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Kinematics of syn-eclogite deformation in the Bergen Arcs, Norway, implications for exhumation mechanisms

Hugues Raimbourg ¹, Laurent Jolivet ¹, Loïc Labrousse ¹, Yves Leroy ², Dov Avigad ³

¹ Laboratoire de Tectonique, UMR 7072, Université Pierre et Marie Curie, T 26-0 E1, case 129, 4 place Jussieu,
75252 Paris cedex 05 France (hugues.raimbourg@lgs.jussieu.fr)

² Laboratoire de Mécanique des Solides, Ecole Polytechnique, Palaiseau, France

³ Institute of Earth Sciences, Hebrew University of Jerusalem, Jerusalem, Israel

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Kinematics of eclogite-facies deformation

Abstract : The northwestern part of Holsnøy island, in the Bergen Arcs, Norway, consists of a granulite-facies protolith partially transformed at depth in eclogite (700°C, >19 kbars) and amphibolite (650°C, 8-10 kbars) facies during the Caledonian orogenesis. Eclogitized zones are mainly planar objects (fractures with parallel reaction bands and centimetric to hectometric shear zones). Eclogitic zones are distributed in two sets of orientations and the associated deformation can be described as “bookshelf tectonics”. The major shear zones strike around N120 and dip to the North, and show consistent top-to-the-Northeast shear sense throughout the area.

In the large-scale kinematic frame of Caledonian northwest-dipping slab, eclogitic shear zones are interpreted as the way to detach crustal units from the subducting slab and to prevent their further sinking. As the retrograde amphibolitic deformation pattern is similar to the eclogitic one, the detached crustal units started their way up along these eclogitic shear zones. Radiometric ages of eclogitic and amphibolitic metamorphism and their comparison with the chronology of Caledonian orogenesis show that the deformation recorded on Holsnøy occurred in a convergent context. The mechanism we propose can thus account for the first steps of exhumation during collision.

Relics of High Pressure (HP) and Ultra High Pressure (UHP) parageneses record the passage at depth of crustal units (Chopin 1984; Smith 1984; Wain 1997; Chopin & Schertl 2000; Ernst & Liou 2000; Jolivet et al.

2003). Such witnesses of a deep history, found in most current or past collision zones, can provide constraints on the deep structure and time evolution of the collision.

In the Norwegian Caledonides, as well as in the Alps or in the Himalayas, plate collision was preceded by the closure of an ocean by subduction. In this context, oceanic and then continental crust can be dragged down to large depths. Downpull by the underlying lithospheric mantle in a subducting slab is indeed a widely accepted mechanism for burial of crust. On the contrary, the processes involved in the exhumation of buried tectonic units are not well understood, and several models have been designed in order to account for the return path to the surface (see review by Platt 1993). Exhumation can result from a drastic change in either vertical or horizontal boundary conditions. Andersen et al. (1991) propose that the exhumation of HP units in the Caledonides is achieved through the exhumation of an orogenic wedge, caused by the detachment of the lithospheric mantle root followed by a large-scale isostatic rebound. Alternatively, deeply buried rocks can be brought back to the surface in a reverse movement, as a result of plate kinematics change from convergence to divergence (Fossen 1992).

A comparison of the ages of Holsnøy eclogites and amphibolites given by Boundy et al. (1992) and Kühn (2002), with the ages of the eclogites in the nearby Western Gneiss Region (WGR) (review by Torsvik & Eide 1997, Carswell et al. 2003; Tucker et al. submitted), indicates that Holsnøy eclogites were exhuming at the same time as WGR was being buried (410-400 Ma). The first steps of Holsnøy eclogites exhumation occurred while the collision was still active, therefore it can only be accounted for by collisional models.

Most collisional models, like corner or wedge flow models (Jischke 1975, England & Holland 1979, Cloos 1982, Shreve & Cloos 1986, see review by Mancktelow 1995), as well as analogue models (Chemenda et al. 1995), do not take into account rheological changes due to metamorphic reactions. The 2D model of Burov et al. (2001) does consider metamorphic reactions caused by rock burial, but the reactions depend only on the P-T conditions and are instantaneous - i.e. 100% of crustal material is transformed to eclogite as soon as the boundary of the P-T eclogitic field is crossed. The simple 1D isostatic model of Dewey et al. (1993) takes into account first-order reaction kinetics. As demonstrated by Austrheim (1987), eclogitization reactions need some fluid input to occur. As a result, the fluid supply determines which fraction of the granulitic unit can be transformed into eclogite, and the fluid transport limits the transformation rate. Eclogitic metamorphic reactions depend not only on variations in P-T conditions but also on fluid availability. Albeit not well accounted for in many models, eclogite-facies reactions are likely to have important consequences on the history of rocks

affected: the complete eclogitization of the Holsnøy granulite leads to a density increase of 7%, as well as a viscosity decrease visible in the field (Austrheim 1987).

The aim of this study is to analyse the deformation recorded within eclogites on Holsnøy and its relations with the tectonichistory of the unit during the Caledonian orogenesis. Eclogite-facies deformation is essentially non coaxial, eclogitic structures showing a “bookshelf” geometry with a top-to-the-Northeast sense of shear on the main set of shear zones. We interpret this deformation as the first step towards exhumation. We propose a geometrical model where the eclogitization reactions enable crustal slivers to detach from the downgoing slab along eclogitic shear zones and to start their way up.

Geological setting

The Scandinavian Caledonides result from the closure of the Iapetus ocean and the northwest-dipping continental subduction of Baltica under Laurentia, in a time spanning from late Ordovician to early Devonian periods. A series of allochthonous nappes, originating from the Iapetus ocean and from the western margin of Baltica were thrust eastward onto the autochthonous shield of Baltica (Krogh 1977; Roberts & Gee 1985).

The Bergen Arcs consist of a series of arcuate thrust sheets centered around Bergen, Norway (Fig. 1). The Bergen Arcs nappe pile is in tectonic contact to the east with the parautochthonous WGR through the Bergen Arc shear zone (BASZ, see Fig. 1). The BASZ involves parts of three tectonic units: WGR, the Kvalsida Gneiss and the Major Bergen Arc zone (Wennberg 1996). Another fault zone, the Main Caledonian Thrust (MCT), constitutes the western border of the Bergen Arcs and separates the structurally lower Oygarden Gneiss Complex from the Minor Arc and Ulriken Gneiss Complex (Fig. 1).

The Lindås nappe lies in the highest tectonic position in the Bergen Arcs nappe pile. This crustal nappe is supposed to be originally a lower crust unit and contains abundant mafic material, from gabbroic anorthosite to pure anorthosite, as well as various rocks of the charnockite suite like mangerite (Kolderup & Kolderup 1940).

The northwestern part of Holsnøy island (Fig. 2a), which is the object of our study, belongs to the Lindås nappe, and is composed of mangerites and anorthositic granulites (Austrheim & Griffin 1985), intensively reworked under eclogite and amphibolite-facies conditions. It is separated from the Meland Nappe (southeastern Holsnøy) by the Rosslund Shear Zone (Fig. 2a), which is up to 2.5 km wide and shows a complex metamorphic history from amphibolite-facies to greenschist-facies conditions (Birtel et al. 1998; Schmid et al.

1998). The Meland Nappe consists of granulites with amphibolite to greenschist-facies mylonites, without any evidence of eclogite-facies metamorphism (Birtel et al. 1998).

Field Relations on northwestern Holsnøy

The geology of the area and its metamorphic history have been studied in detail by Austrheim and co-workers (Austrheim 1987, 1990a, b, 1994; Austrheim & Griffin 1985; Austrheim & Mørk 1988; Austrheim & Engvik 1995; Boundy et al. 1992). During the Caledonian history, the granulitic protolith has recorded successive parageneses on the exhumation path, under eclogite, amphibolite and finally greenschist-facies P-T conditions.

Granulite-facies protolith

Northwestern Holsnøy granulitic anorthosites present two different fabrics. In the well-foliated parts, the granulitic foliation is defined by the alternance of plagioclase-rich and pyroxene-garnet-rich layers. In the more coronitic parts, a plagioclase matrix encloses ellipsoidal granulitic coronas, composed of a core of orthopyroxene surrounded by layers of clinopyroxene and garnet. The strong shape fabric of the coronas defines a granulitic lineation. Both foliation and lineation were acquired during the 900 Ma Grenvillian granulite-facies deformation (Cohen et al. 1988; Bingen et al. 2001).

Eclogite-facies metamorphism

The anorthositic complex was partially reworked under eclogite-facies conditions (Fig. 2b). The predominant eclogitic assemblage in anorthosite is omphacite, garnet, kyanite, zoisite, and minor phengite, +/- rutile, +/- quartz +/- amphibole (Boundy et al. 1992). Gabbroic eclogites consist predominantly of omphacite, garnet, and minor phengite, rutile, quartz, +/- carbonates. Input of fluid was necessary for eclogitic reactions to occur since both assemblages are hydrous. Therefore a shortage in available fluid resulted in the metastable preservation of part of the granulite in the eclogitic P-T field. A heterogeneous distribution of the fluid supply enabled different grades of the transformation to be “frozen in” (Austrheim 1987; Austrheim & Mørk 1988, see Fig. 3). Some parts of the granulitic unit are macroscopically not affected by eclogitization reactions. Elsewhere, the granulite is cut by mm-wide fractures containing hydrous eclogitic minerals and quartz. On both sides of these fractures, a dm-wide dark band corresponds to partially eclogitized granulite. A further progression in the transformation is illustrated by minor eclogitic shear zones. These minor shear zones, 10 cm to 2 m wide and a few tens of metres long, display a well-defined foliation and cut through a coherent skeleton of granulite. Where the density of the shear zones increases, they form an anastomosing network surrounding rounded, 1 to 10 m-

large blocks of granulite. These blocks are no longer connected and their foliations show large relative rotations. This structural type is referred to hereafter as “eclogite breccia” (Austrheim & Mørk 1988). Finally, roughly 100 m wide eclogite shear zones that contains few granulite boudins can be followed along strike for hundreds of metres. The localisation of strain in the eclogitized fraction demonstrates that the eclogite is rheologically weaker than the granulite.

