Svecofennian oblique transpression and strain partitioning in a Paleoproterozoic mid-crustal granite-greenstone setting: An example from the Rombak Tectonic Window, North Norway

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Abstract

The Rombak-Skjomen shear zone (RSSZ) is a major crustal scale Paleoproterozoic ductile structure that cuts through Paleoproterozoic metasedimentary and felsic igneous rocks of the Rombak Tectonic Window, situated within the Paleozoic Caledonian thrust nappes, Northern Norway. This window is an important link to understand and tie the basement rock outliers to the west in Norway and the juvenile Paleoproterozoic rocks of the Fennoscandian shield to the east in Finland and Sweden.

The main deformation in the Rombak window is of Svecofennian age (1.92-1.75 Ga) and located within several N-S running metasedimentary belts consisting of ductile folds, thrusts and anastomosing shear zones. The RSSZ has a complex structural evolution and geometry also involving syn-deformational injection of granitoids and strain partitioning with four phases of deformation; Early pure shear folding event (D_1), pure shear dominated fold-thrust belt event (D_2), two phases of combined simple shear and pure shear oblique systems with a conjugate set of N-S trending sinistral reverse oblique-slip shear zones (D_3), and a NE-SW dextral reverse oblique-slip shear zone event (D_4) where the fold-thrust belt is nearly fully overprinted. The crosscutting relationship between the granite and the structures shows that the granite cuts the fold-thrust belt and parts of the oblique-slip deformation and can also be locally cut by the D_4 event consistent with syn- to late orogenic plutonism.

We present a strain partitioning model of interacting high-low strain domains for the RSSZ, in an overall oblique transpressional setting.The strain partitioning have developed progressively from a monoclinic transpressional symmetry with pure shear and fold-thrust belt to a triclinic transpressional symmetry with combined simple shear and pure shear resulting in oblique-slip shear zones. In this scenario the anastomosing arrays of steep mylonitic shear zones (D_3) may have formed from a strain pattern of triclinic deformation superimposed on the earlier monoclinic fold-thrust belt deformation (D_1-D_2), leaving isolated domains of the monoclinic deformation intact. These four progressive structural events lead to a complex outcrop pattern of remnant fold-thrust belt blocks segmented and attenuated by two later phases of steep reverse oblique-slip ductile shear zone fabrics which shows a regional conjugate pattern with the direction of main principal shortening in a WNW-ESE direction.

Regional EM and radiometric data support the tectonic model and demonstrate that graphitic shales and potentially mineralized bodies in the fold-thrust belt have been dextrally displaced up to 6 km. The understanding of the structural evolution of the RSSZ in the Rombak Tectonic Window is important in order to understand the Svecofennian orogeny in the Norwegian portion of the Fennoscandian shield and to possibly be able to link the structures to the east and also to understand how progressive transpressive margins may develop in general.

Keywords: Transpression, Paleoproterozoic, ductile structures, oblique-slip shear zone, fold-and-thrust belt.

1.0 Introduction

Crustal-scale ductile shear zones are common structures that develop during an orogenic event, and such shear zones may reflect potential terrane boundaries (c.f. Park 2005) between assembled older crustal blocks or intracrustal shear zones. Such boundaries can help to restore the craton outline and the cratonic margin characteristics and to unravel cycles of tectono-magmatic events (cf. Bleeker 2003). It is improbable that two converging crustal plates move in a uniform direction, but more likely oblique to each other forming a transpressional system. This may include both perpendicular and sideway motions of plates relative to the main shortening direction. The resulting complex strain patterns during Precambrian tectonism forming as a result of simple shear, pure shear, dilation, transpression or transtension are still a rather poorly defined issue (cf. Garde et al. 2002).

Transpression was first used by Harland (1971) to explain oblique convergent plate margins and has been used to explain many orogenic belts such as the Gondwanian Orogen (Curtis, 1998) the Torngat Orogen (Girard, 1993), and the Svecofennian Orogen (Beunk & Page, 2001). The composite nature of transpressional orogens has been modelled and tested mathematically (e.g. Sanderson & Marchini 1984; Tikoff & Fossen 1993). Notably, the concept of strain partitioning of the two end-member styles, i.e. pure-shear and simple-shear components of the deformation in transpressive settings, is widely used in order to describe homogenous deformation. However, a number of issues still remain vague, for example the nature of interaction, the mechanisms of initiation and evolution of folds, thrusts and oblique-slip faults in space and time, and the controlling factors such as bed rock anisotropy, pre-existing structures, rheology-lithology, regional versus local stress fields, strain intensity and the angle of convergence (e.g. Tavarnelli et al. 2004 and references therein).

The main structures developing in such regimes are either separate strike/oblique-slip faults occurring in an anastomosing pattern with both pure shear and simple shear components (e.g. Carreras et al. 2010) or contractional (thrust-related) structures and domains (e.g. Tavernelli et al. 2004). Many attempts have also been made to develop models to explain strain partitioning of the strike-slip and contractional components, including simple shear models (Harland, 1971; Sanderson & Marchini 1984), monoclinic models (Jones et al. 2004 and references therein), complex triclinic transpression and inclined extrusion models (Davis et al. 2011 and references therein). These processes may operate independent or in combination, thus accounting for the usually very complex styles of deformation in transpressive settings.

The Rombak Tectonic Window (RTW) within the Caledonides of North Norway (Figs. 1 and 2) is an outstanding well exposed example of a Paleoproterozoic, orogenic mid-crustal granite-greenstone province that experienced a complex evolution and structural history, assumed to be of Svecofennian age (1.92-1.75 Ga; Lahtinen et al. 2005). This window is dominated by Paleoproterozoic metavolcanic and metasedimentary rocks (<2.3 Ga), defining NNW-SSE trending narrow fold-thrust belts and a major ductile shear zone, the Rombak-Skjomen shear zone (RSSZ) (Larsen et al., 2010). These belts and shear zones are intruded by mafic to intermediate 1.9-1.7 Ga granitic batholiths (Korneliussen et al. 1986; Romer 1987, Korneliussen & Sawyer 1989; Bargel et al. 1995).

Previous studies in the area have focused on the bedrock petrology and geochemistry (Korneliussen et al. 1986; Korneliussen & Sawyer 1989. The deformation style is described as N-S striking, steep foliation in the metasedimentary rocks and locally within the adjacent granites. Also NE-SW striking, steep mylonitic shear zones with dominantly dextral shear sense (Priesemann, 1984a; Priesemann, 1984b; Skonseng, 1985 Korneliussen et al., 1986; Naruk 1987), and interpreted to be with relation to the high mineral potential in the area (Coller, 2004).

This paper describes and outlines the geometry, kinematics and relative timing of the RSSZ and discuss its interaction with fold- and thrust structures of the easternmost N-S striking metasedimentary belt and adjacent granites (Fig. 2) in the Rombaken Tectonic window. We present a model of the belt as a transpressive segment in the Svecofennian orogenic belt with strain partitioning structures involving both fold-thrust belt structures and oblique-slip zones (cf. Larsen 2010).

2.0 Regional geology and setting of the Rombak Tectonic Window

The Precambrian Fennoscandian shield (Fig. 1) makes up large parts of Norway, Sweden, Finland and Russia and is composed of Archean to Neoproterozoic crustal rocks. The shield has a long evolution and growth history reflected by a complex array of ductile shear zones, representing different orogens arranged as narrow linear belts (e.g. Hölttä et al. 2008; Lahtinen et al. 2008; Korja et al. 2006). The oldest Archean craton dominates the northeastern part; the Paleoproterozoic Svecofennian domain including the Bothnian basin and Svecokarelian orogen is present in the middle, and Transcandinavian igneous belt and Sveconorwegian orogeny makes up the southwest (Fig. 1) (Gaál & Gorbatschev 1987; Gorbatschev & Bogdanova 1993; Hölttä et al. 2008; Lahtinen et al. 2008). The Fennoscandian shield is bounded in the west by the Caledonian nappes (Bergström & Gee 1985), which itself also includes a number of tectonic outliers west of the Caledonides (e.g. Lofoten, Vesterålen and western Troms) and inliers, or tectonic windows farther east.

The largest of the tectonic windows in the north-Norwegian Caledonides is the RTW (Fig. 2), which accordingly offers an important data source between the autochthonous NW

Fennoscandian Shield and basement provinces west of the Caledonides (i.e. in Lofoten and western Troms; Bergh et al. 2010, 2012) and the eastern basement region (e.g. Braathen & Davidsen 2000). The RTW is dominated by a Paleoproterozoic greenstone-granite suite (Foslie, 1916; Korneliussen et al, 1986; Myers & Krøner 1994) including six narrow N-S and NNW-SSE trending metasedimentary belts. These belts consist of felsic metavolcanic rocks in the southwestern belt and metasedimentary rocks consisting of basal meta-conglomerates, -quartzites, -sandstones, -schists, -greywacke and -tuff in adjacent belts. They are surrounded/ intruded by granitic and syenitic batholiths (c. 1.9-1.7 Ga) and mafic dyke swarms are intruding or surrounding the metasedimentary belts (Fig. 2; Korneliussen et al. 1986). The metasedimentary rocks have been the locus for ductile deformation into zones of NNW-SSE trending major fold-thrust belt systems and subsidiary oblique-slip shear zones. A major regional ductile shear zone, the Rombak-Skjomen shear zone (Larsen et al. 2010), traverses the entire window from north to south (Fig. 2). The structural analysis and understanding of the structural evolution of this shear zone is the main aim for the present work.

The tectonic evolution and metamorphic history of the RTW is poorly investigated (cf. Larsen 2010), despite a general knowledge of the age, petrology and geochemistry of the area (e.g Priesemann, 1984a; Priesemann, 1984b; Skonseng 1985; Korneliussen et al. 1986; Romer & Boundy 1988; Romer 1989; Naruk 1987; Coller, 2004). The metamorphic grade in the metasedimentary units is variable, ranging from upper greenschist facies to locally amphibolite facies conditions during the Svecokarelian (also termed Svecofennian) event (c. 1.82 Ga) (Sawyer 1986; Korneliussen & Sawyer 1986) and during intrusion of granitoid plutons (1.78 Ga). These early episodes were followed by low-grade greenschist-facies retrogression and ductile folding and shearing (mylonitisation), which is also thought to be of Svecofennian age (1.8-1.6 Ga). The metamorphic rocks in the RTW have signs of retrogradation and metamorphosed at temperatures at 575-600ºC. The pressure is moderate to high, at 6kb in the south, decreasing northwards due to a change from deeper to higher structural levels (Apted & Liou, 1983; Flood 1984; Korneliussen & Sawyer, 1986; Sawyer, 1986).

Previous structural studies within the RTW focused on the kinematics of inferred late-post Caledonian structures subjected to extensional reworking along the margin of the window and that metasedimentary rocks in the area is correlated to the lowermost Caledonian Dividalen Group (Cashman 1989; Rykkelid & Andresen 1992). Caledonian reworking in the RTW is discussed (see Birkeland 1976; Romer 1987; Korneliussen & Sawyer 1986; Romer & Boundy 1988; Tull1977; Motuza1998). The objective herein is to document that deformation features within the RSSZ are part of a multiphase transpressional orogen that is Paleoproterozoic in age. This is further backed by recent U-Pb zircon age dating of a granite intrusion intruding along and across the shear zone yielding an age of 1789 ± 6 Ma (Larsen et al., 2013), which verifies that the deformation of the area, as well as the presumed basal Caledonian (Paleozoic) metaconglomerates are truly Svecofennian in age.

3.0 Structure and architecture of the RTW

The dominant major structural feature of the RTW is the Rombaken-Skjomen Shear Zone (RSSZ; Fig. 2). The RSSZ shows a complex geometry, varying in across strike width from 7 km to 20 m (Fig. 2). Our field data, combined with EM gravity and magnetic maps of the RTW (Fig. 3), show an anastomosing deformation pattern with steep ductile, mylonitic shear zones and tight to isoclinal folds segmenting lenses of less intensely deformed blocks, in which primary bedding is often preserved, with macro-scale upright folds and gently dipping reverse faults (fold-thrust belt).

