

33 IGC excursion No 38*



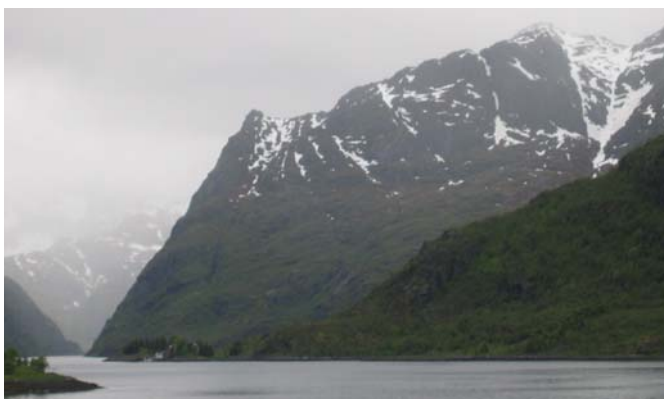
33 IGC, The Nordic Countries



Proterozoic igneous and metamorphic rocks: a template for Mesozoic-Cenozoic brittle faulting and tectonic inherited landscapes in Lofoten-Vesterålen, North Norway

Organizers:

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Abstract

The Lofoten-Vesterålen archipelago of Northern Norway comprises a suite of a suite of anorthosite, mangerite, charnockite and granite (1870-1790 Ma) intruded within an Archaean/Palaeoproterozoic high-grade metamorphic complex of ortho- and paragneisses that was part of the Fennoscandian shield. A few overlying pieces of Caledonian thrust nappes and local eclogites and pegmatites are the only products of the Caledonian orogeny in these islands. In the Palaeozoic through Mesozoic, the Lofoten-Vesterålen region became part of the North Atlantic passive continental margin that underwent multiphase rifting and complex extensional brittle faulting prior to opening and oceanic-crust formation in the Early Cenozoic. As a consequence of these events the Lofoten ridge became an exhumed and tilted basement horst surrounded by major offshore basins and bounding fault-fractures. The present day macroscale, valley- and ridge landscapes of Lofoten, to some extent, reflect Palaeozoic-Mesozoic passive margin fault patterns. Glacial erosion during the Quaternary has subsequently created a fretted, alpine relief of glacial troughs, cirques and ridges which largely follow fracture systems.

Logistics

Dates and location

Timing: 14.08 - 18.08

Start location: Gardermoen Airport, Departure Terminal (place where participants are being picked up and from where costs included in the pre paid fee start to apply).

End location: Gardermoen Airport (place where excursion ends and from which participants continue with their own travel arrangements).

Travel arrangements

The participants will be picked up at the airport by one of the excursion leaders, Fernando Corfu. The best way to reach Gardermoen is to use the main train shuttle (flytoget) departing from the Oslo Central Station (Oslo S). Present price is NOK 170 one way. Alternative travel is by bus (c. NOK 140-180) or taxi (c. NOK 500).

Accommodation

Accommodation in Lofoten will be arranged in chalets and seaside guest houses (rorbuer), mostly in shared bed rooms but a few single rooms are also available. The standard is generally high, and all of the chalets have electric heating (adapter needed for non-Scandinavians), fully equipped rooms, kitchen, dining room, TV, bathroom with shower, w.c., etc. Each bed is inclusive of linen and towels. The overnight schedule is as follows: 14-16/8 Nusfjord Rorbuanlegg AS, Phone 76093020, 16-17/8 Henningsvær Rorbuer, 17-18/8 Sjøhussenteret, Sortland, Phone: 76123749. A number of other accommodation facilities are available in Lofoten (see <http://www.lofoten-startside.no/overnatting.htm>).

Field logistics

The transportation will be by bus to all the localities. Only a few of the localities require some hiking, with a maximum of 2 km in easy terrain on paths. Most of the stops will be near the main road or along easily accessible coastal/shoreline sections. The weather in mid August is generally mild with average temperature c. 15°C. Occasionally during the summer, westerly

winds from the Atlantic may bring lots of rain and quite cold weather. Therefore, be prepared both for sunny and wet weather and bring with you warm clothes, raingear, and good field boots.

General Introduction

The excursion through the Lofoten-Vesterålen archipelago has a threefold purpose as it will examine: (i) the Precambrian-Caledonian basement geology, (ii) the development of post-Palaeozoic/Mesozoic structures related to the opening of the North Atlantic, and (iii) the relationship between tectonics and landscape. The dominant bedrock is made up of a Palaeoproterozoic (1870-1790 Ma) igneous complex of mangerites, charnockites, anorthosites, gabbros and granites, intruded within an Archaean-Palaeoproterozoic high-grade metamorphic complex. At Leknes, and to the east, the Lofoten basement is overlain by Caledonian thrust nappes in a similar setting as the Western Gneiss region of Southern Norway, except that the Caledonian overprint was much weaker in Lofoten. This allows insightful studies of arc-related magmatic rocks and tectonometamorphic processes operating at lower crustal levels. Brittle faults and fractures formed during Mesozoic-Cenozoic break-up of the North Atlantic continental margin can be excellently studied in a transect along the Lofoten ridge to Vesterålen. This ridge is an exhumed and tilted basement horse near the continent-ocean margin and is surrounded by major offshore basins such as the Vestfjorden and Ribban basins. A complex system of multiphase fault-fractures bounding these basins can be studied on the onshore side of the horst, allowing a direct comparison between the offshore and onshore regions. This excursion will also explore pronounced valley- and ridge landscapes resembling tilted fault blocks, and a system of gently-dipping paleosurfaces bounded by steep fault-related escarpments. This high-relief landscape is thought to reflect Cenozoic exhumation of the tilted Palaeozoic-Mesozoic fault blocks.

Regional Geology

The following description of the regional geology is divided into three parts according to the thematic goals of the excursion: 1) The Precambrian-Caledonian basement geology, 2) the Lofoten-Vesterålen passive continental margin: a multiphase Mesozoic-Palaeogene rifted shelf, and 3) the relationship between tectonics and landscape.

The Precambrian-Caledonian basement geology

The Lofoten-Vesterålen islands are underlain by Precambrian basement, which emerges west of the allochthonous nappes occupying the central, NNE-trending axis of the Scandinavian Caledonides (Fig. 1). This basement high stretches to the north into the Western Troms area. In spite of this internal position the rocks of Lofoten-Vesterålen display only subordinate evidence of Caledonian deformation (Griffin et al. 1978). The basement is composed mainly of a metamorphic complex of Archaean and Palaeoproterozoic para- and orthogneisses, intruded by a very extensive suite of plutonic rocks of the anorthosite-mangerite-charnockite-granite (AMCG) suite (Fig. 2). The area is a part of the Svecofennian orogen and lies approximately along the southern boundary of the Archaean craton that stretches from Russia, through Finland and Sweden. A Palaeozoic succession overlies the basement at Leknes, probably remains of a Caledonian nappe.

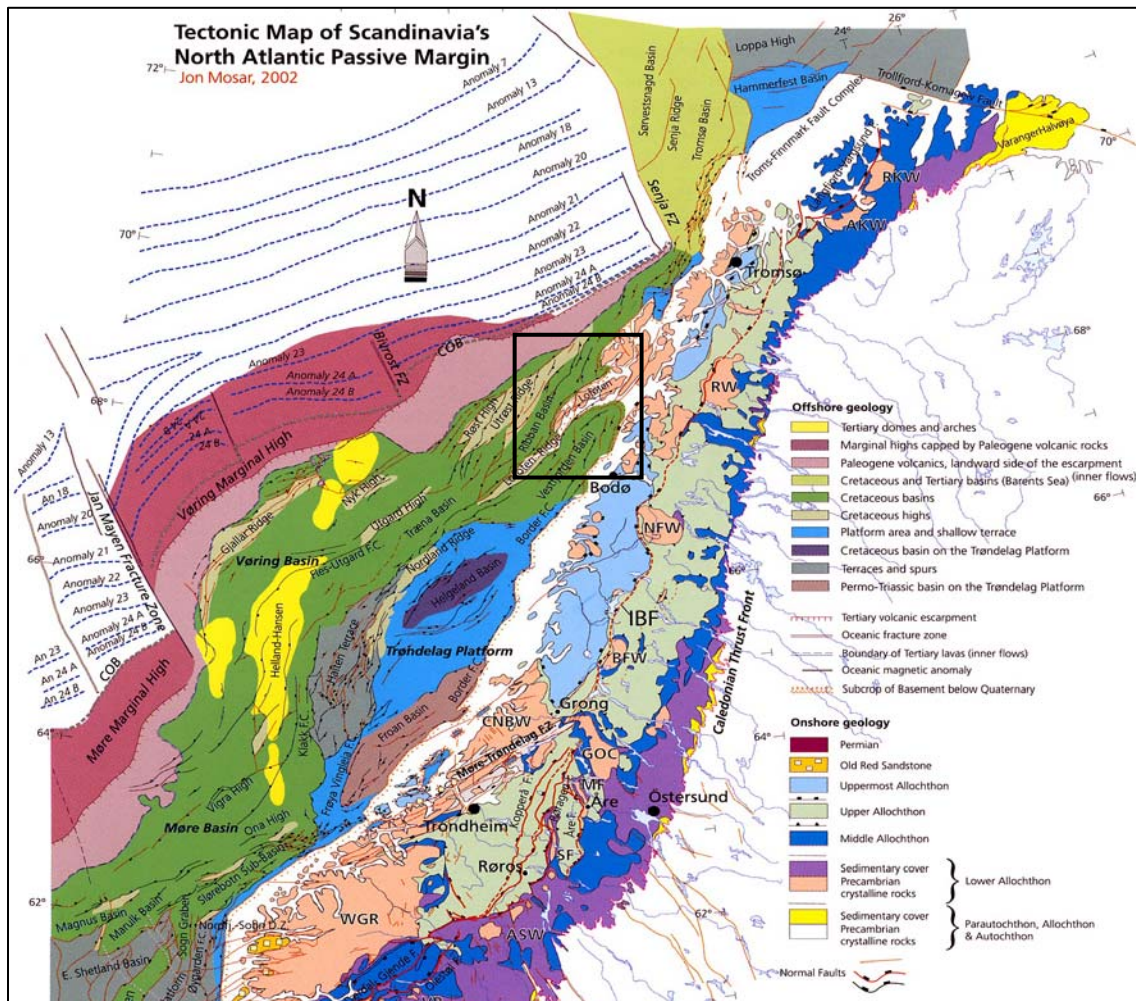


Fig. 1: Regional onshore-offshore geological map of Central/North Norway and the outline of the North Atlantic passive continental margin (after Mosar et al. 2002). The Lofoten-Vesterålen archipelago is framed.

The Lofoten-Vesterålen rocks were shown to be of Precambrian age by Herr et al. (1967) and Heier and Compston (1969), the latter documenting major events at 2800 and 1800 Ma. Subsequent work based primarily on Pb-Pb and Rb-Sr, and eventually Sm-Nd dating, broadly confirmed the two-stage evolution, expanding it to include older events and introducing a number of other apparent sub-stages (Taylor 1974, 1975; Griffin et al. 1974, 1978; Jacobsen & Wasserburg 1978; Andresen & Tull 1983; Wade 1985). There were also some indications of a cryptic event at about 1100 Ma and of a weak overprint during the Caledonian orogeny. Recent work does not substantiate the indications for a Grenvillian overprint, instead documenting a more complex Caledonian history, characterized by several separate stages between the Ordovician and the Permian (Corfu 2004b; Hames & Andresen 1996; Steltenpohl et al. 2004, 2006). The chronology of the basement complex and the AMCG suite has been refined by modern U-Pb geochronology (Corfu 2004a, b, 2007); the results are summarized below while presenting the main rock units.

