Bergvesenet
Postboks 3021, N-7441 Trondheim

Rapportarkivet

Innlegging av nye rapporter ved: John

Bergvesenet rapport nr	Intern Journal nr	Internt arkiv nr	Rapport lokalisering	Gradering
5610				

Kommer fra ..arkiv	Ekstern rapport nr	Oversendt fra	Fortrolig pga	Fortrolig fra dato:
Grong Gruber AS		Grong Gruber a.s.		

Tittel
Deformation of the Joma sulphide deposit, Caledones of Nord-Trøndelg, Norway

Forfatter	Dato	År	Bedrift (oppdragsgiver og/eller oppdragstaker)
Odling, Noelle E.		1988	Grong Gruber AS og NTNF

Kommune	Fylke	Bergdistrikt	1: 50 000 kartblad	1: 250 000 kartblad
Røyrvik	Nord-Trøndelag		19241	Grong

Fagområde	Dokument type	Forekomster (forekomst, gruvefelt, undersøkelsesfelt)
Geologi		Grongfeltet, Joma

Råstoffgruppe	Råstofftype
Malm/metall	Cu, Zn

Sammendrag, innholdsfortegnelse eller innholdsbeskrivelse

Foredrag på "Seventh Quadrennial IAGOD Symposium" av Noelle E. Odling.

The Joma sulphide deposit, Grong, Central Norway, is situated within greenstones which form part of an imbricated sequence witin the Leipikvatnet Nappe. The ore body is deformed by three main phases of deformation. D1 and D2 phases constitute the major deformation with which schistosity and the emplacement of the nappes are assiciated, while the third phase folds the thrust planes. The deposit lies on an inverted F2 fold limb and is cut at depth by a D2 thrust. A change in sulphide mineralogy from chalcopyrite/pyrrotite-dominated to pyrite/sphalerite-dominated ore is associated with a change in D2 deformation style from folding to thrusting. F3 folds deform D2 thrust planes and therefore post-date thrust movements. D2 and D3 deformation phases are coaxial and D3 has caused local reactvation of D2 thrust planes. The presence of an incompetent ore body within competent greenstones is thought to have influenced the location of the thrust marking the base of the middle greenstone unit.

Deformation of the Joma sulphide deposit, Caledonides of Nord-Trøndelag, Norway

Noelle E. Odling

Geologisk Institutt, N.T.H., N-7034 Trondheim, Norway*

With 9 figures

Abstract. The Joma sulphide deposit, Grong, central Norway, is situated within greenstones which form part of an imbricated sequence within the Leipikvattnet Nappe. The ore body is deformed by three main phases of deformation. D1 and D2 phases constitute the major deformation with which schistosity and the emplacement of the nappes are associated, while the third phase folds the major thrust planes. The deposit lies on an inverted F2 fold limb and is cut at depth by a D2 thrust. A change in sulphide mineralogy from chalcopyrite/pyrrhotite-dominated to pyrite/sphalerite-dominated ore is associated with a change in D2 deformation style from folding to thrusting. F3 folds deform D2 thrust planes and therefore post-date thrust movements. D2 and D3 deformation phases are coaxial and D3 has caused local reactivation of D2 thrust planes. The presence of an incompetent ore body within competent greenstones is thought to have influenced the location of the thrust marking the base of the middle greenstone unit.

Regional setting of the Joma sulphide deposit

The Joma sulphide deposit is situated in the northeastern Grong area, Nord-Trøndelag, Norway, some 16 km east of the village of Røyrvik, Limingen. The ore body outcrops in the Røyrvik Group greenstones of the Leipikvattnet Nappe, one of the Middle Köli Nappes in the Upper Allochthon of the Scandinavian Caledonides. Exploration of the ore body began in 1912 and the deposit was first described by Munster (1915). However, exploitation of the ore deposit was not considered until it was taken over by the present operators, Grong Gruber, in 1969. When production started in 1972, the ore body was estimated at 22 Mt of massive sulphides with ore reserves calculated at 6.8 Mt averaging 1.70% Cu and 1.11% Zn.

In the Joma area, the Leipikvattnet Nappe is composed of three greenstone units separated by quartzitic and graphitic phyllites trending subparallel to the bounding thrusts of the nappe (Fig. 1). A thick sequence of calcareous phyllites (Brakkfjället Phyllite) outcrops in the east. All rocks are in the greenschist metamorphic facies.

Four phases of deformation have been identified in the Joma area (Odling 1986). The main penetrative schistosity and mineral lineation belong to the D2 phase of deformation. D1 structures, which are coaxial with those of D2, are only sporadically preserved within well layered quartzitic phyllites. S2 schistosity is subparallel to the lithological layering and L2 mineral lineations trend NW to N. These structural elements are refolded by the major, NE-trending, F3 Joma synform with which a moderately to steeply NW-dipping crenulation cleavage and gently SW- to moderately NE-plunging intersection lineation are associated.

* Present address: IBM, Bergen Scientific Centre, Allégaten 36, N-5000 Bergen, Norway.