The RSSZ shows a complex evolutionary sequence including four Paleoproterozoic deformation events (D_1-D_4); D_1 is an early fold event occurring as refolded folds in D_2 structures. During D_2 deformation a low angle, top-to-east fold and thrust belt developed. D_3 structures are steeply dipping N-S trending ductile oblique-slip shear zones and related steeply-plunging folds that segment the D_2 fold and thrust belt. D_4 structures are steeply dipping NE striking oblique-slip ductile shear zones that diagonally crosscut and displace the D_3 structures.

In our detailed structural analysis, we subdivide the area (Fig. 2) into three geographically distinct localities, from north to south, Jernvann-Haugfjellet, Norddalen and Gaultelisvatten. Each area displays characteristically different structural and tectonic styles reflecting different aspects of the kinematics and strain partitioning evolution.

3.1 D_1 and D_2 Fold-thrust belt structures

D_1 and D_2 folds are preserved in lower strain domains within the RSSZ. In these domains bedding structures are well preserved in meta-sedimentary rocks. Bedding is either flat-lying or forms open, upright, east verging folds which are often cut and displaced by gently west-dipping ductile shear zones (thrusts) consisting of partly-mylonitized schists, which often form duplex structures The thrusts are especially focused in graphitic schists. A weak metamorphic, steeply-dipping, N-S trending axial planar cleavage is commonly developed in the folded strata (e.g. Norddalen and Gautelis localities).

F_1 and F_2 folds are spatially and temporally associated with the low-angle shear zones. Observations of tight to isoclinal F_1 folds are sparse, observed at one locality in the western part of a ca. 3 km wide fold-thrust belt at Norddalen (Fig. 4).F_1 fold wavelengths range from micro scale to several meters, locally overturned towards the east (Figs. 4 and 5) and are locally refolded by upright, asymmetric F_2 folds. The F_1 folds have most commonly sub-horizontal to shallow dipping axial surfaces with moderate to gently-plunging fold axes to the NNW, N and/or SSE (Fig. 4)

The dominant map-scale folds of the RTW are D_2 upright, east-verging and asymmetric with related ductile thrusts. The F_2 folds and thrusts are most prominent in Norddalen, forming a belt up to three kilometers wide. F_2 folds are generally coaxial with F_1. They are upright to asymmetric and east-verging with moderate to gently west-dipping axial surfaces (S_2), sub-parallel to S_1 thrusts. Some F_2 folds are highly sheared along their limbs, within imbricate thrust stacks(Fig. 4). F_2 folds are open to tight with a steep to overturned forelimb and a shallow to steeply-dipping back limb. Fold wavelengths range from mappable scales to micro-scale (Figs. 3, 4 and 5). Cleavage is parallel to the thrust surfaces and is shallow dipping to sub-horizontal (Fig. 5). In Norddalen mappable N-S striking shallow west-dipping ductile S_2-thrusts commonly follow graphite schist horizons . Stretching lineations on the thrust surfaces plunge moderately N and NE with an oblique-slip component (Fig. 4). A similar fold-thrust belt is observed at Gautelis, but consists of either stacked and folded greywacke or conglomerate/breccia on top of thrust-detached marble (Fig 6 and 7). F_2 folds verges to ESE and plunge to NNW (Fig. 6D; subarea A) with associated hanging wall parallel thrusts with a NNW-SSE strike, or WSW plunging fold axis with NE-SW striking thrusts (Fig. 6D; subarea B). Symmetric detachment folds are observed in the basal Gautelis conglomerate in NE to E or SW to W plunging fold axes, similar to F_2 folds in subarea B (Figs. 6D and 7; subarea C). The detachment horizon for the thrusts is assumed to be localized within the thin carbonate bed that is only locally found below and between the green conglomerate beds. F_2 fold development in the Haugfjellet domain is more evolved and therefore the thrusts are not mappable.

3.2 D_3 and D_4 Oblique-slip structures

Regionally, the RSSZ displays two orientations of steep N-S (D_3) and NE-SW (D_4) anastomosing pattern of shear zones (Fig. 3). The dominant N-S trend follows the regional geometry of the metasedimentary belts. The NE-SW trending shear zones, appear to truncate or fold the metasedimentary belts diagonally (Fig. 3). EM gravity and magnetic data from Norddalen shows a regional scale bending of the N-S trending belt and a c. 5km dextrally displacement of the graphitic schist in direction of the NE-SW trending D_4 shear zone (Fig. 3). The D_3 and D_4 shear zones are steep, ductile and reverse oblique-slip shear zones. They are characterised by a sub-vertical mylonite fabric and shallowly-plunging stretching lineations (Figs. 6, 8, 9 and10), localized steeply-plunging drag folds in the metasedimentary rocks (Figs. 5 and 9) and off-set lithologies in cross-section and map view (Fig. 9G).

Internally, the D_3 and D_4 shear zones display a large variation in strain, with high-strain ultra-mylonites alternating with lower strain areas of proto- and ortho-mylonites (Sibson, 1977), where bedding and other primary features are locally preserved in low strain lenses in a complex anastomosing network (Fig.10). The shear zone thickness varies from millimeter to kilometer scale and influence the thickness of the metasedimentary belt. The metasedimentary belt is generally narrower where there is a higher frequency of shear zones and a higher strain gradient. There is a large variation in strain gradient and shear zone frequency (Fig. 11) from both the outcrop scale down to the microscopic level (Fig. 8 and 10). The shear zones commonly follow lithological heterogeneities, particularly in zones of competency contrast along the metasedimentary - granite contacts (Fig. 10) and along more incompetent internal metasedimentary horizons. For example, shear zones are more frequently localised along marble and graphitic schist horizons (Fig. 6). Carbonate beds are also often attenuated and disappear along specific oblique-slip shear zones.

D_3 structures

The D_3 shear zones dominate the geometry of the northern part of the RSSZ from the Norddalen in the south to Haugfjellet area in the north but are pervasive within the whole length of the inlier. Their orientation strikes N-S (set I) to NNW-SSE (set II) and have a dominant reverse sinistral oblique-slip component (Fig. 8). However, in the Haugfjellet area these D_3 shear zones are characterised by an equal amount of both sinistral and dextral reverse steep oblique-slip shear zones. D_3 shear zones in the Norddalen area are parallel to the N-S striking D_2 folds and thrusts. They are mainly observed to be sinistral reverse oblique-slip shear sense indicators in field (Fig. 9E). The dominant D_3 stretching lineation for all localities plunges moderately to steeply to the NNE (Figs. 4, 6 and 8).

These localized steep D_3 shear zones consistently overprint F_2 fold limbs and segments the macro scale fold-thrust structures along the F_2 fold limbs (fig 4 and 8). The fold-thrust belt is highly segmented into steeply-dipping duplex-like geometries by the oblique-slip structures (Fig. 4). Originally shallowly-plunging F_2 fold axes were rotated into steeper orientations (Figs. 4, 8 and 9). The D_3 shear zones are more spatially associated with tighter and steeper plunging fold structures than in the D_1 and D_2 domains.The fold styles vary from asymmetric to isoclinal within the mylonite zones, often forming drag-folds with hinge thickening and limb thinning. In lower strain domains they are open to tight similar folds with a slight limb thinning (Fig. 9A, B and C).

D_4 structures

The D_4 shear zones are localized diagonal to the D_3 shear zone at several localities along the eastern side of the RTW (Fig. 2). These geographically constrained shear zones are best developed in the southerly part of the inlier and can be traced from Gautelis area and NE into the Sjangeli area in Sweden (Figs. 3 and 8). The D_4 structures strike NE-SW and sigma-clasts, duplexes and extensional crenulation cleavages (NSC) suggest a predominantly reverse dextral shear sense (Fig. 9F). In the Gautelis area the D_4 ductile shear zones are characterised by the most intense mylonitic fabrics and the largest D_4 structure in the whole of the RSSZ, the Gautelis

Mylonite Zone (GMZ). This ductile D_4 shear zone is approximately 800m wide and at least 5 km long and parallel to the main direction and part of the large D_4 structure that can be traced into Sweden. The GMZ displays a complex tectonic interfingering of different lithological lenses (Fig: 6 and 11; GMZ). and the presence of internally complex high and low-strain domains (Fig. 10 and 11).

3.3 Crosscutting relationships with syntectonic granites

The deformation sequence is polyphase in the deformed metasedimentary rocks, as we observe consistent cross-cutting relationships between the structural styles. The D_1fold are refolded and thrusted by D_2 structures. The D_3 structures are following, but thin and slightly cut the D_2 fold structures and the D_4 structures cuts and drag fold the D_3 structures.

We also observe crosscutting relationships between the ductile structures and both granitic and mafic intrusions found within the metasedimentary units of the RTW. Both sets of intrusions have a strong spatially association with the RSSZ. Specifically, the intrusive bodies occupy different sites spatially associated with the ductile shear zones; they are localised adjacent to a mylonite zone, they are cut by a mylonite zone, or they are found as randomly spaced undeformed bodies.

The granites are generally coarse grained and cut the stratigraphic beds and folds in all the structural domains. In the Haugfjellet area the granite cuts the steeply plunging D_3-D_4 folds, while on the other hand, it is locally transected by D_3-D_4 shear zones by either cutting dykes diagonally across or cutting into large bodies (Fig. 8). Similarly, in the Norddalen area the granitic intrusions cut the D_2 folded and thrusted metasedimentary rocks, but are also deformed by D_3-D_4 folding and shearing into the granite bodies (Fig. 6). Moreover the same type of shear zone parallel granite dikes within the shear zone in the Gautelis domain is completely mylonitized by D_3 and D_4 shear zones, but are also cut by the major granite body(Fig. 10). This suggests that the granite intrusions are syntectonic to the D_3 and D_4 structures.

The mafic intrusions are found along the whole RSSZ, but are most abundant in the Gautelis area. These mafic intrusions are always parallel to the D_3 and especially the D_4 shear zones, They are either used as deformation paths which are strongly mylonitized of D_4 shear zones or are undeformed and sometimes with shear zones cutting along the boundary sides of the intrusions (Fig 7D).These observation also suggest a syntectonic setting to the D_3 and D_4 structures. Which are confirmed when both the granite and mafic intrusion are present together, the granites and mafic dykes show mutual cross-cutting relationships (Fig. 6).

4.0 Discussion

The structural architecture of the RTW resulting from Paleoproterozoic deformation allow insight into aspects that may have controlled the formation and distribution of the different fold-thrust and reverse oblique-slip strain domains. In order to establish an overall kinematic evolutionary/tectonic model for the RTW and the encompassing RSSZ, we will address specifically, the structural chronology and relative timing of deformation, the mechanical factors controlling the types of deformation, and the kinematics and strain partitioning of the deformation. Similar approaches have been successfully used in many other partitioned tectonic settings of various ages; e.g. the active San Andreas Fault (e.g. Babcock 1974; Sylvester & Smith 1976, 1987; Burgmann 1991; Fossen et al.,1994), Cenozoic transform tectonism in the North Atlantic/Svalbard (e.g. Harland 1979; Braathen & Bergh 1995; Braathen et al. 1999; Leever et al., 2011), and Proterozoic-Archean transpressive tectonism in northern Fennoscandia (cf. Bergh et al. 2010) and Laurentia/Greenland (Garde et al. 2002).

4.1 Structural chronology and relative timing of the deformation

Excellent exposure, aerial photographs and new high-resolution geophysical data allow the relative timing of folds, thrusts, foliations, oblique-slip ductile shear zones and intrusive rocks to be determined (Fig. 3). Detailed structural mapping and interpreted cross-sections (Figs. 4 and 6) provided a framework for defining at least four main structural groups, including contractional fold-thrust structures and steep ductile, dominantly oblique-slip ductile shear zones. We observe a progressive deformation sequence that encompasses; (1) N-S trending isoclinal upright folds (D_1), (2) N-S trending, upright and east-verging, asymmetric folds and low-angle thrusts associated with a fold-thrust belt (D_2), (3) N-S and NW-SE trending steep ductile oblique-slip shear zones (D_3) and (4) NE-SW trending, steep mylonitic, dextral oblique-slip shear zones (D_4). These groups of structures and their chronology are largely responsible for the complex structural architecture of the RTW (Fig. 3), as discussed below.

