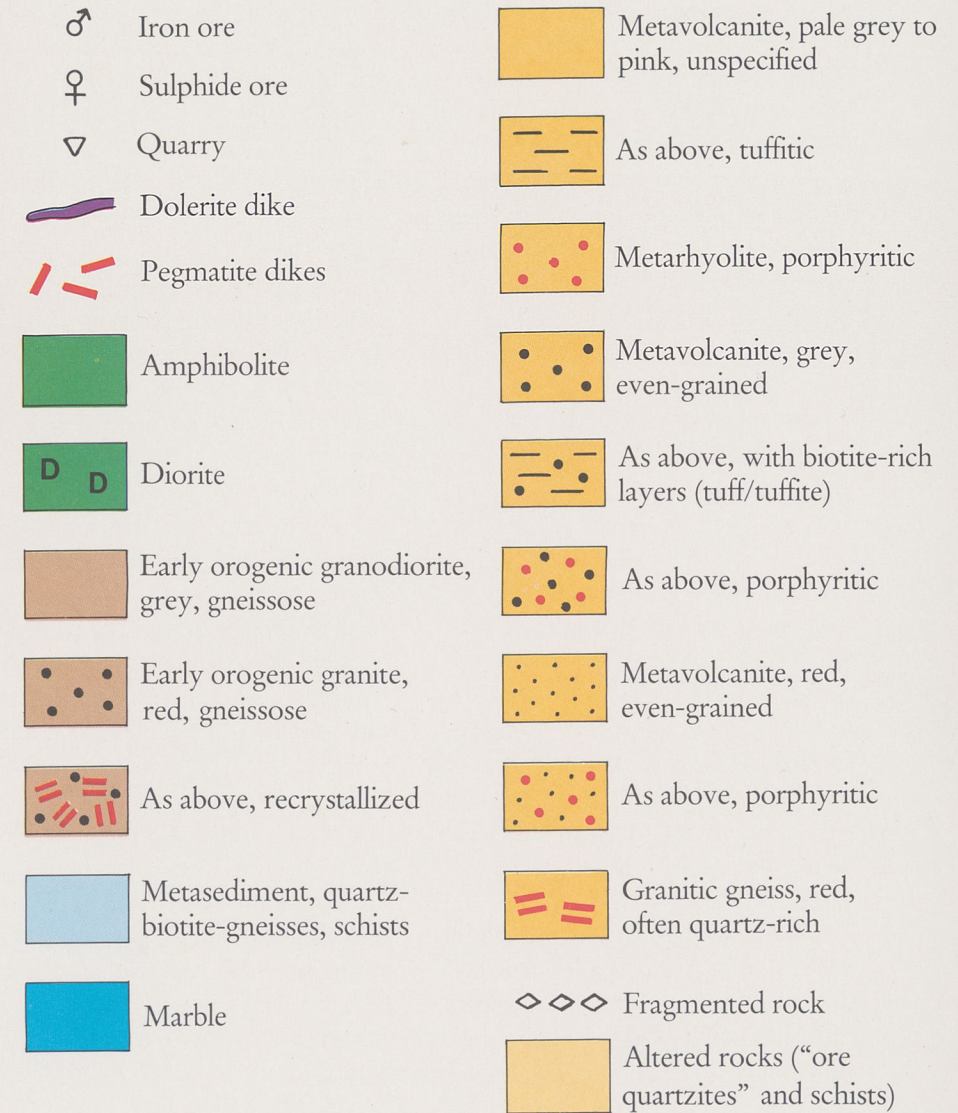
Lower left: Milky quartz in lower right, galena in lower left, and magnetic pyrite in upper part.

Lower right: Sphalerite and yellowish pyrite.





Geological map of the Falu region



most the same chemical composition as the metavolcanites in the Falu area, and most likely represents the feeder dykes to these volcanic rocks. The amphibolite is a dark, fine-grained rock found both separately and together with quartz porphyry veins, and it indicates a less siliceous volcanic activity. The veins are often strongly deformed by later folding of the earth's crust.

Deformation

The bedrock of the Falu mine has its roots in an ancient mountain chain. Since their original formation the rocks, including the ore, have been so strongly metamorphosed and deformed by the processes which gave rise to this mountain chain that it is very difficult to interpret correctly their geological evolution.