Proceedings of the Seventh Quadrennial IAGOD Symposium

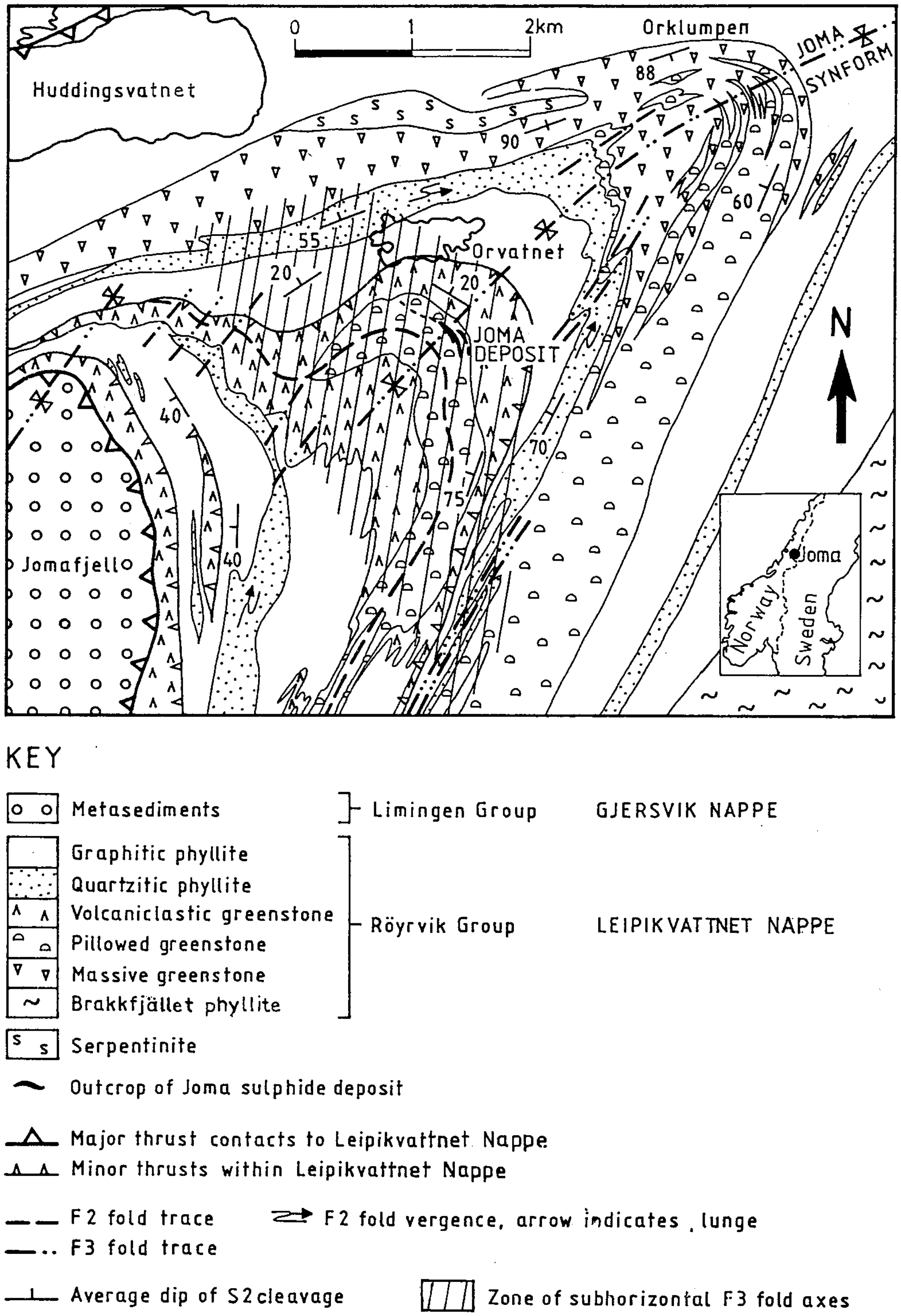


Fig. 1. The regional geology of the Joma area, revised and adapted from Kollung (1979). The Joma sulphide deposit outcrops in the middle greenstone unit and is situated on the overturned limb of a major F2 antiform.

The latest phase of deformation consists of minor folds and kinks trending NE-SW, with variable axial planar dips which are concentrated in the south of the region.

The scheme of deformation events derived for the Joma area agrees with that inferred for the Stekenjokk (Zachrisson 1984) and Ankarvattnet (Sundblad 1981) areas to the northeast of Joma, and the Helgeland Nappe Complex (Lutro 1979) to the west. This corresponds to the general deformation scheme for the Middle Köli in which D1 and D2 predate or are coeval with thrusting, and D3 and D4 post-date thrusting (Stephens 1986). Variations do, however, occur. D1 is not recognized in the overlying Gjersvik Nappe (Roberts 1979, Halls et al. 1977, Lutro 1979) and D2 of the Joma area is replaced by two phases of deformation in the area to the east (Sjöstrand 1978).

The three greenstone units are bounded by D2 thrusts along their lower contacts and the structure is interpreted as an imbricated stratigraphy comprising the sequence: greenstone (oldest) – quartzitic phyllite – graphitic phyllite (youngest). The ore body outcrops in the second greenstone unit, here called the 'middle greenstone', and is situated close to the axial trace of the Joma F3 synform, on the inverted limb of an overturned F2 antiform associated with D2 thrusting. Geophysical data have shown that the ore body approaches the lower contact of the middle greenstone at depth (Logn & Bølviken 1974), inferring that the lower limb of the antiform and the ore body are cut at depth by the D2 thrust. The ore body has an overall, gentle W to SW dip. All deformation phases identified in the Joma region can be recognized in the ore body.

The sulphide lithologies at Joma are interpreted by Olsen (1980) and Reinsbakken (1986) to be syn-depositional and the ore body is thought to have originated as an exhalative deposit which formed in a submarine environment. They established the presence of a feeder zone which now structurally overlies the massive ores. A general stratigraphy within the massive sulphides from an early Cu-rich (pyrrhotite-chalcopyrite) to a Cu-poor, Zn-rich (pyrite-sphalerite) ore is recognized by Olsen (1980) and Reinsbakken (1986) and is consistent with an exhalative origin.

Ore body lithology and geometry

The massive sulphides are composed of varying proportions of pyrite, pyrrhotite, chalcopyrite and sphalerite with variable amounts of matrix quartz, carbonate and amphibole. Textural and compositional layering on scales of millimetres to metres is common. The ore body shows a general compositional change from a sphalerite-rich pyrite ore in the east to chalcopyrite-rich ore in the west. Associated with the chalcopyrite-rich ore are numerous layers of greenstone, chlorite schist, albitite and carbonate which are intercalated with the sulphides. The most chalcopyrite-rich ore is a tectonic breccia composed of silicate and pyrite fragments in a chalcopyrite-pyrrhotite matrix.