Upright isoclinal Fl folds are preserved only within the Norddalen fold-thrust belt domain and are rarely observed. They have NNW-SSE trending fold axes and steep, subvertical axial surfaces, and these early folds have been mostly coaxially re-folded by upright, east-verging D_2 folds and associated low-angle D_2 thrusts (Fig.4). Relative fold geometries suggest D_1 and D_2 folds formed in an overlapping contractional strain regime characterised by, e.g. successive and/or progressive ENE-WSW shortening. Isolated remnants of D_1-D_2 folds and thrusts are preserved within the GMZ, with folds trending NE-SW and with moderately-plunging axes, slightly oblique to D_1 fold axes in the Norddalen domain, and suggestive of NW-SE oblique contraction during their formation (cf. Priesemann 1984b). Alternatively, we interpret this deviation as the result of a ca. 45° clockwise block rotation of the fold-thrust belt structures during subsequent oblique-slip shearing in the GMZ. In the Haugfjellet area, in contrast to Norddalen, primary bedding is scarcely observed in low strain domains between the steep ductile shear zone. Present, bedding is strongly attenuated and D_1-D_2 fold axes rotated into steep plunges. This kind of discontinuous rotation of fold-thrust structures by oblique-slip shearing both across-strike and along-strike resulted in complex structural segmentation and attenuation of the RTW belt.

The oblique-slip ductile shear zones (D_3-D_4) in the RTW consistently post-date the fold-thrust belt related structures. The Norddalen locality displays a clear age relationship between D_2, D_3 and D_4 (fig 4) in that D_3 is consistently parallel to the trend of the fold-thrust belt structures (D_2) by following weak layers and lithological boundaries. D_4 obliquely cross-cuts both bedding, D_2 fold-thrust structures and D_3 shear zones. This locality also demonstrates that the oblique-slip shear zones likely evolved in a time-progression after initial E-W contractional fold-thrust belt generation (Fig. 4), in the form of variably, NW-SE directed sinistral shear zones (D_3) and dextral NE-SW shear zones (D_4) in a dominantly transpressional tectonic setting. The overall N-S trends of the fold and shear zone arrays, their mainly sinistral shear-sense and dextral, mutually cross-cutting shear zones, and the oblique stretching-lineations (Figs 4, 6 and 8) suggest formation during NE-SW directed transpression.

The absolute age of the structures within the RTW has been previously considered as Paleoproterozoic by Korneliussen et al. (1986), Korneliussen & Sawyer (1986) and Bargel et al. (1995), while a Caledonian age was inferred by Birkeland et al. (1976), Naruk (1987), Cashman (1990) and Rykkelid & Andresen (1995). Argumentation for a Caledonian age of the deformation relies on the metasedimentary units in the RTW being interpreted as Neoprotorozoic in age, corresponding to the Dividal Group. In such a context Birkeland (1976) concluded that the D_2 folds in the area were Caledonian in age, as these folds affected the assumed Neoproterozoic Dividalen Group.

The present work demonstrates that the folding pre-dated the deposition of the Neoproterozoic Dividal group, and thus is Proterozoic in age (cf. Larsen 2010). For example, the metasedimentary rocks thought to be Neoprotorozoic in age are strongly deformed and make up distinct attenuated segments of the RSSZ, and furthermore, the steeply dipping ductile shear zones associated with D_3 and D_4 events are discordantly cut by the flat-lying Caledonian thrust sheet structures (Andresen, 1988). New radiometric age determinations (Larsen et al., 2013) of syn- to post-tectonic granite intrusions discussed above, which are spatially and temporally related to the shear zone development, suggesting a Paleoproterozoic age, thus precluding a Caledonian age for the deformation.

4.2 Mechanical control

There are mechanical controls on oblique convergent plate settings, which include lithospheric boundary conditions, lithological heterogeneity, rheology, heterogeneities in the strain field (pure- and simple-shear), relative angle of principal stress in oblique transpression, and the presence of intrusive melts (e.g. Fossen & Tikoff, 1993; Jones & Tanner 1994; Tikoff & Fossen 1993; Teyssier et al. 1995; Brown & Solar, 1998; Barraud et al. 2001; Tavarnelli et al. 2004: Whitney et al. 2007; Schrank et al, 2008). Our data suggests that the overall controlling element of the deformation in the RTW is the RSSZ and the nature of its evolution. This regional scale ductile shear zone is localized in contrastingly different rock types and borders different deformation domains from pure shear dominated in the contractional fold-thrust belt in the Norddalen locality, to combined pure and simple shear domains in the Haugfjellet and Gautelis localities, and with several sets of oblique-slip shear zones. This suggests that the mechanical control excerted by the RSSZ have been influenced by spatial subdivision of low and high strain domains and distinct differences in rheology resulting in distributed and localised deformation zones. Notably, high-strain localised deformation occurs along heterogeneities within the bedrock: (i) along weak sedimentary horizons, (ii) along geometrical shapes defined by pre-existing structures, (iii) parallel with mafic intrusive rocks, and (iv) along the boundaries of granite intrusions. For example, in the contractional Norddalen domain, the main D_2 thrust zones are located within stacked black schist, grey schist and marble horizons, suggesting the formation of fold-thrust structures are largely lithologically controlled (Fig. 4). Similarly, remnants of fold and thrust structures in the Gautelis oblique-slip domain are preserved as detachment folds and thrusts in carbonate and graphite schists. Therefore, we conclude that the internal sedimentary rheology, i.e. pre-existing anisotropy (cf. Evans et al. 2003; Montési & Hirth 2003; Tavarnelli et al. 2004; Schrank et al. 2008; Larsen et al., 2010), played a major mechanical control in partitioning of the deformation, at least on the earliest, contractional stages of the deformation in the RTW.

Weak sedimentary rocks and pre-existing structures may also control the formation of later ductile structures, in this case the D_3 and D_4 oblique-slip structures in the RSSZ. In the RTW the stratigraphic units in the Norddalen domain and the carbonate horizon at Gautelis, in which a major mylonitic shear zone developed (GMZ), provided the locus for oblique-slip reactivation. For example, the major SET III (D_4) shear zone at Gautelis is localised along the highly competent interface between the metasedimentary units and the tonalitic basement complex to the east (Fig. 6). These oblique-slip shear zones are mostly steeply-dipping and developed preferentially parallel to steeply-oriented fabrics, e.g. bedding and cleavages of D_1-D_2 folds and steep thrusts (D_2) in the fold-thrust domains. In Norddalen, the sinistral oblique-slip folds adjacent to D_4 shear zones have the same trend as the upright D_1-D_2 folds. At Haugfjellet, steep oblique-slip shear zones are mostly confined to the steep limbs of steeply-plunging folds (Fig. 8). Several of the shallow dipping D_2 thrusts were steepened and reactivated as D_3 and D_4 oblique-slip shear zones.

These observations suggest that the contrasting deformation styles in segments/domains across as well as along-strike in the RTW were influenced by lithological heterogeneities. Similar conclusions have been reached by e.g. Jones & Tanner (1994), Tavernelli et al. (2004) and Bergh et al. (2010) from the study of interacting contractional and oblique-slip features in various transpressive settings. Jones & Tanner (1994) described how partitioning of transpressive strain occurs when stress is applied oblique to pre-existing weakness zones. Tavernelli et al. (2004) showed how the deformation evolution and geometry is highly depending on the anisotropy of the rocks. Bergh et al. (2010) demonstrated progressive Paleoproterozoic deformation in the West Troms Basement Complex, north Norway, that involved early formed ductile thrusts and upright macrofolds whose steep limbs and corresponding steepened early-stage thrusts were reactivated by orogen-parallel, steep oblique-slip shear zones and subvertical folds.

In a constantly evolving strain field, in the middle crust level and at medium grade metamorphic conditions as in the RTW, the fine-grained metamorphic rocks deform easier than their coarse-grained counterparts, and the deformation will thereby be localized in the fine grained rocks and modified by deformation processes such as ductile flow, recrystallization and recovery (e.g. Evans et al. 2003; Montési & Hirth 2003). Examples include fine-grained mafic dykes in the Gautelis domain and graphitic black schist in the Norddalen domain. Similarly, high-strain mylonitic shear zones in the Gautelis domain localised along steep boundaries of rheologically different schist and granitic intrusive rocks (fig. 11) and mafic dykes and the surrounding host rock (Fig. 7). Such relationships have been observed across the entire RTW, suggesting regional-scale control of mechanical anisotropies. At Gautelis, mafic dykes have a NW-SE trend (Fig. 7), and they likely acted as both incompetent deformation channels and competent lenses. Dykes intruded along NE-SW shear zones were also ductily deformed (Fig. 4), supporting synchronous intrusion and deformation. However, some granitic bodies which are intruded after the initial phase of D_2 folding are subsequently cut by steep ductile shear zones (D_3 and D_4). It is also notable, that the mafic dykes in general intruded in two or more generations as they mutually cross-cut the granites (cf. Korneliussen et al. 1986). Therefore, we can clearly document the syn-tectonic nature of both the granitic and mafic intrusions, and thus enable to infer their controlling effect on the deformation features. Syn-tectonic intrusion (melt) paths are known from many studies (e.g. Barraud et al. 2001; Brown & Solar 1998; Pavlis 1995), and they may control the channelized melt flow pattern and thus localize the intrusion on the deformation fabrics. For example Brown & Solar (1998) showed that granite melts found in dilatant shear fractures are driven by both buoyancy forces and tectonically induced melt pressure. In accordance with their findings, we have demonstrated that granite and mafic dykes associated with RSSZ consistently intruded parallel to the D_3 and D_4 steep ductile shear zones, the shear zones and the melts forming a complex interplay. If these shear zones controlled the melt pathway, the intrusions likely modified the competency contrast with the surrounding metasedimentary rocks to influence the nucleation sites of the shear zones.

4.3 Kinematic models with emphasis on strain partitioning

The concept of strain partitioning is widely used to explain simultaneous interaction of pure shear contraction and strike-slip (simple shear) deformation in a transpressive setting both in the ductile and brittle regimes (cf. Harland & Wright, 1979; Sanderson & Marchini 1984; Tavarnelli et al. 2004). The nature of interaction is however, generally hard to evaluate, since e.g. the regional and local strain-stress fields, strain intensity and the angle of obliquity can be highly variable in such settings (Sanderson & Marchini 1984). In a simple shear setting, the structures formed as a result of instantaneous strain will have an angle of obliquity ca. 45° to the main shear zone and the resulting strain will be fully distributed (e.g. Harland 1971; Sanderson & Marchini 1984; Zoback et al. 1987). During progressive oblique convergence the direction of the maximum instantaneous shortening direction becomes increasingly perpendicular to the shear zone boundary and the degree of strike-slip partitioning increases (Sanderson & Marchini 1984). The overall result may be full partitioning of the contractional and strike-slip components and the formation of domains with localized ductile shear zones and corresponding off-fault contractional domains. Alternating complexities of deformation partitioning may arise if the nature of strain varies between monoclinic and triclinic transpression (Fossen & Tikoff, 1994; Jones et al. 2004; Tavernelli et al. 2004) and inclined extrusion (Jones et al. 2004).

In the RTW there is evidence for interacting pure shear and simple shear structures in segments or domains along the RSSZ, thus inferring strain partitioning. The fold-thrust belt in the Haugfjellet and Norddalen domains and the dominant GMZ in the Gautelis oblique-slip domain are all well-constrained examples of such segments. On the other hand, the documented relative timing between the contractional and oblique-slip structures is partly in conflict with a full partitioning model (Sanderson & Marchini 1984). Accordingly, in the RTW, the deformation domains may have developed independently, in a time-progressive manner, either as fold-thrust belt or oblique-slip features.