The steep dip of the rocks and ores is the result of very intense regional folding of the originally horizontal beds. This first phase of folding resulted in a large trough-shaped

structure (synform) with an almost horizontal E-W axis between the granite bodies to the North and South (see centrefold map).

A second phase of folding can be deduced from, e.g., the configuration of the massive ore body in the ground level (Fig. 3). This second folding involved shearing of the upfolded rock layers on both sides of the ore, and was caused by the granite bodies moving on collision course. The massive ore was then deformed into a Z-shaped fold with major thickening of the ore in one of the fold limbs. A steep south-dipping fold axis indicates this fold phase, which greatly changed the form of the ore body. The direction of this fold axis deviates somewhat from the ore field's dip (its longest dimension), which is steep to the SSE (Fig. 4).

“Sköl” zones and sharply broken intrusive veins indicate that fault movements have occurred at a later stage in the geological evolution. The stratigraphy is interpreted in terms of younging towards the centre of the synform, the synform being a syncline.

Figs. 13–16. Minerals from the Falu mine. Photo: Anders Damberg, SGU.©

Upper left: Brown botryogen – from the type locality – with dust-like white halotrichite.

Upper right: Halotrichite needles on botryogen from the type locality.

Lower left: Botryogen from the type locality.

Lower right: White halotrichite on botryogen from the type locality.