The basement complex and the timing of metamorphism

The basement complex in western parts of Lofoten-Vesterålen comprises granulite facies rocks, whose distribution also coincides with a major magnetic and gravity high due to the

presence of dense rocks in the crust and an elevated Moho discontinuity (Heier 1960; Griffin et al. 1978; Mjelde et al. 1993; Olesen et al. 1997). The latter is the result of differential uplift and extension in the aftermath of the Caledonian orogeny and the subsequent Late Palaeozoic and Mesozoic processes that led to the opening of the North Atlantic. The eastern part of the region consists instead of various amphibolite-facies gneisses, migmatites, greenstone belts and granitic plutons.

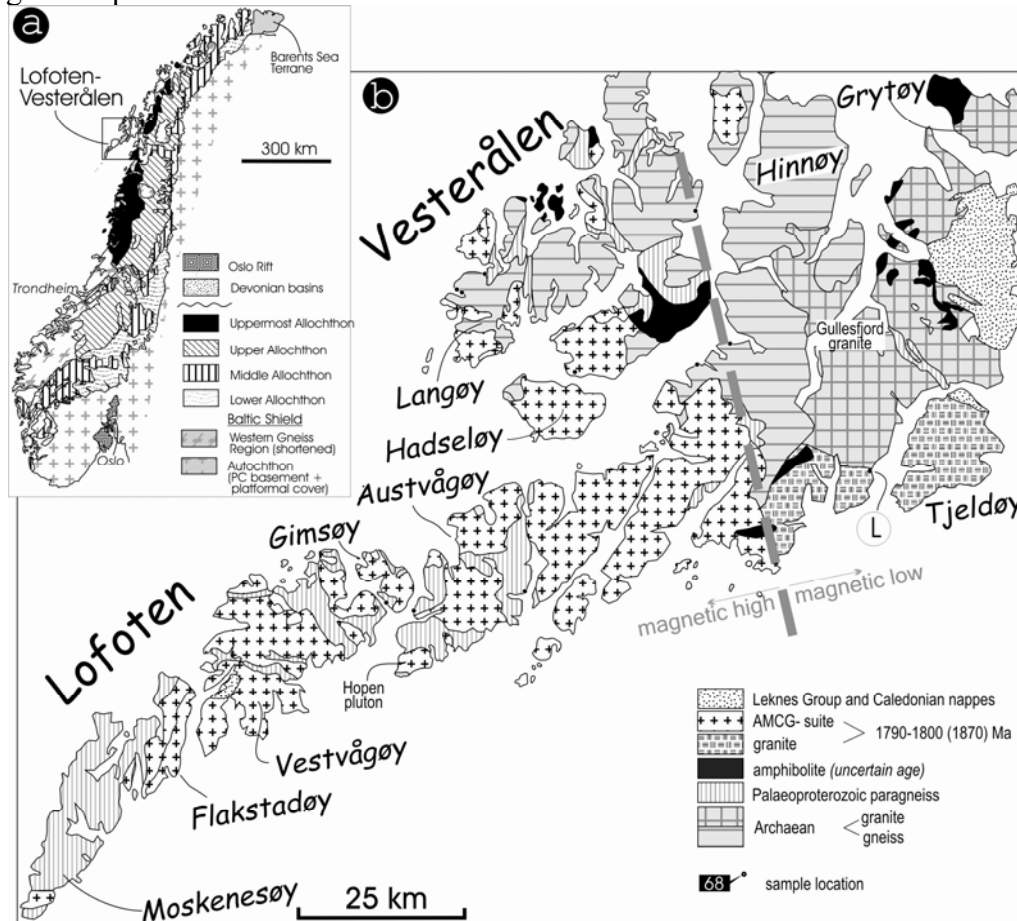


Fig. 2: Geological map of the Lofoten-Vesterålen islands showing the Archaean-Palaeoproterozoic basement and intruding plutonic suite (modified from Tveten 1978, Andresen & Tull 1983 and Corfu 2004a).

Archaean crust occupies large parts of the islands of Langøy and Hinnøy (Fig. 2). Small remnants are also present at the southwestern tip of Austvågøy (Wade 1985). A younger sequence of metasedimentary rocks is dominated by fine-grained gneisses, locally quartzitic, with subordinate graphite schist, iron formation and marble. Although they have been overprinted by the same granulite-facies metamorphism as the Archaean rocks the paragneisses are of more homogeneous appearance and have been interpreted as a Palaeoproterozoic supracrustal succession of volcanogenic derivation as deduced from geochemical compositions (Griffin et al. 1978). The boundary between the two metamorphic domains corresponds to the eastern limit of the magnetic high. It was defined initially by Heier (1960) who mapped the first appearance of orthopyroxene along a line running south to southwest in eastern Langøy (Fig. 2). In the south he linked the line to a local thrust that juxtaposes the Eidsfjord anorthosite on retrogressed mangerite (Heier 1960; Markl 1998), but subsequent studies modified the trajectory, suggesting that the orthopyroxene isograd is folded and continues southeastward across Hinnøy (Fig. 2; Griffin et al. 1978). Glassley (1975) investigated carbonate bodies in the region and defined isograds for the reactions

hornblende = diopside + spinel and diopside + dolomite = forsterite + calcite. In northeastern Langøy these two isograds deviate considerably from the orthopyroxene isograd, a fact interpreted by Glassley (1975) to indicate a complex thermal structure of the crust.

The granulite facies gneisses equilibrated at 3 to 4 kbar and 750 to 780 °C (Olsen 1978). These rocks tend to be rather massive, with faint banding visible in weathered outcrop but hardly recognizable in fresh cuts. They have been considered to be orthogneisses (Taylor 1974) or migmatized supracrustal rocks of intermediate composition (Griffin et al. 1978). Mafic enclaves occur locally.

The nature of the amphibolite to granulite facies transition has been the subject of debate. In the early literature it has been customary to consider the transition as the result of one single metamorphic event. On the basis of Rb-Sr whole-rock data of metamorphosed supracrustal rocks this event was estimated at 1830 ± 35 Ma (Griffin et al. 1978). The dominant interpretation has been that of a metamorphic progression with westward increasing temperature and pressure. The possibility of a retrograde transition has also been considered but found to be inconsistent with the known evidence (Olsen 1978). The third alternative is that the transition is a tectonic boundary (Corfu, 2004b, 2007).

Recent U-Pb data confirm the general understanding of the Lofoten-Vesterålen crustal history (Heier & Compston 1969; Griffin et al. 1978) providing additional evidence for two major periods of crust accretion and stabilization in the late Archean and the Late Palaeoproterozoic. Archean U-Pb ages are found in zircon and monazite both in the high- and the medium-grade parts of the region and define distinct events. The available data indicate magmatism in the period between about 2750-2680 Ma with a subsequent event at about 2640 Ma involving the emplacement of tonalite and high-grade metamorphism including migmatization, thus, adding new magmas and reworking existing crust. The original crust had formed during a major crustal accretion event recorded at 2850-2700 Ma throughout the region (Corfu et al. 2003; Kullerud et al. 2006). The new data are consistent with the existing Pb, Sr and Nd isotopic constraints (Jacobsen & Wasserburg 1978; Wade 1985).

The Proterozoic metamorphic history falls broadly in the time frame between the AMCG precursor-stage (Hopen pluton) at about 1870 Ma and the main AMCG stage at 1800-1790 Ma (see below). The data indicate high-grade metamorphism 5 to 10 million years before emplacement of the main AMCG stage, with a less clearly defined metamorphic event broadly coeval with the AMCG precursor stage. A third group of metamorphic ages coincides with the main stage of AMCG magmatism. There is then a late phase of retrogressive metamorphism between 1780 and 1760 Ma (Corfu 2004a, 2007).

The documentation of a complex polymetamorphic evolution raises questions on the nature of the metamorphic boundary. The validity of the postulated Proterozoic prograde metamorphism (Olsen 1978) rests on the achievement of complete mineralogical re-equilibration during the main-AMCG stage at 1800-1790 Ma, which is not a very safe assumption. At least in some cases, the boundary separates unrelated amphibolite and granulite facies terrains, e.g., at Sigerfjord a 2640 Ma migmatite complex from 1800 Ma granulites. These relationships are more consistent with a tectonic boundary. On the other hand, however, one has to consider the close age correspondence of events in both terrains, i.e. events at 2640, 1870 and 1800 Ma, which suggests that the two terrains were in close proximity prior to formation of a tectonic contact, thus supporting the traditional view (e.g., Griffin et al. 1978).

Plutonic rocks

Plutons of the AMCG suite occupy about 50 % of the islands (Malm & Ormaasen 1978). The suite is dominated by mangerite and charnockite and their retrograded equivalents, with local but important occurrences of gabbro, anorthosite and granite. The mafic and felsic phases locally grade into, or mutually cross-cut, each other indicating that some of the intrusions may be genetically related. Markl (2001) proposed a multistage evolution with a basaltic parental melt undergoing polybaric crystallization and differentiation to form anorthosites as cumulates and ferrodiorites and jotunitites as residual melts. The mangerites and charnockites are inferred to represent feldspar cumulates and residual liquids, respectively, derived from magmas broadly syenitic in composition, which may or may not be directly related to the ferrodiorites. The mangerites and charnockites were shown to have intruded at about 4 kbar and >925 to 850 °C whereas the anorthosite on Flakstadøy records a polybaric crystallization history from 9 kbar to about 4 kbar at 1180 to 1120 °C. The data imply that anorthosites, mangerites and charnockites in Lofoten were emplaced at the same depth of about 12 km (Markl et al. 1998).

Isotopic data show that Archaean crust played an important role in the genesis of these rocks, both as a source and as a contaminant (Wade 1985; Markl & Höhndorf 2003). The Pb isotopic data define a linear trend, interpreted to represent mixing between Archaean lower crustal components and late Palaeoproterozoic juvenile additions, whereby the mangerites and charnockites contain more Archaean Pb than the mafic rocks. Most anorthosites, ferrodiorites and the felsic rocks yield overlapping ϵ_{Nd} values ranging from -3 to -9. Exceptions yielding more primitive ϵ_{Nd} - values between -1 and +1 are ferrodiorite to gabbro from the Eidsfjord Complex (Markl & Höhndorf 2003) and mangerite from northern domains of Austvågøy and Flakstadøy (Wade 1985). The distribution of Sr isotopic compositions broadly matches that obtained from Nd.

Charnockites and mangerites are widespread throughout the region, especially in the form of large plutons such as the Raftsund, Hopen, Sund-Ølkona and Southwest Lofoten intrusions (Griffin et al. 1974; Ormaasen, 1977; Malm & Ormaasen 1978). Anorthosite occurs at three different sites: on Moskenesøy, Flakstadøy and at Eidsfjord. Gabbro forms smaller plutons in all the islands, the largest one is the Eidet-Hovden pluton on Langøy (Heier 1960; Romey 1971; Markl 1998; Markl et al. 1998; Markl & Frost 1999). There is one distinctive body of granite-syenite, the Torset pluton on Langøy (Heier 1960; Brueckner 1971). In addition, a widespread and diffuse network of feldspathic veins is present throughout the granulite facies domain, especially on Langøy, and it is difficult to distinguish this late veining from the original migmatitic structures described by Griffin et al. (1978).