The shape of the ore body and the orientation of the major structures have been traced using profiles constructed for the upper part by Olsen (1984) and for the lower sections by Reinsbakken (1986). Fig. 2 shows a three dimensional schematic representation of the ore body indicating the orientation and distribution of the major structural features. The eastern portion of the ore body dips gently W to SW while the western portion, due to F3 folds, dips steeply E to SE. The zone of F3 folding is minor in the northeast and becomes increasingly intense to the southwest. Due to F3 folding, the ore horizon outcrops in an arcuate zone, the discontinuous nature of which is caused by F2 folding and thrusting. In the northeast, a large thrust wedge of massive sulphides parallels the main ore horizon and is exposed at the surface in a second minor trend known as the 'elvegangen' or river lode (Fig. 2).

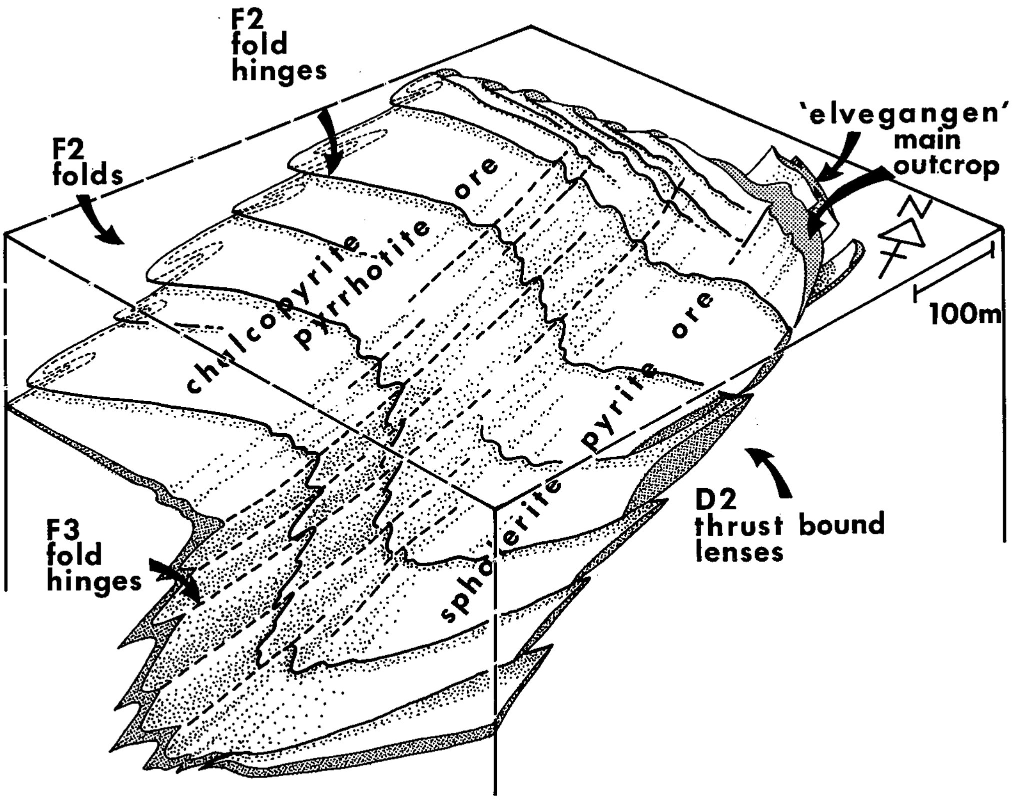


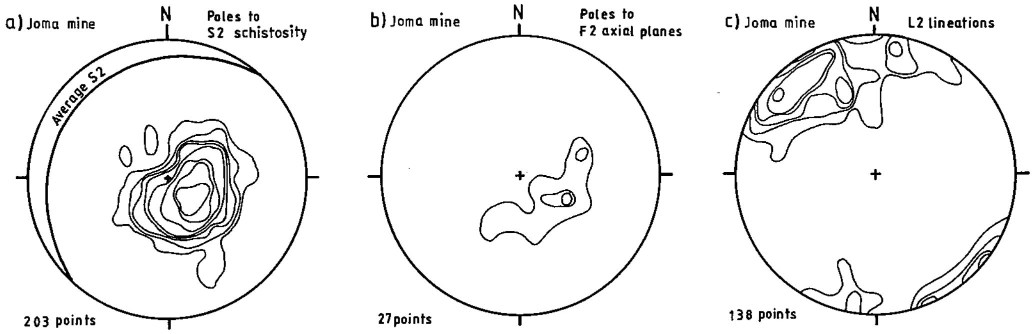
Fig. 2. Schematic block diagram showing the structural features of the Joma sulphide deposit. The ore outcrups in two arcuate trends: the main outcrop, and a lesser trend to the northeast ('elvegangen'). F2 fold hinges trend NW and pass eastwards into tips of thrust lenses as the ore changes from chalcopyrite/pyrrhotite-dominated to sphalerite/pyrite-dominated. F3 folds are clustered in a NE-trending zone in the western part of the ore body.

Major F2 hinges show the characteristic northwesterly trend of the regional L2 lineation except where refolded by the D3 Joma synform. The folds are gently NW-plunging in the eastern part and gently SW-plunging in the western and northern parts of the ore body. F2 fold hinges in the western part of the ore body can be traced eastwards into the tips of thrust lenses. This change in structural style corresponds to a change in ore composition from chalcopyrite/pyrrhotite-rich ores with intercalated silicate and carbonate horizons in the west, to massive sphalerite/pyrite ores in the east (Fig. 2). F3 folds show the characteristic NE-SW trend of the Joma synform and are clustered in the western part of the ore body. The folds plunge gently SW, and are laterally imperistent both along trend and down dip of their axial planes, forming pod-like zones of strong D3 deformation.