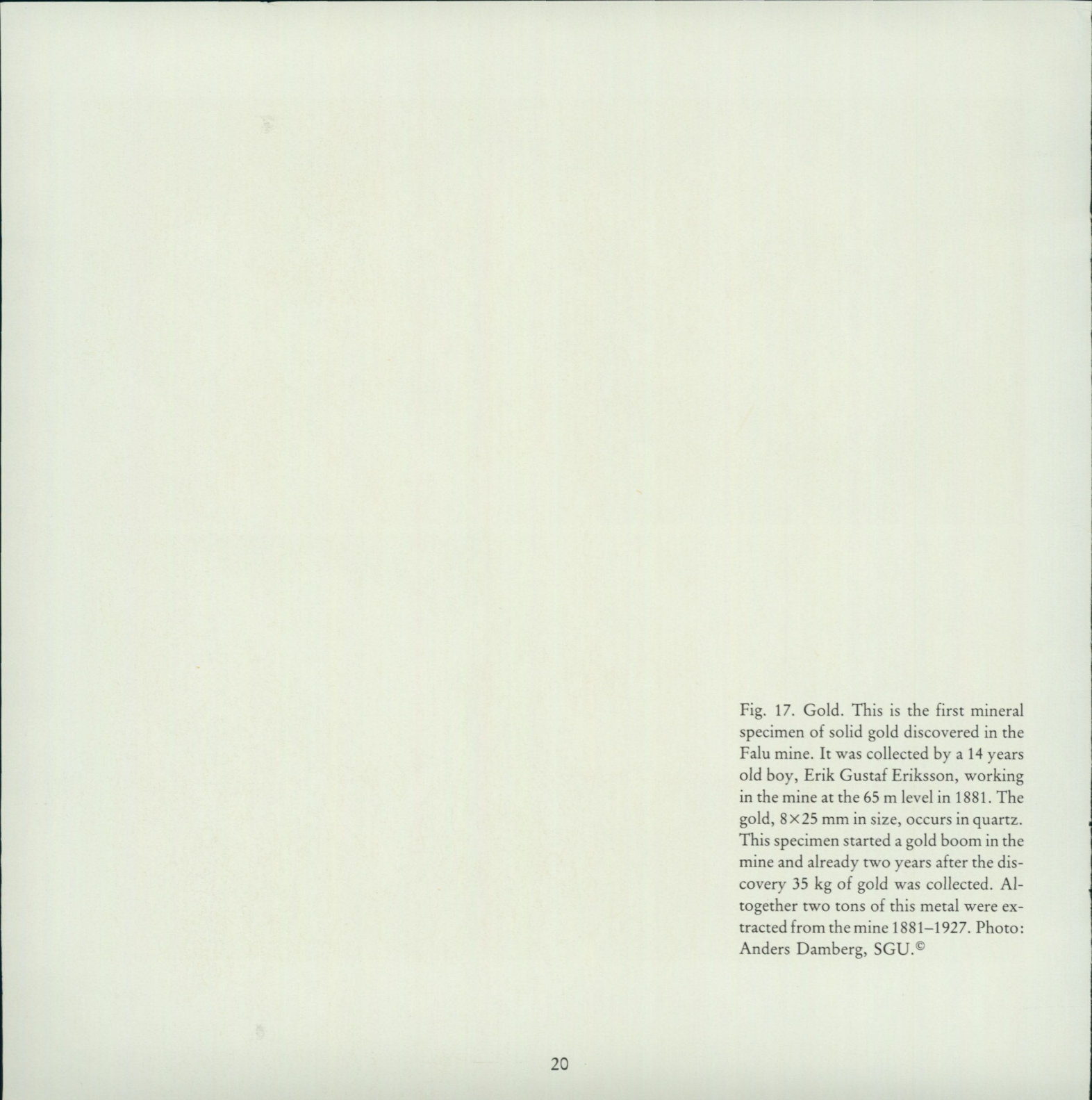


Fig. 17. Gold. This is the first mineral specimen of solid gold discovered in the Falu mine. It was collected by a 14 years old boy, Erik Gustaf Eriksson, working in the mine at the 65 m level in 1881. The gold, 8×25 mm in size, occurs in quartz. This specimen started a gold boom in the mine and already two years after the discovery 35 kg of gold was collected. Altogether two tons of this metal were extracted from the mine 1881–1927. Photo: Anders Damberg, SGU.©