Amphibolite-facies metamorphism

Amphibolite-facies metamorphism locally affected preserved granulite-facies areas as well as eclogitized areas. Typical amphibolitic assemblages comprise amphibole, phengite, margarite, paragonite, plagioclase, zoisite and chlorite (Kühn 2002).

Structurally, the amphibolite-facies metamorphic rocks occur as: 1) patches in contact with eclogitized zones, 2) halos around quartz-feldspar veins that crosscut eclogitized zones and 3) variable size (cm to m wide) shear zones (Kühn 2002). Textural relations, such as amphibolitic symplectites formed after omphacite, show that eclogite-facies predates amphibolite-facies metamorphism. This is further supported by structural evidence such as crosscutting relations between amphibolitic veins and eclogite, and the dragging of eclogitic foliations into amphibolitic shear zones where both coexist.

Greenschist-facies

On northwestern Holsnøy, the greenschist-facies retrogression is recorded only by the reactivation of eclogite-facies and amphibolite-facies fabrics (Schmid et al. 1998). Greenschist-facies metamorphism is much more conspicuous on the Meland Nappe, with the formation of shear zones of various sizes, up to 100 m thick, which crosscut the higher grade shear zones or simply reactivate them. A late greenschist stage is also recorded by the formation of tight to open folds, especially along the southeastern coast of Holsnøy. In metagabbros and amphibolites, the typical greenschist mineralogy is actinolite and plagioclase, +/- epidote, +/- biotite, +/- sphene, while metasyenites and metagranites are typically composed of biotite, plagioclase, +/- quartz, +/- epidote, +/- muscovite, +/- chlorite, +/- calcite, +/- actinolite.

P-T-t evolution of Lindås Nappe

The Lindås nappe has been intensively affected by granulite-facies metamorphism associated to the Grenvillian orogeny around 900 Ma (Cohen et al. 1988; Bingen et al. 2001).

During the Caledonian orogenesis, the Lindås nappe was buried and then exhumed, experiencing eclogite, amphibolite and greenschist-facies metamorphism. The granulitic protholith and eclogitized and

amphibolitized zones are particularly well preserved on northwestern Holsnøy. Eclogitic parageneses in eclogitic shear zones of northwestern Holsnøy yield P-T conditions of 700-800 °C and 16-19 kbars (Austrheim & Griffin 1985), 650-750°C and 16-19 kbars (Jamtveit 1990), 670+/-50°C and >14.6 kbars (Boundy et al. 1992) and 700°C and 17 kbars (Mattey 1994). Boundy et al. (1996) estimated P-T conditions of 690°C and 8-12 kbars for high-grade amphibolite in the northern and eastern areas in the Lindås Nappe, whereas estimates by Kühn (2002) on amphibolites on Northwest Holsnøy, using PT pseudosection and amphibole thermometry, yield 600°C and 8 kbars.

The chronology of the HP-LT metamorphism is still debated. Two scenarii can be proposed, corresponding to a metamorphism of Lindås Nappe early in the Caledonian history, or coeval with the main collisional phase (Scandian phase, dated c. 425 Ma, Torsvik et al. 1996), as follows.

-Ages around 460 Ma for the eclogite metamorphism (U/Pb on sphene and epidote by Boundy et al. 1997a and U/Pb on zircon by Bingen et al. 2001), followed by rapid cooling to 500°C at 455-445 Ma (Ar/Ar on hornblende, Boundy et al. 1996), and to 375 °C at 430 Ma (Ar/Ar on muscovite, Boundy et al. 1996).

-Ages around 420 Ma for the eclogite metamorphism (419+/-4 Ma with U/Pb on zircon on Holsnøy, Bingen et al. 1998) consistent with a highly unconstrained age of 421+/-68 Ma with Rb/Sr mineral isochrone (Cohen et al. 1988). Amphibolite-facies metamorphism dating yielded 409 +/-8 Ma (Rb/Sr isochron age, Austrheim 1990a) and 418+/-9 Ma for the Fonnes trondjhemite dyke intruding Proterozoic rocks under PT conditions of 8-10 kbars and 650-700°C, at Austrheim locality, in the northeast of Lindås nappe (Kühn 2002). This short time span between amphibolite and eclogite-facies metamorphism may result either from rapid exhumation or from the fact that, at the same time within Lindås Nappe, Holsnøy was more deeply buried than Austrheim.

Kinematics of eclogitic deformation

Eclogitic lineations

Eclogitic stretching lineations are present in the field at two different scales, as described by Rey et al. (1999) and Boundy et al. (1992):

- At the mm scale, the orientation of rod-shaped omphacite defines a mineral lineation.

- At the cm-dm scale, the ellipsoidal granulitic coronas, where eclogitized and deformed, form elongate dark mineral aggregates.

At the microscopic scale, crystallographic preferred orientations (CPO) of omphacite show a strong correlation with structural directions (Boundy et al. 1992; Bascou et al. 2002; Labrousse 2001).

Strain regime from previous studies

Boundy et al. (1992) concluded that the strain regime was non-coaxial. This was based on CPO patterns of omphacites from 4 samples in the Lower Eldsfjellet Shear zone, but the analysis was extremely local and did not yield any sense of shear. A top-to-the-NE sense of shear was inferred from the offset of one metagabbro dyke, from offsets across minor eclogitic shear zones (Boundy et al. 1992) and from asymmetric mineral clusters and crystallisation tails (Rey et al. 1999). These observations are nevertheless too few to draw any conclusion at the scale of granulite unit. We therefore extensively collected kinematic indicators in major shear zones, as well as in less transformed areas, to decipher whether consistent kinematics could be found at large scale.

Eclogitic deformation in large shear zones

Geometry of major shear zones and lineation directions

The granulitic unit is cut by a set of 10-100 m large shear zones that can be followed along strike for several hundreds of metres (Fig. 4). These shear zones trend in average between N90 and N120, except East of Skurtveit and in Lower Eldsfjellet, where they swing to strike around N60. All shear zones have a northward dip between 10 and 40°. Our collected measurements of lineations and foliations in the major eclogitic shear zones are in agreement with the data of Rey et al. (1999). In average, the lineations in Hundskjeften strike N90, N70 in Upper Eldsfjellet and N40 in Lower Eldsfjellet. The Skurtveit shear zone show two distinct sets of lineations. The scarcity of data collected on this shear zone prevents us from trying to explain the coexistence of these two sets. In all shear zones, lineations have a northeastward plunge between 10 and 30°.

Kinematic indicators in major shear zones

Formerly spherical objects, when deformed by simple shear, get an asymmetrical shape (Passchier and Trouw 1998). At the same time the foliation in the matrix wrapping around the objects adopts a sigmoidal morphology. This morphological description that is scale-independent was applied to two different classes of objects on northwestern Holsnøy: eclogitized omphacite-rich former coronas embedded in a kyanite-zoisite rich

matrix (1 to 10 cm in size) and untransformed granulite boudins embedded in eclogite matrix (50cm to 10m in size) in eclogitic shear zones (Fig. 5b and a, respectively). The sense of shear can also be inferred from the deformation of the internal granulitic foliation in granulitic boudins. In the relatively narrow transition zone between preserved granulite in the core of the boudin and eclogite shear zones, the granulitic foliation, when oblique to the eclogitic foliation, is bent to become parallel to the eclogitic foliation, giving shear sense along the border of granulitic boudins (Fig. 5a). The study of large scale asymmetric features such as granulitic boudins is particularly relevant for kinematics analysis : The progressive formation of eclogitic shear zones tends to isolate large blocks, from one to several tens of meters large, of undeformed and resistant granulite in an eclogitic matrix. The pertinent characteristic “grain size” is thus very large and the search for regionally significant kinematic indicators requires observations at a large scale.

Both within cm-scale coronas and m-scale boudins, most collected criteria yields top-to-the-northeast sense of shear throughout the granulitic unit. This sense of shear is compatible with the overall sigmoidal shape of the eclogite foliation over the island.

Although asymmetrical objects can be found in every shear zone, their density is highly variable. They are sparse in the Upper and Lower Eldsfjellet shear zones and much more ubiquitous in the Hundskjeften shear zone and to a smaller extent in the Skurtveit shear zone. In order to demonstrate this density we carried out a detailed mapping of a 100x100 m area in the Hundskjeften shear zone containing many metric sized boudins (Fig. 6). The asymmetrical shape of most boudins, the sigmoidal eclogitic foliation around them and the deflection of granulitic foliation along boudins borders demonstrate a consistent dextral sense of shear at the map scale. The average eclogitic foliation in this area is N120 40N and the lineation trends N80. The apparent dextral sense of shear results from top-to-the-ENE movement.

Eclogitic deformation in little transformed zones

In little transformed zones, eclogitization is present only in 1 to 10cm wide bands, either on both side of a mm wide fracture or as narrow shear bands without central fracture.

A large proportion of eclogitic fractures – i.e. mm wide fracture with 1 to 10cm wide eclogitic reaction bands on both sides – do not show any brittle nor ductile deformation. These “static” fractures seem to be randomly oriented.

