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The Main Joma Project: The Second Progress Report For Grong Gruber A/S

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Råstoffgruppe	Råstofftype
Malm/metall	Cu,Zn

Sammendrag, innholdsfortegnelse eller innholdsbeskrivelse

Prosjektet er et sammarbeid med Geologisk Institutt på NTH.
Inneholder en bergartsbeskrivelse av de typer som opptrer i gruven, referert til forskjellige nivå og de forskjellige malmtyper.
Straigrafi og strukturer er hovedtemaet. Kompliserte geometriske elementer blir introduert og diskutert.
Deformasjonsrekkefølge blir foreslått.

THE MAIN JOMA PROJECT

SECOND PROGRESS REPORT
FOR
GRONG GRUBER A/S

by
BRIAN MARSHALL

November, 1984.

I. INTRODUCTION

This report, which supercedes the First Progress Report dated October 1 1984, reflects 5 weeks at Joma mine and 10 weeks at NTH. Report writing and microscope work will continue concurrently until November 28 when I leave Trondheim.

In the present report, a full account will be given of data collected at Joma and data generated by work at NTH. Separate sections will be devoted to interpreting the data and discussing unresolved problems. Matters meriting specific attention in the upcoming season will be emphasised.

Throughout the report, AR is Arne Reinsbakken, NEO is Noelle Odling and MJP is the Main Joma Project. Where localities are referred to, a locality number and figure number will be given and will relate to the field maps in appendix A. Additional appendix sections are denoted B, C etcetera.

Standard symbols are used for sulphides (e.g. po = pyrrhotite, cp = chalcopyrite) and carbonate is written CO_3. These and other abbreviations that may be used are in accordance with common practice. Symbols for fabric elements basically follow Bell and Duncan (1979), but minor modifications have been made to satisfy current needs.

Grain size in sulphides is classified according to the following handspecimen system:

very coarse	greater than 5 mm
coarse	2-5 mm
fine	unresolvable with the unaided eye
very fine	unresolvable with a X10 handlens

Throughout the report, amphibole needles are loosely termed actinolite since, in thin section, some have proved to be pleochroic with an extinction angle of 14-15^{o}. In most cases, the amphibole probably belongs to the actinolite-tremolite series, but orthorhombic amphibole has been recorded and hornblende is possible.

Time constraints will probably preclude adequate drafting of many figures and may similarly preclude typing. This is because I have aimed to make the report comprehensive rather than cosmetic.

Although previous work has been examined, it will not be evaluated. Reference to previous work will be minimised and sources of data will be cited only when deamed essential.

Much of the remaining portion of this introduction comes from the First Report but the subsection on progress has been revised.

1. OBJECTIVES

(a) To document the differential response of sulphide, sulphide-silicate and silicate rocks at meso- and micro-scales, to the structural events in the immediate mine area.

(b) To place physicochemical constraints on the structural-metamorphic environment.

2. PROGRAM

2.1. In Røyrvik

(a) Opencut and subsurface mapping of mesoscale data from the viewpoints of:
- (i) defining planar and linear fabric elements in terms of their hand-specimen characteristics;
- (ii) defining fold styles;
- (iii) ordering (i) and (ii) by way of overprinting relations;
- (iv) obtaining representative orientation data.

(b) Sampling of quartz veins and bodies for the purposes of fluid inclusion studies relative to 1 (b).

(c) Sampling for possible stable isotope and geobarometric studies pertinent to 1 (b).

(d) Sampling for microstructural investigations as in objective 1 (a)

2.2. <u>In Trondheim</u> (Sept. 10 - Nov. 28)

(a) Compilation of data from 2.1 (a) and effecting an orientation analysis on the Lambert equal area net.

(b) Slabbing of samples and preparation of polished thin sections as a basis for refining mesoscale data and effecting microscale analysis.

(c) Microstructural investigation of sulphide, sulphide-silicate and silicate assemblages.

(d) Writing up the results as an internal report and preparation of data for publication.

(e) Preparation of samples for fluid inclusion, stable isotope and geobarometric work.

2.3. <u>In Sydney</u> (post-February, 1985)

(a) Effect fluid inclusion, stable isotope and related studies.

(b) Compile results into a final internal report and prepare data for publication.

3. PROGRESS

As of Nov. 7, slabbing is complete, and oriented slices have been submitted for thin section, polished thin section and polished mount. One-third of these have been received and have been subjected to preliminary microscopic examination. The remainder should be received by late November, but this will only permit a cursorary examination. Supplementary work will be necessary in Australia.

A stratigraphic evaluation of the immediate mine sequence has been effected, but results are problematical in that one has to <u>assume</u> an original stratigraphy in order to interpret rock relationships disrupted by extensive folding and thrusting. The structural analysis is complete and the differential response of sulphides and silicates to the differing events can be documented.

Sample preparation for fluid inclusion and other laboratory studies will not be possible in the remaining weeks. Some specimens have therefore been forwarded to a colleague in Sydney for fluid inclusion work. It is hoped that additional samples will be available for sending to Australia by month-end.

II. ROCKTYPES AND SEQUENCE

1. INTRODUCTION

AR is principally concerned with documenting the differing ore and host rock types in terms of their chemistry and mineralogy. The ensuing sections are therefore, at best, a framework for AR's investigations. They constitute a personal assessment, will not necessarily express AR's views and may not withstand AR's detailed investigations in 1985-86. Further, since many mounts and slides are unavailable, it could eventuate that much of this section will be based on mesoscale data.

The section will examine the lithology of silicate rocks and ore types before presenting an account of rock sequence on the various mine levels mapped. Stratigraphic interpretation of these data necessarily depends on the structural interpretation which is itself partly dependent on stratigraphy. In consequence, although stratigraphy will be considered here, it will be reviewed in section......

2. SILICATE ROCKS

The principal units comprise:

(a) the HW and FW greenstones;
(b) chlorite schists;
(c) albite laminite.

None of these were systematically sampled from the viewpoint of establishing mineralogical variation within a rock unit.

2.1. HW and FW greenstones.

In an area of isoclinal folding it is conceivable that the FW in one level is the HW in the next (Fig. 1a); it is also conceivable that the HW and FW are the same rock unit (Fig. 1b). I therefore emphasise that the HW and FW terms are only applicable to the particular level specified and have no stratigraphic implication.

(a) Open cut - level 560 (Fig. A1)

The HW greenstones contain abundant pillows (10-20 cm across) in sequences in the order of 50 cm thick. The sequences have intercalations up to 3 cm thick of finely laminated tuff(?). Abundant py-po veins and laminae with diffuse margins crosscut and parallel the principal layering close to the albite laminite. This "stockwork" appearance is partly due to remobilization of sulphides during the structural-metamorphic history, but the suggestion that these rocks are part of the feeder system has considerable merit.

The FW greenstones at the NE end of the open cut also have pillows and intercalated tuffs, but along the E side, the pale grey-green greenstones have a discontinuous layering (1-3 cm thick). This could represent a tuff layering or extremely flattened pillows; I favour a tuff origin. The rocks contain abundant CO_3 as an integral component and as segregations.

At locality 8 (Fig. A1) a lenticular layer of zoned exhalite (qtz-CO_3-magnetite) is developed approximately 1 m from the sulphide contact.

(b) Level 495.

The HW rocks at the S end (101, Figs. A2, B1) of 495 consist of 1-5 m of layered (1-3 cm) and well foliated greenstone, overlain by 0.5 m of layered darker green greenstone with abundant py-po disseminations and laminae. This passes upward into lighter coloured, less well layered greenstone.

At the N end (111, Figs. A2; B1), the sulphides abut 20 cm of chlorite-rich, darker green, cleaved (S_2) greenstone with CO_3 bands, before passing upward into layered lighter coloured greenstone.

The FW rocks consist of chloritised greenstone with thin (110-30 cm) po-exhalite bands near or at the contact (101, Figs. A2, B1); or a light to dark grey chlorite-muscovite-albite-sphene phyllite (with lenticular po-exhalite intermittently developed at the contact) over 'normal' layered greenstone (104, 108, 114, Figs. A2, B1). The phyllite-greenstone relationship was not seen.

(c) Level 387.

The stope height impeded examination of HW rocks. However, at localities 1 and 25 (Figs. A3, B2) it appeared to be a chlorite-rich dark coloured greenstone, whereas at 17, 19 and 21 (Figs. A3, B2) the rocks are well layered pale greenstone.

FW rocks at localities 3 and 5 (Figs. A3, B2) consist of a very pale grey-green layered greenstone. In thin section the rock comprises (by estimation) zoisite-clinozoisite 20-30 %, tremolite-actinolite 35-45 %, albite 10-20 %, chlorite 15-25 % and sphene 5 %. The layering reflects the variation of amphibole against albite-zoisite. A similar rock is at locality 24 (Fig. A3), but 3 m south along the wall the greenstone is darker, contains po disseminations and is chloritized.

(d) Level 375 and 375 synk.