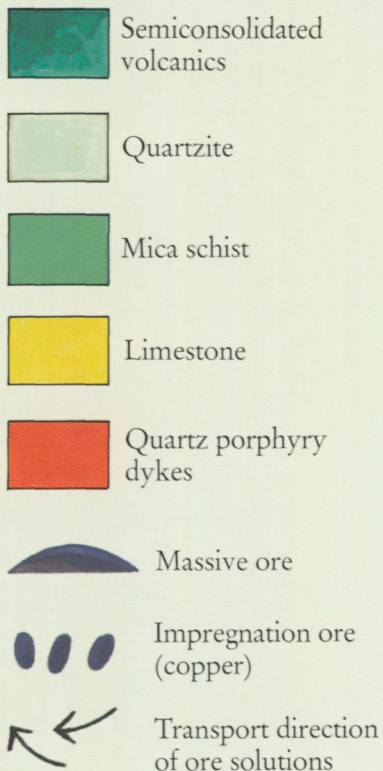


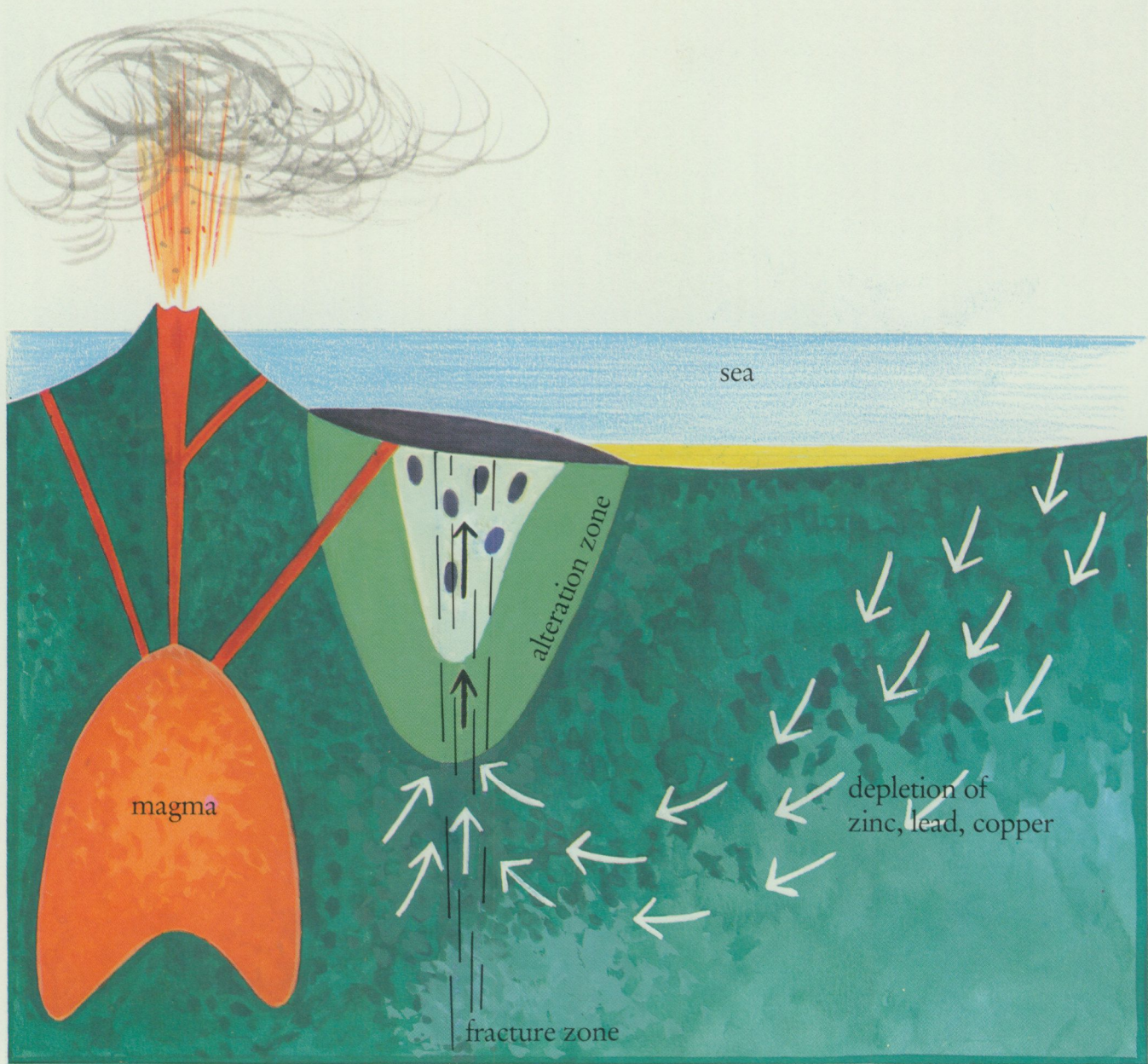
Formation of the ore

Because of the strong deformation and metamorphism to which the ore and its country rocks have been exposed, it is difficult to interpret how the ore was formed. Many different theories have been proposed over the years. The remarkable progress made in geology during the last 20 years has included advances in our knowledge of ore forming processes in the Falu area.

A possible model for explaining the formation of the Falu ore is shown in Fig. 18. About two billion years ago the Earth experienced a period of volcanic activity. Lavas and tuffs were formed in volcanic eruptions and were deposited on the sea bottom and forming bed after bed.

Fig. 18. Proposed model for explaining the formation of the Falu ore. See chapter "Formation of the ore" for a discussion. Artist: Karin Feltzin.





These siliceous volcanic products were later metamorphosed to so-called leptites. Heat produced by the volcanic activity gave rise for a time to a hot water circulation system in the semi-consolidated rock pile. Through cracks in the sea-floor cold sea water filtered into the underlying bedrock. The water became warmer with depth and could leach out e.g. copper, zinc and lead from the bedrock. Gradually these hot ore solutions reached a wider fissure zone. They were then forced upwards to the sea-floor where they formed hot springs. As a result of the great flow of hot and acid ore solutions the volcanic rock-pile was altered to quartz-rich rocks nearest to the fissure zone and to mica-rich rocks further outwards. Simultaneously metals, primarily copper, precipitated in the quartz-rich rocks. Today they form the impregnation ores. Due to mixing of sea-water and ore solutions in the upper part of the fissure zone the temperature of the solutions dropped. This caused precipitation of metals directly on the bottom of the sea around the hot springs. They are represented by the massive ore in the Falu mine. Through chemical precipitation limestones were also formed on the sea bottom. Thereafter the massive

ore was covered with new volcanic rocks, probably mixed with clastic sediments such as sand and clay.

Later this part of the earth's crust was exposed to mountain building processes which strongly metamorphosed and deformed both the ore and country rock. Finally, through millions of years of weathering and erosion, the ore at Falun was exposed and became accessible for mining, with all the far-reaching consequences it had for Sweden's development.