The more recent U-Pb results show that the Lofoten AMCG suite was emplaced during two quite distinct events (Fig. 3), the first one at 1870-1860 Ma (Hopen pluton and Blokken orthogneiss) followed by a second and dominant magmatic event at 1800-1790 Ma. A concluding period, lasting some 20-30 m.y., was characterized by local hydration of the dry AMCG rocks, and by the infiltration of pegmatitic melts (Corfu 2004a). Local granitic pegmatites belong to distinct generations, one Palaeoproterozoic (ca. 1770 Ma) and the other Caledonian (Corfu 2004a, b, 2007).

The zone east of the metamorphic boundary is dominated by intrusive rocks of tonalitic to granitic composition, migmatitic domains, and local greenstone belt remnants. Preliminary data indicate an Archean origin for the basement units (Taylor 1974; Griffin et al. 1978; Corfu

unpubl. data). They are cut by Palaeoproterozoic plutons such as the Lødingen granite with a zircon and titanite age of 1870 Ma (Corfu 2004a). The Tysford granite covers a large area on the mainland (Andresen & Tull 1986) and has given U-Pb ages between 1800 and 1700 Ma (Romer et al. 1992).

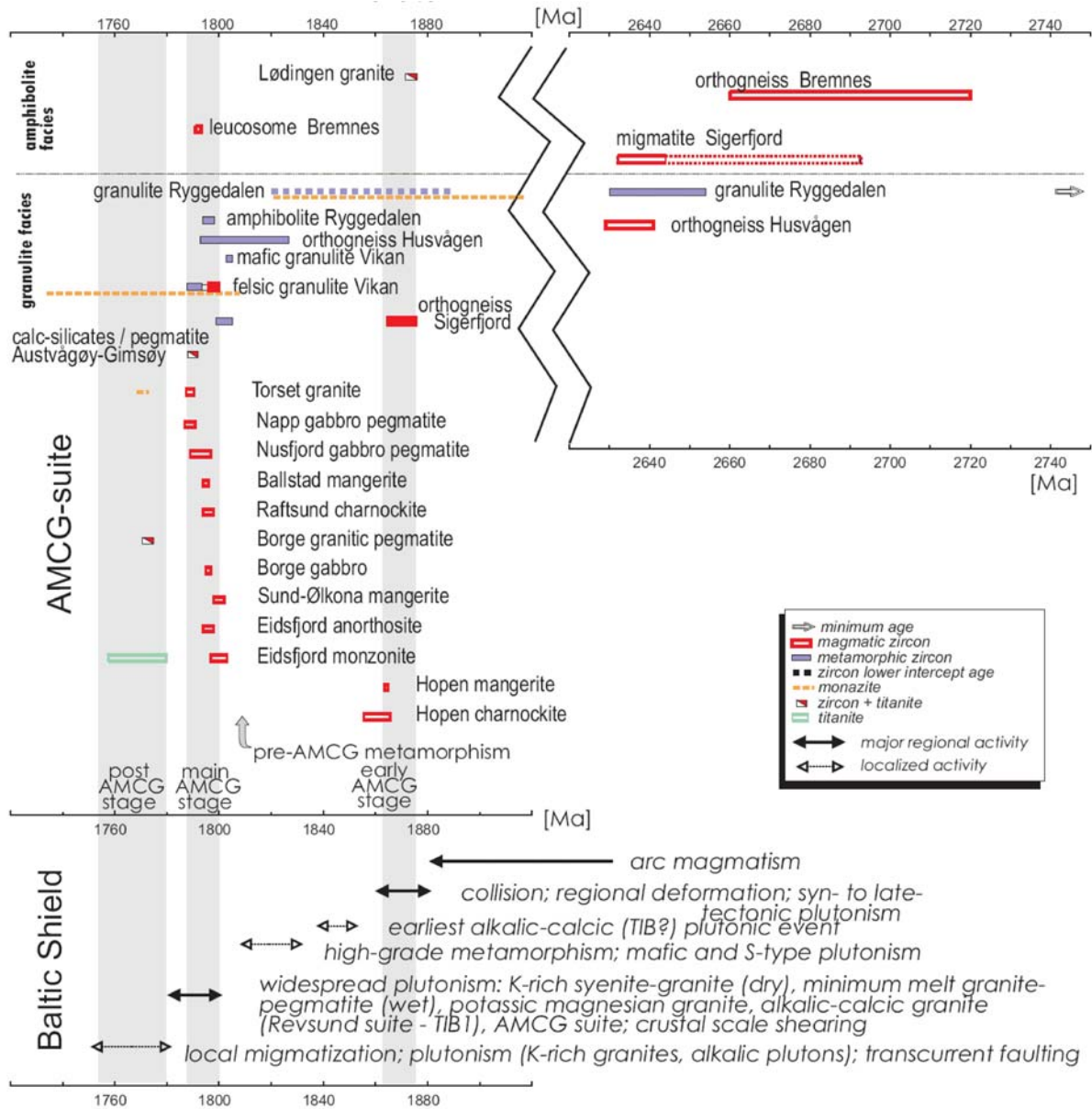


Fig. 3: Summary of U-Pb ages for the Archaean and Palaeoproterozoic magmatic and metamorphic rocks of Lofoten Vesterålen, with a comparison to the general scheme for the tectonic evolution of the Svecofennian orogen (from Corfu 2004a, 2007).

Regional correlations

The 1870-1860 Ma phase of magmatism, marked by the emplacement of one mangeritic-charnockitic pluton and a granite body, was coeval with the main collisional and arc

amalgamation event in the Svecofennian orogen. The second and dominant period of magmatism in Lofoten-Vesterålen at 1800-1790 Ma coincides with the emplacement, throughout the Svecofennian orogen, of widespread and compositionally variable plutonic associations of both mantle and crustal origin and also corresponded to a shift in convergence rates, possibly related to more distant continental collision. It appears that the AMCG suite was formed as a consequence of these major tectonic events. Geometric and kinematic factors such as the position of the area at the margin of the Archaean craton, the changing plate kinematics may have been the most important variables that led to the development of this unique rock association in Lofoten-Vesterålen.

The region also underwent a Caledonian high-pressure event, although that is only locally recorded (Wade 1985; Markl & Bucher 1997; Kullerud et al. 2001; Steltenpohl et al. 2006). Eclogite-facies rocks with relics of omphacite in addition to garnet as main minerals occur at five localities on two islands (Flakstadøy, Austvågøy). At five additional localities on Flakstadøy and Vestvågøy, mineral textures and field aspects of garnet amphibolite bodies suggest that they represent retrogressed eclogites. Most of the eclogites occur within gabbros, on Flakstadøy also in troctolites. With two exceptions they are always related to zones of deformation, occurring in lenses of 2 m to 70 m in length. The peak eclogite assemblage is garnet + omphacite + magnetite + rutile but most occurrences are retrogressed. High-pressure parageneses have also been documented in pseudotachylites (Steltenpohl et al. 2006). Based on original Rb-Sr data, Markl & Bucher (1997) had concluded that the eclogite facies event was probably related to Mesoproterozoic orogenic activity, but this inference has not been confirmed by more recent data. Although there is no firm direct age for this event, all the circumstantial evidence point to a Caledonian origin (Steltenpohl et al. 2006).

Leknes Group

On Vestvågøy the basement is overlain by the Leknes group, a distinct assemblage of amphibolite-grade paragneisses and schists in tectonic contact with the Palaeoproterozoic basement, and which was multiply deformed and metamorphosed during the Caledonian orogeny (Tull 1977; Corfu 2004b). The metasedimentary assemblage was intruded by tonalitic dykes at 469 ± 3 Ma. Such dykes are absent in the underlying basement supporting an allochthonous origin of the Leknes Group. Structural and U-Pb radiometric evidence shows that the main metamorphic and structural overprints occurred in the Mid-Ordovician, between 470 and 460 Ma, but there was also a younger metamorphic event with zircon growth at 412 ± 2 Ma, the latter coinciding with early stages of extension and enhanced fluid activity; in southern Lofoten this episode is also associated with the intrusion of 410 ± 3 Ma pegmatites. The Leknes Group shows an affinity with some terranes of peri-Baltic affinity in the Upper Allochthon of the Caledonides. It probably developed in a marginal basin close to Sveconorwegian basement, before being thrust onto the Lofoten basement.

The Lofoten-Vesterålen passive continental margin: a multiphase Mesozoic-Palaeogene rifted shelf

The Lofoten-Vesterålen continental margin (Fig. 1) marks the transition between the much wider Møre-Vøring passive margin (Blystad et al. 1995; Brekke 2000) and the sheared, transform Barents Sea margin (Talwani & Eldholm 1977; Gabrielsen et al. 1990; Faleide et al.

1993). It is a key region for plate reconstruction and tectonic linkage of the Norwegian-Greenland Sea margins as well as for onshore-offshore structural comparison. The shelf comprises a narrow and thin crustal segment underlain by a Permian through Palaeogene clastic sedimentary wedge and bounded seaward by Palaeocene to Eocene ocean-floor volcanites (Eldholm et al. 1979; Sellevoll et al. 1988; Mjelde et al. 1993).

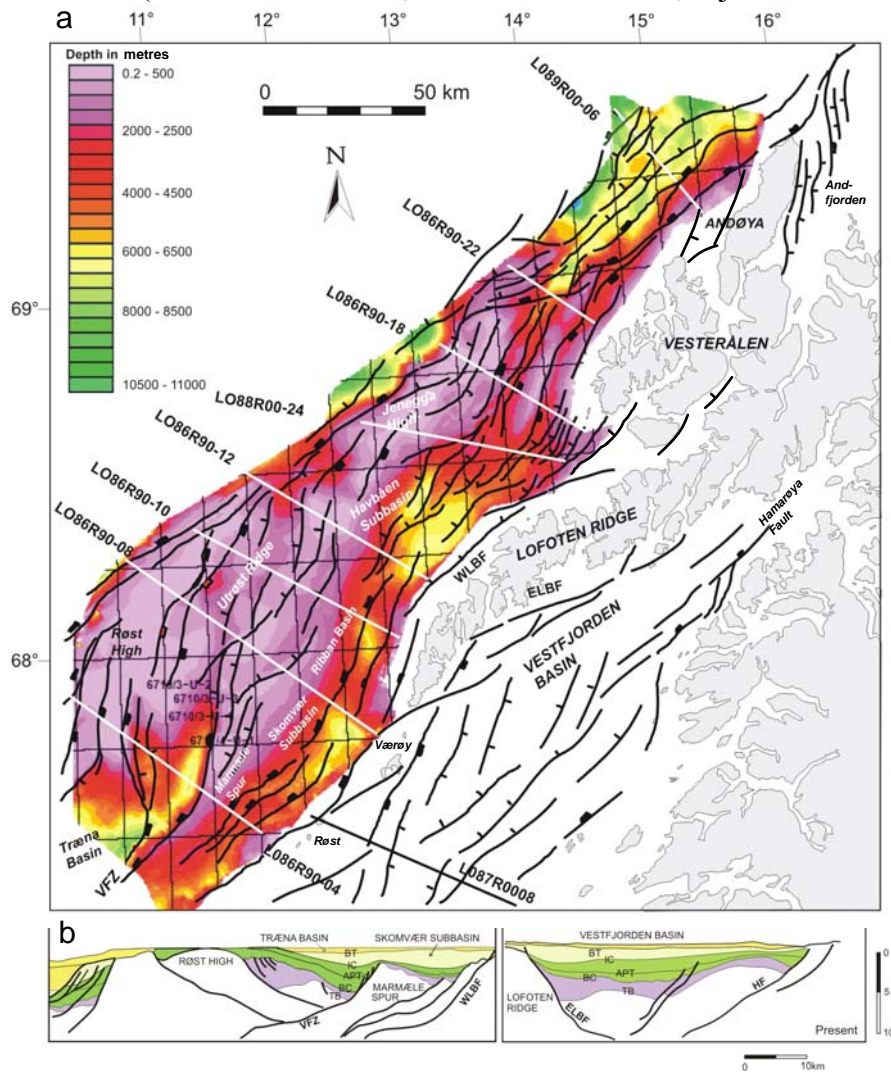


Fig. 4: (a) Depth-converted structural contour map of the top-basement reflection and interpreted major faults for the offshore shelf areas (Bergh et al. 2007). Note location of the seismic sections outlined in Fig. 7. (b) Interpreted cross-section (lines L086R90-04 and L087R00-08) across the shelf margin from the Røst High to east of the Vestfjorden Basin. See Fig. 7 for legend to the cross-section. Abbreviations are: TB = Top-Basement, BC = Base-Cretaceous, APT = Intra-Aptian, IC = Intra-Cenomanian, BT = Base-Tertiary, HF = Hamarøya Fault, ELBF = East Lofoten Border Fault, VFZ = Vesterdjupet Fault Zone, WLBF = West Lofoten Border Fault.