A fold-thrust character of the deformation was likely favoured in the early stages of deformation, at least in the Norddalen domain, and this may have been due to a high angle of obliquity of the regional strain axes relative to the metasedimentary units/basins and their boundaries to the surrounding rocks. In the Haugfjellet domain, there is an equal amount of contractional structures relative to oblique-slip shear zones, and both sinistral and dextral shear-senses occur in the oblique slip shear zones. Most of the stretching-lineations in the fold-thrust structures are perpendicular to the structural trends, while they are mostly oblique to slightly oblique on the steep ductile shear zones (Fig 8). This may imply that the finite strain of the Haugfjellet domain was more pure-shear dominated, at least in the initial stages, and that the strain axes were rotated during progressing deformation and orogenic accretion/wedge build-up and switched into a weakly partitioned system characterised by sinistral and dextral oblique-slip shearing (i.e. a conjugate system) rather than a fold-thrust belt. Similar interpretations were made by e.g. Tikoff & Greene (1997), Curtis (1998) and Holdsworth et al. (2002). The Haugfjellet domain also differs somewhat with respect to strain orientation from the interpreted regional strain (Fig. 8), and this may be explained by local strain partitioning largely unrelated to the regional strain axes (cf. Jones & Tanner 1993). The Gautelis domain, on the other hand, is composed mainly of the RSSZ including the GMZ, and thus may be considered a oblique-slip (simple shear dominated) segment of the RTW.

The sinistral dominated oblique-slip shear zone recorded in the Norddalen domain and the oblique-dextral shear zones in the Norddalen and Gautelis domains show a clear dextral off-set and bending of structures and corresponding lateral displacement (Fig. 4). However, these shear zones display moderate-plunging stretching-lineations supportive of a deformation regime with a combination of pure shear and simple shear (e.g. Sullivan & Law 2007; Davis et al. 2011), rather than a distributed simple shear displacement mechanism (e.g. Ramsay & Graham 1970; Harland 1971; Sanderson & Marchini 1984). The sinistral ductile shear zones in these domains show a dominating stretching-lineation plunging to the NW, whereas the dextral shear zone has stretching-lineations plunging towards the NE. This supports a model with a changing regional strain field (axes) from NW-SE to NE-SW during progression of the deformation, generating two localized transpressional ductile shear zones.

Transpressional models involving monoclinic symmetries were first developed by Sanderson & Marchini (1984) and followed by several authors (e.g Fossen & Tikoff 1993; Simpson & De Paor 1993) and compared with field examples (e.g. Ring 1998; Baird & Hudleston 2007; Vitale & Mazzoli 2009). A monoclinic symmetry model can be explained by a distorted "cube" where two of the angles are not normal to each other, producing either strike- and dip-parallel lineations depending on the amount of accumulated deformation and the angle of convergence across the shear zone (Fossen & Tikoff 1993; Ghosh 2001; Dewey 2002). The Norddalen domain may be an example of a monoclinic deformation symmetry, since the stretching-lineations on both the steep shear zones and the low-angle thrusts are dip-slip (i.e. pure shear dominated). The Gautelis domain also displays remnant blocks of pure shear dominated fold-thrust belt structures within the more oblique-slip dominated domain.

The monoclinic model, however, cannot be used to explain oblique-plunging lineations (Sullivan & Law 2007; Davis & Titus 2011). Oblique-plunging lineations may either form in coupled boundary models (Robin & Cruden 1994; Dutton 1997) or during triclinic transpression (Jones & Holdsworth 1998; Lin et al. 1998; Jones et al. 2004). In case of a coupled boundary model cleavage/foliation formed during folding and/or lateral shearing will dip away from the center of the shear zone and be vertical in the central, high-strain portion of the shear zone (Dutton 1997). The margins of the shear zone, on the other hand, will experience the most pronounced pure shear component and the maximum plunge of the lineation (Robin & Cruden 1994; Dutton 1997). The transpressive triclinic model combines the end-member pure shear and simple shear components, and in such a model all stretching lineations will be oblique to the strike of the shear zones (e.g. Hudleston et al. 1988; Sullivan & Law 2007; Davis et al. 2011).

In the RTW, the overall internal character of the RSSZ would suggest synchronous pure-shear and simple-shear deformation although elements of the earlier-formed fold-thrust structures may have been locally preserved (see earlier discussion). The fact that both sinistral and dextral oblique-slip shear zones occur there, and that the stretching-lineations for the sinistral and dextral shear zones both display major oblique trends (Figs. 4, 6 and 8), the most likely interpretation would be that of a triclinic transpressional model (cf. Holdsworth et al. 2002; Tavarnelli et al. 2004). In cases where a monoclinic symmetry of structures exist, this may be explained by a high ratio of pure shear relative to simple shear, and progressive transition into triclinic geometries through time if the ratio of simple versus pure shear increases (Kuiper et al. 2011).

The intensity of strain in the RSSZ may be used as well, to infer lateral segmentation and strain partitioning in the RTW, since strain intensity commonly increases towards the center of the shear zone (Ramsay & Graham 1970; Robin & Cruden 1994). The strain pattern of the RTW is characterised by an anastomosing high-strain dominated shear zone pattern enveloping less deformed or low-strain fold-thrust belt domains and/or segments with highly variable width and extension along strike of the metasedimentary belt (Figs. 2, 4, 6 and 8). Notably, the width of the metasedimentary belts appear to correspond to the strain intensity, i.e. wide segments up to 10 km in the Haugfjellet and Norddalen fold thrust domains, while narrow (< 100 m) domains such as in the southern part of Haugfjellet define high-strain oblique-slip domains. These variations are also clearly inferred from the magnetic and gravity data of the RTW (Fig. 3).

4.4 Tectonic model

With regard to the discussion of relative timing of the deformation in the RTW, the mechanical factors controlling the deformation, and the kinematics and strain partitioning of the deformation, in particular along the RSSZ, we propose a kinematic and evolutionary model as follows (Fig. 12):

(1) D_1-D_2 event: An early deformation event involved E-W contraction and formation of N-S trending tight to isoclinal D_1-folds locally within the metasedimentary belts. Coaxial refolding and generation of major N-S trending upright D_2-folds likely formed in a progression of events, producing a fold-and thrust belt, as observed in the Norddalen domain, and associated axial-planar detachment folds, cleavages and low-angle thrusts. As the orogenic contraction proceeded, and likely also due to a shift to greater obliquity in the regional shortening direction relative to the fold- thrust belt, the initial gently west-dipping strata and low-angle D_2-thrusts were rotated into a steeper orientation. In conjunction with steep D_2 fold limbs these zones of weakness became the controlling factor for subsequent partitioning of the oblique strain.

(2) D_3 event: The overall oblique-convergent strain then was split into NW-SE directed transpressional domains with sinistral oblique-slip-slip shear zones (D_3) sub-parallel to the fold-thrust belt, effectively segmenting and attenuating the fold-thrust belt.

(3) D_4 event: During the latest ductile event, some of the reverse oblique-slip-slip shear zones of the RTW were subjected to NE-SW dextral transpressional shearing (D_4), and the strain was distributed diagonal relative to the metasedimentary units, causing further segmentation of the fold-thrust belt. At this stage, the RSSZ most likely formed as a through-going crustal feature within the overall and dominantly oblique strain-field. Strain partitioning proceeded and the fold-thrust belt structures and the sinistral ductile shear zones were modified by dextral shear zones (D_4) and were rotated or bent into steeply-plunging folds. We interpret the formation of these D_4 shear zones as forming an extensional crenulation cleavage type geometry, further attenuating the already segmented fold-thrust belt and steep D_3 shear zones.

The resulting complex geometry of the RTW and RSSZ included many different structural geometries and kinematic domains with isolated, steep shear zone bounding remnants of fold-thrust belt structures surrounded by an anastomosing network of ductile shear zone arrays (Fig. 3).

(4) Intrusions: Synchronous with the formation of the oblique-slip D_3-D_4 shear zones along the RSSZ, the metasedimentary belt was intruded by fine-grained mafic dyke swarms and granitic injections that may have played a critical role during the progressive evolution and further strain partitioning of the RTW. The oblique-slip shear zones may have been confined to areas undergoing very high end-member strain where the RSSZ split into subsets and detached or splayed into less competent rocks (black schists, marbles) or steep pre-existing fabrics (fold limbs), producing a variety of oblique mylonitic shear zone fabrics. This could have occurred along the boundaries of more competent granites, intrusives and mafic dykes. For example do mafic dykes intruded parallel to the shear zone and acted as nucleation sites for further shearing.

5.0 Conclusions

- A crustal scale steeply-dipping ductile shear zone with associated fold- thrust domains has been identified and systematically documented in Paleoproterozoic igneous and meta-supracrustal rocks of the Rombak Tectonic Window northern Norway.

- The Rombaken-Skjomen shear zone (RSSZ) shows temporal and spatial strain partitioning with four phases of deformation including: 1) D_1: early pure shear fold event 2) D_2: a pure shear dominated fold-thrust belt event, 3) D_3: two phases of combined simple shear and pure shear oblique systems with a conjugate set of N-S trending reverse oblique-slip shear zones, and 4) D_4: NE-SW dextral reverse oblique-slip shear zone event where the fold-thrust belt is nearly fully overprinted. These four progressive structural events likely originated in an overall oblique transpressive regime, leading to a complex outcrop pattern of remnant fold-thrust belt blocks surrounded and segmented by two later phases of steep oblique-slip ductile shear zone fabrics effectively attenuating the RSSZ along strike.

- Deformation in the RTW appears to have a strong mechanical control, both internally within the metasedimentary successions and between the metasedimentary rock and the surrounding granites and gneisses. Syn-tectonic granites intruded at various stages within the complex deformation sequence and played an important role in the mechanical control and resulting geometry of the RSSZ.

- The granitic bodies are interpreted to be syn-tectonic, and therefore, may display both cross-cutting and/or synchronous intruding relationships with respect to the early fold-thrust belt structures (D_1-D_2) and subsequent later strike slip structures (D_3-D_4).

- The RSSZ developed in successive stages during the same progressive deformation event in which we suggest that all stages of 1) detachment folding, 2) fold-thrusting, 3) reverse sinistral strike-slip shearing and 4) reverse dextral oblique-slip shearing have developed during strain partitioning.

- The strain partitioning may have developed from a monoclinic transpressional symmetry (pure shear or strike-slip shear) to a triclinic transpressional symmetry during progressive deformation through time, with oblique stretching lineations and combined fold-thrust belt and oblique-slip shear zones (sinistral and dextral). In this scenario the anastomosing arrays of steep mylonitic shear zones may have formed from a strain pattern of triclinic deformation superimposed on the earlier monoclinic fold-thrust belt deformation, leaving domains of the monoclinic deformation.