In the rest of eclogitic bands, the kinematics can be deduced from the offset/deflection of granulitic foliation/lineation across the eclogitized zone. The orientations of these bands, as well as the deformation that affects them, show a very consistent structural pattern and can be separated in two main sets (Fig. 7a). The first

set of bands strikes between N90 and N120, dips northeastward and displays normal-dextral movement associated with NE striking lineations. The second set strikes between N30 and N80, dips northwestward and displays normal-sinistral movement associated with NW striking lineations. Representative outcrops (Fig. 7b) show either sinistral bands (B), dextral bands (C), or both (A and B'). Where both sets of bands are present, the dextral bands are wider than the sinistral ones. The geometry and kinematics of narrow eclogitic bands suggest a bookshelf mechanism : the rhomboedric blocks of granulite are bounded by a dominant set of normal dextral shear bands and a smaller conjugate set of normal sinistral shear bands (Fig. 8).

Moreover, the dextral set of eclogitic bands is comparable in orientation and shear direction with the major shear zones observed in the more eclogitized areas. The bookshelf-type deformation in little eclogitized areas is thus fully compatible with the top-to-the-northeast shear sense on major shear zones.

Kinematics of amphibolitic deformation

Within the granulitic unit, amphibolite-facies retrogression is less conspicuous in the field than eclogite-facies metamorphism. Amphibolitic shear zones are typically 10cm to 1m wide and cannot be followed along strike for more than a few metres. These shear zones, that crosscut the granulite foliation, strike in average NW-SE with a large scatter (Fig. 9). The deflection of the granulitic foliation near the shear zones gives an average top-to-the-SE sense of shear.

The Rosslund amphibolitic shear zone, which separates the Meland Nappe from the granulitic unit, is at least a few hectometres wide and can be followed for hundreds of metres in an ENE-WSW direction. This shear zone contains a few asymmetric granulitic boudins indicating a dextral sense of shear, similar to the sense of shear observed in the minor shear zones in northwestern Holsnøy. Shear criteria are nevertheless relatively rare, due to an extensive greenschist-facies overprint. The dextral sense of shear is roughly compatible with the early amphibolitic top-to-the-SE phase Sd-1 described by Schmid et al. (1998) in the Rosslund Shear Zone.

Discussion

Geodynamic interpretation of the northwestern Holsnøy kinematics-geometrical model

Our field study of eclogitic shear zones reveals top-to-the-NE shear deformation. The deformation in the amphibolitic field is in average top-to-the-SE (first amphibolitic deformation (Sd-1) in Schmid et al. 1998), with a nevertheless much larger scatter than the eclogitic data. Despite these variations, there is a continuum of deformation from eclogitic to amphibolitic conditions, which leads us to interpret the eclogitic deformation as the first recorded stage of exhumation for the granulite unit.

A collisional eclogitic deformation

The history of the Caledonian orogenesis is traditionally decomposed in a collisional stage in the late Ordovician-Silurian, followed by an extensional stage starting from the Devonian. Fossen (1992) states that extension started around 400 Ma with kinematics reversal along the basal decollement zone of the Caledonian nappes. As noted earlier (see “geological setting”), there are controversies on the age of eclogite metamorphism, either 460 or 420 Ma. Whatever the age, the shortest time span of 20 Ma between all eclogite ages and the start of extensional tectonics (syn- or post-collisional) shows that the eclogitic deformation studied on Holsnøy is coeval with the collisional phase. The presence of eclogite-facies metamorphism as young as 405 +/-5 Ma (Root et al. 2001; Root et al. in review) or Ultra-High-Pressure metamorphism dated 401.6 +/-1.6 Ma (Carswell et al. 2003) or 402 +/-2 Ma (Tucker et al. submitted) in the WGR also illustrates that while Holsnøy started to exhume, the whole orogen was experiencing convergence.

Holsnøy eclogitic deformation within Caledonides and Bergen Arcs kinematic framework

The general structure of the Caledonian orogen is thought to result from the northwest dipping subduction of Baltica under Laurentia (Krogh 1977). This subduction geometry is inferred from nappe-thrust kinematics and from variations in the degree of metamorphism in the WGR (Griffin et al. 1985). The nappes of western Norway were thrust onto the Baltic shield toward the southeast. Furthermore, the difference between the maximum burial (more than 100 km) for coesite-bearing units in the NW of the Western Gneiss Region (Smith 1984; Wain 1997; Carswell et al. 2001) and the much shallower burial (pressure peak of 13 kbars, ~40km) in the SE of the WGR (eclogites in the vicinity of the Solund basin (Chauvet et al., 1992, Hacker et al. in press) is roughly in agreement with the SE-trending metamorphic gradient defined by Griffin et al. (1985). This direction is inferred to be parallel to the thrusting direction. On a more regional scale, other units of the Bergen Arcs were deformed during the Caledonian orogenesis. Within the highly-sheared Major Bergen Arc, a

garnet-amphibole micaschist recorded a top-to-the-SE sense of shear, corresponding to Caledonian contractional deformation (Wennberg 1996). The contractional phase in the Ulriken Gneisses and its psammitic cover is recorded in sheath-like folds and S-C structures, both indicating thrusting toward the East (Fossen 1988). In the Øygarden Gneisses structures indicating top-to-the-east sense of shear developed under upper greenschist-facies during the Caledonian collision (Fossen & Rykkelid 1990).

Caledonian contractional structures in southwestern Norway are thus characterized by sense of shear and transport directions top-to-the-SE in the SE of the Caledonian nappes, and top-to-the-E in the Bergen Arcs (Fossen 1992). This sense of shear is roughly in agreement with the top-to-the-NE movement shown by eclogitic shear zones on northwestern Holsnøy. Late-caledonian extensional shear zones such as BASZ (Wennberg 1996) and the formation of the arcuate structure of the Bergen Arcs may have caused the slight misorientation.

Post eclogitic rotation of northwestern Holsnøy

To place the eclogitic deformation in northwestern Holsnøy within the overall Caledonian collision geometry, we also need to assess the rotation that affected the granulite unit during its exhumation. In their tectonic model of Caledonian orogenesis, based on the south Norwegian Caledonides, Andersen et al. (1991) proposed that the orogenic extensional collapse was initiated by the detachment of the subducted lithospheric mantle. This resulted in isostatic rebound and exhumation of deeply buried crust. Geometrically, during exhumation, the exhumed crust undergoes top-to-the-SE rotation (clockwise when looking north-east in a NW-SE section of the subduction zone, see Fig. 10a). This general top-to-the-SE rotation, related at large scale to the NW-dipping subduction may, in detail, be expressed as top-to-the-E rotation in the Bergen Arcs, where tectonic features are slightly misorientated with respect to general geometry of the orogen (see above the distribution of shear senses, as described by Fossen (1992)). In addition, some rotations may stem from late-orogenic extension. The mode II extension proposed by Fossen (1992, 2000), is made through large and deeply-rooted normal shear zones/faults, among which is the Bergen Arc Shear Zone. Normal movements on these listric faults cause rotations: Large normal displacements along the WSW dipping BASZ, on the eastern border of the Bergen Arc, results in top-to-ENE rotation of the nappe pile. Therefore, both processes proposed above lead roughly to top-to-the-E rotation of the Lindås nappe after eclogitic metamorphism.

To restore the eclogitic shear zones to their original position at depth, within the Caledonian slab, we rotate them counterclockwise with respect to a NS horizontal rotation axis (Fig. 10b). After about 20° rotation, shear zones dip toward the WNW instead of the NE, and their normal sense of displacement becomes reverse

(Fig. 10b shows the situation after an arbitrary rotation of 60°). Both the restored geometry (~WNW dipping) of the shear zones and their reverse sense of shear are thus much more compatible with the general frame of the NW dipping subduction.

Interpretation of eclogitic deformation

As a result of this geometric reconstruction, we propose the following scheme for the history of crustal units affected by HP-LT metamorphism (Fig. 11): The crust, whose lower part is relatively rigid and coherent, is dragged down by the dense lithospheric mantle as the upper part of the subducting slab. During burial, P-T changes make minerals metastable and, depending on the supply of fluids, a fraction of this crust is transformed into weaker and denser eclogite. Deformation is localized in eclogitized parts that constitute shear zones setting apart units of undeformed granulite. The crust is cut out in nappes, which can start their ways up to the surface by thrusting toward the East and piling up onto each other. Such an interpretation also implies that a normal shear zone separates the rigid buttress (Laurentia) from the exhuming units within the continental accretionary wedge (see arrows along the upper boundary of the subduction wedge in Fig. 11). To our knowledge, there is no evidence for such a zone in the Bergen Arcs. An easy but not completely satisfactory explanation for this absence is that there is not a single but several units stacked in the subduction wedge. The unit affected by the normal sense of shear may not have been exhumed up to the surface, unlike units affected by reverse sense deformation. Another reason for the lack of a large normal shear zones may be that the extent of reverse sense deformation within the subduction wedge is larger than the extent of normal sense deformation: reverse movements are caused by exhumation and by the displacement of the subducting slab relative to units in the subduction wedge, whereas normal movements are caused by exhumation only.

Collisional exhumation models

Strain localisation

Collisional exhumation models can be described in terms of two end-members, penetrative corner/wedge flow models (Jischke 1975; England & Holland 1979; Cloos 1982; Shreve & Cloos 1986; Mancktelow 1995) and localizing rigid slab models (Chemenda et al. 1995). The two types of model differ first by the spatial distribution of strain (see review by Platt (1986)): in wedge/corner flow models strain varies smoothly within exhumed units, whereas in Chemenda's models strain is extremely localized into two shear

zones, one normal at the top and the other one reverse at the bottom, enabling a unit of undeformed crust to reach the surface after its burial. The distribution of eclogitic strain on Holsnøy is highly heterogeneous at the kilometer scale: undeformed kilometric crustal units (i.e. untransformed granulite) are separated by highly strained hectometre scale bands (i.e. eclogitic large shear zones). This heterogeneity must be accounted for in modelling km-scale structures and phenomena, such as subduction channel or wedge dynamics. In contrast, an average rheology that smoothes such strain-localisation effects is relevant to model geodynamics of the whole orogeny.