The Lofoten shelf is structurally complex and made up of shelf-parallel basement ridges and shallow-seated, mainly Cretaceous basins bounded by complex extensional fault systems with variable orientations (Mokhtari & Pegrum 1992; Blystad et al. 1995; Løseth & Tveten 1996; Olesen et al. 1997; Tsikalas et al. 2001, 2005). The main basement high is the Utrøst Ridge (plus the Røst and Jenegga Highs), which is parallel to the Lofoten Ridge (Figs. 1 and 4). Major basins include the Røst Basin on the seaward side of the shelf, the Ribban Basin (including Skomvær and Havbåen sub-basins) on the central part of the shelf, the Træna Basin

to the southwest and the Vestfjorden Basin on the landward side (Mokhtari & Pegrum 1992; Blystad et al. 1995; Løseth & Tveten 1996). Major faults include the West Lofoten and East Lofoten Border faults bounding the Lofoten Ridge, the Hamarøya Fault (Olesen et al. 2002) on the landward side of the Vestfjorden Basin, and the Vesterdjupet Fault Zone bounding the eastern flank of the Træna Basin (Fig. 4). These intra-crustal basins are all bounded by normal faults and filled with predominantly Lower to Upper Cretaceous sedimentary rocks that are locally almost 7 km thick. Pre-Cretaceous (Permo-Jurassic) sedimentary strata are recognized in the Træna Basin, Havbåen Sub-basin and the Vestfjorden Basin (Blystad et al. 1995). Late Cretaceous through Early Cenozoic strata overly these faulted basin successions and lap onto the basement highs. To the south of Lofoten, the shelf margin widens at the transition to the Møre-Vøring margin by gradual diminishing of the Skomvær Sub-basin and widening of the Træna Basin (Fig. 1). These *Lofoten-line* elements (Doré et al. 1997) are all parallel to the Møre-Trøndelag Fault Complex (Blystad et al. 1995). North of Lofoten, the shelf is underlain by basins and is further linked to the transform plate margin of the Barents Sea along the NNW-SSE trending Senja-Fracture Zone (Gabrielsen et al. 1990). This transform is inferred to step onshore east of Andøya (Forsslund 1988; Olesen et al. 1997). Jurassic and Lower Cretaceous sedimentary rocks also occur in localised basins onshore Andøya (e.g. Dalland 1981) and in near-shore basins adjacent to Sortlandsundet and Gavlfjorden (Fig. 5), as indicated by shallow-level seismic data (Davidsen et al. 2001; Fürsich & Thomsen 2005).

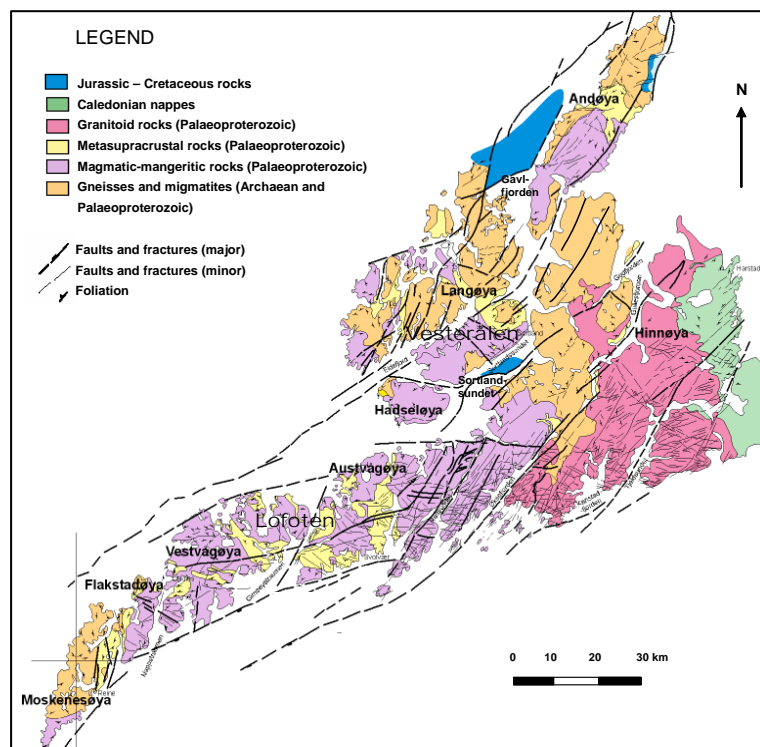


Fig. 5: Generalised bed rock geological map of Lofoten and Vesterålen including main foliation trends (modified after Tveten 1978) and interpreted traces of major and minor brittle lineaments (see more details in Fig. 8).

Offshore fault populations

Major faults cutting the basement-cover contact and those detaching in Jurassic-Cretaceous basin strata are outlined on the top-basement depth-converted structural map (Fig. 4). Two dominant fault trends are observable, (i) NNE-SSW striking, and (ii) NE-SW to E-W striking. The major faults bounding the Lofoten Ridge and Vestfjorden Basin display a left-stepping geometry, whereas the NNE-SSW striking fault sets typically are arranged oblique to and

often in between the former (Fig. 4). An apparent curvature of the NNE-SSW faults into the NE-SW faults produces a zigzag or curved rhombic pattern. On a local scale, relay and horsetail geometric fault arrays exist. Some faults die out along strike and/or are replaced by the more NE-SW striking, regionally extensive faults. The map pattern also shows local anastomosing faults with breaching and rejoining of the two dominant fault groups, as seen adjacent to the Utrøst Ridge and Jenegga High. Bouguer gravity and aeromagnetic anomaly maps combined with 3D images constructed from 50 km high-pass filtered gravity data (Fig. 6) confirm the presence of step-wise, rectilinear NNE-SSW and NE-SW-trending lineaments near the basement ridges and surrounding basins (Åm 1970; Talwani & Eldholm 1972; Olesen et al. 1997; 2002; 2007). Also visible on the filtered magnetic data (Fig. 6) is a set of distinct NE-SW trending lineaments that truncate the entire margin from the Røst High in the southwest to Andøya in the northeast, corresponding to the offshore West Lofoten Border Fault and onshore trends bounding the Lofoten Ridge.

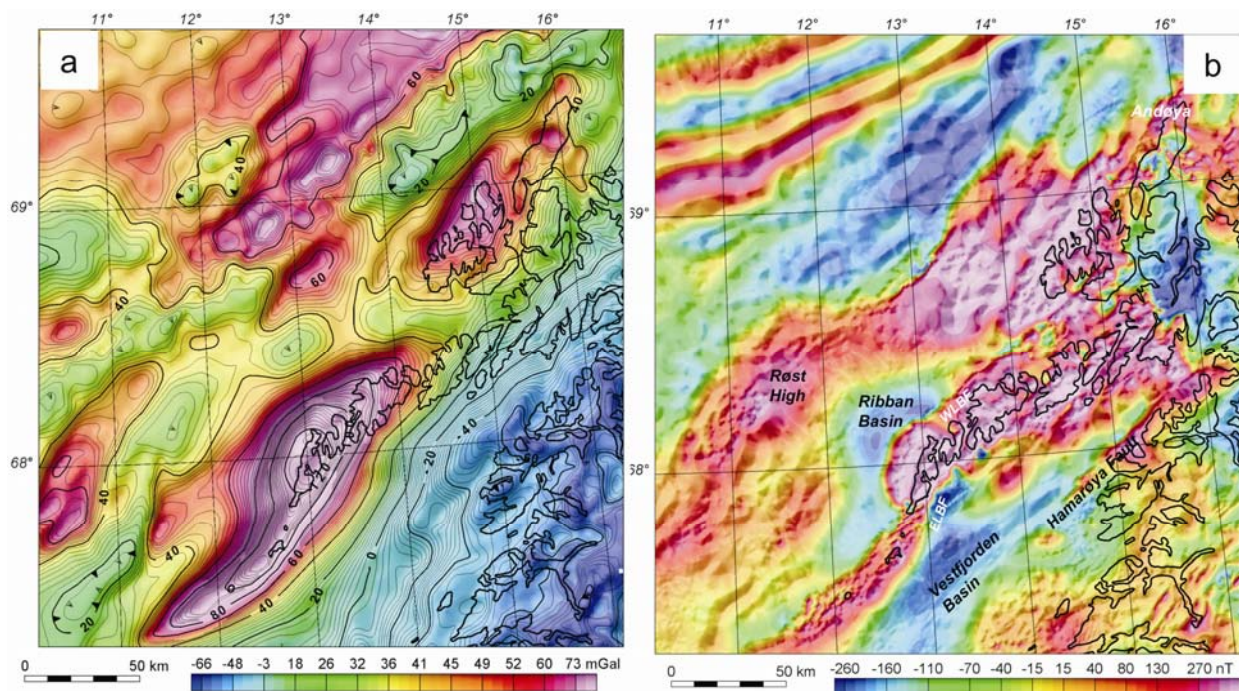


Fig. 6: (a) Residual gravity after isostatic correction of Bouguer gravity data from the Lofoten-Vesterålen region (Olesen et al. 2007). The contour intervals are 2.5 mGal (thin lines) and 20 mGal (bold lines). A shaded relief version of the 100 km Gaussian high-pass filtered Bouguer gravity dataset is superimposed in colour on the gravity residual map. (b) Compilation of aeromagnetic surveys in the Lofoten-Vesterålen region (Olesen et al. 2007). The contour intervals are 25 nT (thin lines) and 100 nT (bold lines). A shaded relief version of the 20 km high-pass filtered aeromagnetic compilation is superimposed on the aeromagnetic residual map in colour. The 'illumination' of both shaded relief versions in (a) and (b) is from the southeast. Note the presence of rhombic shaped blocks bounded by stepped, rectilinear features and trends of magnetic basement that largely follow the major fault-bounded ridges and basins.