Main phase of deformation (D2)

The main penetrative schistosity and mineral lineation of the country rocks belong to the main D2 deformation phase. This schistosity is expressed in the sulphides as a compositional streaking of sphalerite, chalcopyrite or pyrrhotite and as a preferred orientation of silicates, e.g. amphibole, in the sulphide matrix.

Large scale isoclinal F2 folds with fold limbs up to 300 m long occur in intercalated chalcopyrite-pyrrhotite ores and in silicate and carbonate horizons of the western part of the ore body. Minor F2 folds, parasitic to the major folds, are common in thin silicate and carbonate layers. F2 axial planes are parallel to S2 schistosity (Fig. 3a and b). L2 lineations (F2 fold axes and L2 mineral lineations, Fig. 3c) show an arcuate distribution of subhorizontal WNW to NNE trends, the maximum of which trends NW, parallel to the regional trend of L2 lineations (Fig. 3 d).



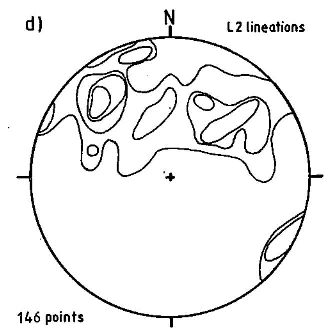


Fig. 3. D2 structures from the Joma mine (a–c) and Joma area (d) plotted on Lambert equal-area projection stereonets (lower hemisphere). S2 schistosity (a) and F2 axial planes (b) show similar distributions. L2 lineations for the mine (c) show a similarly oriented maximum to those for the area containing the outcrop of the massive sulphides (d). Contour intervals at 2, 4, 6, 8, 10, 15 points per 1% area.

Major F2 folds show thickened hinges and thinned limbs along which thrusting is a common feature. In the fold hinges, silicate horizons have suffered strong ptygmatic folding, demonstrating the higher competence of the silicate lithologies with respect to their sulphide matrix. Along fold limbs, chlorite schist layers have, in extreme cases, been sheared out to leave fold cores as isolated rafts in a sulphide matrix (Fig. 4). Where intercalated silicate horizons are less abundant, numerous thin slivers of sulphide are developed subparallel to the axial plane. These occasionally show folded, relict, compositional and textural layering in their cores, indicating that they represent original F2 fold cores. D2 quartz-calcite veining along the contacts and at sulphide layer terminations is common.

The majority of sulphide-greenstone contacts are sharp, close to planar over several metres, and commonly show highly polished surfaces. Layering within the sulphides and S2 schistosity are both cut by the contacts. Since the contacts show a high degree of planarity and crosscut S2 schistosity with no development of minor F2 folds, they cannot be older than D2 in age and this together with other features listed above, indicates that they are tectonic in nature. These sharp contacts are folded by F3 folds and are thus interpreted as being of syn-D2 age. Less common, gradational contacts between greenstone and sulphide which are folded and cut by layers of sulphides with sharp contacts, represent probable original contacts. These types of contacts are, however, rare and the majority of sulphide-greenstone contacts are tectonic.

A chalcopyrite-rich breccia ore commonly occurs along F2 fold limbs as en echelon lenses and interconnected layers in the sulphides and greenstone country rocks. The breccia fragments include banded pyrite-magnetite and fine grained pyrite ores, chlorite schist, greenstone, quartz, carbonate and pyrite grains set in a chalcopyrite-pyrrhotite matrix. The contact between breccia and other sulphide ore types is commonly gradational, showing the progressive formation of the breccia by the development of tectonic lenses separated by chalcopyrite-pyrrhotite matrix. The presence of a pre-existing foliation in the fragments, now disorientated and folded, indicates a tectonic origin for the breccia. This ore type is interpreted as a primary copper-rich pyrrhotite ore containing layered pyrite-magnetite horizons, which was part of the massive sulphide sequence (Olsen 1980, Reinsbakken 1986). Due to the extreme competency contrast between the pyrite-magnetite and pyrrhotite-chalcopyrite horizons, the ore was rapidly transformed into a breccia during deformation. Textures such as rolled and contorted fragments, rounded pyrite and quartz fragments and an increasingly finely streaked texture in the matrix towards the contacts, indicate that the breccias have acted as zones of concentrated shearing, allowing differential movement of adjacent blocks. Similar breccia ores of interpreted tectonic origin have been described from Bleikvassli and Birtavarre, Norway, by Vokes (1973) and from Ankarvattnet, Sweden, by Sundblad (1981). Vokes (1973) compares the textures of these breccias with the 'Durchbewegung' of German workers (e.g. Ramdohr 1960), a term used to describe the tectonic milling of rock fragments in a sulphide matrix.

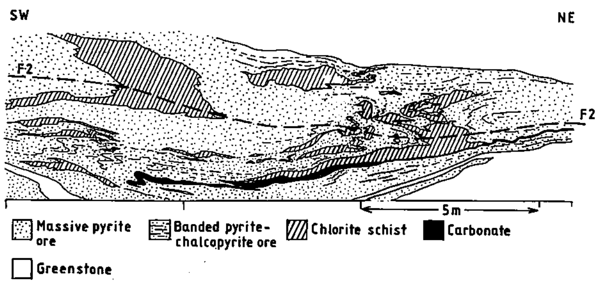


Fig. 4. F2 hinge zone in chalcopyrite/pyrrhotite-rich ores with intercalated carbonate and chlorite schist horizons showing disruption in the fold core. Minor F2 limbs have been sheared out leaving fold cores as isolated rafts in a sulphide matrix. Level 382, Joma mine.