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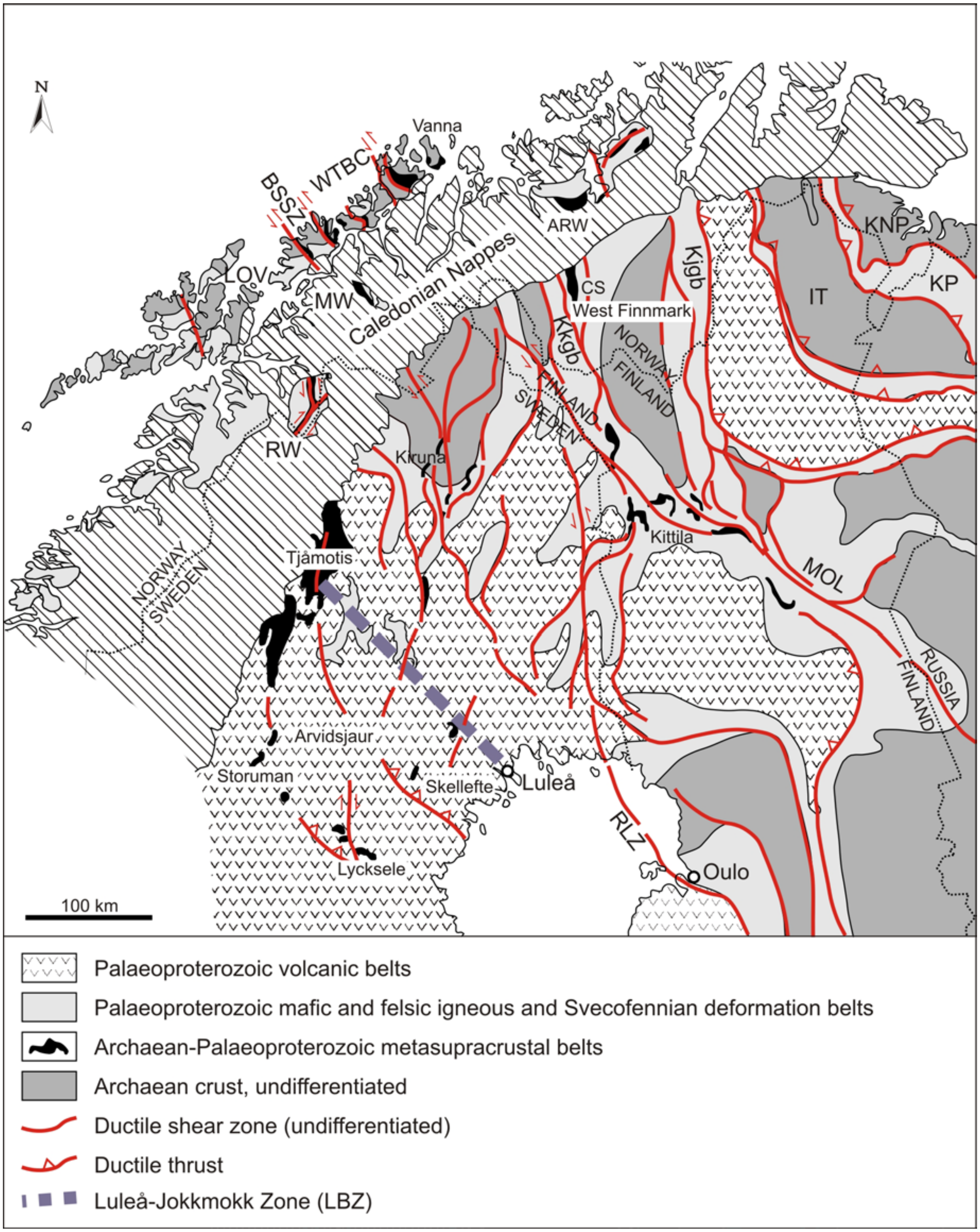

Fig. 1: Overview geological map of Fennoscandia shows the Orogenic domains and the location of Rombaken tectonic window (Fig. 2) in Northern Norway. Abbreviations: BSSZ=Bothnian-Senja shear zone, Kkjgb= Karasjokk Greenstone belt, Kkgb=Kautokeino Greenstone belt, KNP=Kola-Norwegian province, KP=Kola province, MW=Mauken Tectonic Window, NP=Norrbotten province, RW=Rombaken Tectonic Window, WTBC= West Troms Basement Complex, The map is modified from, Korsman et al 1997; Cagnard et al 2007; Bergh et al., 2012.

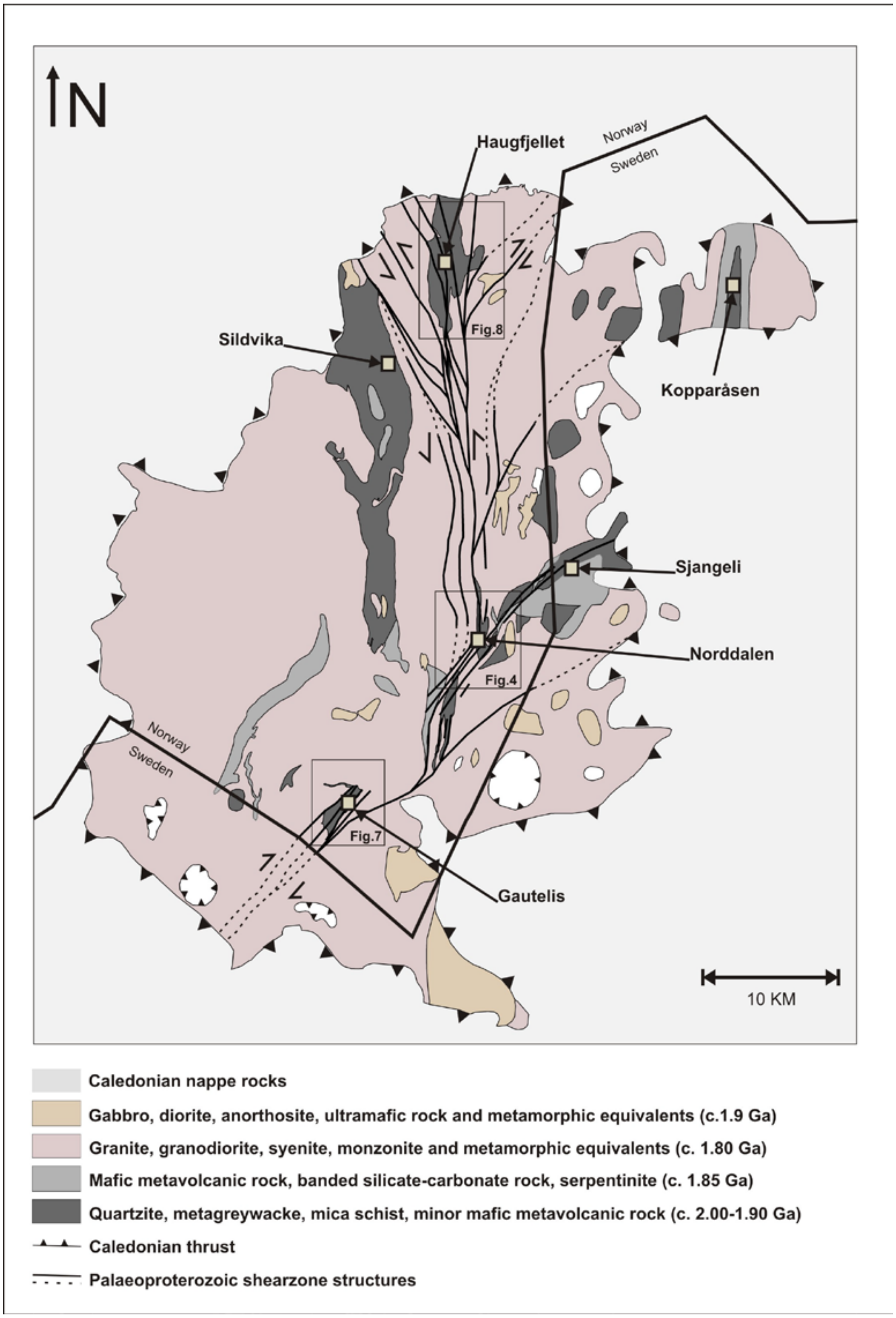

Fig. 2: Geological and tectonic map of Rombaken tectonic window, showing several N-S trending supracrustal belts with surrounding granitoid rocks, and the network of ductile shear zones (Rombak-Skjomen Shear Zone) that frame the window. The map also shows the location of the three main localities Haugfjellet (Fig. 8), Norddalen (Fig. 4) and Gautelis (Fig. 6) marked with a square and a point in addition to Sjangeli, Sildvika and Sjangeli, which are relevant localities for comparison. The map is modified from Arc GIS maps provided by SGU and NGU.

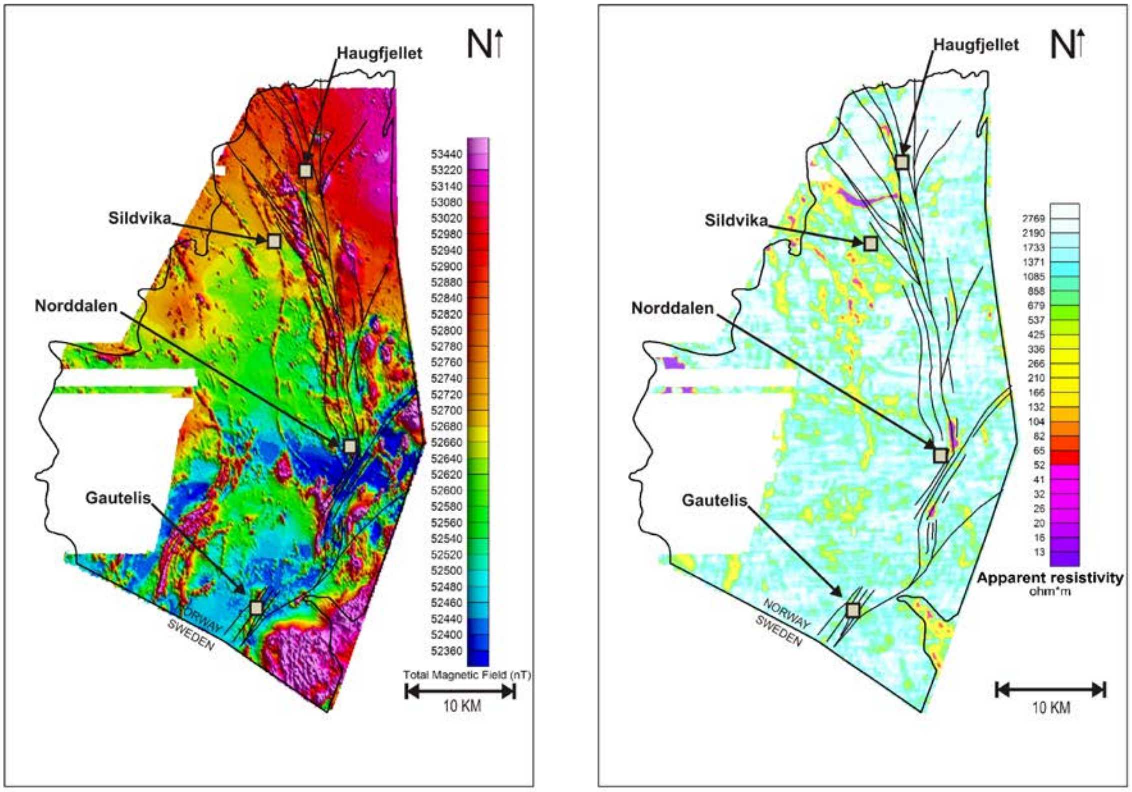

Fig. 3: A) Aeromagnetic map with structural interpretation. Note the presence of the N-S trending anomaly lineaments (shear zone arrays) that are truncated by NE-SW trending lineaments. B) EM gravity map showing N-S trending anomaly patterns that are displaced ca. 5 km by NE-SW trending lineaments (shear zones). The graphitic schist in Norddalen can be seen with its high anomaly and purple colour. Both the magnetic and EM data were collected from a helicopter based survey and flown with 200 m line spacing and line direction of 90° East West (Rodionov et al., 2012).