Neither HW nor FW rocks were closely examined on level 375. However, well layered medium grey-green greenstone is in the HW at 91 to 93 (Fig. A4).

The HW greenstone in 375 synk was examined at two accessible locations (75, 122, Figs. A4, B3). Specimen 75 is a very fine grained homogeneous chlorite rock with CO_3 layers paralleling the contact; specimen 122 is similar. In thin section the rock comprises (estimation) high birefringent (1st order white) chlorite 70-80 %, actinolite-tremolite 15-25 %, sphene up to 5 % and sulphides up to 5 %.

The FW rocks in 375 synk comprise a dark grey "transition" sequence (section 2.2), which is intermittent, over medium grey-green CO_3 rich greenstones.

(e) Level 362.

The FW at 39(a) (Fig. A5) consisted of medium grey-green to pale green layered greenstone. The HW rocks were not examined.

2.2. <u>Chlorite schists.</u>

Chlorite is a constituent of all greenstones, the white mica phyllites (section 2.3) and albite laminites (section 2.3). However, chlorite+actinolite$\pm$biotite$\pm$sulphide assemblages are developed independent of this and form characteristic rocks which are here grouped as chlorite schists. These rocks are described as a function of the principal situations in which they occur.

(a) 'Transition' rocks.

The term may seem inappropriate because the zone generally has sharp contacts with the abutting greenstones and massive sulphides. However, transitional boundaries probably existed before the deformation events and since the term was used in the field it is retained here.

The rocks are dark green-black, have a moderately well developed foliation and vary from phyllites to schists, the boundary being the ability to resolve grains with a X10 handlens. The mineralogy is chlorite, brown mica (often porphyroblastic), actinolite needles, albite, sphene, CO_3 and sulphides. Although py, cp and sp may be present, po is the principal sulphide and occurs as laminae parallel to layering, ellipsoidal blebs within cleavage, and irregular late stringers. The sulphides range from 5 to 20 % of the rock.

The 'transition' rocks are well developed on level 375 synk (60 to 69, Figs. A4, B3), throughout level 375, and on level 387 (3, 24 Figs. A3, B2).

In polished thin section (64A, 64C Fig. A4), estimated silicate percentages (silicates 100 %) are anomalous brown and higher birefrency chlorites 50-55 %, actinolite-tremolite needles 20-25 %, albite 20-25 % and sphene up to 5 %.

Estimated sulphide percentages are po 60 %, cp 15 %, py 15 %, sp <10 % and gn < 3 %. Brown mica was absent, its place probably being taken by one of the chlorites.

(b) Spatially associated with albite laminite and cp ore.

This association has been described by Olsen (1980, p. 751) and was not examined in the present investigation. However, 'transition' rocks and Olsen's chloritic schist are patently similar and are probably the same unit.

Examples of the association occur on level 387 at localities 1-3, 8-10, 19, 22, 23 and 25 (Figs. A3, B2).

(c) As screens in massive sulphide.

These are well displayed at the S end of the open cut, but occur on most levels. They are discontinuous, irregular layers rapidly varying from a few mm to tens of cm in thickness; CO_3 layers and segregations are common associates. They vary from medium to dark green-grey chlorite dominated rocks to lighter coloured chlorite-mica assemblages. The screens are interpreted as slivers along thrust surfaces.

2.3. Albite laminite (Abl).

Olsen (1980) described massive and fragmental albite rocks, but in the levels examined for the MJP, the rock comprises white, pale grey and faun laminae (1 to 15 mm thick) intercalated with pyrite laminae of similar thickness. Other than where folded intrafolially or thickened in hinge zones, Abl was less than 40 cm thick in the underground levels; a much thicker development occurs W of the open cut.

Variations between levels is expressed in two ways: first, Abl is absent from 375 and 362; second, there are mineralogical differences.

(a) Level 495.

Two rocks from the same locality (108, Fig. A2) vary as follows:

Slide 108 B Sulphide laminae
45-55 % sulphide
40-45 % chlorite (1st order grey-white)
5-10 % white mica
<1 % sphene
<1 % albite

Silicate laminae
75-85 % white mica
5-10 % chlorite (as above)
5-10 % sphene
5 % albite

Obviously the term albite laminite is inapplicable yet the rock was collected from the Abl horizon and could be 'walked into' Abl over a few m.

Slide 108A Sulphide laminae
55-65 % sulphide (py+sp)
15-25 % whitemica
15-25 % albite
<1 % sphene

Silicate laminae
80-85 % albite
5-15 % white mica
5-10 % sphene
<5 % sulphide
<5 % chlorite

(b) Level 387.

The mineralogy includes albite, brown mica, chlorite (anomalous brown-blue interference colours), sphene and sulphides in proportions that vary with differing laminae. Brown mica has take over from white mica and the chlorite character has changed sympathetically.

Thus, Abl varies from chlorite-white mica-sulfide laminated phyllite (minerals listed in decreasing abundance order) through albite-sulphide-white mica laminite to albite-brown mica-chlorite-sulphide laminite. Perhaps not surprisingly the trend continues and they pass along and across strike into darker green chlorite schists of 'transition' affinity.

The percentage of sulphide is very variable. At the open cut sulphides parallel and crosscut the lamination in a manner which supports the notion that Abl is part of the feeder alteration assemblage. In 387 sulphides are a minor constituent.

White mica is used above to cover the possibility of phengite and paragonite. Lack of K_2O (Olsen, 1980) would indicate that paragonite is the dominant white mica.

Brown mica (above) is either biotite or phlogopite. Olsen (1980) reports phlogopite but this has not been verified in the present work.

3. SULPHIDE ROCKS

Olsen 1980 established two principal oretypes; massive pyritic ore and 'durchbewegt' chalcopyrite-pyrrhotite ore. This is overly simplistic since there are many variations within these two broad categories. Nevertheless, a balance must be struck between subtle variations of limited extent and the more persistent variations that are of concern to exploitation. With this constraint in mind, the following subtypes are recognised within the umberella of Olsen's principal types.

This account is based on mesoscopic examination since polished sections are currently unavailable.

3.1. Pyritic oretype.

Py, po, cp, sp and rare traces of gn characterise most Joma pyritic ore, the subtype character is therefore based on dominant sulphide, gangue constituents and structural features.

3.1.1. Massive fine grained (MFG) subtype.

This comprises extremely homogeneous very fine and fine grained ore. The dominance of pyrite in the subtype is conveyed by the very pale silvery yellow colour of fresh ore; the very fine grainsize by the subconchoidal blasting-induced fracture. In the truly massive subtype gangue is not visible with a X10 handlens and there is no effervescence with HCl. With oxidation the surface yellows (moreso than with other subtypes) but maintains a homogeneous aspect.

Due to secondary tectonism, the subtype has suffered brecciation and recrystallization healing such that the very fine grained ore is cut by usually diffuse-margined veins of medium grained pyrite and gangue (Fig.2a). The veins may be irregular and decrease in spacing away from, for example, a phyllite screen (Fig. 2b), or be systematic and define a crude foliation designated s_{fv} (Fig. 2c).

Some fractures have retained sharp boundaries and in consequence are largely infilled by gangue (Figs. 2b, c). Because of this, I believe that dilatancy produced discrete fractures, that fracture propagation was enhanced by fluid pressure (hydraulically assisted fracturing) and that the extent of sulphide recrystallisation was influenced by the local fluid chemistry. Whether the gangue was introduced by the fluid phase or recrystallized in situ remains uncertain. However, lack of the gangue constituent (not confirmed microscopically) in the fine grained ore would favour introduction.

Variants of the subtype may be distinguished by gangue mineralogy. The chief variant has CO_3, often accompanied by po and cp enrichment; other variants include actinolite+CO_3 and chlorite or brown mica.

The subtype is well developed at the S end of the open cut and on levels 495, 362, 402 (AR) and 416 (NEO). It has been termed "breccia ore" but should be distinguished from 'Durchbewegungen' structure that has also been termed brecciated and breccia ore (e.g. Juve, 1974).

3.1.2. Massive actinolite-rich (MA) subtype.

Where massive fine grained ore has actinolite mainly confined to veins in breccia ore, it is included in 3.1.1. However, when actinolite needles (oriented and/or disoriented) are distributed throughout the rock, a separate subtype is recognized. Whether the actinolite is wholly metasomatic, partially so, or totally metamorphic is not known, but relations in another subtype (section 3.1.5.) would suggest metamorphism in a relatively closed system.

The subtype is extensively developed on levels 495, 375 and in the open cut (localities 23 and 2, Fig. A1)

3.1.3. Massive medium-coarse grained (MMG) subtype.

Subtype 3.1.1. grades into MMG along the E side of the open cut (16-17, Fig. A1). Typical breccia ore appears to pass into a rock containing fine grained remnants gradational into an anastomosing network of wider veins of medium grained sulphide. In turn, this passes into more homogeneously recrystallized massive medium-coarse grained pyrite that has a "jewel box" appearance on the rare sunny day.