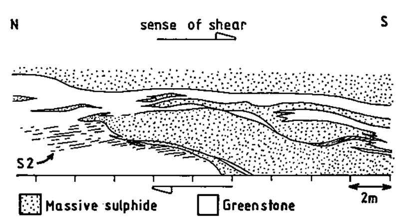


Fig. 5. Tectonic lenses of massive pyrite ore in greenstone showing sharp contacts which crosscut S2 schistosity in the greenstones. The relationship between S2 schistosity in the greenstones and greenstone-sulphide contacts indicates a sense of shear in which the overlying rocks have moved in a SE direction. Level 362, Joma mine.

Eastwards through the ore body, the silicate and carbonate horizons become less abundant and chalcopyrite-pyrrhotite ores give way to dominantly pyrite ores, with locally abundant sphalerite. This transition is accompanied by a change in the style of D2 deformation from folding to thrusting. Thus, in the eastern part of the ore body, large scale folds are rarely seen and the ore is composed of a series of thrust-bounded lenses. Smaller scale lenses of massive sulphide separated by greenstone are common at the terminations of larger lenses (Fig. 5), and thin layers of sulphide interleaved with the greenstones commonly occur at massive sulphide lens contacts. Within the massive sulphide lenses, thin layers (1 mm to 0.5 m) of chlorite schist, actinolite schist and carbonate, laterally continuous over several tens of metres, commonly separate different ore types. These layers often split and rejoin, enclosing lenses of massive ore and can be traced to the major sulphide-greenstone contacts. The lateral continuity of the layers regardless of thickness and their separation of different ore types suggests that they mark the location of thrusts within the massive sulphide ores. As in the western part of the ore body, all sulphide-greenstone contacts are sharp and commonly display discordance with internal layering in the sulphides and S2 schistosity in the greenstones, showing that they are tectonic in nature.

Evidence for early D1 deformation

In the above discussion, the sharp sulphide-greenstone contacts are interpreted as tectonic in nature. If all tectonic contacts in the ore horizon were of D2 origin, original sulphide-greenstone contacts should be preserved in the major F2 fold hinges. However, original gradational contacts do not preferentially occur in F2 fold hinges and features of tectonic origin, e.g. thin chlorite, greenstone and carbonate horizons interpretated as thrust planes and thrust-bounded sulphide layers and lenses, are folded in F2 hinge zones. This suggests a phase of deformation pre-dating F2 folding which can be correlated with the D1 phase identified in the quartzitic phyllites of the Joma area. No major D1 structures, S1 schistosity or L1 mineral lineation have been identified in the ore horizon, and it is therefore likely, as is the case of D1 in the quartzitic phyllites, that this phase of deformation represents an early expression of the D2 deformation which has become refolded later in the same event.

Determination of the D2 sense of shear

The main phase of deformation, D2, correlates with thrusting on the lower contact of the middle greenstone and with the major nappe emplacement event. D2 deformation can therefore be expected to have involved a large component of simple shear which is consistent with the abundance of tectonic contacts and thinning of F2 fold limbs. Within the ore horizon, the sulphide-greenstone contacts represent thrust planes and the mineral lineations in highly sheared country rock probably approximates the shear direction.

The vergence of minor folds in a shear zone is commonly used to determine the shear sense. However, due to the large competence contrast between the sulphide and silicate or carbonate lithologies, minor fold hinges which develop initially perpendicular to the shearing direction rotate rapidly towards this direction with progressive shear. All F2 fold axes measured in the ore horizon plunge subparallel to the L2 mineral lineation (shear direction) and therefore could not be used to determine the shearing sense.

In simple shear, schistosity first develops at an initial angle of 45° to the shear zone boundary, rotating towards it with increasing shear. The intersection between the schistosity and the shear zone boundary remains, in theory, perpendicular to the shear direction. In the ore body, the angle between S2 schistosity and the sulphide-greenstone tectonic contacts ranges from 0° to 30°, and a plot of the intersection lineations calculated from schistosity-contact orientation pairs shows a wide range of subhorizontal trends with a concentration subparallel to the L2 mineral lineation (Fig. 6a). Thus, in practice, inhomogeneous shear causes the intersection trend to become highly variable as the schistosity approaches the shear plane, with a tendency to rotate towards the shear direction (L2 lineation). Where the intersection lineation has remained oblique to the shearing direction, the relationship between the schistosity and contact orientations gives the shear sense.

The shear sense is most easily determined in sections oriented subparallel to the shear direction (L2 mineral lineation), i.e. NW-trending. The majority of sections with this orienta-

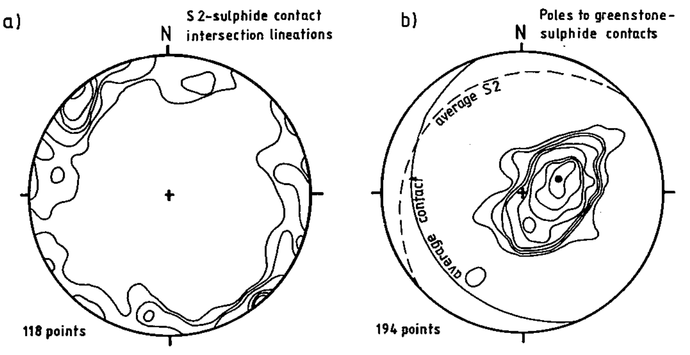


Fig. 6. The relationship between S2 schistosity and sulphide-greenstone contacts. (a) Stereoplot of intersection lineations formed by S2 schistosity in greenstone and greenstone-sulphide contacts. The maximum for the distribution is subparallel to the maximum for L2 lineations. (b) Poles to sulphide-greenstone contacts show a point distribution with a maximum indicating a gentle westerly dip. The intersection of the average sulphide-greenstone contact and average S2 shows a similar orientation to the maximum for intersection lineations in (a). Contours at 2, 4, 6, 8, 10, 15, 20, 25 points per 1% area.

tion give a SE movement direction for the overlying rocks, an example of which can be seen in Fig. 5. This is in agreement with the shear sense indicated by small scale dulpex, imbricate structures and folds in the breccia ore and thrust slivers of sulphide in greenstone at the margins of the massive sulphide lenses. In some cases, the reverse sense of shear is indicated by internal thrusts, suggesting that some lenses have moved faster than others, thus producing reversed shear on some internal tectonic contacts.