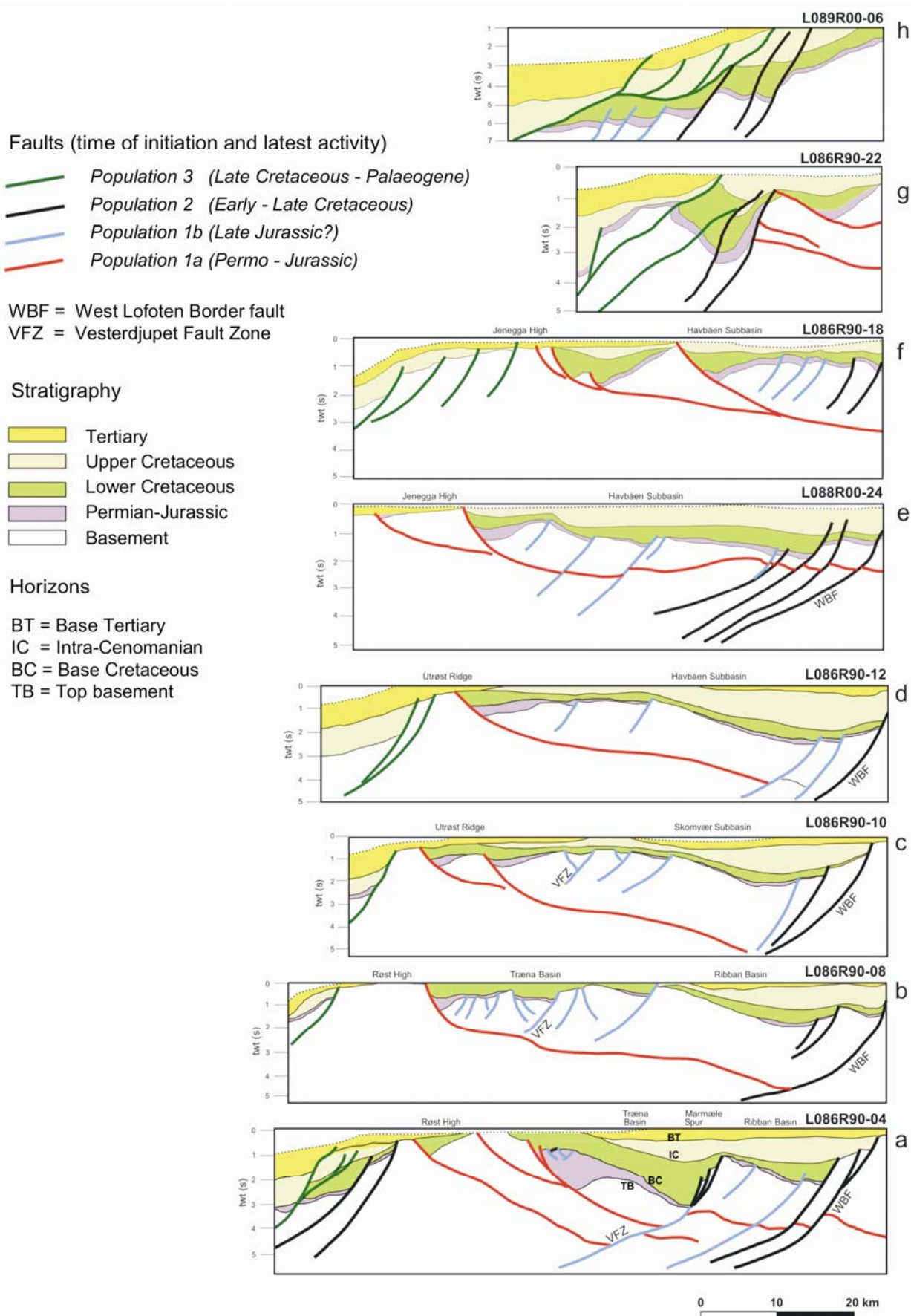


Fig. 7: NW-SE key seismic sections (a-e) from the Lofoten-Vesterålen shelf (Bergh et al. 2007). See figure 4 for location of the sections.

Three genetically related fault-fracture populations (Fig. 7) were identified on regional 2D seismic sections (Bergh et al. 2007). Population 1a defines ESE-dipping extensional normal detachments that bound the Træna Basin against the Røst High, the Havbåen Sub-basin against the Jenegga High, and the Vestfjorden Basin against the Lofoten Ridge. Their old age is supported by wedge-shaped pre-Cretaceous (Permo-Jurassic?) strata in the hanging-wall (Fig. 7a). An antithetic subset, termed population 1b faults dip consistently WNW and affected strata up to the base-Cretaceous level in the hanging wall, e.g. east of the Røst High/Utrøst Ridge, on the landward side of the Havbåen Sub-basin and in the Vestfjorden Basin (Fig. 7). Population 2 represents NW-dipping normal faults bounding the margins of main basins and the western Lofoten Ridge. This dominant fault population is represented by normal faults that bound NE-SW trending and repeatedly eastward-tilted blocks and half-grabens filled by thick, wedge-shaped Cretaceous strata east of the Træna and Ribban Basins. (3) Population 3 faults are the youngest set of NW-dipping normal faults that affected the Late Cretaceous to Palaeogene post-rift sedimentary wedge, e.g., west of the Røst High and on the outermost shelf of Andøya, at the continent-ocean transition. They break through the base-Tertiary reflection and obliquely truncate all other fault sets.

Onshore fault-fracture groups

Onshore brittle faults and fractures in Lofoten and Vesterålen are easily recognized on satellite and aerial photograph and 3D images (Fig. 8), and in field outcrops. Detailed structural analysis indicates the existence of three lineament sets striking: (i) NNE-SSW, (ii) ENE-WSW to E-W, and (iii) NW-SE, respectively (cf. Gabrielsen & Ramberg 1979; Gabrielsen et al. 2002; Bergh et al. 2007). The first lineament set is arranged parallel to many narrow fjords and sounds in Lofoten, e.g. Tjeldsundet, Øksfjorden, Gullesfjorden, Raftsundet, Gimsøystraumen and Nappstraumen (Fig. 8). They all show a straight to parallel, locally right-stepping and relay geometry, where individual fault traces die out or breach along strike. Curved fault traces characterise the central and eastern Lofoten archipelago (Fig. 8). The second set is parallel to the main NE-SW to ENE-WSW trend of the Lofoten islands and Vestfjorden (Gabrielsen et al. 2002). It is marked by linear escarpments along the coastal cliffs to the north and south of Lofoten (e.g. Eggum and Henningsvær), linear valleys of the interior such as Olderfjorden on Vestvågøy, and the linear depression along Hadsselfjorden and Ingelsfjorden (Fig. 8). In Vesterålen, these lineaments can be traced across Langøya to Andøya, where they bound the southern margin of a Jurassic-Cretaceous basin on land (Dalland 1981). Similar basins exist offshore in Gavlfjorden and Sortlandsundet (Fig. 5). In all these areas the basins are bounded by NNE-SSW (S1) and ENE-WSW (S2) striking faults producing zigzag-shaped basins. The third, NW-SE striking set is well displayed as rectilinear fault-fracture strands in the westernmost Lofoten islands and on Langøya (Fig. 8).

The relative timing of these lineament trends was established from critical observations in the field: (a) the NNE-SSW set is the most irregular-traced and is off-set and/or truncated by more linear ENE-WSW and E-W sets, (b) an apparent curvature of the NNE-SSW set into the ENE-WSW and E-W sets, and (c) the NW-SE-striking set in the west is rectilinear and consistently truncates all other sets. The systematic cross-cutting relationships in the field throughout Lofoten (Eig et al. in prep.) suggest that the NNE-SSW set is the oldest (termed S1), the ENE-WSW and E-W sets are of intermediate age (termed S2), and the NW-SE set is the youngest (termed S3). This interpretation deviates from Wilson et al. (2005, 2006) who applied a uniform WNW-ESE extension vector for eastern Lofoten. In their model, various fault patterns were activated synchronously in segmented domains at different angles to the presumed regional extension.

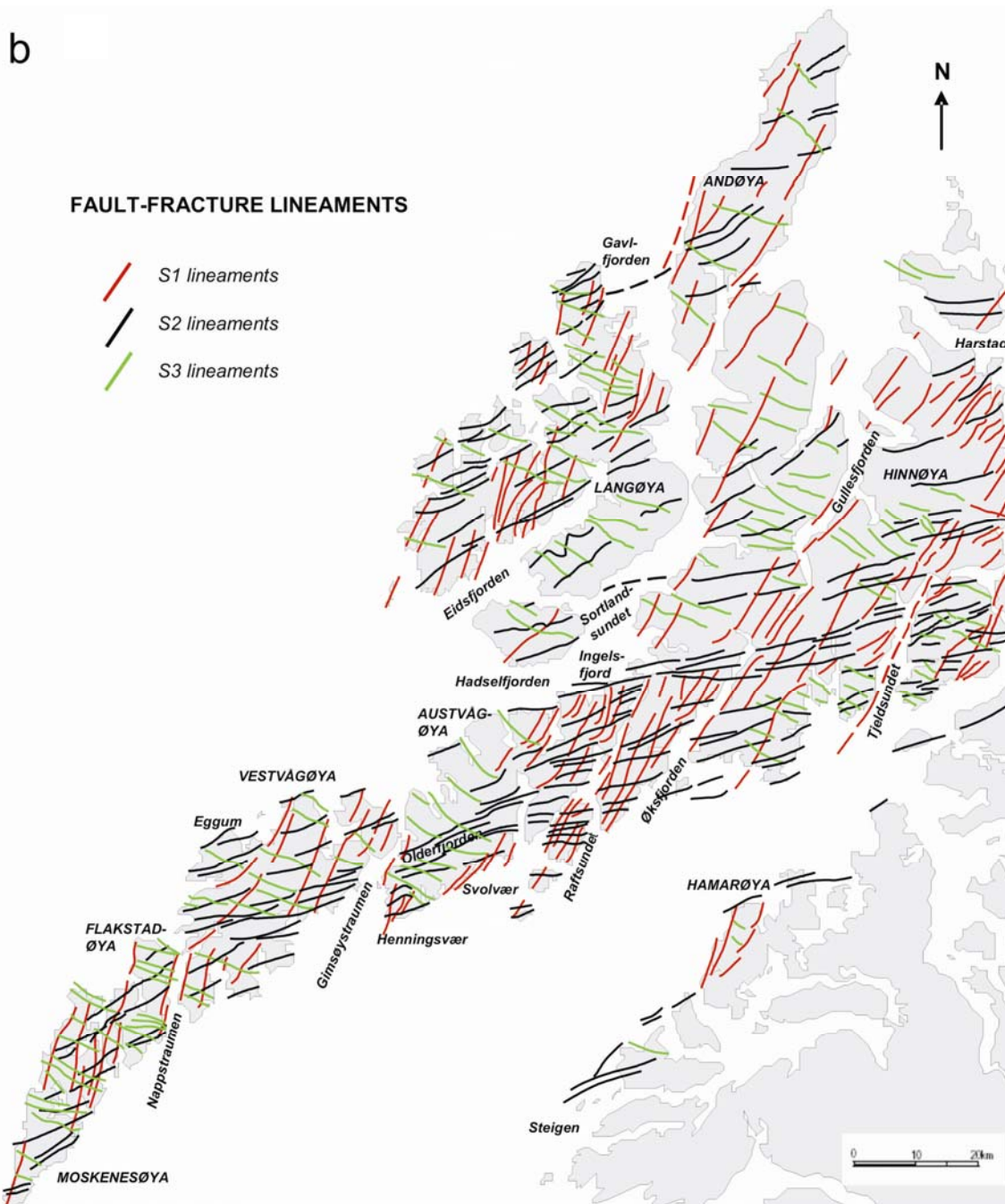


Fig. 8: Summary of the main onshore lineaments in Lofoten-Vesterålen, interpreted from Landsat satellite images (Bergh et al. 2007). The different fault-fracture sets are grouped according to their geometric characteristics and relative timing (S1, S2 and S3).