3.1.4. Banded fine grained (BFG) subtype.

This subtype (possibly because oxidation facilitates recognition) was only seen at the S end of the open cut (14, 15 Fig. A1).

The banding comprises layers (often < 1 cm) of very fine grained and fine grained pyrite (Fig. 3 a,b) which may pass into layers akin to subtype 3.1.1. (Fig. 3c). I have no doubt that the banding is primary and represents bedding. Whether the layering reflects direct chemical precipitation or mechanical redeposition is less certain, but I favour the former.

In most cases the very fine grained layers are preferentially overprinted by S_{fv}. This suggests that at the time of deformation they were relatively more brittle and less able to accommodate stress by intergranular adjustments. The compositional and grainsize differences have not been investigated microscopically.

3.1.5. Banded actinolite-rich (BA) subtype.

The subtype comprises fine to medium grained banded ore, on a scale of 0.25 to 1.5 cm, in which alternate bands contain numerous actinolite needles. The distinctive regular banding, with the exception of po which in one case was totally discordant, is interpreted as bedding and possibly expresses direct chemical precipitation; actinolite is therefore believed to be a metamorphic reflection of primary compositional variation.

The subtype occurs (inter alia) on level 375 (71, 75 and 89, Fig. A4).

3.1.6. Banded quartz-CO_3 (BQC) subtype.

This comprises fine to medium grained py in < 5 mm to 3 cm bands, within which are irregularly spaced (< 1 to 20 cm) discontinuous layers and streaks of grey-black fine grained rock. The layers (< 3 mm to 2 cm) frequently display intrafolial F_2 folds and consist of CO_3 (confirmed by HCl), quartz (probable and usually dominant) and possibly chlorite. In some cases a brown tinge is due to abundant magnetite. The pyrite banding, due to differential recrystallization, probably reflects the pegging influence of trace amounts of silicate and other minerals.

An exhalite origin is favoured for the silica rich compositional layering which is therefore construed as bedding.

The subtype is well developed at 69-72 (Fig. A4) and 17 (Fig. A3).

3.1.7. Banded sp (BS) subtype.

This is a major subtype and comprises fine to medium grained py, often displaying recrystallization banding, in which sp-rich layers (< 5 mm to > 5 cm) may range from regularly and closely spaced to irregularly and widely (around 1 m) spaced. A CO_3 rich gangue is usually present and may form streaks and somewhat more continuous laminae. The weathered ore has a pale faun to kahki colour.

A variant of this subtype has more siliceous gangue and may have abundant silica laminae that are possibly exhalogenic. Thus, a vertilateral gradation between BQC and BS is a distinct probability.

The CO_3 variant is seen in the W and E walls of the open cut and in most underground levels. The SiO_2 variant is best seen in 375 synk above locality 78 (Fig. A4).

3.1.8. Sulphides other than sp.

Throughout the banded and, less obviously, the massive subtypes, slight variations in po and cp characterise different bands and are ascribed to primary variation. In addition, deformation and recrystallization is invariably accompanied by migration (on the scale of mm) and coalescence of po and cp such that primary effects are enhanced and recrystallization zones are preferentially enriched.

3.2. Cp-po ore types.

As with 3.1 the ore microscope reveals traces of other sulphide species in addition to abundant pyrite and in places magnetite. Much of the ore type is 'durchbewegt' and thereby variable, but subtypes are recognisable on the bases of:

(a) the dominant sulphide;
(b) the character of silicate and pyritic subtypes in type (a) host;
(c) the structural setting.

I have done insufficient work to justify detailing the various subtypes, most of which would be restricted to levels 375 and 387. However some elaboration of (a), (b) and (c) is necessary.

Because all developments of cp and po are included in the ore types, one may recognize rich cp and po end members (e.g. cp layer at 77, Fig. A4; po layers at 61, 62, 69 Fig. A4) and a more "typical" cp-po 60:40 mix. "Typical" is parenthesised because despite my estimate that much of the cp-po has these rough proportions, po rich mixes were also observed.

In differing parts of level 375, the breccia fragments or clasts are chlorite schist, actinolite-chlorite rock, magnetite laminite, banded pyritic ore subtypes and vein quartz. I believe that all these are locally derived and that detailed mapping would yield a dismembered stratigraphy within the cp-po host. An obvious limitation to this is where the tectonism results in extreme mixing and transport away from the site of generation; few convincing examples were seen.

'Durchbewegt' structure can result from competence contrasts during fold-dominant or thrust-dominant deformation. Cp-po mineralization lacking 'durchbewegt' structure can concentrate during folding or thrusting. As a generalization fold-dominant deformation is likely to cause less clast mixing than cross-stratal thrusting; and at Joma, D_2 has produced 'durchbewegt' ores whereas D_3 has produced cp-po concentrations.

In summary, because the ore type is a tectonostratigraphic unit, subtypes must inevitably recognise tectonic and stratigraphic inputs.

4. ROCK SEQUENCE

The HW and FW sequence at selected localities on each level other than the open cut and 362 are in appendix B. The localities may be found on the respective figures in appendix A. Where folding has influenced the sequence, this is indicated on the sections. Possible thrusting is also shown but this is not comprehensive since most sharp contacts could be thrusts.

4.1. Level 560 - open cut.

A representative column from HW to FW or W to E is in Fig. 4a, the ensuing items being in elaboration of the figure.

(a) The silicate HW variously comprises pillow lavas (section 2.1 (a)), albite laminite and veinite (section 2.3.(a)) and blue-grey chloritic phyllite; thinly layered greenstone occurs as an infold (3, Fig. A1).

In section 2.3 it was suggested that the phyllite is part of the albite laminite stratigraphy, but irrespective of that, the contact with sulphides abuts two silicate rock types. This is due either to:

(i) the Abl facies having a limited distribution; or,

(ii) the contact being at least partly faulted.

Item (ii) is the more probable.

(b) The HW sulphides are mainly the BS subtype although in places (between 2 and 11, and 13 and 4, Fig. A1) there is very little sp and scarce banding is due to po. In the SW and NW corners of the open cut, BA and MA subtypes occur. Thus, the contact abuts at least two sulphide subtypes. This could result from either:

(i) faulting or thrusting along the contact and/or within the sulphides; or,

(ii) facies variation in the sulphides.

Whilst 'vertilateral' facies changes in sulphides are well established, there is no good reason to invoke it when faulting has been already advocated in (a).

(c) The HW sulphides are underlain by MFG and BFG subtypes.

(d) The FW sulphides variously comprise BS, MMG, MFG abd BFG subtypes. Thrusting of the contact again seems the most likely explanation.

(e) Pillow lavas and layered greenstones with abundant CO_3 abut the contact.

(f) The thickness of sulphide, uncorrected from folding or thrusting is:

(i) 25-30 m at the S end on a 50^{o} dip;
(ii) 25-30 m at the N end using a 60^{o} dip.

These figures match borehole intersections from beneath the open pit. The amount of thickening induced by thrusting and folding cannot be gauged.

4.2. Level 495.

The sequence based on Fig. B1 and schematically presented in Fig. 4b is:

HW greenstones with well developed layering and disseminated sulphides (section 2.1. (b)).

MFG with minor MA subtypes - CO_3 layers are common, particularly near the HW.

CO_3 layer (10-20 cm) together with intermittent slivers (?) of chlorite schist (section 2.2 (b)) and Abl (section 2.3 (b)) separate the MFG subtype from underlying BS.

BS subtype with intermittent thin layer of Abl and/or chlorite schist or phyllite - the Abl overlies chlorite schist when both are present.

MA subtype in one part of the level (between 102 and 105, Figs. A2, B1).

FW chlorite-white mica phyllite with exhalite, passing down into greenstone.

The sulphide sequence has an uncorrected thickness varying from 3.25 to 10 m. The effects of thrusting cannot be unraveled. One may adopt Occam's razor and construct the simplest section in which each unit is present only once (this yields 6.5-7.5 m), but it is a construction of preference rather than geologic fact.

4.3. Level 387.

Much thrust repetition occurs (e.g. 25, Fig. B2), but a large D_2 fold is seen between localities 17 and 19. Provided there has been no deformation before F_2, a section along the hinge surface should yield original stratigraphy. Such a section is in Fig. B (locality 19-17); thicknesses used are from the limb just before hinge zone thickening commences. The section from core to outer hinge comprises:

core The core greenstones were not seen - this to be anticipated since the competence contrast with sulphides would induce hinge zone décollement.

cp-po ore type of unknown thickness - interlayered CO_3 and chlorite schist - at locality 9 (Fig. B2), nearly 2 m of cp-po are in sharp contact with the HW greenstones.

Dark, po-rich chlorite schist of 'transition' type (sections 2.2 (a) and (b)) - the maximum thickness of 1 m at locality 10 is due to F_3 - 0.5 m is the 'normal' upper limit.

Abl - a maximum thickness of 0.5 m at locality 5 is influenced by F_3 - 0.3 m is a realistic upper limit.