D3 deformation

D3 deformation is expressed in the ore body as tight to open F3 folds superimposed on D2 structures. They are associated with an S3 crenulation cleavage developed in the greenstones and silicate layers intercalated with the sulphides. F3 folding is most intense in the western part of the ore body, where it causes a steepening of the ore body dip (Fig. 2). D3 deformation is characteristically inhomogeneous and F3 folds, impersistent both along strike and down dip of their axial planes, are grouped in lens-like pods of strong D3 deformation.

F3 folds in the greenstone country rocks of the ore body have moderately to steeply NW-dipping axial planes and gently SW-plunging axes, in agreement with the regional orientation. F3 folds which involve the greenstone-sulphide contacts show a rotation towards more shallowly dipping axial planes and more westerly hinge trends in the sulphides. Thus, a plot of poles to D3 axial planes and crenulation cleavage in the mine area (Fig. 7a), shows a trend overlapping with that of the regional F3 orientation (Fig. 7c) but with a maximum indicating shallower dips. D3 fold axes and lineations (Fig. 7b) show a maximun corresponding to the regional orientation (Fig. 7d) with a further trend towards more westerly plunges. Such rotation of F3 folds towards F2 orientations suggests a reactivation of shearing along D2 thrust planes during D3.

The reactivation of D2 thrust planes is also suggested by the discontinuity in F3 folding of adjacent contacts of silicate pods and layers within the sulphides. F3 folds in one contact die out along the trace of their axial planes, within the distance of one fold wavelength,

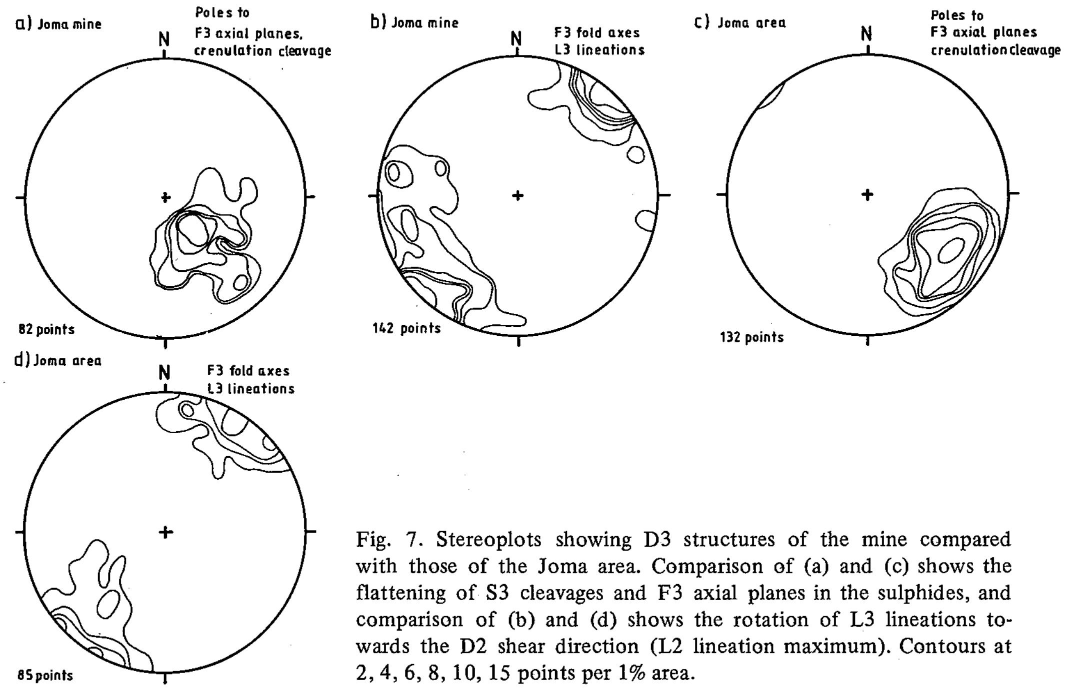


Fig. 7. Stereoplots showing D3 structures of the mine compared with those of the Joma area. Comparison of (a) and (c) shows the flattening of S3 cleavages and F3 axial planes in the sulphides, and comparison of (b) and (d) shows the rotation of L3 lineations towards the D2 shear direction (L2 lineation maximum). Contours at 2, 4, 6, 8, 10, 15 points per 1% area.

suggesting that the shortening accomplished by the folding in one contact has been accommodated by shearing on the adjacent contact (Fig. 8a, b and c). The breccia ore also