A delicate balance between shear stresses and buoyancy forces

The two end-member models also deal differently with the way shear forces are handled in exhumation processes. In Chemenda's models, exhumation is only caused by the positive buoyancy of crustal units dragged into the denser mantle. The presence of a weak decoupling layer between rigid crustal units and underlying mantle, in the sinking slab, decides whether the ascent of buoyant crust is possible or not. In corner/flow models, shear forces alone can cause upward motion: if the subduction channel that contains the subducting crust and its sedimentary cover is narrowing, the downward circulation created by basal shear stresses is balanced under certain conditions by upward flow. Despite this difference, the concept of subduction channel also assumes partial decoupling of the crustal units and the lithospheric mantle within the subducting slab.

Decoupling being partially controlled by the mechanical behaviour of the buried crust, a question is to what extent a change in crustal rheology affects the processes in subduction and collision zones. Looking at complete P-T loops of a crustal unit, from near the surface to the mantle and back to the surface, a decrease in viscosity has a two-fold consequence: at depth, it increases the decoupling of the crust from the downgoing lithospheric mantle and therefore it enhances its capacity to exhume. On the other hand, early exhumation of buoyant crust may prevent a large fraction of the crust to reach and equilibrate at high pressures. The balance between both effects could only be analysed through the study of metamorphic terranes at the scale of the whole orogen, which is by far beyond the scope of this paper. In addition, on Holsnøy we do not deal with permanent rheological changes but with a change in viscosity that happens only when the crust reaches high pressures. In such circumstances the consequences of eclogitization are quite straightforward: rigid granulite is dragged down until it gets partially eclogitized; the eclogitized zones, weaker than the granulite, act as decoupling surfaces which enable granulitic slivers to start their way up. Therefore, in terms of rheology, eclogitization unambiguously favours exhumation and is the first necessary step toward exhumation. An important question

still to be answered about this rheological weakening is whether it is induced by hydration and grain size reduction only or also by the mineralogical change.

The second major physical consequence of eclogitization is the density change, which can be up to 15% (Austrheim 1987). As a result, a completely eclogitized lower crust becomes denser than the surrounding mantle (Le Pichon et al. 1992, 1997; Dewey et al. 1993), annihilating the buoyancy force, which in all models is a major driving force to exhumation, if not the only one.

In terms of exhumation, eclogitization has thus two opposite consequences. Eclogitization is a evolutionary process, in time – i.e. the set of reactions progresses continuously between transformed and untransformed states –, and in space – i.e. some parts of the granulitic unit are still pristine while other are completely reacted. The balance between viscosity decrease and density increase, respectively promoting and impeding exhumation, depends on the way metamorphic reactions progress and propagate. The eclogitic shear zones cutting through preserved granulite, as observed on Holsnøy as well as in Flatraket (Krabbendam et al. 2000; Wain et al. 2001), enable mechanical decoupling without large density increase when averaged over the whole granulitic unit. One may imagine another situation, where very large fluid advection would induce much more pervasise eclogitization. There, the associated density increase would lead to the further sinking of eclogitized crust. Of course, such situation is purely hypothetical, since what we observe is only what has finally been exhumed; therefore, only a comprehensive mechanical modelling of eclogitization propagation could help to understand deep processes affecting rocks that finally come back up, as well those that allegedly disappear in the mantle.

Conclusion

The northern part of Holsnøy Island is a granulitic unit that experienced HP-LT metamorphism during the Caledonian orogenesis. This metamorphism heterogenously affected a granulite-facies protolith terrane, resulting in the juxtaposition of well preserved granulitic zones and eclogitic zones. The eclogitic zones range from 10 cm-wide reaction zones along fractures, involving only fluid diffusion from the fracture and little deformation, to eclogitized zones that are strongly deformed, forming shear zones of size ranging from 1 cm to 100 m.

The comparison of P-T-t paths of the rocks on Holsnøy with paths of rocks in the surrounding areas or in the WGR indicates that exhumation of northern Holsnøy unit occurred while some close units were still being

buried to large depths. A detailed study of eclogite-facies deformation in large shear zones (in particular that of asymmetrically deformed objects such as granulitic boudins or coronas) shows a consistent pattern of normal-dextral shear zones with top-to-the-East sense of shear throughout northwestern Holsnøy. In little transformed zones, a second set of minor shear zones, showing normal-sinistral sense of shear, mimics a bookshelf mechanism.

A small amount of amphibolite-facies retrogression occurs in thin shear zones crosscutting both granulite and eclogitic shear zones. The deformation in these amphibolitic shear zones reproduces roughly the eclogitic kinematic pattern, showing that eclogitic deformation recorded on Holsnøy corresponds to the first stages of exhumation.

The Caledonian orogenesis resulted from the subduction of Baltica under Laurentia, in an NW-SE convergent context (Mckerrow et al. 1991; Torsvik et al. 1996). When replaced in a geodynamical context of northwest-dipping subduction, the eclogitic deformation pattern can be interpreted as the deep thrusting and piling-up of several crustal slivers.

We thus propose the following scheme for the history of crustal units affected by HP-LT metamorphism : The crust, whose lower part was relatively rigid, was dragged down by the dense lithospheric mantle as the upper part of the subducting slab. During burial, P-T changes made the protolith granulite-facies minerals metastable and, depending on the supply of fluids, a fraction of the crust was transformed into weaker and denser eclogite. Deformation was localized in eclogitized shear zones setting apart units of undeformed granulite. The crust was cut out into nappes that started their way up to the surface by buoyant ascent, by thrusting onto each other.

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Figure Caption

Fig. 1 Geological map of the Bergen Arcs (after Ragnhildsveit & Helliksen 1997). General map of Norwegian Caledonides by Roberts & Gee (1985).

Fig. 2(a) Geological map of Holsnøy by Birtel et al. (1998), Boundy et al. (1997a), Kühn (2002), Ragnhildsveit & Helliksen (1997). Location of Figures 2b, 5 and 9. Coordinates correspond to UTM grid, zone 32 : 22 = 67 22 000, 81 = 2 81 000. (b) Northwestern Holsnøy (Austrheim et al. 1996; Boundy et al. 1997b) with heterogeneous distribution of eclogitic overprint on granulite. Eclogite, Breccia and Granulite correspond to degrees of eclogitic

metamorphism >80%, 40%-80%, <40%, respectively. Location of figures 5a-b, 6, 7b. Hunskejften, Skurtveit, Lower Eldsfjellet and Upper Eldsfjellet are the four eclogitic shear zones studied.

Fig. 3 Schematic drawings of the different stages of eclogite-facies metamorphism, associated with shear zone formation, after Boundy et al. (1992). (a) Eclogite-facies reaction zone along hydrous mineral filled fractures cutting through granulite, without macroscopic deformation. (b) Minor eclogitic shear zone, with internal foliation and no trace of a former central fracture. The deflection of the granulitic foliation in the transition zone indicates a dextral shear sense. (c) Eclogite breccia made of rotated granulite boudins in a network of anastomosing eclogitic shear zones. Some blocks have an asymmetrical shape. (d) Eclogitic major shear zone mainly made by a well foliated and lineated eclogitic matrix and sparse granulite boudins. Photographs (a') and (c') corresponds to diagrams (a) and (c), respectively. Note the different scales.

Fig. 4 Eclogitic foliations and lineations in the major shear zones. Arrows: sense of shear. Hund., Skurt., L.Elds. and U.Elds. refer to Hunskejften, Skurtveit, Lower Eldsfjellet and Upper Eldsfjellet, respectively.

Fig. 5(a) Sense of shear deduced from S-C structures and from asymmetrically deformed coronas or mafic aggregates. These criteria show consistent top-to-the-NE sense of shear. See locations on Figure 2b. (b) : Sense of shear deduced from asymmetrical shapes of granulite boudins, sigmoidal eclogite foliation around boudins and deflected granulite foliation along boudins borders. Locations on figure 2b.

Fig. 6 Map of asymmetrical boudins in the Hunskejften "breccia" zone showing consistent to-to-the-NE sense of shear. See location on Figure 2b.