MMG with some thin exhalite banding (BQC affinity) and actinolite needles (BA affinity) - the maximum thickness of 1.3 m at locality 5 is an F_3 effect - 0.75 m is realistic based on localities 9 and 10.

Actinolite-chlorite schist - maximum thickness in locality 17 (8 m position) is due to the F_2 hinge - 0.2 m as in locality 18 is realistic.

MMG with some actinolite (MA affinity) passing down into BQC with thin exhalite bands locally thickened and "balled up" by folding - combined thickness 1.25 m. SW along the foldlimb (17, 20 m section) MMG has developed sp banding; this fits BS underlying the actinolite-chlorite schist at localities 3, 5 and 8.

Chlorite-actinolite schist with CO_3 layering - thickness about 0.3 m - also present at localities 1 and 3.

Outer hinge BQC and BS with much po and cp mobilised in the fold nose - a thickness of less than 0.5 m is likely.

The outer hinge greenstones are not seen.

Thickness of the above sequence is a possible 7.5 m and a probable 6.00 m. Because the section is incomplete, 6.5-7.5 m would seem a realistic estimate.

The section raises two questions:

(a) Is it the true stratigraphy ?
(b) If not, then what is the reason ?

If (a) is answered 'yes', the stratigraphy differs from Olsen (1980) and the supposed feeder assemblage (chlorite schist and Abl) lies between cp-po and pyritic ore types. Further, the section is no less complex than other sections affected by thrust repetition and omission.

If (a) is answered 'no', it is because the sequence fails to conform with previous work and preconceived ideas. Nevertheless, I do not accept the sequence as the stratigraphy and must therefore address question (b).

The following hypotheses are conceivable:

(i) The fold is a late (D_3) structure.
This is rejected because F_3 mesofolds overprint the planar and linear elements generated by the larger fold.

(ii) The sequence has been disrupted, subsequent to F_2, by thrusts oblique to the hinge surface. Careful examination in the mine and subsequently of photographs shows that there is no evidence to support this notion.

(iii) The sequence was disrupted by folding and thrusting before the D_2 event. Support for this comes from Stekenjokk where Zachrisson (1971) identified pre-F_1 folds and from Marsfjällen (Trouw, 1973). The probable correlation between these areas and the Joma district is:

Event	Joma (NEO)	Stekenjokk	Marsfjällen
D_1	?	pre-F_1	F_1
D_2	F_2	F_1	F_2
D_3	F_3	F_2	F_3
D_4	F_4	F_3	F_4

The basis for correlation rests on the D_3 event which produced regional folds that can be mapped between the respective areas. Less certain is the correlation between F_2 Joma and F_2-Marsfjällen and Stekenjokk, since orientation is widely acknowledged as an unreliable basis for correlation in a multiply deformed area.

Against the proposal is the lack of other evidence (to date!) for a D_1 event in the mine levels examined and in the region (NEO) surrounding the mine. Microstructural work could yield evidence for D_1 regionally, but at this stage the existence of D_1 (folding and thrusting) at Joma is tentatively rejected.

(iv) The fold is a 'one-off' late F_2 structure that is folding thrusts resulting from 'normal' F_2 folds. This is possible, but two things mitigate against it: first, invoking special circumstances to explain unpalatable data is suspect; second, the timing is complex in that one would require folding and cleavage formation, thrusting, more folding AND CLEAVAGE FORMATION, and more thrusting. This is because the fold on 387 has a penetrative non-crenulate hinge surface foliation, and appears to be separated from greenstones by D_2 thrusts. In essence, two periods of deformation are placed under a progressive deformation umberella. The proposal is conceivable but contrived; subject to microstructural work it is rejected.

(v) Thrusting in D_2 was pre- or early syn-F_2. This has the merits of explaining the sequence, explaining thrust slices folded by F_2, satisfying the observation that cleavage is oblique to thrust contacts in many parts of the mine, and overcoming the mechanically improbable explanation of thrusting in greenstones oblique to a penetrative foliation. The proposal is akin to (iii) in that the thrusting could be related to a D_1 event that, in the Joma area, produced no folds or penetrative fabric (to date!). This is unnecessarily complex; the simpler notion of early D_2 thrusting is preferred.

(vi) The sequence is true stratigraphy. This has already been rejected and so I consider that pre- or early syn-F_2 thrusting in the D_2 event best fits currently available data.

4.4. Level 375 and synk.

Figs. B3 and C1 portray relations in this level; they are made complex by thrusting, F_2 folding and the tectonostratigraphic character of the cp-po ore type. Thrusting appears to have formed in D_2 and D_3 events.

The following composite sequence is based largely on 375 synk.

HW Pale chlorite rich greenstones with much CO_3 at the contact (section 2.1.(d)). The finegrained chlorite rock could well be a retrograde rock developed along the tectonised contact.

Variably banded pyritic ore types - mainly BA and a more recrystallized variant of BFG - localities 73-76.

Cp-po ore types - where not 'durchbewegt' this comprises interlayered banded py-po ore and cp-po ore (Fig. 5a) with actinolite and magnetite laminae - localities 60, 61, 73, 74. Where 'durchbewegt' the cp-po ore tends to incorporate abutting pyritic ore type (Fig. 5b) and migrate across sequence as may be seen from Fig. C1. The matrix of 'durchbewegt' ore may be cp or po dominated.

Variably banded pyritic ore types - initially BA and then BQC - localities 71, 73.

MFG subtype - the position is enigmatic since it abuts HW and FW greenstones (localities 77 and 66), does not abut 'transition' rocks and has uncertain relations with banded pyritic oretypes.

'Transition' rocks - section 2.2. (a).

FW Well layered greenstone with quartz-magnetite exhalites.

At the S end of the 375 gallery (78A to 124) thinly laminated py-SiO_2 (BQC subtype) and py-sp (BS subtype) layers are developed in FW greenstones. The py-sp layers pass down into > 2.5 m of massive BS. The relationship of this ore to members of the above sequence is not understood, but the structural relations are interpreted in terms of braided thrust slices folded about F_2 and rethrust (Fig. 6).

The uncorrected thickness is extremely variable (Fig. C1), but including the F_2-core 'transition' rocks (Fig. C1, sections 95010 and 95020), the maximum thickness attained is 7 to 7.5 m. The maximum limb thickness is 4.5 to 5 m.

4.5. Level 362.

Detailed columns have not been constructed. The plan and section (Fig. C2 a and b) show that the sulphides comprise HW and FW pyrite breccia bodies with intervening layers (slices ?) of chloritic greenstone, abundant CO_3 and BS.

The similarity to sections in C1 is striking, the essential difference being the subtypes sandwiched between the MFG bodies; 362 has BS, whereas 375 has the cp-po oretype and pyritic oretypes other than BS. Uncorrected thickness is in the order of 15 m, with only 3.75 m of this being intercalated BS and greenstone. Correlation with the BS at the S end of 375 level seems probable.

The dominant cleavage in Fig.C2b has been imposed across HW and FW contacts. If the interpretation of this cleavage as S_2 is correct, it follows that any fold attempting to relate the HW and FW MFG bodies must be pre-F_2.

Before commenting on the pre-F_2 implications, the question of S_2 identification will be resolved. The cleavage must relate to F_2 or F_3 or a previously unrecognised event. F_3 is rejected since the gross vergence is wrong and F_3 mesofolds crenulate the cleavage (47, Fig. A5). There is no evidence for an "unrecognised" event and neither is there any event in the nearby areas with which such a foliation could correlate; the possibility must remain open but improbable.

Thus, the S_2 identification is most probably correct, and this means that thrust mechanisms to explain relationships in 362 must be pre-S_2 and fold mechanisms pre-D_2.

4.6. Summary and conclusions.

The rock sequence on all levels is the product of thrust repetition and omission and folding, such that the ore comprises a stack of imbricate thrust slices. In the only F_2 fold where the hinge surface succession could be established, the evidence for pre-F_2 thrusting is compelling. On levels 362 and 375, where distribution of the MFG subtype and 'transition' rocks (375 only) could result from folding, there is evidence that the folding would need to be pre-D_2.

A stratigraphic sequence cannot be evolved from the levels mapped. In effect, one must assume an original stratigraphy in order to evolve a stratigraphy from the thrust and folded package. Only at mine scale, as recognised by Olsen (1980), is it possible to establish a gross pattern, and even this could be the pattern of the mine scale thrust package (made more complex by braiding and imbrication at level scale), rather than true stratigraphy.

Table 1 is a tabulation of the sequence from each level.

Table 1: ROCK SEQUENCE IN SELECTED LEVELS OF JOMA MINE:

SEQUENCE	LEVEL				
	506	495	387	375	362
HW	*Pillows+	layered	cp-po	BA BFG	layered
	sulphide	g'stone			g'stone
	veins		Chl schist	cp-po	
	Abl/chl	BS	Abl		MFG
	phyllite			BA	
		Abl	MMG		BS
	BS BA MA	(MFG)**	BQC		?
				(MFG**	
	MFG BFG	Chl-mica	BS	BS)	
		phyllite+			
	BS	exhalite		'transition'	
				rocks	
	pillows	g'stone		g'stone	
FW	layered				
	tuff				
Apparent*** Younging	down	up	?	up	?