Fig. 19. The ore minerals of the Falu mine according to Stig Adolfsson, STORA.

Malm-
mineralen
i Falu gruva

The ore
minerals of
the Falu mine

Die Erzmineralen
der Faluner Grube

Koppar	Copper	Kupfer	Cu
Guld	Gold	Gold	Au
Vismut	Bismuth	Wismut	Bi
Svavelkis	Pyrite	Pyrit	FeS ₂
Magnetkis	Magnetic pyrite	Magnetkies	Fe ₉ S ₈
Blyglans	Galena	Bleiglianz	PbS
Zinkblände	Sphalerite	Zinkblende	(ZnFe)S
Kopparkis	Chalcopyrite	Kupferkies	CuFeS ₂
Gudmundit	Gudmundite	Gudmundit	FeSbS
Arsenikkis	Arsenopyrite	Arsenkies	FeAsS
Löllingit	Löllingite	Löllingit	FeAs ₂
Tennantit	Tennantite	Tennantit	Cu ₁₂ (AsSb) ₄ S ₁₃
Tetrahedrit	Tetrahedrite	Tetrahedrit	Cu ₁₂ (SbAs) ₄ S ₁₃
Bournonit	Bournonite	Bournonit	PbCuSbS ₃
Cubanit	Cubanite	Cubanit	CuFe ₂ S ₃
Stannit	Stannite	Zinnkies	Cu ₂ FeSnS ₄
* Geocronit	* Geocronite	* Bleiantimonspiessglanz	* Pb ₁₄ (AsSb) ₆ S ₂₃
Achantit	Achantite	Akanthit	Ag ₂ S
Galenobismutit	Galenobismuthite	Galenobismutit	PbBi ₂ (SSe) ₄
Cosalit	Cosalite	Cosalit	Pb ₂ Bi ₂ (SSe) ₅
* Weibullit	* Weibullite	* Weibullit	* Pb ₅ Bi ₈ (SSe) ₁₇
* Wittit	* Wittite	* Wittit	* Pb ₉ Bi ₁₂ (SeS) ₂₇
Ikunolit	Ikunolite	Ikunolith	Bi ₄ SeS ₂
Laitakarit	Laitakarite	Laitakarit	Bi ₄ Se ₂ S
Vismutglans	Bismuthinite	Wismutglanz	Bi ₂ (SSe) ₃
* Nordströmit	* Nordstroemite	* Nordströmit	* CuPb ₃ Bi ₇ (SSe) ₁₄
Pekoit	Pekoite	Pekoit	CuPbBi ₁₁ (SSe) ₁₈
* Botryogen	* Botryogen	* Botryogen	* MgFe(SO ₄) ₂ (OH) 7H ₂ O
Epsomit	Epsomite	Epsomit	MgSO ₄ 7H ₂ O
Halotrichit	Halotrichite	Halotrichit	FeAl ₂ (SO ₄) ₄ 22H ₂ O