Fig. 7(a) Stereographic plot of the two sets of minor eclogitic shear zones/fractures. The major set (solid lines) corresponds to normal-dextral movement. The minor set (dotted lines) corresponds to normal-sinistral movement. (b) Representative outcrops showing the distribution of eclogitic fractures and narrow shear zones, with two sets of orientations (minor set striking N30-60, with apparent sinistral movement, major set striking N90-120, with apparent dextral movement). Relative movement is deduced either from deflected granulite foliation or from offsets of pyroxene-garnet lenses. Sketch (B) shows shear zones with apparent sinistral

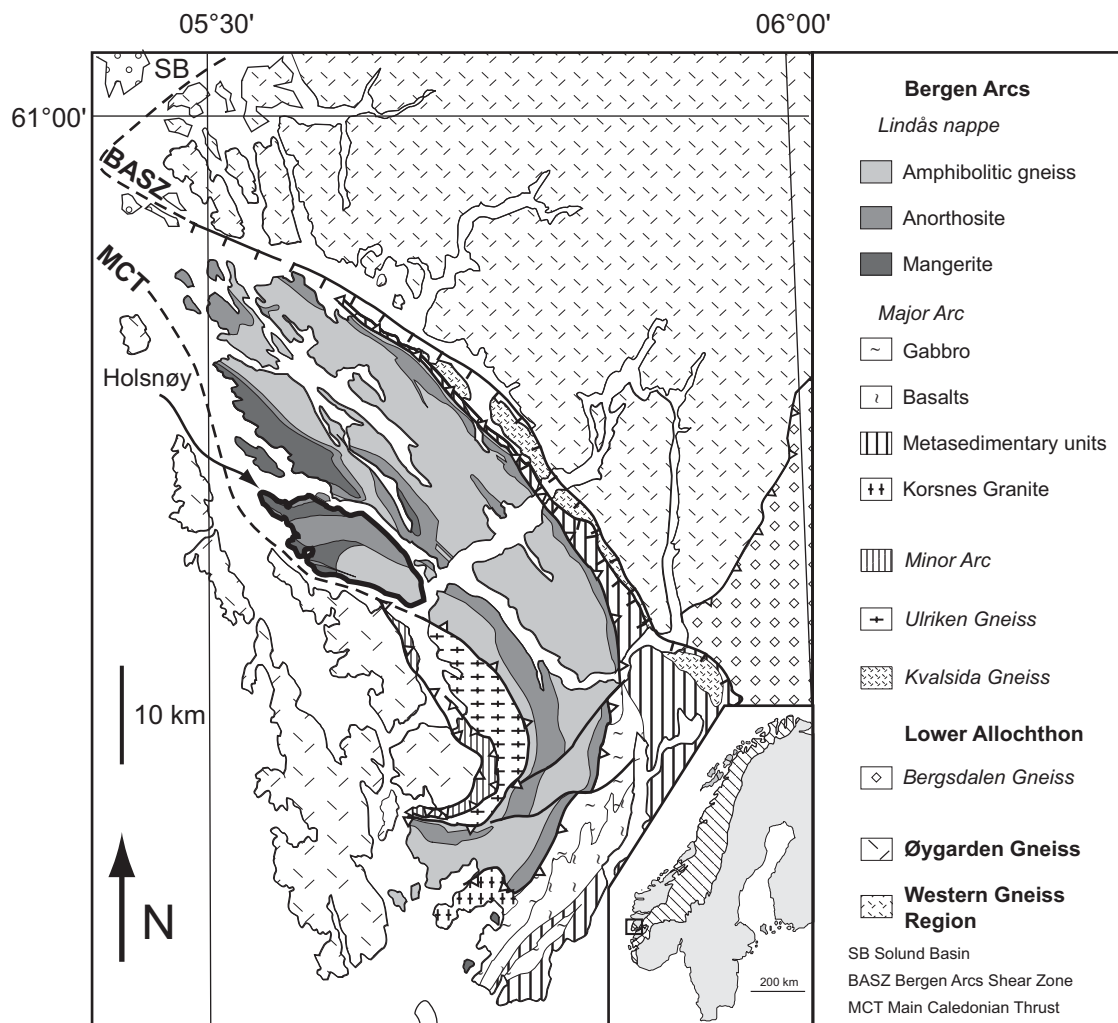
movement, sketch (C) shows eclogite-facies shear zones/fractures with apparent dextral movement. Sketches (A) and (B') show the two sets of shear zones/fractures. See locations on Figure 2b (same location for B and B').

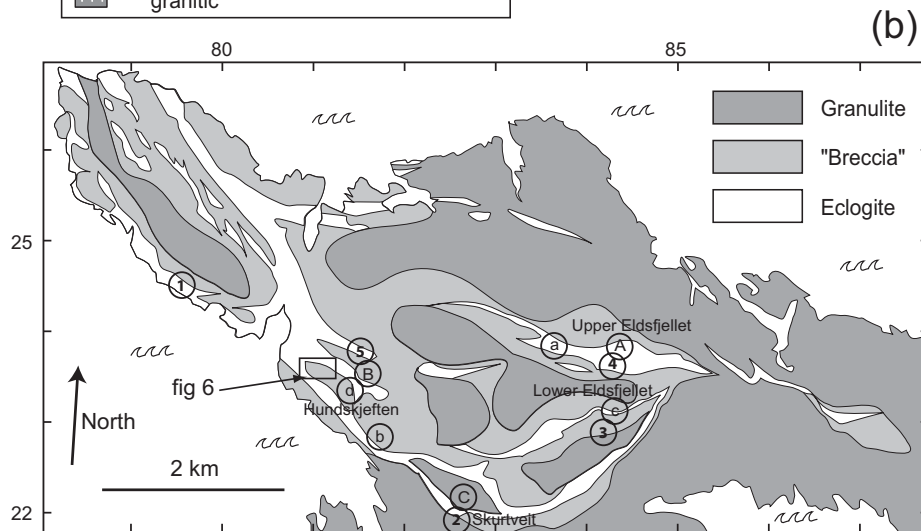
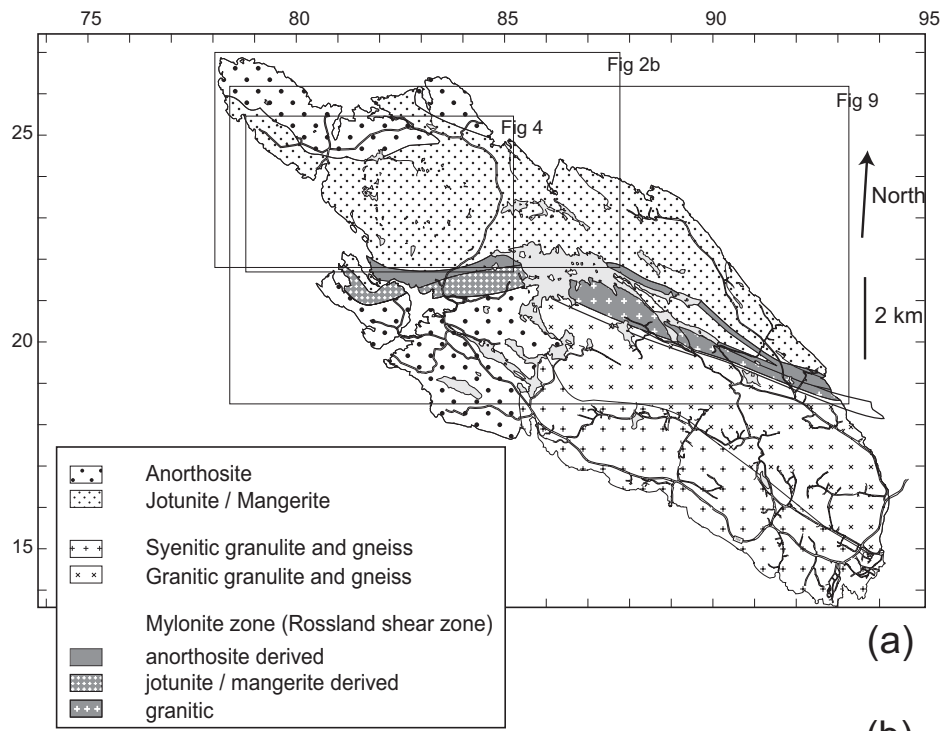
Fig. 8 Bookshelf geometry with top-to-the-NE major shear zones and conjugate subordinate shear zones related to counterclockwise block rotation. Minor shear zones strike between N30 and N60, with normal-sinistral sense of shear. Major shear zones strike between N90 and N120, with normal-dextral sense of shear.

Fig. 9 Map of amphibolitic deformation on northwestern Holsnøy, Rosslund Shear Zone and north of Meland Nappe.

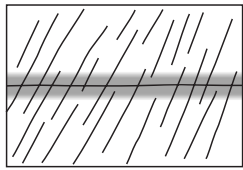
Fig. 10(a) Model for “top-to-the-SE rotation” : the present geometry is rotated clockwise about a horizontal NE trending axis, when looking to the NE. (b) Restoration of Holsnøy in its original position within the Caledonian slab. The rotation shown on the stereographic plot corresponds to a top-to-the-W 60° rotation about a NS axis. As a result, eclogite-facies shear zones, oriented in their present position (direction: N120, dip: 20NE) with normal-dextral movement, are rotated into new position (direction: N20, dip: 50W) as reverse-dextral shear zones, corresponding to their former position in the Caledonian subducting slab.

Fig. 11 Interpretative sketch of processes occurring in the buried crust. The zoom shows large eclogitic shear zones wrapping decoupled crustal units, while eclogitic reactions propagates into untransformed crust through fractures and shear zones distributed in two main sets of orientation.

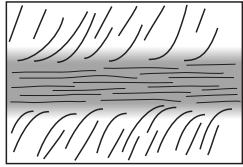




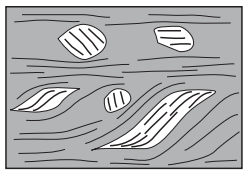
Granulite Eclogite



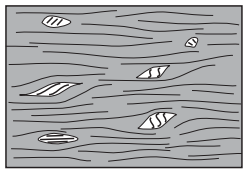
(a) 30 cm



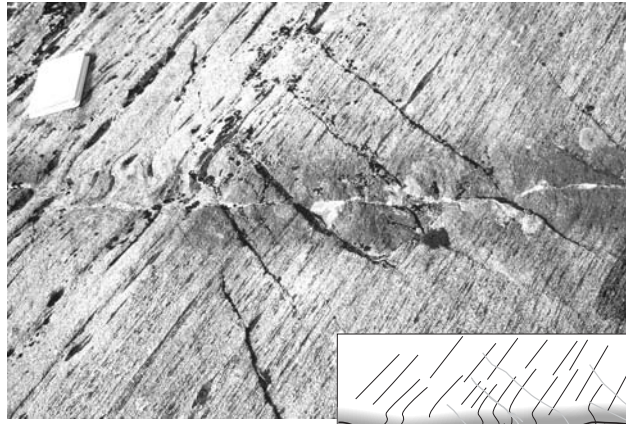
(b) 30 cm



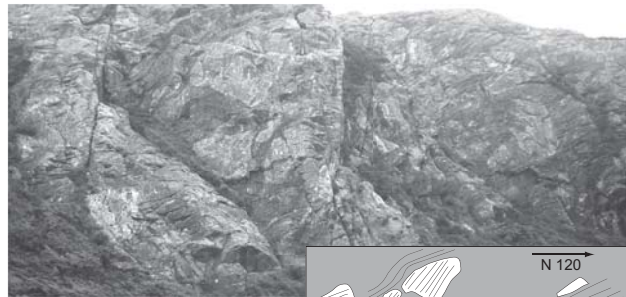
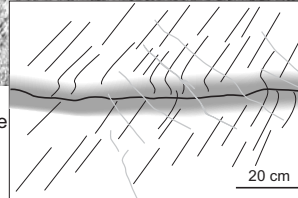
(c) 2 m



(d) 10 m



Eclogitic fracture



80

85

25

1 km

North

22

Hund.