Passive margin tectonic evolution

Plate reconstructions of the Norwegian-Greenland Sea and passive margins (Ziegler 1988, 1989; Lundin & Doré 1997; Doré et al. 1999; Roberts et al. 1999; Mosar et al. 2002) and recent reviews of palaeomagnetic anomalies (Roest & Strivastava 1989; Torsvik et al. 2001a, b; Mosar et al. 2002; Olesen et al. 2007; Torsvik & Cocks 2005) suggest progressive E-W directed rifting from the Permo-Jurassic (250-150 Ma) to Early Cretaceous (100-90 Ma), followed by a more WNW-ESE to NW-SE opening trend in the Early/Late Cretaceous and Palaeogene, and ending with uniform NW-SE oceanic spreading in the Eocene.

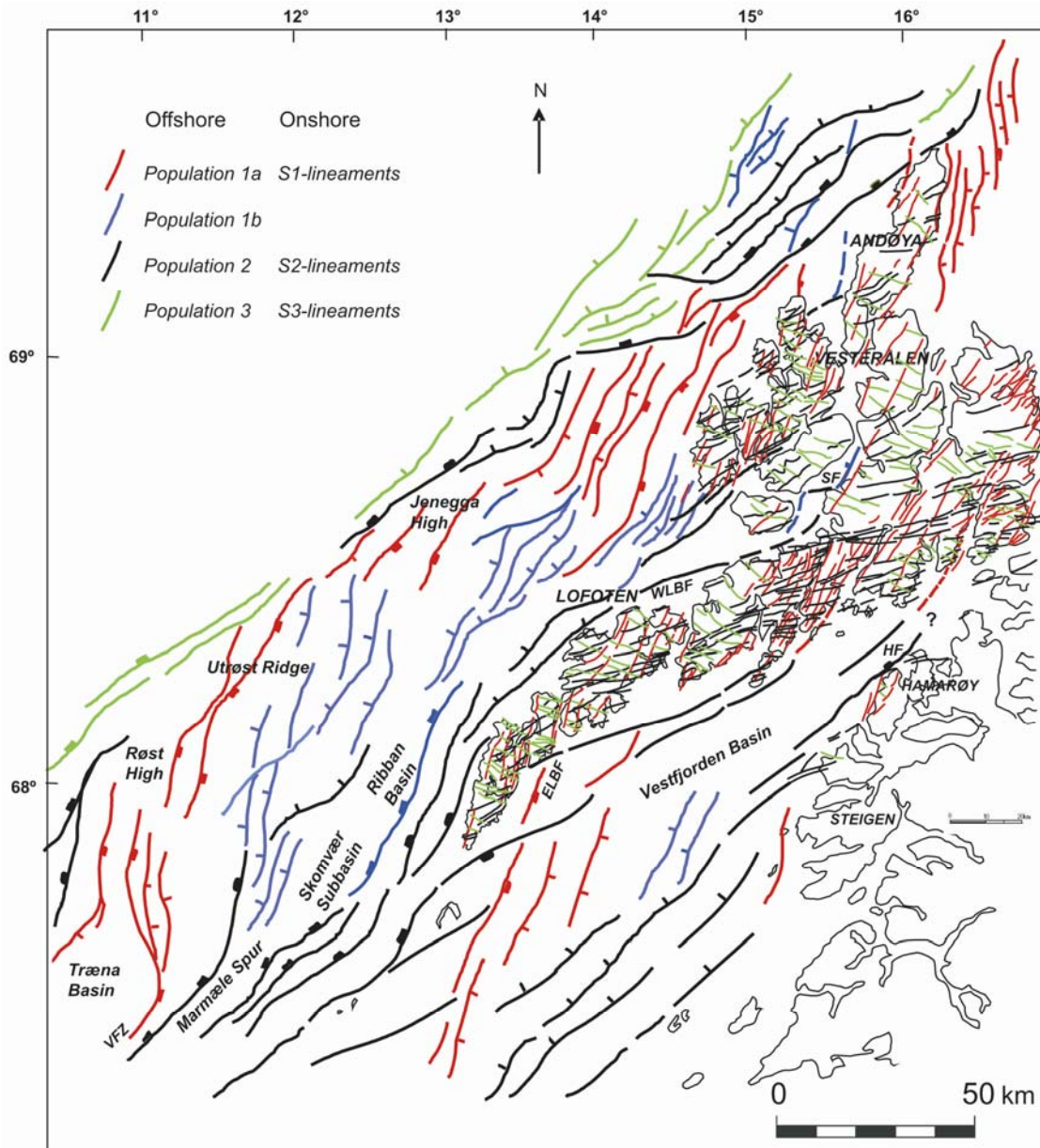


Fig. 9: Regional offshore-onshore fault-fracture map of the Lofoten-Vesterålen margin (Bergh et al. 2007). Abbreviations: ELBF=East Lofoten border fault, HF= Hamarøya fault, SF=Sortlandsundet fault, VFZ=Vesterdjupet fault zone, WLBF=West Lofoten border fault.

A three-phase passive margin fault evolution was proposed by Bergh et al. (2007) and includes (Figs. 9 and 10): (1) Population 1a (S1 onshore) faults initiated in the Permo-Jurassic proto-rift phase where WNW-ESE orthogonal extension was pervasively distributed across weakly interacting, stepwise arrays of NNE-SSW-striking normal faults and basins. Local NNW-SSE oblique extension later in the Jurassic (?) generated antithetic faults offshore (population 1b) and probably reactivation onshore as well in transition zones between major S1 faults and basins. (2) A main, syn-rift stage of Early to Late Cretaceous basin-and-margin fault evolution was accomplished by a change to a NNW-SSE extension direction and oblique reactivation of population 1a-1b and S1 faults producing major ridge-basin bounding extensional and dextral strike-slip faults (population 2 and S2 faults). (3) Continued regional NNW-SSE extension with local incremental rotation and NNE-directed shear stresses produced post-rift population 3 and S3 faults and fractures. All the established fault-fracture

sets may have been accomplished by further brittle reactivation in the Cenozoic. This multiphase fault evolution model requires a progressive clockwise rotation of the regional stress axis from c. E-W to NNW-SSE within the Mesozoic-Palaeogene intervals. In this context, earlier stepping normal faults (population 1a-1b and S1) and oblique basins and ridges may have acted as precursors to the subsequent transtensional faults (population 2-3 and S2-S3) and linked, margin-parallel basins.

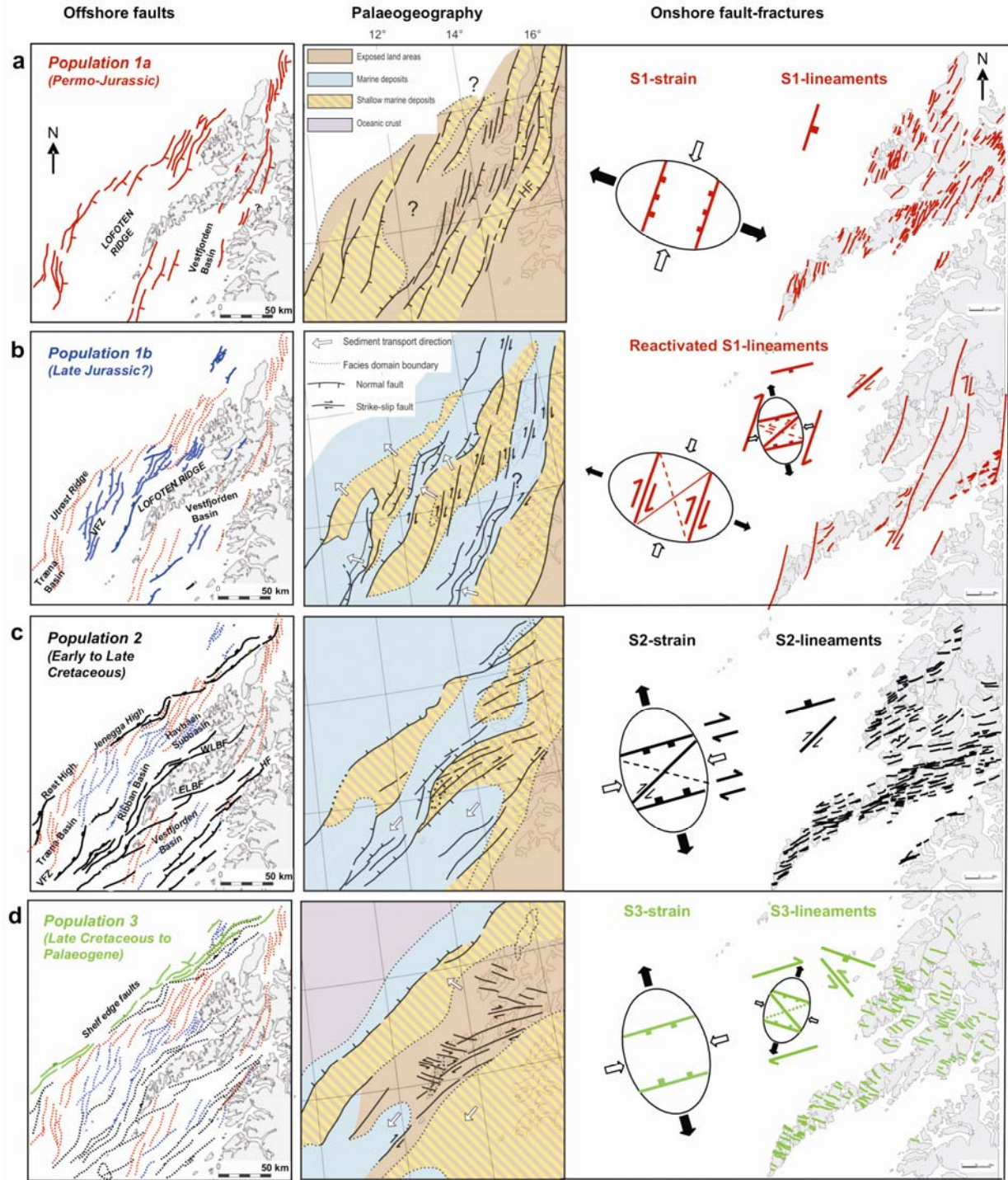


Fig. 10: (a-d) Chronologic and kinematic evolution model for offshore (left) and onshore (right) fault populations and lineaments combined with fault-basin restoration, sediment deposition and palaeogeography (Brekke et al. 2001; Henriksen et al. 2003; Bergh et al. 2007; Statoil, unpublished data). Note the clockwise rotation of inferred strain field onshore used to explain the separate fault patterns.

The relationship between tectonics and landscape in the Lofoten-Vesterålen archipelago

The Mid/North Norwegian passive margin formed through several stages of rifting from the Late Palaeozoic to the Palaeogene (e.g. Dore et al. 1999). During the late-stage or post-rift uplift stages, the Fennoscandian margin underwent c. 2500 m uplift accompanied by deposition of more than 4 km of sediments in adjacent offshore basins. New evidence shows that extensional faulting continued, as well, after the onset of seafloor spreading (Reston et al. 2004). This is well demonstrated in, e.g., the Lofoten-Vesterålen area, where Cenozoic uplift was accompanied by active faulting (Redfield et al. 2005). The cause(s) and consequences of this post-rift uplift (i.e. denudation age and geometry, drainage evolution, landscape formation and structural control) are still incompletely understood and lack a unifying framework.