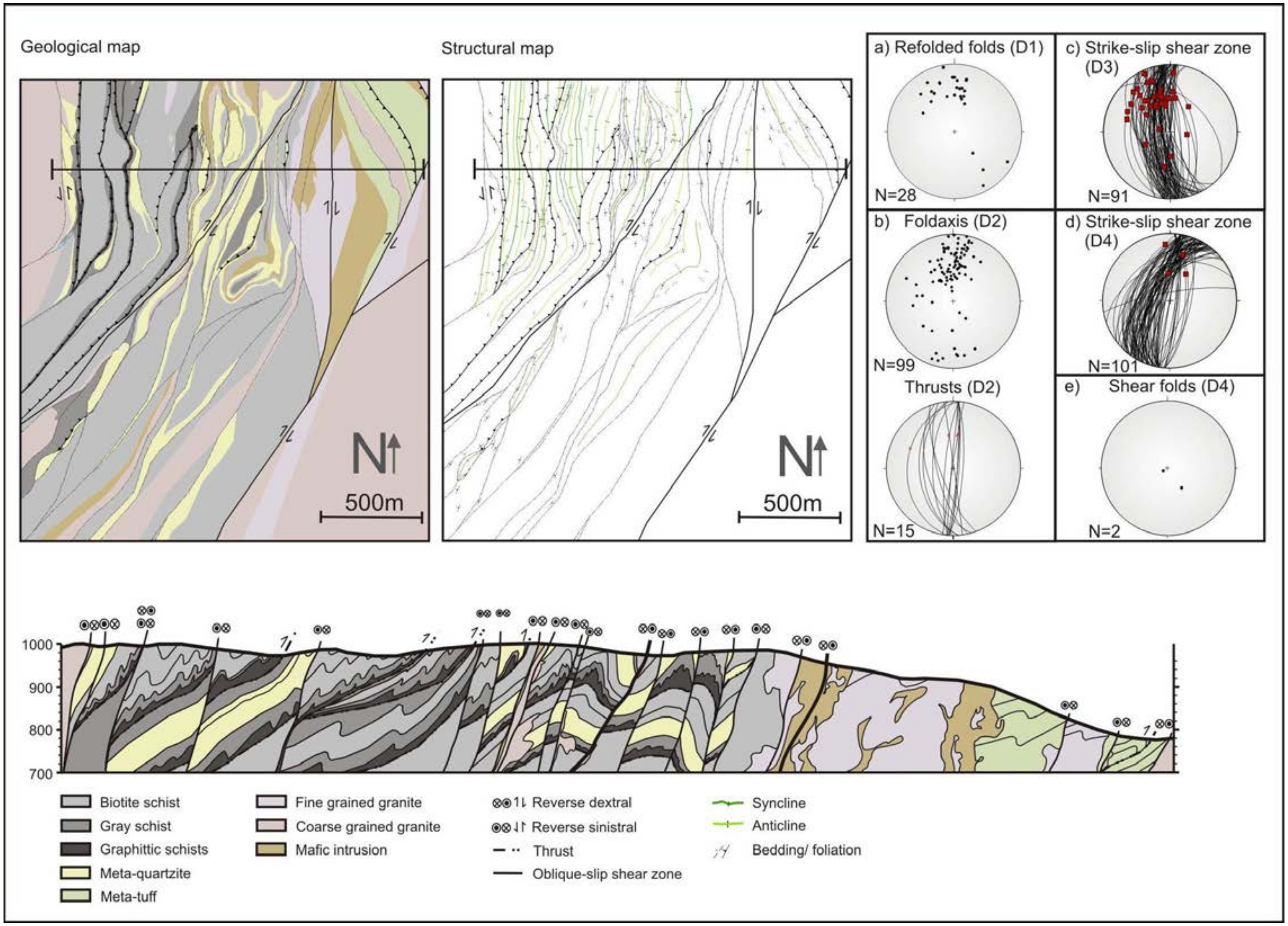

Fig. 4: Geological and structural map of the Norddalen fold-and thrust belt domain and a cross-section from the area. The stereo nets (Schmidt net, lower hemisphere) show the attitudes of: a) fold axes of refolded D_1 folds, b) D_2 fold axes in the dissected fold-thrust belt and its thrusts with lineations shown as great circle girdles with poles, c) N-S striking D_3 shear zones (as great circle girdles), d, e) NE-SW striking D_4 shear zones and e) steeply dipping fold axes (dots).

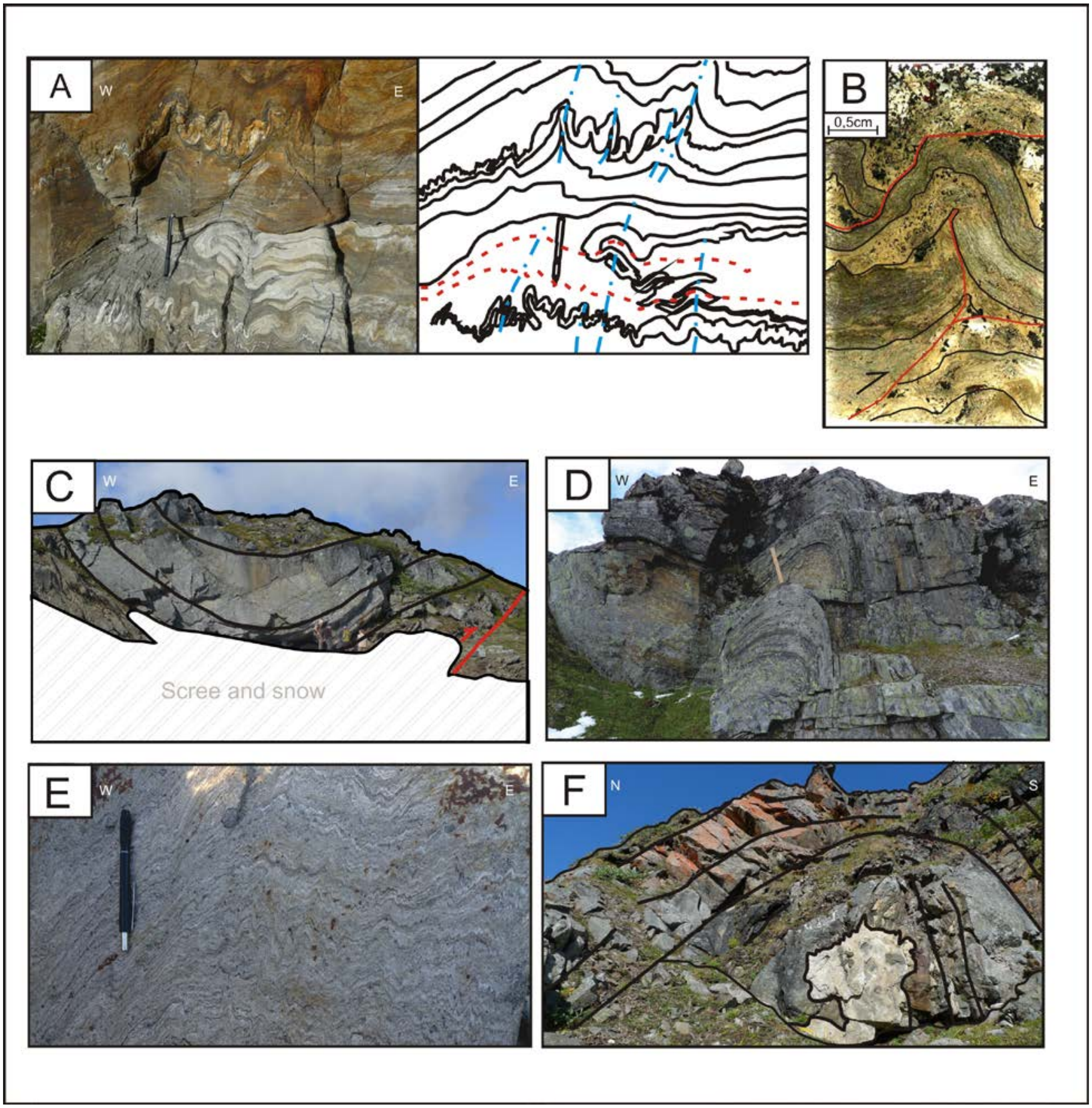

Fig. 5: Outcrop and microscale features of contractional (fold-thrust belt) structures with sketch interpretations from the Norddalen and Gautelis domain: A) Iron-rich mafic and felsic schists showing three generations of folds; the limbs and F_1 fold axial surfaces have been modified from a near-horizontal attitude parallel (red line) to the overlying and underlying enveloping surface of primary layers, into F_2-F_3 folds with nearly vertical axial surfaces (blue line). View is toward north. B) Microphotograph of thin section from the fold-thrust belt in Norddalen showing a complex fold and thrust pattern. C) A syncline in quartzittic conglomerate and sandstone on top of a thrust cutting through graphitic schist in Norddalen. D) Open asymmetric upright fold in Norddalen, verging east. E) S-Z-M shaped parasitic folds. F) Open asymmetric fold in Gautelis showing a thrust that cuts through and deforms the soft marble in the core.

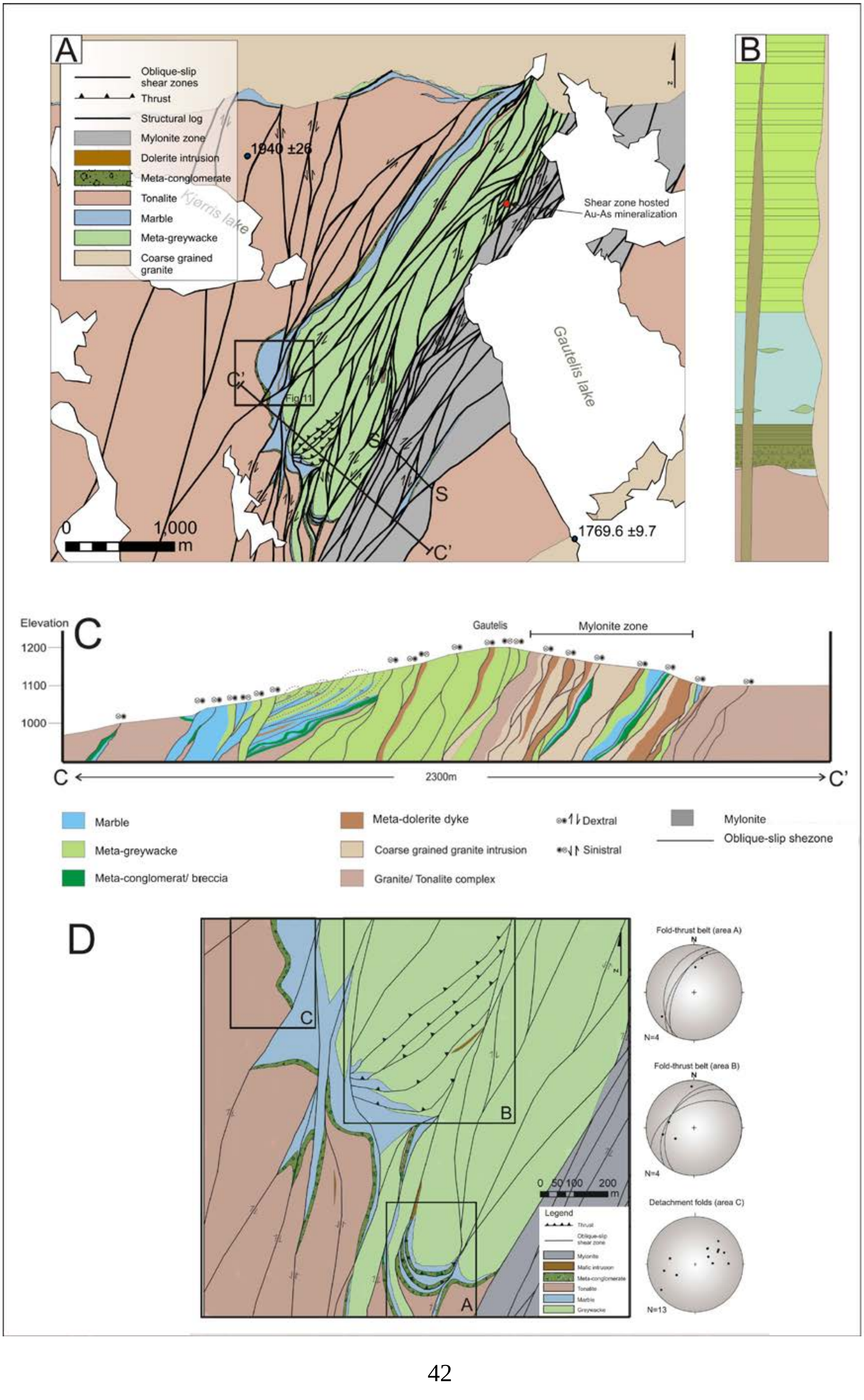
A
Oblique-slip shear zones
Thrust
Structural log
Mylonite zone
Dolerite intrusion
Meta-conglomerate
Tonalite
Marble
Meta-greywacke
Coarse grained granite
1940 ±26
Kjerris lake
Shear zone hosted Au-As mineralization
Gautelis lake
C'
Fig 11
C
S
C'
0
1,000
m
1769.6 ±9.7
B
C
Elevation
1200
1100
1000
Gautelis
Mylonite zone
C
2300m
C'
Marble
Meta-greywacke
Meta-conglomerat/ breccia
Meta-dolerite dyke
Coarse grained granite intrusion
Granite/ Tonalite complex
Dextral
Sinistral
Mylonite
Oblique-slip shezone
D
C
B
A
0 50 100 200
m
Legend
Fold-thrust belt (area A)
N
N=4
Fold-thrust belt (area B)
N
N=4
Detachment folds (area C)
N=13

Fig. 6: Geologic and structural map of the oblique-slip dominated Gautelis domain. A) Geological overview map of the Gautelis area. Location of cross-section lines (Fig. 6C; line C-C'), structural log (Fig. 11; line S'-S) and Fig 6D (frame) is marked on this map. The added radiometric ages are from Romer et al. (1992). B) Stratigraphic log of the Gautelis domain. C) Interpreted cross section of the main ductile shear zone of the Gautelis domain. D) Close-up geological map of the south-western part of the Gautelis domain, showing small remnants of the D_2 fold-thrust belt (in frames) with stereoplots showing the thrusts (great circles) and fold axis (poles) for each frame.