U. Elds.

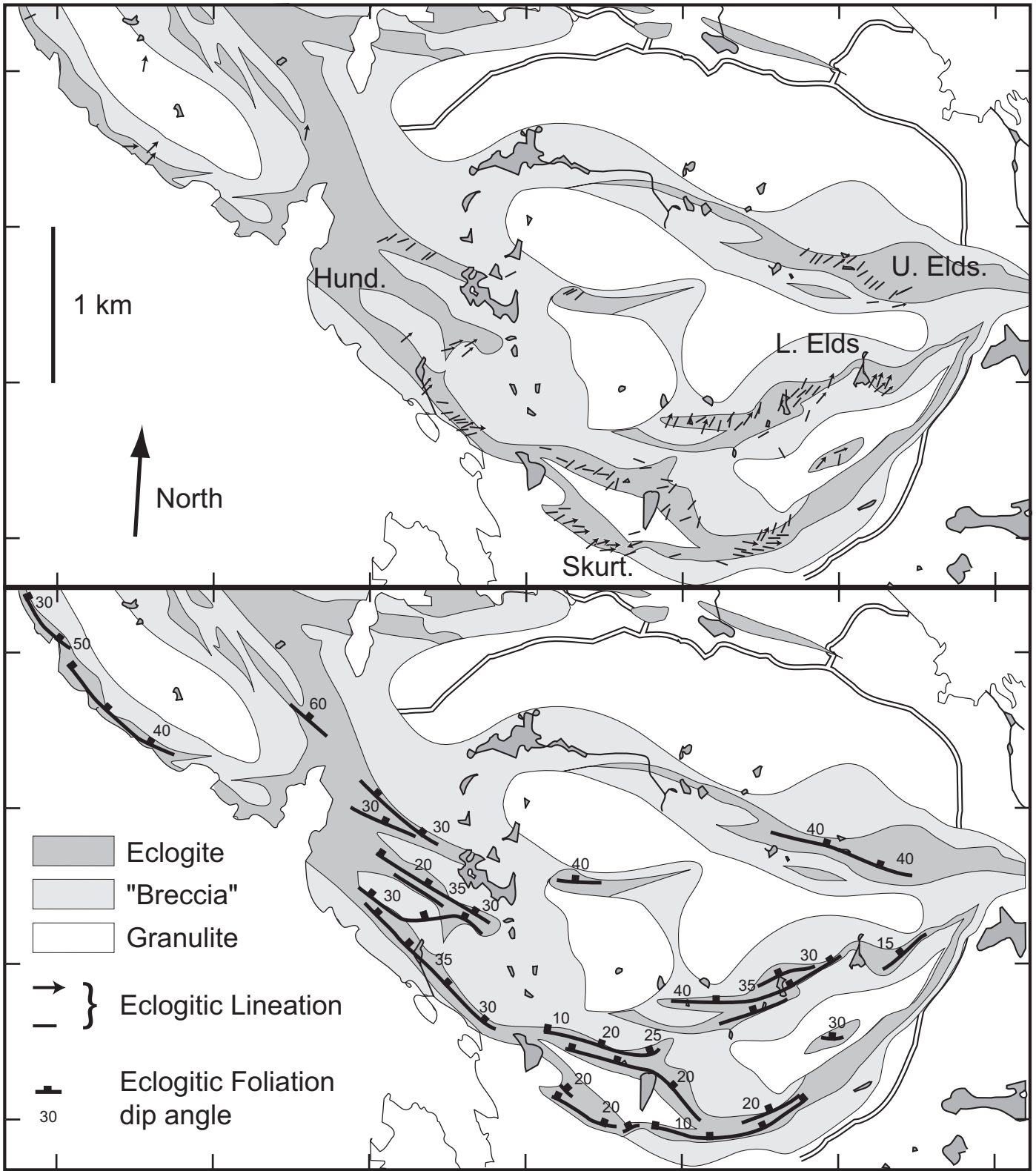
L. Elds.

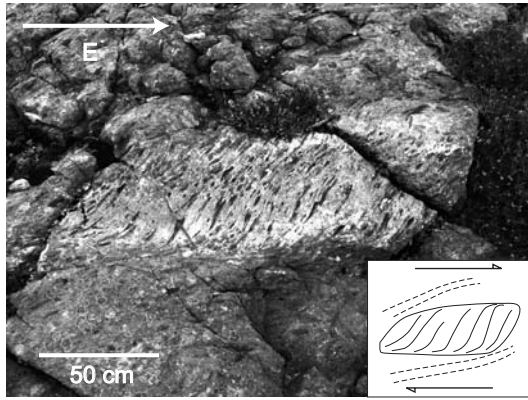
Skurt.

- Eclogite
- "Breccia"
- Granulite

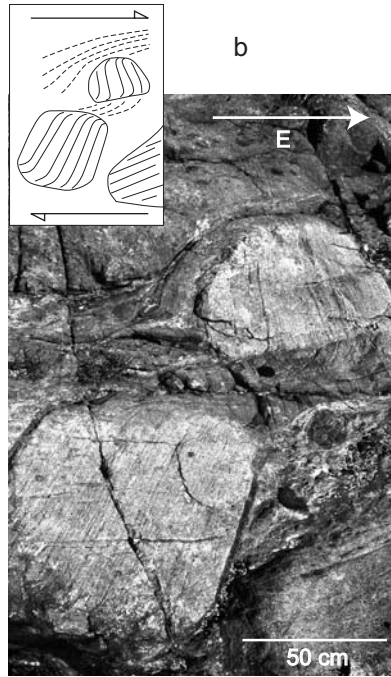
Eclogitic Lineation

Eclogitic Foliation dip angle

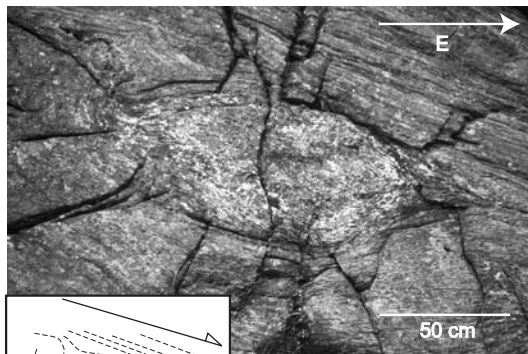




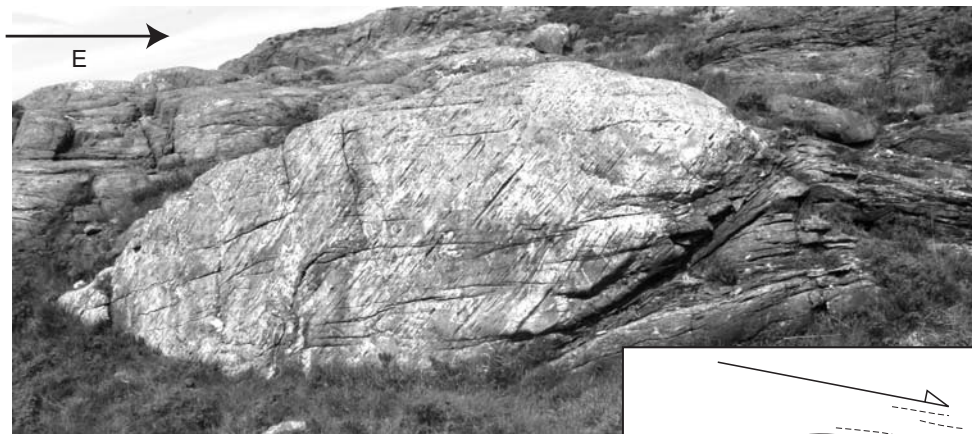
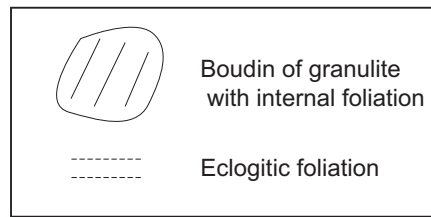
a