* lateral correlation is not implied

** position most uncertain

*** based on the position of Abl or 'transition' rocks relative to ore and greenstones.

By applying Olsen's (1980) sequence to these columns and making the reasonable assumptions that:

(a) the chlorite-mica phyllite is distinct from the chlorite schist between cp-po and Abl;

(b) transition rocks are equivalent to the Abl and chloritic schist;

(c) copper and zinc are antipathetic as in many basemetal ore bodies in the Norwegian Caledonides;

one may evolve the ensuing top to bottom sequence.

Top pillow lavas and layered greenstones with rare
quartz-CO_3-magnetite exhalite.

Zn-rich sequence	Cu-rich sequence
BS(?)	BA/BFG
MFG, MA	BA/BQC
BFG, MMG	
BS	Cp-po with dark chlorite alteration rocks

not mutually exclusive

Abl	'Transition' rocks dark green-black chl-actin.-Ab-po schists
chl-mica phyllite with qtz-po-(mag) exhalite	

Bottom pillow lavas and layered greenstones
with qtz-po-(mag) exhalites.

If the Cu- and Zn-rich sequences originally formed distinct facies or were spatially distinct for some other reason, early thrusting has resulted in their intercalation (level 375) or further isolation (level 362). In essence, the deposit was scalped and dismembered by a series of subhorizontal thrusts such that lenticular slices were transported and stacked or isolated with little regard for original relationships.

Although the Abl-dark chlorite schist-(cp-po) sequence does not constitute a sound way-up criterion, it does provide a useful directional criterion at level scale. Thus, on level 387 the same sequence (from HW downwards) of chlorite schist-Abl-pyritic sulphide-actinolite chlorite schist-(cp-po) is recorded at most localities from 1 to 25 (Fig. B2). Between localities 17 (8 m position) and 20, the sequence can be mapped relative to the large F_2 fold, and not surprisingly it inverts from lower to upper limb.

This observation proves that the greater part of the level (localities 1-10, 18, 22, 23 and 25) lies on the lower limb of a NE closing F_2 fold. Any structural interpretation of the level must take this into consideration.

III STRUCTURAL GEOLOGY

1. INTRODUCTION

Whereas AR has concentrated on stratigraphy and geochemistry, NEO has mapped subsurface structure in terms of the sulphide/silicate interface. NEO has paid little attention to sulphide type and is attempting correlation with regional structure. The present analysis is an evaluation of mine structure with specific reference to sulphide-silicate relations at 'level' scale and modes of deformation within differing sulphide ore types. The ensuing sections therefore overlap NEO's work (in the same way that section II overlaps AR's work), but although discussions have occurred, the work and ideas presented are essentially independent and may not express NEO's views. Nevertheless, disagreement is more likely to be a matter of detailed interpretation than of mine fact.

Strong mesoscale evidence exists for at least two substantial fold-generating deformation events in the immediate sulphide-host rock environment. Most fabric elements can be assigned to these events and, in isolation, they would be designated D_1 and D_2. However, previous workers in nearby regions have identified more complex deformation sequences, and since regional folds of the D_2 event continue into the Joma district AR and NEO opted to effect a correlation early in the MJP. Because correlation was made with work in Sweden rather than Norway, the Joma synform has been assigned to D_3 and the earler folds to D_2 (section 4.3 (iii)). The matter of correlation will be reviewed in section......

2. MESOSCALE STRUCTURE

2.1. Introduction.

The data for the structural investigation come from levels 560 (the open cut and its immediate surrounds), 495, 387, 375 and 375 synk and 362. A more widespread data base is desirable, but older parts of the mine were too oxidised to allow detailed observation.

Further, the logistics of access to the level and hosing down the walls meant that work tended to be restricted to active areas. Time was also a constraint.

2.2. Geometric fabric elements.

Geometric fabric elements comprise all primary and secondary foliations, lineations, linear structures and folds. Each category will be briefly described and the data presented as a tabular summary in section 2.3.

2.2.1. Planar elements.

(a) S_o, bedding.

Provable bedding in silicate rocks is restricted to the pillow lava and thin tuff intercalations in greenstones on level 560. These sequences were described previously (section II, 2.1. (a)). The pillows are reasonably well preserved and have characteristic radial fracturing and texturally distinct margins. They have nevertheless been flattened, elongated and subjected to short wavelength (2-10 cm) flexing such that many false cusps have formed. Their confident use as a way-up criterion is therefore precluded.

Probable bedding in silicate rocks consists of 1-3 cm layering in greenstones (section II.2.1.) and the fine lamination within albite laminite (Fig. 7a). In sulphide rocks it is believed to be the exhalite laminae in BQC (section II,3.1.6; Fig. 7b), and the banding in the BFG, BA and BS subtypes (section II. 3.1.). However, data from these sulphide surfaces were grouped as S_b (item (c) below).

Gradational contacts between sulphide layers and laminae (excepting po and cp) and their silicate hosts were construed as bedding. Most other contacts have been grouped in (b) below.

(b) S_s, contacts.

Sharp contacts between the main sulphide bodies and greenstone (Fig. 7c), thin sulphide layers and greenstone, sulphide layers and Abl and sulphides and chlorite schist screens, are all frequently parallel or subparallel to S_o and/or S_b (below); they could be bedding and in many cases are a proxy for bedding. The same applies to the interface between differing ore subtypes, thick CO_3 layers in sulphides and greenstone abutting 'transition' rocks. However, bedding cannot be assumed because, in some cases, the contact parallels S_o in the silicate rock but truncates S_b, or vice versa, or is shallowly oblique to both. Such contacts are tectonic and are interpreted as thrusts.

The amount of thrusting is documented in section II.4. It would seen that the majority of contacts are tectonic but that over much of their length they follow bedding before climbing across sequence on shallow ramps (Fig. 8a). Such flat and shallow ramp combinations between relatively rigid upper and lower plates (the greenstones) rapidly leads to imbrication and duplex structures, all of which are believed to characterise the sulphide sheets in the levels examined. Because of the abundance of thrusting and its implications for stratigraphy, all sharp contacts have been grouped as S_s.

Some thin discordant and concordant sheets of sulphide are metahydrothermal veins, but these are readily recognised by the quartz$\pm CO_3$ gangue mineralogy.

(c) S_b, sulphide banding.

Thin compositional layering and lamination in the various pyritic ore subtypes (section II.3) are believed to be bedding. This is particularly the case for sp-rich, actinolite-rich and exhalite laminae in a pyritic host; po in cp is usually of secondary origin and was excluded from this category; thin magnetite laminae are most probabbly bedding but are usually dismembered in 'durchbewegt' ore and no longer have bedding significance.

Although S_b may become activated by thrusting, the many other surfaces across which there are greater competence differences are believed to preferentially accommodate the tectonism.

(d) S_2, schistosity and phyllitic foliation.

This is the oldest penetrative surface of secondary tectonic origin. It is the dominant foliation on all levels and commonly parallels or sub-parallels S_o or S_s. In greenstones it is a fine grained, closely spaced, poorly defined schistosity that in many cases fails to control the way the rock breaks. It can be recognised by the planar and linear preferred orientation of actinolite in some layers. In chlorite-white mica phyllites and mica bearing Abl it is a well developed cleavage with a phyllitic sheen or a fine grained schistosity. A mineral lineation and less commonly an intersection lineation may be resolved.

In some dark chlorite-rich schists, a schistosity partly defined by po blebs and initially thought to be S_2 is now assigned to S_c based on microfabric evidence.

There is no easily recognised S_2 surface in sulphide rocks. A diffuse foliation defined by the preferred orientation/distribution of sparse silicate gangue is present in the hinges of some early folds, but in limb regions is indistinguishable from S_b or S_s at mesoscale.

(e) S_{o-2}, S_{s-2}; S_2 paralleling S_o or S_s.

Because of very tight to isoclinal folding in the first period of deformation, S_2 commonly parallels S_o or S_s. In such circumstances the surface is a transposition foliation in which S_o or S_s is the transposed foliation and S_2 the imposed transposing foliation. S_{o-2} and S_{s-2} were initially treated as separate fabric elements, but trial plots on an equal-area net showed that there was no merit in maintaining the distinction.

(f) S_c, crenulation foliation.

In greenstones and low mica Abl, a spaced (5-15 mm) zonal crenulation is associated with small wavelength (a few cm) folding developed in S_{o-2} (Fig.8b, c). In chlorite-white mica phyllites and high-mica Abl, S_c constitutes a closely spaced (< 1 mm) intense zonal crenulation.