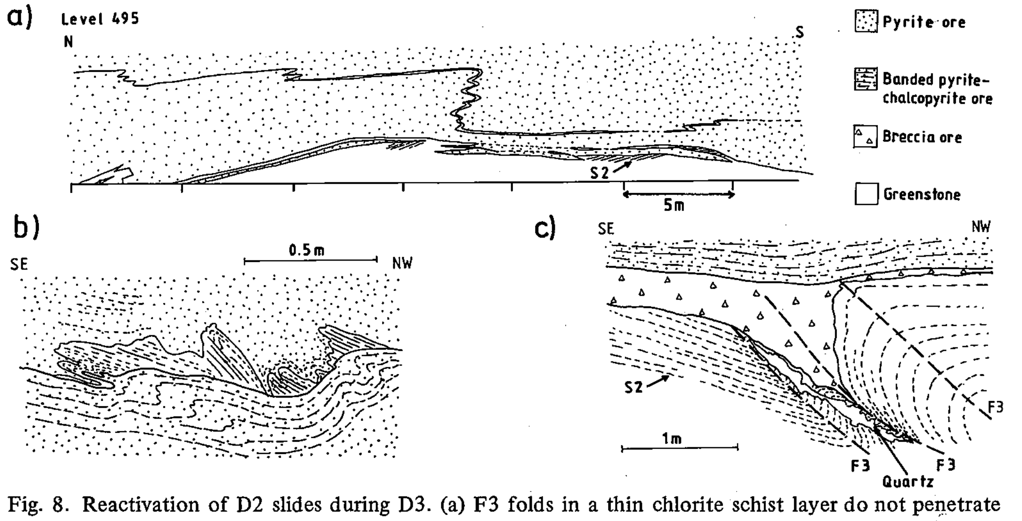


Fig. 8. Reactivation of D2 slides during D3. (a) F3 folds in a thin chlorite schist layer do not penetrate the main sulphide-greenstone contact. Level 495, Joma mine. (b) Minor F3 folds in a greenstone lens, lying on a D2 thrust plane, do not fold the lower contact. Level 387, Joma mine. (c) F3 fold in sulphide-greenstone contact does not fold the layering in the overlying sulphides. Level 375, Joma mine. In all cases the discrepancy in D3 shortening has been accommodated by slip on D2 thrust planes.

shows reactivation in F3 hinge zones, in which the chalcopyrite-pyrrhotite matrix has penetrated along F3 axial planes partially fragmenting the adjacent silicate lithology.

Abundant fractures of D3 age, crosscutting S2 schistosity, occur in the greenstones and, to a lesser extent, in the silicate layers intercalated with the sulphides and massive pyrite ores. They occur as single or en echelon sets of fractures forming lensoid veins up to 2 m long and 15 cm broad which are filled dominantly by quartz and calcite (sometimes fibrous), with variable amounts of chlorite, stilpnomelane, actinolite, chalcopyrite and pyrrhotite. Two sets of fractures occur (Fig. 9a). The dominant set is subparallel to S3 and is found most commonly along F3 axial planes. The sense of displacement across these fractures is in agreement with the sense of shear required to produce F3 folds. The fractures of the subdominant set, dipping steeply SE, are smaller and show lesser amounts of offset with an opposing sense of shear. The two sets variably offset each other and are therefore coeval.

Reactivation of the D2 thrust planes during D3 is indicated by the behaviour of D3 structures in the sulphides. Since this reactivation has not produced a new mineral lineation or rotation of the L2 lineations, the shear direction was probably similar to that of D2 shearing. Fig. 9b shows a synthesis of D2 structures with the average D2 sulphide-greenstone contact representing the D2 shear plane and the L2 mineral lineation, the shear direction. Also shown is the initial orientation of the foliation developed in such a shear zone which forms at 45° to the shear plane and intersects the D2 shear plane parallel to the D2 Y strain direction. The average F3 fold axial plane shows an orientation very close to that for the initial foliation. The average F3 fold hinge also lies close to the D2 Y strain direction, i.e., perpendicular to the D2 shear direction (L2) which is the expected initial orientation of fold hinges formed by D2 shearing. D3 fractures occur in two sets, one subparallel to F3 axial planes and the second subperpendicular to the D2 thrust planes. This second set has a similar orientation and sense of offset to D2 antithetic shears, i.e. 90° to the D2 shear plane (Fig. 9c). D3 structures therefore show a close relationship to D2 deformation, indicating that D2 and D3 phases of deformation are essentially coaxial.

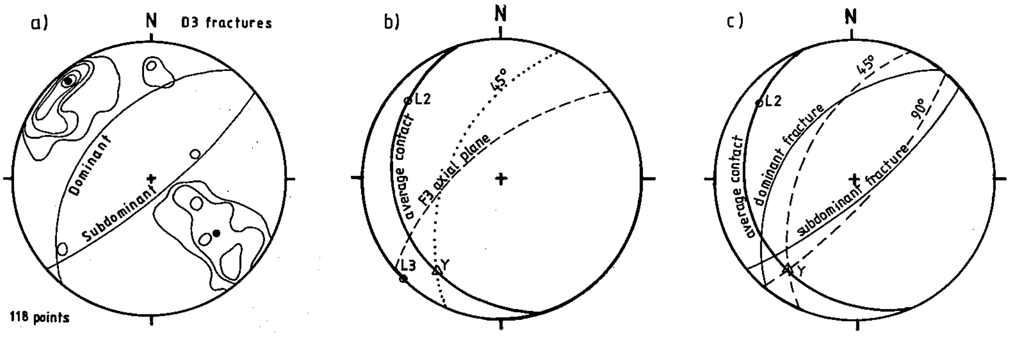


Fig. 9. (a) Stereoplot showing the distribution of D3 fractures and veins showing two maxima. Contours at 2, 4, 6, 8, 10 points per 1% area. (b) Stereoplots showing the relationship between D2 and D3 structures and (c) the relationship between D3 fractures and D2 structures. See text for explanation.

Summary and conclusions

The variation in deformation style across the Joma ore body, which can be correlated with present sulphide mineralogy, reflects a change in the mechanical properties of the ore. In the western section of the ore body, the ptygmatic folding and disruption of silicate layers within the sulphides indicate a high competence contrast between the sulphides (incompetent) and their silicate country rocks. This has led to the development of large scale F2 folds with thickened hinges and sheared limbs. High mobility of chalcopyrite and pyrrhotite is indicated by the formation of breccia ore and the presence of thin breccia layers tectonically emplaced into the greenstones. The extreme attenuation of F2 folds and the modification of F3 fold orientations within the sulphides indicate a concentration of deformation in the sulphides during both D2 and D3 phases.