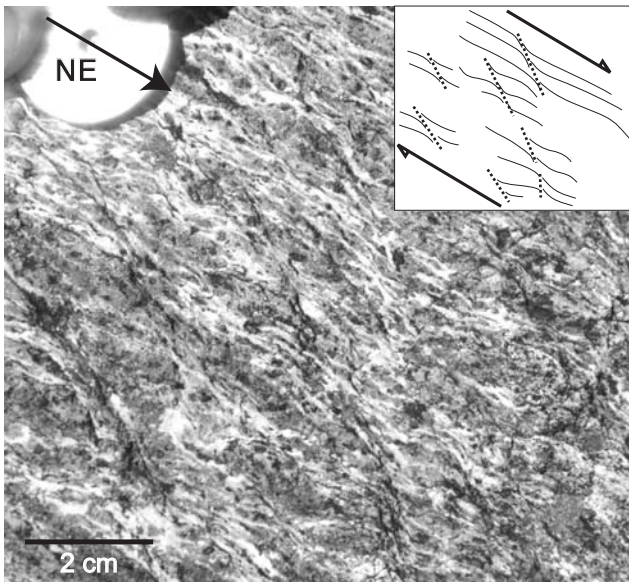
b



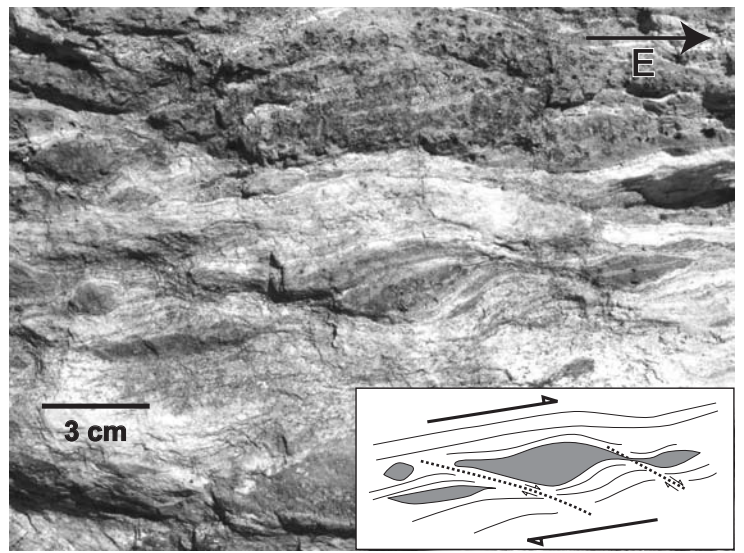
c



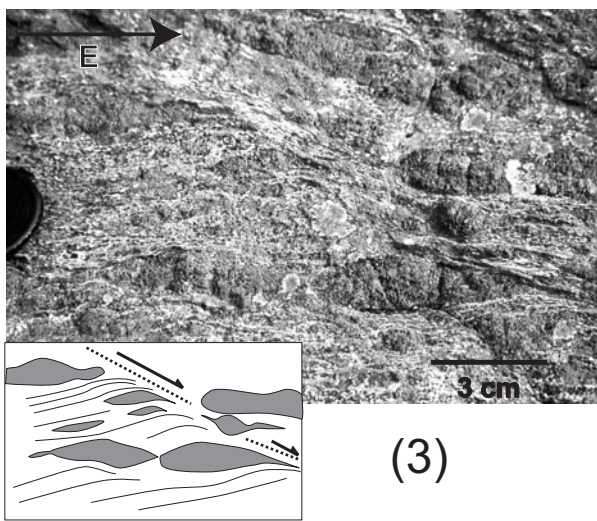
d



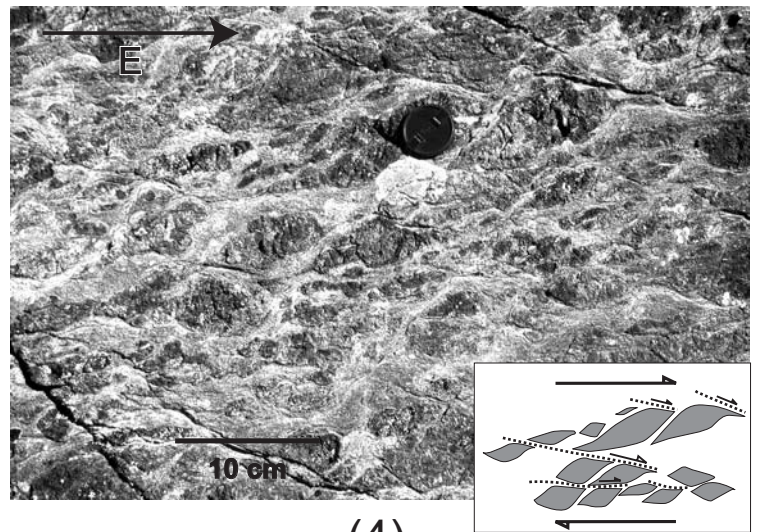
(1)



(2)

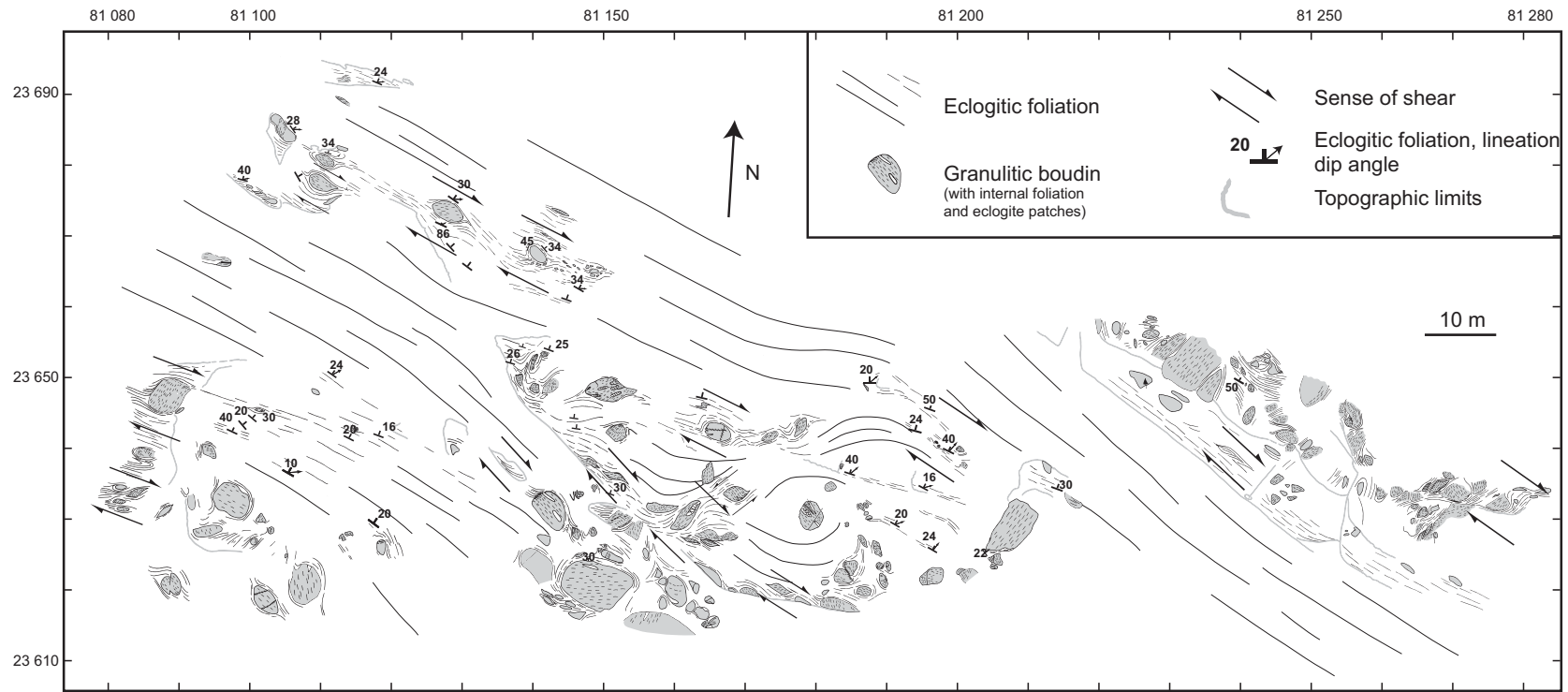


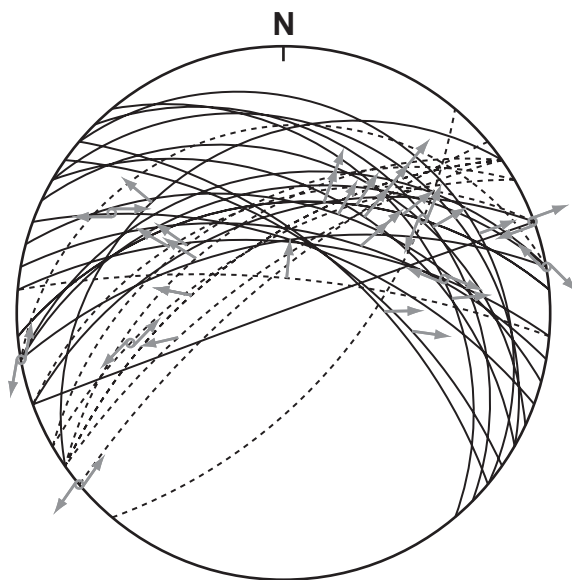
(3)