New regional apatite fission-track (AFT) ages in Fennoscandia (Hendriks et al. 2004, 2007) have revealed a large-scale inverse relationship to the topographic elevation, indicating that the gross-scale topography resulted from 'post-rift' differential denudation (Redfield et al. 2005). For example, AFT age-jumps across tectonic lineaments in Lofoten and Vesterålen indicate that kilometer-scale faulting took place onshore later than c. 70-90 Ma (Fig. 11; Redfield et al. 2005), and controlled formation of prominent geomorphic lineaments and eastwards back-tilt of high-level palaeosurfaces (Bergh et al. 2006, Lidmar-Bergström et al. 2007, Osmundsen et al. 2007a). Thus, faulting appears to have continued to play an important role in the creation of the Cenozoic landscape. Movements along some of these faults may have continued to present day (Osmundsen et al. 2008).

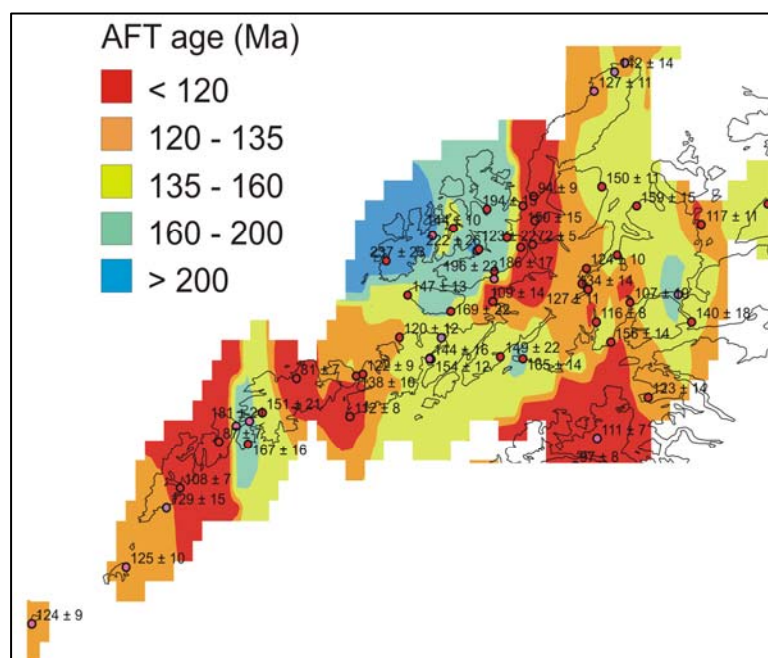


Fig. 11: Apatite-fission track ages for the Lofoten-Vesterålen region (Redfield et al. 2005).

In the Lofoten-Vesterålen archipelago and adjacent offshore passive continental margin the multiphase pre/syn-rift extension and post-rift crustal rejuvenation during the Mesozoic and Cenozoic resulted in a system of basins and ridges bounded by major extensional and oblique-normal faults (S1 to S3; Bergh et al. 2007) with step-wise to zigzag geometries and variable orientations and dip polarities (Fig. 9). These faults were superimposed on steep ductile fabrics in the crystalline basement rocks trending variably N-S and NW-SE.

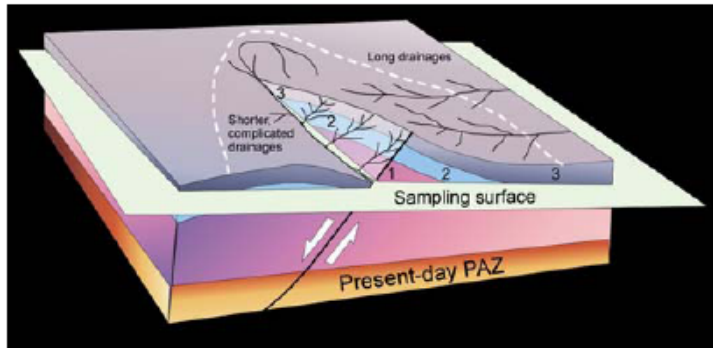


Fig. 12: Conceptual model indicating relationships between displacement gradient along a normal fault and resultant topography, AFT age-pattern and fluvial drainage pattern (Redfield et al. 2005). PAZ=palaeo-zone

A model of structural controls on denudation, uplift and landscape evolution by Cenozoic fault re-activation is currently being tested in Lofoten, where truncation, offset and rotation of geomorphic surfaces have been proposed (Fig. 12), and where jumps in AFT ages are apparent (Bergh et al. 2006, 2007, Hendriks et al. 2007). Fault displacement probably had a profound control on the spatial and temporal evolution of drainage basins and on the tilting of palaeosurfaces, at least on the local scale (Redfield et al. 2005). The age of tilted surface(s) in Lofoten-Vesterålen is unknown, but this local, high-relief landscape likely reflects pre-Quaternary geomorphological features, e.g. Cenozoic exhumation of tilted Palaeozoic-Mesozoic fault blocks and paleosurfaces bounded by extensional faults of the type recognized in offshore seismic data (Fig. 13: Bergh et al. 2007). Alternatively, the faults cut and rotate surfaces similar in age to the *Paleic surface* of southern Norway. The *palaeic* surface (Reusch 1901) is a term that refers to the elevated ‘old’ land surface that stands in marked contrast to ‘young’ landforms incised into it, such as cirques, deep valleys and coastal cliffs. It is generally assumed to have been uplifted prior to the Quaternary, but its morphology, age and mode of formation is not well constrained (Japsen & 2000; Corner 2005b). Whereas Ahlman (1919) and Gjessing (1967) argued that the Paleic surface consists of one surface generation formed by deep weathering processes and hill slope retreat, Lidmar-Bergström et al. (2000) reconstructed five separate palaeosurface generations at different altitudes in southern Norway, and it has been proposed that they reflect uplift events followed by fluvial landscape formation (Bonow et al. 2003, Lidmar-Bergström et al. 2007).

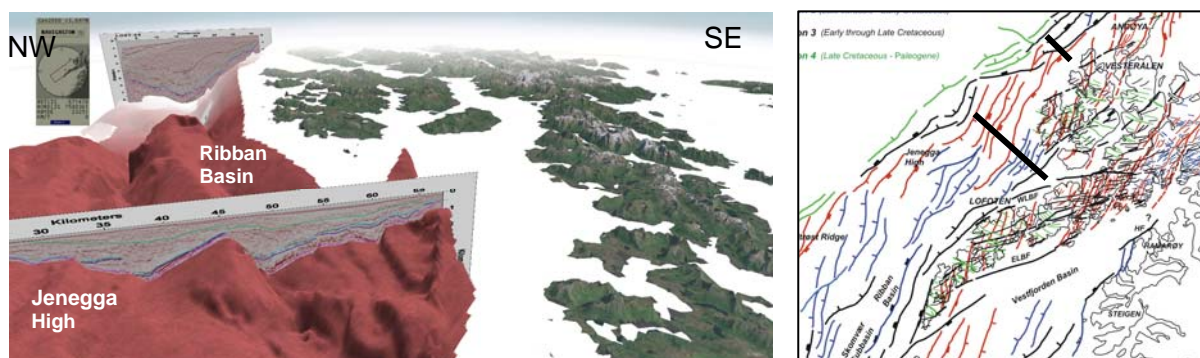


Fig. 13: 3D image of the continental shelf offshore Lofoten-Vesterålen showing the tilted fault blocks and adjacent basins (left), Statoil's terrain model. Bold lines on the map to the left locate the seismic sections (Bergh et al. 2007).



Fig. 14: High-alpine landscape in Moskenesøy, westernmost Lofoten.

In Lofoten and Vesterålen, small remnants of the palaeic surface are preserved at high levels above glacial troughs and on mountain massifs fretted by cirque erosion. The relationship of these typical, high-level palaeic geomorphologic elements to other, lower or tilted palaeosurfaces has yet to be established. Recent studies indicate that pronounced contrasts in landscape type occur across some of the major faults in Lofoten, such as at Nappstraumen (East Lofoten Border Fault), Sortlandsundet and Raftsundet (Fig. 9). The westernmost islands (Moskenesøy and Flakstadøya), reflect the youngest uplifts and are characterized by high-alpine landscapes (Figs. 14, 15). Further east, the landscape is more subdued with gently dipping surfaces, defined by flat-topped summit remnants, cut by valleys throughout. These features resemble tilted paleosurfaces bounded by steep escarpments, i.e. faults. Many valley and ridges display planar and steeply dipping slopes resembling a series of domino-style fault blocks bounded by both ESE-WSW and NNW-SSE dipping normal faults (Fig. 13). The gently dipping paleosurfaces suggest tilting due to footwall uplift adjacent to these main S1-S3 faults bounding the Lofoten Ridge and Vestfjorden basins (Figs. 4,7).

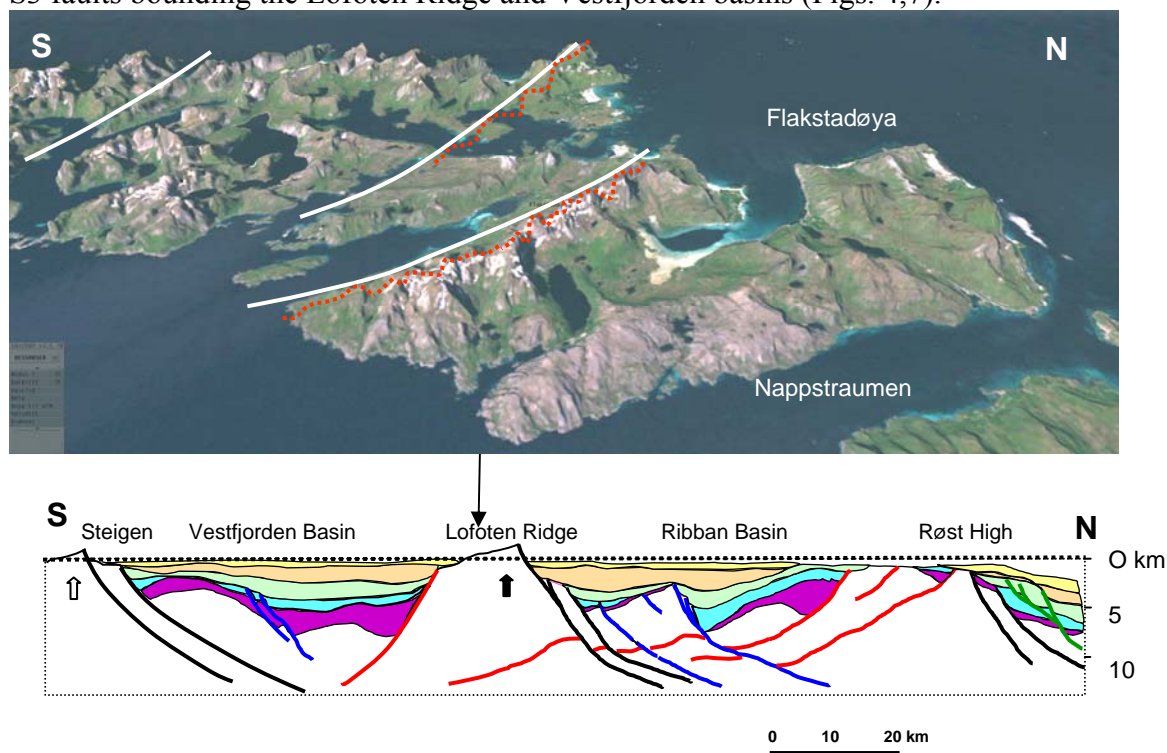


Fig. 15: 3D satellite and terrain image of western Lofoten illustrating an erosional surface marked by flat-topped summit remnants dipping gently to the SSE. When compared with the offshore seismic data, a possible mechanism of formation is by tilting due to footwall uplift adjacent to the West Lofoten Border Fault (see Fig. 9; Population 2; Early-Late Cretaceous?)