In the eastern section of the ore body, where the ore is dominantly pyrite and sphalerite with quartz or carbonate as matrix minerals, deformation is expressed as movements along thrust planes marked by thin silicate horizons. While deformation within the particularly sphalerite-rich ores can be intense, producing a strongly streaked appearance, most pyrite ores contain only minor sphalerite and show generally low states of internal deformation, occasionally preserving original framboidal textures (Horbach & Leissmann 1985). The dominance of thrusts and slides over folds and the lower states of internal deformation indicate that pyrite ores are more brittle and less mobile than the chalcopyrite-pyrrhotite ores. However, the abundance of thrust and slide planes suggests that the pyrite dominated ores have a markedly lower brittle strength than the greenstone country rocks. Thus, under the conditions of greenschist facies metamorphism, all sulphide ore types show a lower competence than greenstone but the pyrite dominated ores, having a lower fracture strength, deform in a brittle fashion whereas the chalcopyrite-pyrrhotite ores, which are more mobile, deform largely plastically.

D3 deformation folds the D2 thrust planes, indicating that major movement on them had ceased by D3 times. During D2, the differing intensities of deformation in sulphides and silicates were accommodated by movement along thrust planes, leading to the development of tectonic lenses and interlayering of sulphide and greenstone country rock. Fracturing and vein development occurred largely along these thrust planes or parallel to S2 schistosity in the country rocks. During D3, however, these thrust planes became locked with respect to major movements and the greater amount of shearing occurring in the sulphides could not then be accommodated by movement along them. This could have resulted in tension within the greenstones adjacent to the sulphides which may have caused the extensive fracturing along F3 axial planes.

The Leipikvattnet Nappe is composed of a series of imbricate slices of greenstone and phyllite. This imbrication formed as thrusts cut up section through the relatively competent greenstone layer, so that a thrust now forms the base of each greenstone unit. In the middle greenstone, the ore body shows increasing deformation towards, and is cut by, the thrust at the greenstone lower contact. It is probable that the heterogeneity produced by an incompetent sulphide body in competent greenstone country rocks provided a weak point in the greenstone unit which then acted as a focussing mechanism during the initiation of thrusting.

Acknowledgement. The above work was completed as part of a postdoctoral project at Geologisk Institutt, N. T. H., Trondheim, Norway, while the author was in possession of an N.T.N.F. postdoctoral fellowship. The work formed part of a project on the Joma ore deposit which was financed by N.T.N.F., grant No. NB10.15042, and by Grong Gruber A/S. I would like to thank Prof. F. M. Vokes and A. Reinsbakken for their help during the project and Prof. F. M. Vokes, E. Zachrisson and A. G. Milnes for critically reading the manuscript.

References

Halls, C., Reinsbakken, A., Ferriday, I., Haugen, A. & Rankin, A., 1977: Geological setting of the Skorovas orebody within the allochthonous stratigraphy of the Gjersvik Nappe, central Norway. – I.M.M., Geol. Soc. London, Spec. Pap. 7, 128–151.

Horbach, R. & Leissmann, W., 1985: Lagerstättenkunde schichtgebundener Sulfidvererzungen: Paragenese, Geochemie und Genese der Vererzungen im Joma-Gebiet (Norwegen). – Unpubl. prog. rep. Univ. Clausthal, Germany, 120 pp.

Kollung, S., 1979: Unpublished 1:50,000 geological map of the Huddingsvatnet area.

Logn, O. & Bølviken, B., 1974: Self potentials at the Joma pyrite deposit, Norway. – Geo-exploration. Elsevier Sci. Publ. Co., Amsterdam, 11–28.

Lutro, O., 1979: The geology of the Gjersvik area, Nord-Trøndelag, central Norway. – Norges Geol. Unders. 354, 53–100.

Munster, K., 1915: Rapport over Joma kisforekomst. – Publ. Kongsberg, 185 pp.

Odling, N. E., 1986: The geology of the Joma sulphide deposit, Nord-Trøndelag, Norway. Part I: Structural studies of the ore and surrounding area. – Unpubl. rep. Geol. Inst. N.T.H. Univ. Trondheim, 58 pp.

Olsen, J., 1980: Genesis of the Joma stratiform sulphide deposit, central Norwegian Caledonides. *In* Ridge, J. D. (ed.): Proceedings 5th Quad. IAGOD Symposium. – E. Schweizerbart'sche, Stuttgart 745–757.

Olsen, J., 1984: Joma – geologisk beskrivelse, sammenstilling av resultater fra kartlegging 1975–1977. Intern. rep. Grong Gruber A/S, 54 pp.

Ramdohr, P., 1960: Die Erzmineralien und ihre Verwachsungen. – Akademie Verlag, Berlin, 1089 pp.

Reinsbakken, A., 1986: The geology of the Joma sulphide deposit, Nord-Trøndelag, Norway. Part II: Stratigraphical, petrological, mineralogical and geochemical studies of the ore and its surroundings. – Unpubl. rep. Geol. Inst. N.T.H. Univ. Trondheim, 70 pp.

Roberts, D., 1979: Structural sequence in the Limingen-Tunnsjøen area of the Grong district. – Norges Geol. Unders. 354, 101–114.

Sjöstrand, T., 1987: Caledonian geology of the Kvarnbergsvattnet area, northern Jämtland, central Sweden: stratigraphy, metamorphism, deformation. – Sveriges Geol. Unders. C 735, 107 pp.

Stephens, M. B., 1986: Metallogeny of stratabound sulphide deposits in the central Scandinavian Caledonides. *In* Stephens, M. B. (ed.): Stratabound sulphide deposits in the Central Scandinavian Caledonides. – Sveriges Geol. Unders. Ca 60, 5–16.

Sundblad, K., 1981: Chemical evidence for, and implications of, a primary FeS phase in the Ankarvattnet Zn-Cu-Pb massive sulphide deposit, central Swedish Caledonides. – Mineral. Deposita 16, 129–146.

Vokes, F. M., 1973: 'Ball texture' in sulphide ores. – Geol. Fören. Stockh. Förh. 95, 403–406.

Zachrisson, E., 1984: Lateral metal zonation and stringer zone development, reflecting fissure-controlled exhalations at the Stekenjokk-Levi stratabound sulfide deposit, central Scandinavian Caledonides. – Econ. Geol. 79, 1643–1659.