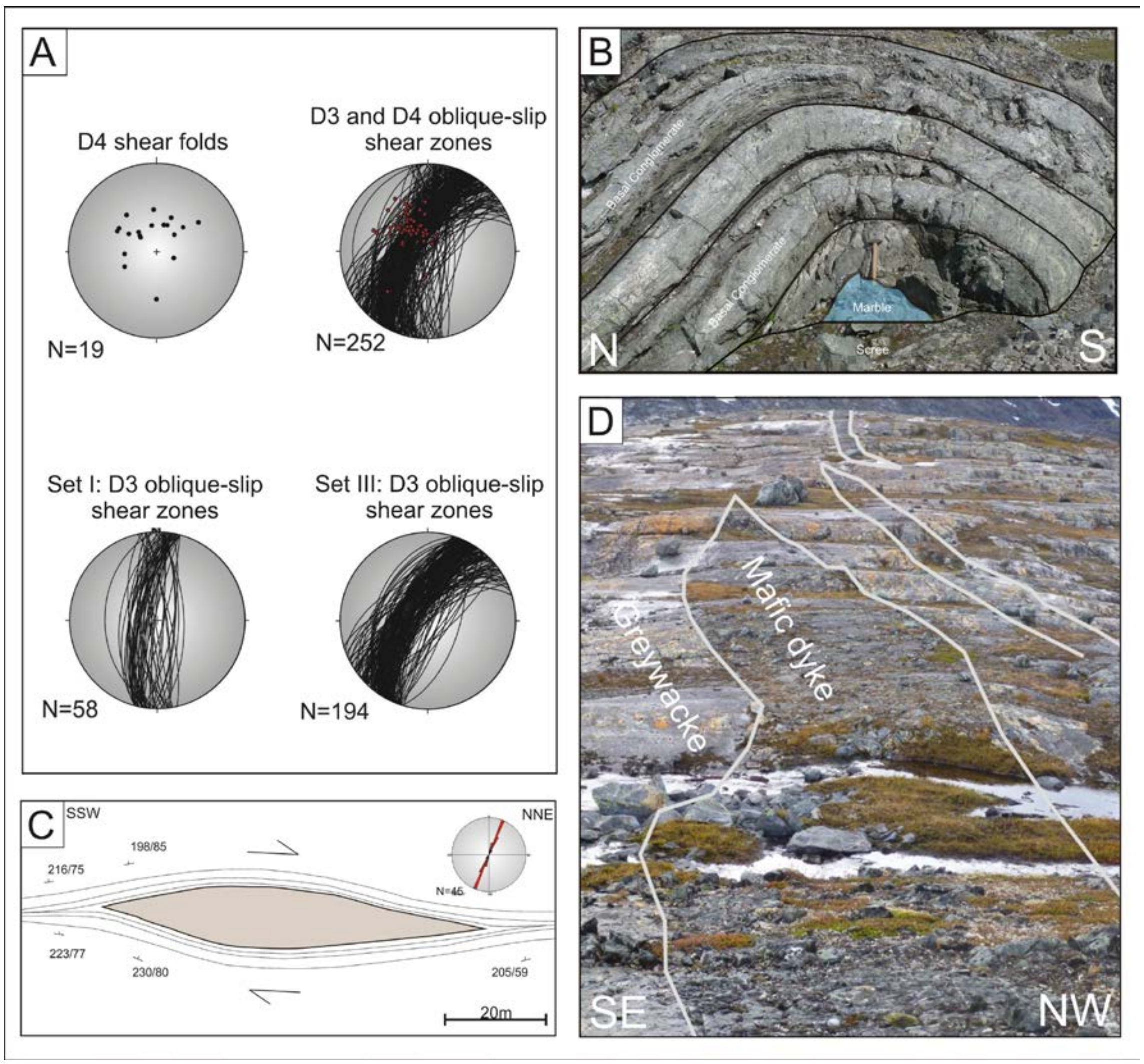

Fig. 7: A) Structural orientation data from the Gautelis domain shown as stereo plots: D_4 shear fold axes, D_3 oblique-slip shear zones (great circle girdles) and D_4 oblique-slip shear zones (great circles) with stretching lineations (dots). B) Slightly asymmetric upright fold in the basal conglomerate overlying the tonalittic basement rocks. The fold core consists of marble and shows that there is a possible detachment thrust in the tonalite below. C) The sketch shows a mafic dyke with D_4 shear zones bending around the dyke body. The sketch is from the same dykes as in the photograph. D) Mafic dykes are found as strike-parallel dykes within the D_4 shear zone.

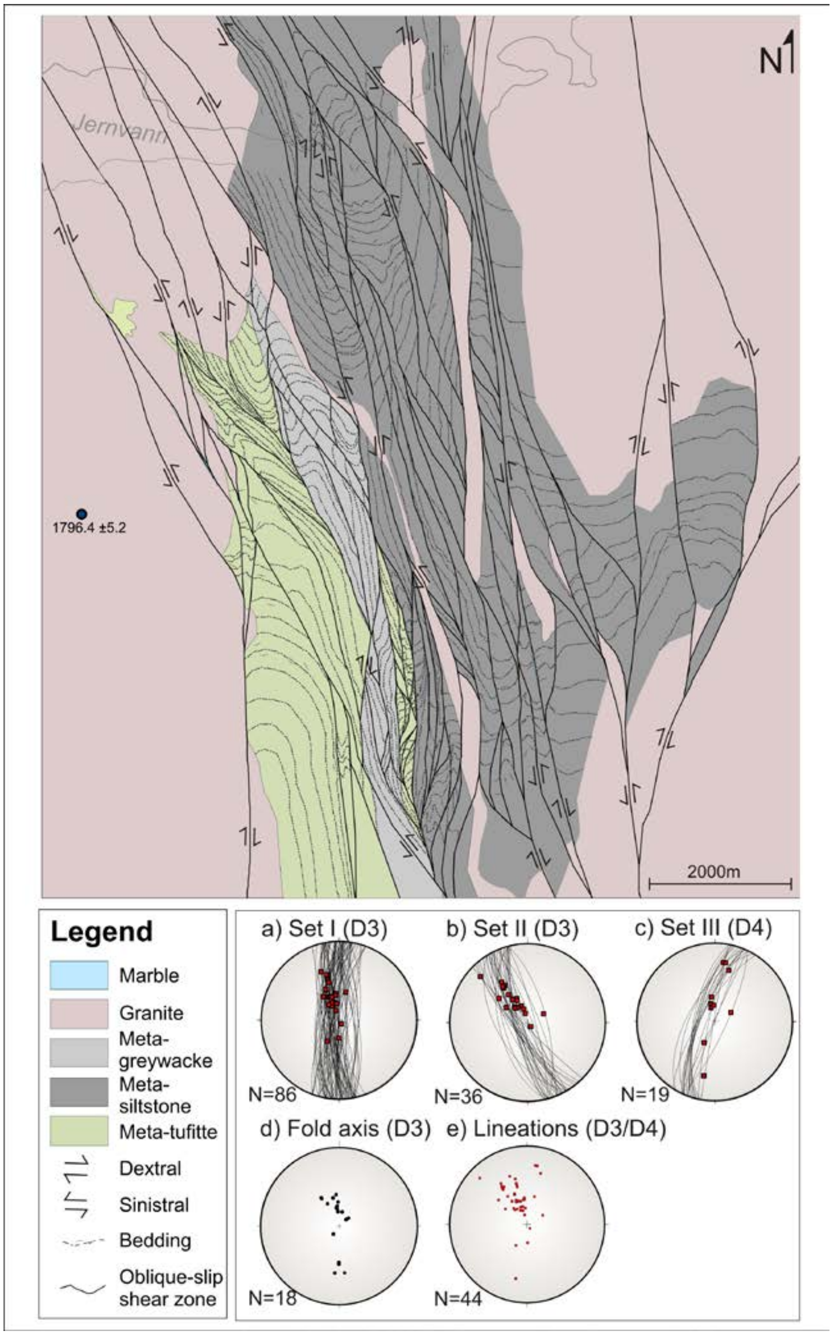

Fig. 8: Geologic and structural map of the combined contractional and oblique-slip dominated (transpressional) Jernvann-Haugfjellet domain with structural data. The map shows how the bedding (dotted line) are cut and folded by D_3-D_4 sinistral and dextral oblique-slip shear zones (black unbroken lines, arrows indicate sense-of-shear). The stereo plots a-c) show three differentiated oblique-slip shear zone sets (I-III; shown as great circles) with their belonging lineations (dots). d) Show stereo plots of steep plunging D_3 fold axis marked as dots. e) Stereo plot with all lineations from D_3-D_4 shear zones collected as dots in one stereo net. The zircon dated granite dated to 1796.4 ± 5.2 Ma, marked at the left of the map, is from Romer et al (1992).

Fig. 9: Outcrop photos of oblique-slip structures and related folds of the Gautelis, Norddalen and Jernvann-Haugfjellet domain. A) Steep N-plunging dextral asymmetric folds in a D_4 oblique-slip shear zone in Gautelis. View is on horizontal surface. B) Steep N-plunging folds in the greywacke sequence with a mafic intrusion along the cutting D_4 shear zone. View is from moderate dipping surface C) Steep plunging D_3 folds from Haugfjellet on horizontal surface. D) Steep plunging fold at Haugfjellet, segmented by D_3 oblique-slip shear zones on horizontal surface. E) Sinistral sigma clast of quartz in the greywacke D_3 oblique-slip shear zones in Norddalen. View is on horizontal surface. F) Steep, dextral duplex of D_4 oblique-slip shear zones in a granite dyke on a horizontal surface. G) Reverse sinistral oblique-slip shear zone south of Haugfjellet, here seen with a sinistral shear sense. Photo is taken on a vertical surface towards the south.