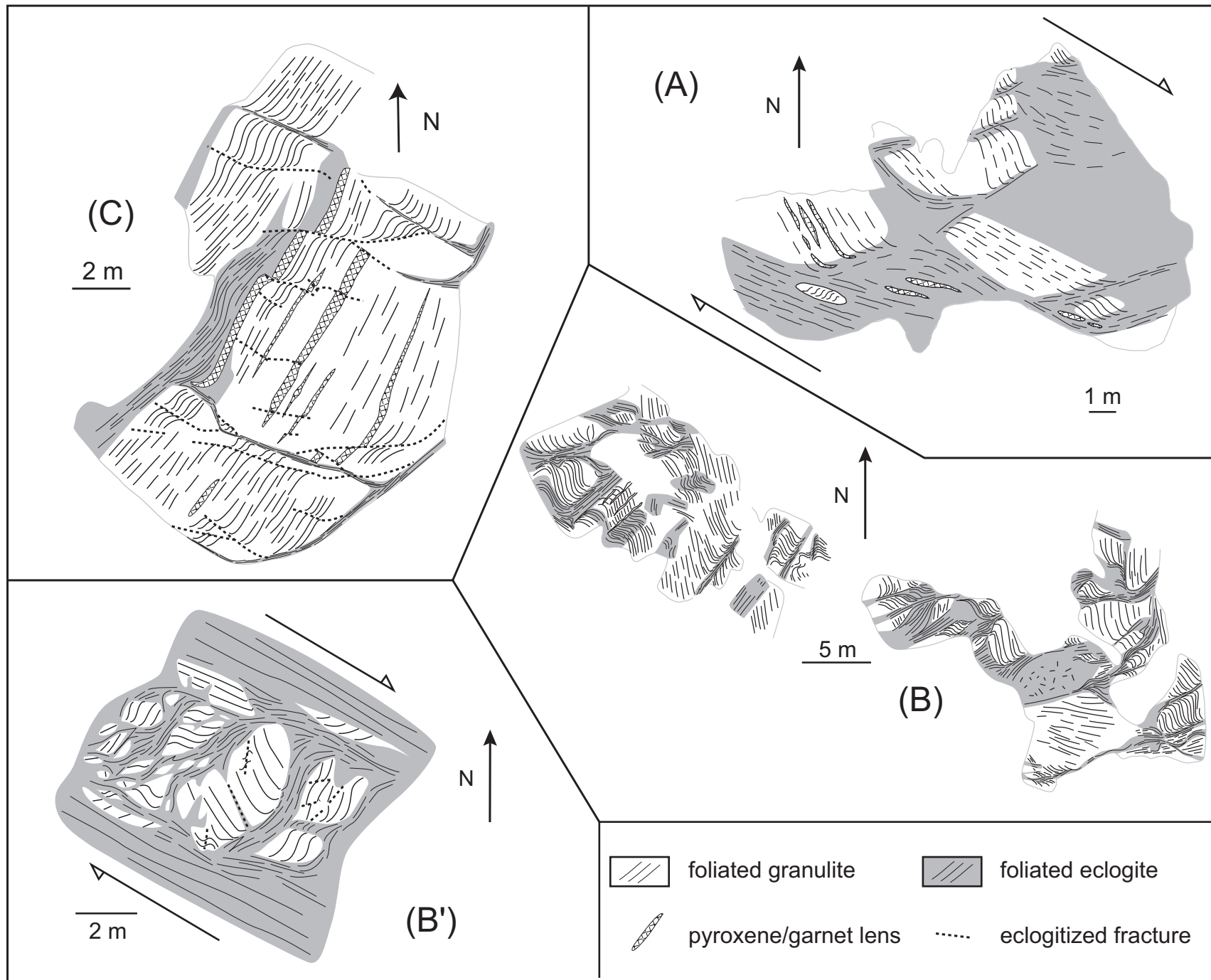
(4)

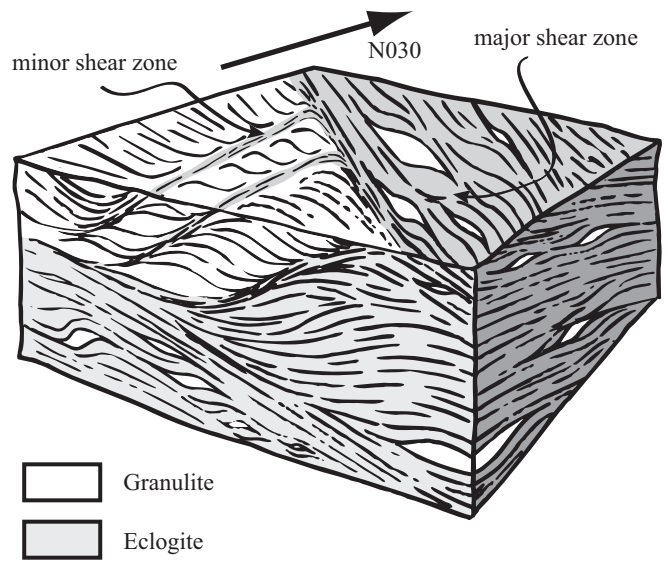
	<p>Asymmetrically deformed corona (or mafic aggregate)</p>		<p>Eclogitic foliation</p>
	<p>Sense of shear</p>		<p>Eclogitic shear band</p>

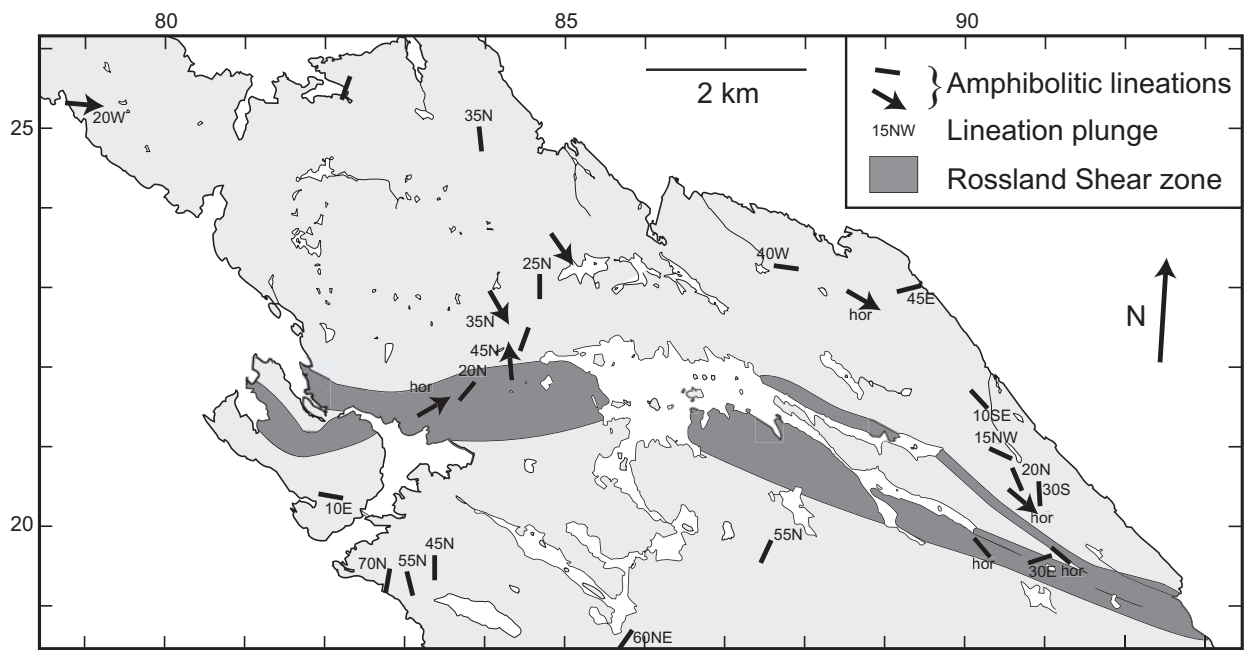


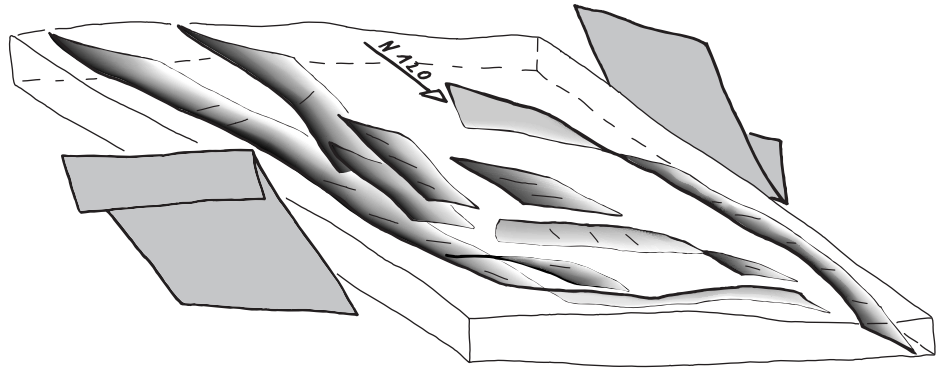


- Shear zones/Fractures with dextral movement
- - - Shear zones/Fractures with sinistral movement

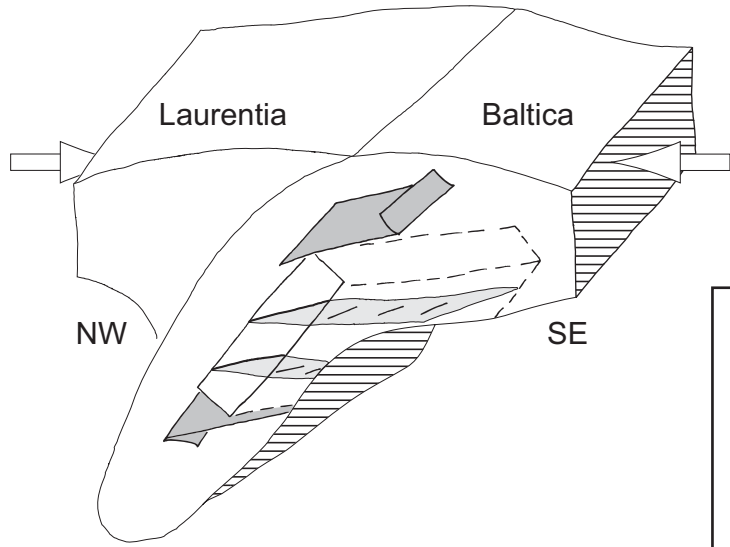








Present geometry (1)



Proposed Caledonian geometry (2)