Certain foliations in pale chlorite schists and, partly defined by po blebs, in dark chlorite$\pm$brown mica-actinolite schists are progressively overprinted by new chlorite or mica, such that the crenulation is lost at hand specimen scale, and the new foliation is indistinguishable from S_2. The overprinting which can usually be recognised by its structural setting (hinge surface foliation to D_3 folds) has been confirmed at the microscale.

(g) S_c', crenulation foliation.

Mica-bearing Abl, chlorite phyllites and rarely greenstones have two crenulations developed in S_{o-2} or S_2. One is designated S_c by orientation and the other S_c' because age relations usually can not be established in hand specimen. Microscale examination has confirmed conjugate relationships and thereby vindicated the S_c and S_c' nomenclature. However, conjugate crenulation structures commonly display local and inconsistent overprinting relations which register subtle variations in their propagation rates at the time of formation. Numerous thin sections are required if a non-conjugate consistent overprinting relationship between weak crenulations is to be proved.

(h) S_3, hinge surface to folds lacking a hinge surface foliation.

Many mesofolds with an S_2 form surface in sulphide-dominated sequences either lack a hinge surface foliation or have it insufficiently penetrative to permit satisfactory measurement. When the hinge surface of such folds have an S_c orientation they are designated S_3.

(i) S_3', as above.

In the absence of consistent overprinting relations, hinge surfaces of rare folds in S_2 are designated S_3', provided that they have an S_3' orientation and lack a hinge surface foliation.

(j) S_{fv}, recrystallisation veining.

This breccia controlled structure is restricted to MFG and BFG pyritic subtypes and was described above (section II, 3.1.1.). It varies from being crudely planar (Fig. 2c) to completely irregular (Fig. 2b). It is possible that more than one generation of brecciation exists.

(k) S_f, close spaced shear fractures.

In MFG and MA subtypes, planar widely spaced (1-20 cm) shear fractures define a crude fracture foliation that overprints (by offset) S_{fv}. Antitaxial amphibole fibres linear and convoluted, express the movement characteristics. At least two orientations of these fractures occur.

2.2. Linear elements.

(a) L_2^o, intersection lineation.

An intersection lineation between S_o and S_2 may be observed as follows: in some Abl occurrences, between thin diffuse margined sulphide laminae and S_2, in dark chlorite schists of the 'transition' type and rarely in chlorite schist screens in massive sulphide; never in greenstones. In all cases, the trace of bedding on cleavage rather than the reverse was measured.

(b) L_2^s, intersection lineation.

The intersection between S_s and S_2 is far more common than L_2^o.

Because direct measurement of the lineation was in some instances difficult, L_2^s was calculated from measurements of the respective surfaces. In contrast with L_2^o, direct measurement was usually of the trace of cleavage on S_s.

(c) L_m, mineral or mineral aggregate lineation.

The lineation lies in S_2 and is an integral part of S_2 development. In Abl it imparts a grain to the S_2 surface, but in chlorite schists and greenstones it is defined principally by amphibole needles. This can be a problem since some of the amphibole is post-S_2 and, particularly in sulphides, may reflect D_3 linear elements. Some of the dispersion of L_m encountered in the orientation analysis (section 2.4.2 (d)) could result from failing to discriminate between D_2 and D_3 amphibole lineations.

(d) L_c, crenulation lineation.

Crenulation of S_2 produced L_c and, when penetrative S_c and an intersection lineation L_c^2. The latter parallels L_c and has not been recorded as a separate element. L_c is common in Abl, chlorite schists and screens, and on thin silicate films in banded sulphides. In greenstones it is often hard to define because of the nature of S_2.

(e) L_c', crenulation lineation.

As for L_c, but with S_c' and L_c^2'. The latter is apparently uncommon but this, in part, is due to identification problems. If the rock has developed penetrative S_c and S_c', L_c and L_c' are easily identified. However, where the crenulation fabrics are restricted to thin skins in Abl mica layers or to chlorite films in sulphides, L_c' will only be distinguished if it is at an angle to L_c. An angle of up to 15^o would be dismissed as falling within the vagaries of a slightly anastomosing crenulation fabric (crenulations do not develop as ruler parallel straight lines).

For the L_c to L_c' angle to exceed 15^o, the line of intersection of the potential S_c and S_c' surfaces must be oblique to S_2 (Fig. 9). The geometric constraints are the same, irrespective of whether L_c and L_c' are conjugate or separate events, although in the latter situation the likelihood of their diverging significantly is greater.

In conclusion, I believe that L_c' was masked by L_c due to the negligible divergence angle and the non-penetrative nature of S_c' and (less so) S_c.

(f) L_f, slickensides.

L_f includes slickensides and rare pyrite trains in s_f. They mainly comprise antitaxial amphibole fibres which show linear and more complex deformation paths.

2.2.3. Group 1 folds.

Group 1 folds are defined as those forming the regionally penetrative S_2 foliation. They comprise F_2^o,F_2^b and F_2^s structures, collectively referred to as F_2 folds. They are the first recognisable mesofolds in the mine and are tight to isoclinal, highly attenuated, equant to inequant depending on vergence character, and angular to subrounded with high limb/hinge ratios; they are asymmetric in that the hinge surface foliation does not bisect the interlimb angle. On the planar limbs of F_3 folds they are plane to non-plane cylindrical and plunging inclined to reclined folds.

F_2^o folds are uncommon because of the restricted nature of S_o. Where developed in layered greenstones they essentially have S_2 as their hinge surface foliation and L_2^o paralleling their hinge lines. Lm may parallel or be oblique to the local hinge line. F_2^o(?) folds in Abl are intrafolial and tend to be rootless. It is usually not possible to establish whether S_2 is their hinge surface foliation, but the hinge surface is certainly coplanar with S_2.

F_2^s are the most common F_2 structures and were it not for their conspicuousness, F_2^o folds in their greenstone cores would probably be missed. If, as has been suggested above (2.2.1.(b)), most contacts are tectonic and S_o is correspondingly restricted, it follows that folds of contacts are deforming pre-F_2 thrusts (cf. sections II. 4.3., II. 4.6.). The argument that the contacts in which F_2 folds are recognised are true S_o lacks conviction in the face of section II. 4.3. The objection that all thrusting postdated F_2 because an F_2 fold is cut off against a thrust is specious; some thrusting certainly occurred after F_2 and more thrusting accompanied F_3, but a large proportion of the thrusting that disrupted stratigraphy was pre-S_2.

F_2^b(?) folds are particularly common in banded pyritic ore of the BQC, BS and BA subtypes. Because the sulphides do not develop (at least at mesoscale) penetrative S_2, the fold's identification must rest on its:

(a) core or outer arc position relative to F_2^o or F_2^s;
(b) being folded by F_3;
(c) style and orientation.

Item (a) in combination with (b) and/or (c) is proof that the fold is F_2^b. Item (b) proves that the fold is pre-F_3, but not necessarily F_2, although in conjunction with (c) this is most likely. Item (c) is weak since pre-F_2 folds would probably have similar styles and could be similarly oriented; there is also overlap with the orientation and style of F_3 folds.

F_2^b(?) folds also occur in magnetite and silicate bands in db ore. The identification is largely unsupported since the structures have commonly suffered rotation or modification.

2.2.4. Group 2 folds.

Groups 2 folds are defined as those folding the regionally penetrative S_2 foliation. They potentially comprise F_3^o, F_3^b, F_3^s, F_3^2, F_3^{o-2}, F_3^{b-2} and F_3^{s-2} structures, collectively refered to as F_3 folds, together with the same spectrum of F_3' folds.

Post-F_3/F_3' folds in the same form surfaces would (unless they generated a penetrative hinge surface foliation) be included in group 2 and distinguished by orientation and superposition. In practice, no major post-F_3/F_3' folding exists in the mine area.

F_3 folds are of close to near isoclinal styles depending upon whether they are folding sulphide layers in dominant silicate packages or vice versa. They are typically inequant (other than at the NE end of the open cut where F_3 comprises low amplitude `M´ folds), rounded, have low to moderate limb/hinge ratios, and are symmetric in keeping with minimal limb attenuation (Fig. 10 a). In contrast, on level 375 F_3 is asymmetric due to short limb attenuation. These folds are mainly developed at the interface between sulphides and structurally underlying 'transition' rocks and greenstones. The sulphide-'transition' rock competence difference results in cuspate penetration or piercement, of the 'transition' sequence, whereas the 'transition' rock-greenstone competence difference has arrested the cross-layer piercement and allowed lateral penetration through delamination (Fig. 10 b). Consequent upon delamination, a locally (?) developed metahydrothermal phase induced limited hydraulic fracturing. Quartz, CO_3 and cp filled the fractures which would have been held open by fluid pressure. The composition of these fluids will be obtained from fluid inclusion work, and this should enable determination of the volume of fluid needed to produce the vein.