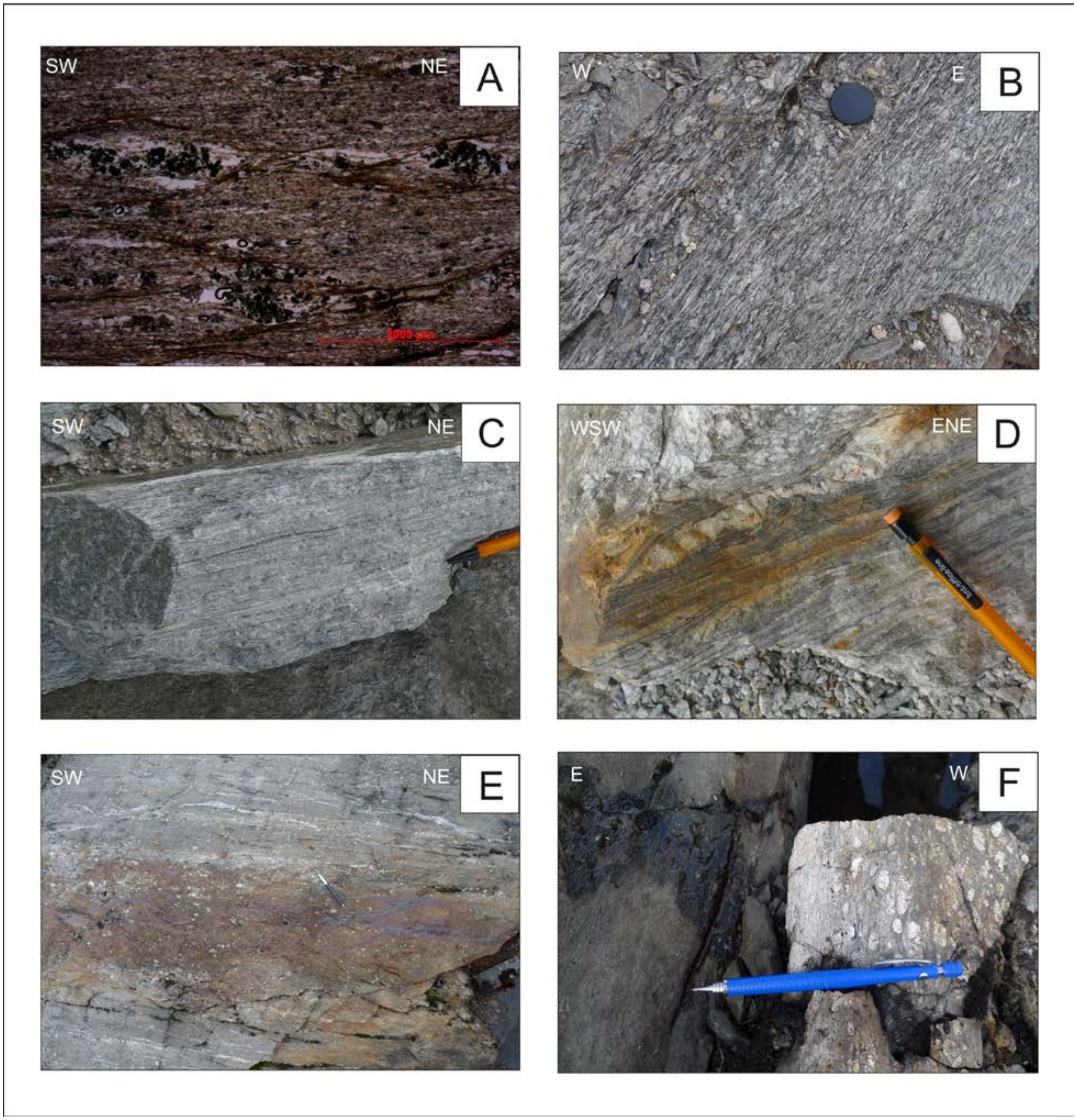

Fig. 10: Oblique-slip features from the Gautelis and Jernvann-Haugfjellet domain. A) Anastomosing shear zone pattern from a thin section of meta-greywacke from Gautelis. Note asymmetric clasts of ore minerals enclosed by Fe-enriched shear zone networks. B) D_4 Proto-mylonite in granite C) D_4 Ortho-mylonitic shear zone in granite D) D_4 Ultra-mylonitic granite in steep, localized shear zone. E) Anastomosing D_4 oblique-slip shear zone pattern from Gautelis carrying sulphides. C) Sheared granite (ultramylonitic) cutting steep plunging D_3 folds at Haugfjellet.

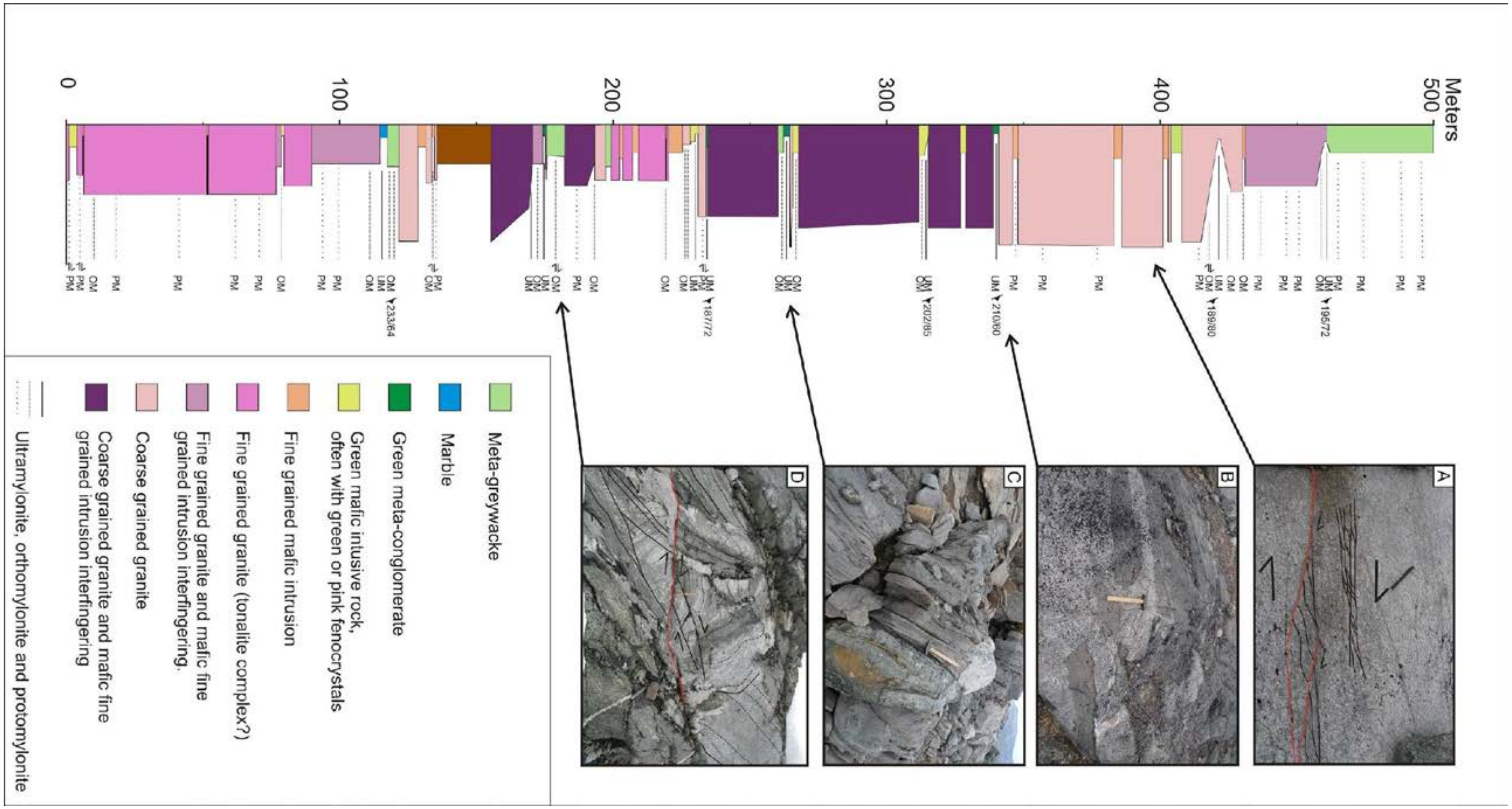

Fig. 11 Detailed structural log across the ca. 600 m thick D_4 mylonite shear zone in Gautelis (location line is shown in fig. 6A). Note the rapid variation in rock types across this anastomosing shear zone pattern suggesting high strain segmentation and formation of lens shaped units of the host rocks. The photographs show examples from the rapid variations of structures: A) Dextral duplex and extensional crenulation cleavage in the same outcrop of coarse grained granite seen on a horizontal surface. B) Greywacke rafts in coarse grained granite. View at horizontal surface. C) Strongly deformed marble with isoclinal folds in the lower right corner. D) A complex, dextral duplex (black line) with folded greywacke (dotted lines) and granite intrusions which are again cut by oblique-slip shear zones (red line). Photo is taken on moderate dipping surface. Abbreviations: OM: D_4 Proto-mylonite (Fig. 10B), PM: D_4 Ortho-mylonite (Fig. 10C) and UM: D_4 Ultra-mylonite (Fig. 10D).

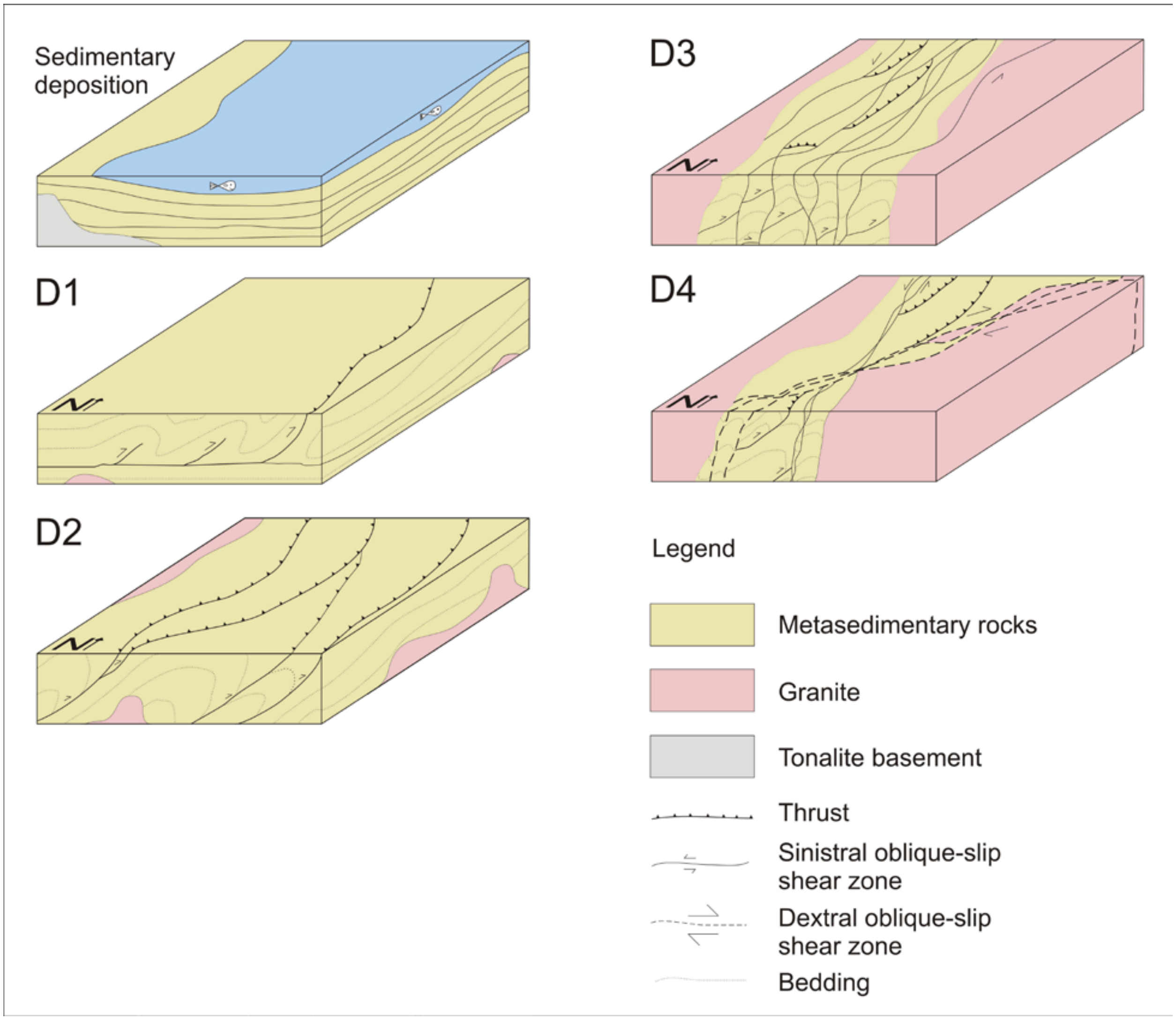

Fig. 12: A structural model with the four deformation stages. Formation of a sedimentary basin deposited on a stable, passive margin setting in the Paleoproterozoic (2.4-1.9 Ga) with deposition of strata on top of eroded tonalittic basement rocks. D_1) Initial E-W shortening of the sedimentary basin and formation of thrust detachments and related folds (Fig. 7B). D_2) Continued E-W shortening with folding and thrusting towards east in the sedimentary rocks. These structures refolded the D_1 structures coaxially (Fig. 5A and B). Granit started to intrude at this stage, syn-tectonic with D_2 folding and thrusting. D_3) N-S striking steep sinistral oblique-slip shear zones developed parallel to the steeply dipping forelimbs of D_2 folds, and granite dykes intruded into the sedimentary rocks and along the late-stage, steep shear zones. D_4) NE-SW striking steep dextral shear zones developed oblique to the N-S going lineament. This major structure cut and folds the metasedimentary belt at several places. The granite dykes intruded into and parallel with these shear zones, and also interfingering with mafic dykes.