Mineral påträffade endast i östra hårdmalmsområdet

Minerals found only in east hard ore area

Die Mineralen sind nur im östlichen Harterzgebiet
gefunden worden

* Falu gruva är mineralets typlokalitet

* The Falun mine is type locality for this mineral

* Die Grube Falun ist das Typusvorkommen des Minerals

Glossary

amphibole	group of minerals, calcium-magnesium-iron silicates with water	sediment	material deposited by air, ice or water, e.g., sand and clay
amphibolite	metamorphic rock composed mainly of amphibole and plagioclase	skarn	rock consisting of calcium silicates
andalusite	aluminium silicate (Al_2SiO_5)	supracrustal rock	rock formed at the earth's surface
anthophyllite	amphibole rich in magnesium	synform	trough-like fold structure
antiform	saddle-like fold structure	tuff	consolidated volcanic ash
biotite	dark mica mineral	volcanite	volcanic rock in general, e.g., lava and tuff
chalcopyrite	important copper ore, gold-coloured		
chlorite	group of minerals, magnesium-iron-aluminium silicates with water		
cordierite	mineral, magnesium-aluminium silicate, brown or green		
fahlerz	group of minerals, copper sulphide with arsenic or antimony, often containing silver, grey to black		
feldspar	group of minerals, aluminium silicate with potassium, sodium and calcium		
garnet	group of minerals, silicates of calcium, iron, manganese and aluminium, often brown or reddish brown		
gneiss	metamorphic rock composed chiefly of feldspar and often quartz and mica		
granite	igneous rock formed at great depth, consists of quartz, feldspar and mica		
leptite	light metamorphic rock rich in silica, chiefly metamorphosed volcanic rocks		
magma	molten rock		
magnetite	iron oxide, important ore mineral, black, strongly magnetic		
marble	metamorphic rock consisting mainly of calcite and/or dolomite		
meta-	prefix designating metamorphic rocks		
metamorphic	alteration of rocks due to changes in pressure and/or temperature		
porphyry	igneous rock with crystals of quartz or feldspar in a fine-grained to dense matrix		
pyrite	iron sulphide, FeS_2 , light yellow		
quartz	mineral, SiO_2 , often white		
quartzite	metamorphic rock with quartz as dominating mineral		

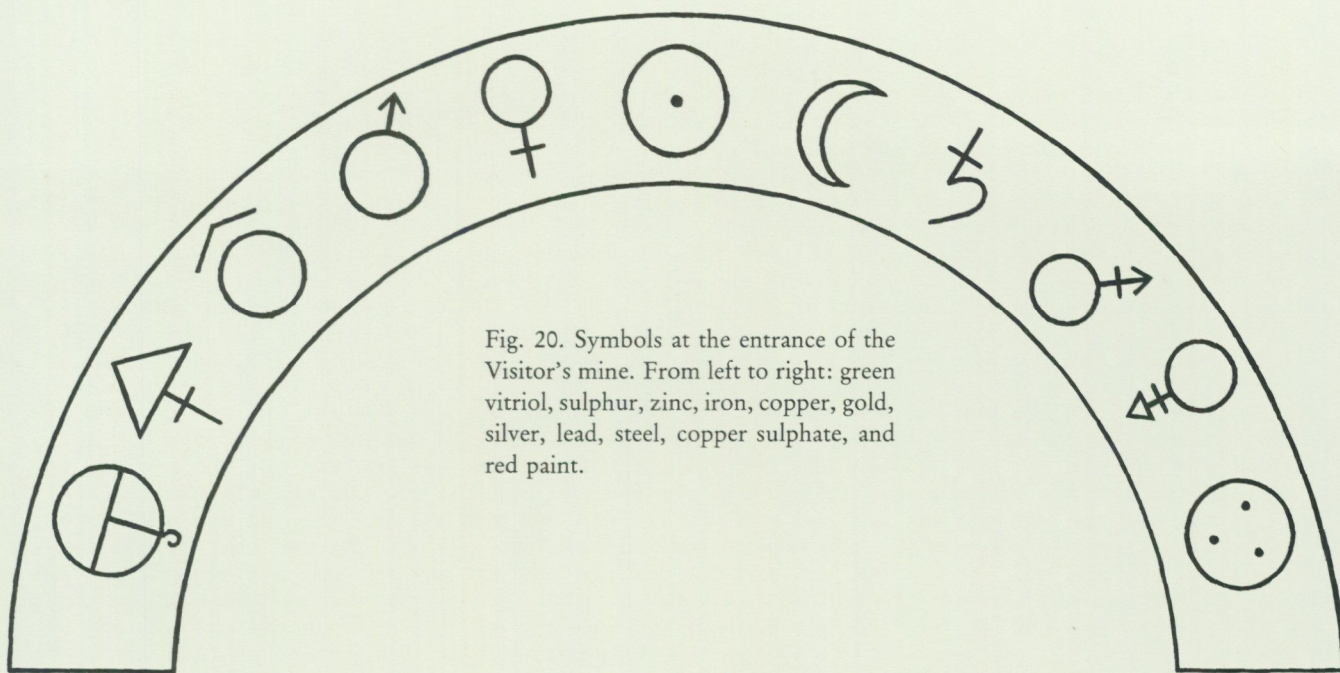


Fig. 20. Symbols at the entrance of the Visitor's mine. From left to right: green vitriol, sulphur, zinc, iron, copper, gold, silver, lead, steel, copper sulphate, and red paint.

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