F_3 folds are plunging inclined and range from plane cylindrical in close styles to non-plane non-cylindrical where tight. Thus, on level 375 in the one fold the hinge surface dip decreases up dip from 60^o to 11^o, whilst the plunge decreases from 28^o to 8^o. In general, as the hinge surface shallows, the plunge trend backs from NE to NNE. The change in plunge and dip is particularly noticeable when F_3 folds propagate into sulphides (Fig. 10 c). Cleavage refraction with changing competence is well known from interbedded sandstone-slate sequences; the hinge surfaces of small parasitic folds in such sequences similarly refract. At Joma, "cleavage" may not be visible in the sulphides; but the refraction effect in F_3 hinge surfaces from competent silicate to incompetent sulphide most certainly is!

F_3' folds are uncommon but were noted on levels 362, 387 and 495 where they form open to close flexures in CO_3 layers and thin (<10 cm) actinolite chlorite layers. Conjugate and polyclinal relationships are developed in thinly layered quartz rich phyllites SE of Joma mine, where D_3 has caused intense mesoscale folding. Underground the conjugate nature of F_3 and F_3' was affirmed on level 387 by mutual interference where the hinge surfaces came together (Fig. 11 a). Elsewhere, F_3' was insufficiently continuous down hinge surface to study its interference with F_3. Because F_3' is the subordinate structure, it is most probably the younger of the two approximately coeval fold structures. Thus, occurrences of F_3' folding F_3 would not be surprising; F_3 folding F_3' is less probable but can be anticipated where fold propagation rates fluctuate in a penecontemporaneous 'conjugate' system.

2.2.5. Miscellaneous structures.

(a) Mullion structure.

In the open cut (5, Fig. A1) and level 362 (45, Fig. A5), pyritic ore with inward cuspate skins of chlorite phyllite has developed log-like F_2^s fold noses that are interpreted as mullions. A less regular, but similar structure is seen in an F_2^s fold nose (Fig. 11 b) at locality 7 (Fig. A1).

The cuspate penetration of the sulphide by the phyllite forms secondary tectonic flame structure and suggests that the massive pyritic ore (MFG subtype) was more competent during F_2 than the chloritic phyllite.

(b) Boudinage.

Boudinage in actinolite-chlorite with formation of CO_3 partitions is well displayed on levels 387 (Fig. 11 c) and 375. The partition plane is approximately at 90^o to L_m, which suggests that boudinage was a consequence of extension along L_m during D_2. However, Fig. 11 c shows that the partitions progressively widen over an F_3 fold with its hingeline essentially parallel to the partition plane.

Thus, boudinage was possibly enhanced by stress relaxation following favourable F_3 deformation.

(c) D_3 and D_4 (?) "rolls".

Substantial rolls or undulations occur in S_s in the open cut (8 and 41, Fig. A1). At locality 8 they are steeply plunging and clearly relate to F_3. At locality 41, they appear to plunge shallowly NE and have shallow E dipping hinge surfaces. They are probably flexures associated with a shallow crenulation cleavage (dip 24/086) observed at locality 6. The cleavage was assigned to the S_c' category, but it could conceivably express a D_4 event, since a subhorizontal crenulation foliation is characteristically developed in nearby regions (e.g. Roberts, 1979) and has been mapped by NEO.

(d) Faulting.

Much of the faulting is covered by s_f (2.2.1 (j)) which consists of steeply WNW dipping, dip and oblique slip normal faults. Additional local faulting is seen as dipslip movements subparallel to S_3 (Fig. 12 a) in greenstones; and as rotational NW side down extensional fractures (boudinage) in greenstone layers in sulphides (Fig. 12 b). The common movement sense suggests that all these structures are stress relaxation effects following F_3. Alternatively, they could be a local, expression of the subvertical compression associated with the development of a subhorizontal crenulation foliation ((c) above).

(e) Dilational veins.

Dilational quartz-CO_3 veins and fibrous amphibole overprint F_3 on levels 387 (3, Fig. A3) and 375 (62, 67, Fig. A4). Their dip orientation (~70/135) is consistent with either of the hypotheses above.

2.3. Fabric catalogue and event sequence.

The fabric elements (section 2.2) have been ordered into a fabric catalogue based on mesoscale overprinting and superposition data. The fabric catalogue is in Table 2. Because the aim of a fabric catalogue is to present an objective assignment of factual data to deformation periods, conjectural matters such as the existence of D_1 folds based on stratigraphic arguments (section II. 4.6.) are not included.

TABLE 2 : FABRIC CATELOGUE - MESOSCALE ELEMENTS

DEFORM-ATION	FORM SURFACES	FOLDS FORMED	ELEMENTS GENERATED	COMMENTS
D_1	S_o	No elements proved to belong to D_1. S_s in part pre-S_2 but not provably pre-D_2.		
Early D_2	S_o,S_b	?	S_s	Not all S_s generated
	S_o,S_b	Group 1 folds:	S_2, L_m	F_2^o//F_2^b//F_2^s
	S_s	F_2^o, F_2^b	L_2^o, L_2^s	L_2^s//to sub//L_2^o
		F_2^s	S_{o-2},S_{s-2} S_{b-2}	Transposition foliations
			S_{fv}	S_{fv} approximates S_2
				S_s reactivated (?)
Late D_2	Not perti-nent		S_s reativated and extended (?) - new thrust form	
Strong component	S_{o-2}	Group 2:	S_3,S_c	S_o etc. included in transposition foliations
	S_{s-2}	F_3 in all form	L_c	

DEFORMATION	FORM SURFACES	FOLDS FORMED	ELEMENTS GENERATED	COMMENTS
D_3	S_{b-2} S_2	surfaces	S_{fv}	$S_3//S_c$ $F_3//L_c$ S_{fv} reactivated - fractures formed
Weak component	As above	Group 2: F_3' in all form surfaces	S_3', S_c' L_c'	$S_3'//S_c'$ $F_3'//L_c'$
D_4		As above plus S_c Faulting - possible folding and crenulations but data sparse - could be S_3'		S_c' is not a significant form surface

The table substantiates the existence of two principal deformation events at mesoscale. These two events are shown to have sequential components in the case of D_2 and conjugate components for D_3. A post-D_3 event is shown to be a possibility, but the D_4 structures could be treated as sequential components of D_3-F_3 for faulting and D_3-F_3' for shallow crenulations.

The strongest arguments against assigning the structures to D_3 are:

(a) the range of orientations (subhorizontal to subvertical) that this gives S_3';

(b) the knowledge that subhorizontal crenulations are widely developed throughout the region (Roberts, 1979);

(c) the fact that NEO has mapped D_4 structures in the district, although it is of interest that her D_4 surfaces range from steep to shallow. She would seem to have the reciprocal problem of that in (a); conceivably she has S_c' structures mixed with S_4.

The deformation sequence evolved above is summarised in table 3 together with a confidence statement.

TABLE 3 : DEFORMATION SEQUENCES - MESOSCALE EVIDENCE

EVENT		COMPONENT EVENT	SUPPORT
D_1	(a)	Isoclinal, large amplitude folding	None at mesoscale
	(b)	Thrusting along and shallowly oblique to S_o forming imbricate stocks	Strong but D_1 age not proved
D_2	(a)	As in (b) above - (b) and (a) are alternatives	Strong for pre-S_2
	(b)	Tight to isoclinal folding with short limbs exceeding 30 m in level scale folds.	Very strong
	(c)	Thrusting along old and newly formed surfaces	Strong
D_3	(a)	Folding with close to isoclinal styles and moderate to shallow NW dipping hinge surfaces.	Very strong
	(b)	Thrusting along old(?) and newly formed surfaces.	Strong
	(c)	Folding with open to close styles and moderate to steep SE dipping hinge surfaces.	Limited
	(d)	Relaxation faulting and development of dilation veins - NW dips for both structures.	Weak

(a)	As above in (d) - (d) and (a) are alternatives.	Weak
(b)	Folding with open style and shallow SE dipping hinge surfaces.	Very weak

2.4. Orientation analysis.

2.4.1. Introduction.

Measurements of elements described in section 2.2 were examined on a Lambert equal area stereographic net. Trial plots were effected to test the significance of distinctions recognised in the field for example, did S_o, S_s and S_b data yield differing distributions. Depending on the results, elements were grouped and plotted for their respective mine levels, the level plots then being consolidated into synoptic plots (of the particular element) for the mine. Contouring of data points was effected where merited.

Having completed the mechanical part of the analyses comparison was made between synoptic and component plots for each element (or element group) and for differing elements. The results are the basis for the ensuing sections.

2.4.2. D_2 elements (Table 4).

TABLE 4 : D_2 ELEMENTS

ELEMENT	SOB	S_2	SOBxS_2	FL_2	L_m	FL_m
S-max	20/292	22/324				
F_2 πaxis	20/302	22/324				
L_2			21/310			
FL_2-max				20/310		
L_m-max					30/340	
			(double maximum)		30/320	
FL_{2m}-max						22/317

(i) a broad flexure with a vertical hinge surface and 130° interlimb angle;

(ii) a reclined isoclinal fold system flexed as in (i) by a second period of deformation or initially cylindrically curviplanar;

(iii) a reclined tight to near isoclinal system where the girdle dispersion results from overlapping limb maxima.

(a) S_o, S_s, S_b (abbreviated to SOB).

No significant difference existed between plots of S_o + S_b against S_s on either a level or mine scale. This suggests that all thrusting, irrespective of age, has tended to be along or close to original layering.

The synoptic SOB plot (Fig. 13A) shows a point maximum within an incomplete girdle defining a πaxis of 20/302 (Table 4). Because F_3 trends NE (section 2.4.3; Fig. 14) the data are unaffected by mesoscale or mine scale redistribution. This is consistent with the mine lying on the planar limb of a much larger F_3 structure (the Joma synform), and with data being recorded only from long limbs of level scale F_3 folds.

Component plots from the levels have similar girdle distributions, but the position of the point maximum varies. For example, in 375 the point maximum defines a plane (S-max) dipping 20/277 whereas S-max for 362 is 38/236. The synoptic and component plots can be explained by:

A fourth possibility is that the girdle reflects thrusting on curviplanar surfaces along 0/032 (thrust direction at 90° to the S-pole maximum within the plane of the girdle). However, if this were the sole explanation S-max should be constant between levels.

Bearing in mind the S_2 data (Fig. 13 b) and field observations, (i) may be rejected; and so may (ii) in terms of a second period of deformation about a WNW trending axis. It is not possible to discriminate between (ii) and (iii) within the context of the thrust effect. I conclude that the pattern reflects tight to isoclinal reclined folding with cylindrically curviplanar hinge surfaces, possibly modified by the thrust effect.

(b) S_2

Synoptic S_2 (Fig. 13 b) shows a point maximum within a weak girdle distribution defining a π S_2 of 22/324. Because most6 of the spread (girdle length) is subscribed by the open cut component plot and the π-circle is subjective, the difference between π axes (Table 4) is insignificant.

The interpretation of SOB (above) is consistent with a weak S_2 girdle. The width of the girdle reflects curviplanar behaviour around the thick ore mass in the open cut and possible F_3 redistribution.

S_2-max is 22/324; the intersection lineation $L^{SOB}_{S_2}$ is 21/310 and this is consistent with the F2 π-axis data (Table 4).

(c) F_2/L_2 (abbreviation FL_2).

No significant variation between F_2 and L_2 was recorded in trial plots. This is supported by the F_2 π-axis and $L^{SOB}_{S_2}$ relationship in (b) above.

Synoptic FL_2 (Fig. 13 c) defines a great circle distribution that approximates S_2. The contained maximum of 22/310 is skewed towards the N, but regardless of that, the overall geometry confirms the negligible effect of F_3 on a mine scale or, more specifically, the location of the mine on a regional F_3 limb.

The great circle and skewed distribution could be explained by:

(i) a non cylindrical F_2. This is consistent with SOB being weakly curviplanar, as would be likely with pre-S_2 thrusting.

(ii) The spread in orientations of SOB and S_2 on the scale of a single level and between levels; this is certainly responsible for the extent of the girdle almost around the entire great circle and could result in a skewed maximum.

(iii) Simple shear during late D_2 thrusting causing rotation of FL_2 towards a NNE oriented shear direction akin to that postulated in (a) above. This would require L_m (which trends NW - Fig. 13 d) to parallel the Y strain axis rather than the more logical X direction, bearing in mind the simple shear strain that was part of the thrust-generating deformation phase. It is possibly significant that to the N in the Limingen district Lutro (1979) finds a discordance between NNE trending hingelines and intersection lineations and a NW trending pebble elongation, whereas Trouw (1973) and Sjöstrand (1978) find mixed relations but predominant parallelism between L_m, hingelines and intersection lineations. Sjöstrand (p. 68-79) has a particularly complex relationship and variously forms the regional lineation in his D_2 and D_3 events. (He perhaps failed to separate two different lineations.) The change between Limingen and Sweden could be progressive and mark differing levels/positions in the tectonic pile; Joma would then have closer similarity to the Swedish picture.

(iv) Stemming from (iii) is the possibility that the structural evolution is from Norway into Sweden. If so, it is conceivable that the rotation of FL_2 has been from NNE towards the NW.

(v) SE trending thrusting associated with D_3 reactivation of the early thrust surfaces caused minor rotation of D_2 linear elements towards the thrust vector.

I am unable to discriminate between these various mechanisms, but consider that item (ii) operated irrespective of the contributions from the remainder. On a purely subjective basis I believe that (i) and (v), in conjuction with (ii), can satisfactorily explain the FL_2 distribution without resorting to a dubious thrust direction and massive rotations ((iv) only).

(d) L_m: FL_2+L_m (abbreviation FL_{2m})

L_m was plotted independent of FL_2 because in several cases a discordance was observed and the component plot for 387 showed L_m plunging N of Fl_2. The synoptic L_m (Fig. 13 d) neither confirms nor disproves the discordance; the double maximum plunges a little N of FL_2 (Table 4) and the spread is less extreme, but this could be due to a lesser number of points rather than a fundamental difference in orientation. It was therefore decided to compound the L_m and FL_2 data as FL_{2m}.

Synoptic FL_{2m} (Fig. 13 e) yields the same type of great circle distribution and skewed (almost double) maximum as seen in L_m and FL_2. The best fit great circle (23/305) is closer to SOB-max than S_2-max, but the differences between the three are too small to assign this significance.

(e) Summary.

The D_2 planar elements are consistent with a reclined, very tight to isoclinal, non-plane cylindrical fold, possibly influenced by thrust plane curvature. The D_2 linear elements support a WNW to NW plunge for the folding but their distribution within S_2 could imply modification by simple shear in late D_2 or in D_3.

2.4.3. D_3 elements.

(a) S_3+S_c (abbreviation S_{3C}).

Trial plots of S_3 and S_c showed that they behaved sympathetically, but that the data were influenced by the nature of the folded package. Thus, in silicate dominated assemblages S_{3C} dipped quite steeply whereas in sulphide assemblages it flattened considerably (cf. section 2.2.4). The net result of this behaviour is that the distribution in the synoptic plot (Fig. 14 a) is drawn out in the dip direction, but that S_{3C}-max is relatively steeply dipping (50/318).

In order to examine the rock package effect more closely, data from the open cut and level 387 were contoured separately. The open cut was chosen because most measurements were made in greenstone and this would therefore portray one end member. 387 was selected because of the abundant data from sulphides, but it had the additional advantage of many greenstone readings such that the behaviour could be examined on one level. Thus, the possibility that any dip change was level related was partly overcome.

The open cut data (Fig. 14 b) define a maximum (66/286) and a submaximum (66/336) within a partial girdle distribution. The submaximum corresponds to data from the NE corner of the cut and the girdle expresses the strike variation in the vicinity of the orebody. However, the main point is that S_{3C} dips steeply (~65^o) NW. Fig. 14 c shows that the data from 387 also define a maximum (54/325) and submaximum (24/332), respectively corresponding in this case to S_{3C} in silicate rocks and sulphides.

The influence of Figs. 14 b and c on the synoptic plot (Fig. 14 a) are self evident. There could indeed be a shallowing of S_{3C} with depth, but any such trend is swamped by the rock package effect.

(b) S_3' + S_C' (abbreviation S_{3C}')

The few data obtained (Fig. 14 a) suggest a steep SE dipping surface with "scatter" to very shallow dips. The distribution might be explained:

(i) by shallowing due to a rockpackage effect.

There is little support for this because some of the shallow dips were from crenulations in greenstone in the open cut and some of the steep dips were from folds in CO_3 in massive sulphide. Perhaps the only reasonable conclusion is that too few observations were made to justify reaching conclusions.

(ii) By the data coming from two separate populations, one being S_{3C}' the other being a shallow D_4 surface, as discussed in section 2.2.5. (c). Although this is possible, the lack of superposition evidence and paucity of data preclude a substantive statement.

Allowing that the steeper dipping surfaces are S_{3C}', estimated S_{3C}'-max is 70/124 and this yields an intersection with S_{3C}-max of 10/037. For this geometry (Fig. 14 d) the intermediate principal stress (σ_2) is 10/037 and, because S_{3C}-max is dextral viewed down the line of intersection, σ_1 and σ_3 approximate 10/128 and 75/266 respectively. Precise data cannot be given because of the asymmetric distribution of the conjugate system about S_2-max. Also from Fig. 14 d, the traces of S_{3C}-max and S_{3C}'-max on S_2-max form an angle approximating 10^o. This supports the proposal (section2.2.2.(e)) that L_c masks L_c'.

(c) F_3 + L_c (abbreviation FL_3).

Trial plots of F_3 and L_c demonstrated their essential parallelism, but as with S_{3C} the orientations of FL_3 are rock package dependent. On level 387 for example sulphide hosted data trended NE to ENE, whereas data from silicate rocks trended NNE.