There is also a consistent and straight attitude of narrow sounds and steep coastal cliffs and escarpments (Figs. 16-19), marking common breaks in slope (e.g. Øksfjorden, Raftsundet, Nappstraumen, Eidsfjord, Sortlandsundet). Many fault escarpments are aligned in a zigzag, partly curved pattern that mimics the S1 through S3 brittle fault trends of Bergh et al. (2007) (Fig. 9). Similarly, interferences of two or more glacially eroded valley-and ridge systems locally produce cirques that may be explained by interaction of S2 and S3 fault-fracture trends (Fig. 17). Thus, the Cenozoic landscape and glacial erosion and drainage in Lofoten appear to have been significantly controlled by Palaeozoic-Mesozoic tectonics (Bergh et al. 2006, 2007; Hansen et al. 2006; Osmundsen et al. 2007a).

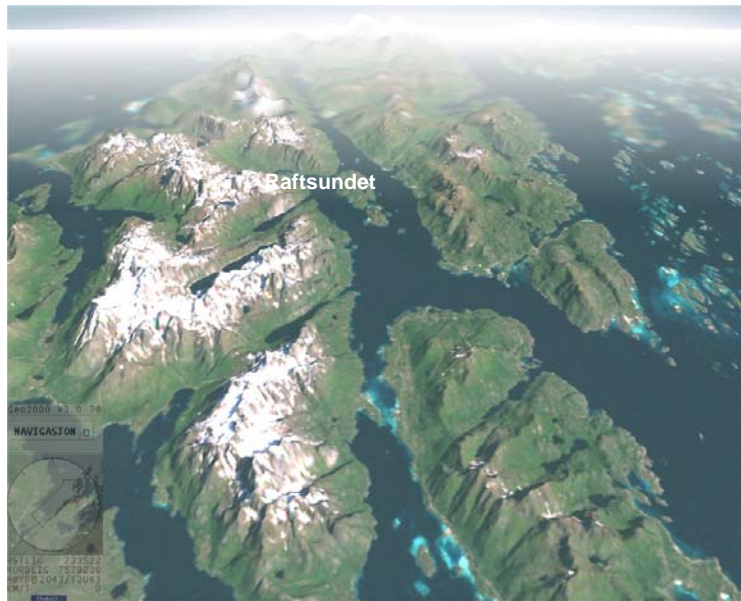


Fig. 16: 3D satellite and terrain image of eastern Lofoten, showing straight attitude of sounds, ridges, glacially eroded valleys and lakes. Note also steep coastal cliffs and escarpments aligned in a zigzag pattern that mimics the NNE and NE to ENE striking brittle fault trends. View is to the NE.



Fig. 17: 3D satellite and terrain image of the westernmost island of Lofoten. Note the glaciated, alpine landscape with eroded U-shaped valleys, linear ridges and valley cirques that are strongly influenced by structure.

Tilted Mesozoic basin remnants and bounding normal faults are locally preserved inside fjords and sounds (i.e. Sortlandsundet Basin, Davidsen et al. 2001) and provide markers of pre-depositional basement surfaces. These marker faults can be extrapolated to, and compared with, adjacent offshore basement topography, providing a glimpse of the Mesozoic landscape

and its subsequent evolution (Fig. 9). The final phase of landscape evolution, following Tertiary uplift and fluvial rejuvenation, occurred during the Quaternary Period (last 2.6 Ma), when extended periods of local, cirque-glacier erosion alternated with more extensive valley-glacier and ice-sheet erosion, and when glaciers reached the shelf edge and inundated all but the highest summits. Glacial erosion selectively followed fluvial valleys and tectonic zones of weakness, creating the deeply incised, preferentially oriented landscape we see today. At the same time, frost weathering and marine erosion around a fluctuating sea level, created the *strandflat*, a coastal rim of rock platforms and skerries lying between c. 50 m above and below present sea level, which cuts across rock structure (Corner 2005a). The subaerial part of the strandflate is well exposed at many places, e.g. around Reine on Moskenesøya.

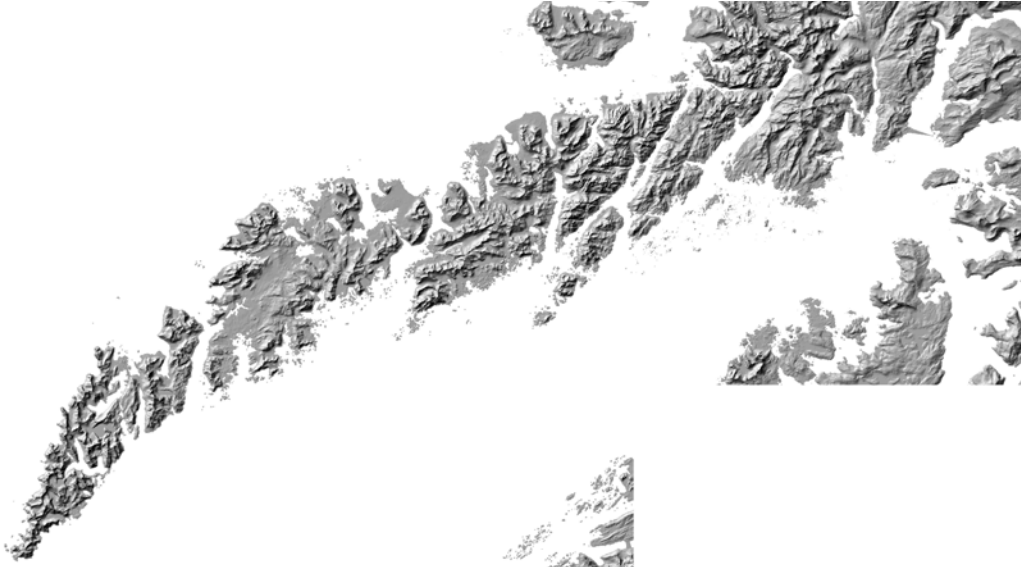


Fig. 18: Grey shaded topographic relief map of Lofoten.

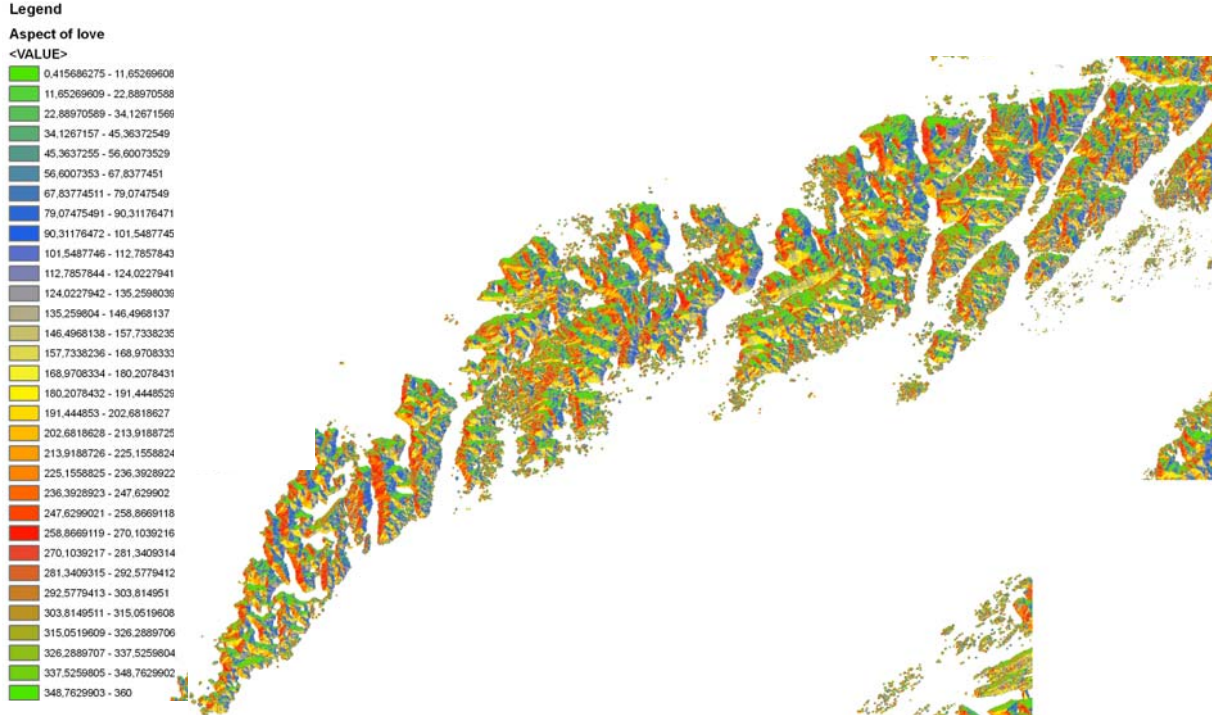


Fig. 19: Aspect map of hillside slope directions (coloured) in Lofoten and Vesterålen.

Excursion Route and Road Log

An overview map of the excursion route is shown in Fig. 20.

Day 1: Flight from Oslo to Leknes (via Bodø) and bus drive to Nusfjord

On the way to Nusfjord, brief overview of the bedrock geology, brittle fault patterns and palaeosurfaces in westernmost Lofoten. Evening seminar: Introduction to the geology and tectonics of Lofoten and Vesterålen.

Overnight in Nusfjord

Day 2: Flakstadøy and Moskenesøy

Petrology: Palaeoproterozoic gneisses intruded by 1.7-1.8 Ga suites of anorthosites, the Moskenesøy anorthosite and the large Flakstadøy anorthosite, associated with gabbroic and troctolitic rocks (Flakstadøy Basic Complex) and mangerites (the South-West Lofoten mangerite, Sund-Ølkona Mangerite suite). Eclogitic shear zones and pegmatite dykes.

Tectonics: Study of Cretaceous-Palaeogene brittle faults and fractures along the shore. At Vareid-Vikten we will observe the trace of the major West Lofoten Border Fault, bounding the north side of the Lofoten Ridge. The famous village of Reine is surrounded by high-alpine landscapes controlled by brittle fault-fracture systems. Outcrop study of brittle faults-fractures near the village of Å in Moskenes. Overnight in Nusfjord

Day 3: Through Vestvågøy and part of Austvågøy, Central Lofoten

Petrology: The Caledonian Leknes Group, the South-west Lofoten Mangerite and Borge gabbro pluton, metasupracrustal gneisses at Eggum, calc-silicate schists at Gimsøy, mangerite-charnockites of the Hopen Pluton near Henningsvær.

Tectonics: Fault escarpments and tilted palaeosurfaces near Leknes, S1-S2 brittle fault-fractures at Henningsvær-Rørvika, East Lofoten Border Fault, fault history of central Lofoten. Overnight in Henningsvær

Day 4: Raftsundet in eastern Lofoten and southern part of Langøya, Vesterålen

Petrology: Raftsundet mangerite-charnockite complex, ductile shear zones in mangerites along the LOFAST road.

Tectonics: Multiple generations (S1-S3) of brittle fault-fracture sets at Raftsundet, fault rocks, gouges, pseudotachylites and kinematic striated fault surfaces. Langøya: The Heier Zone mylonites representing an exhumed Permian (?) detachment and underlying metamorphic core complex. Overnight in Sortland

Day 5: Sortlandsundet – Rødsand - Evenes

Petrology: Study of the Eidsfjord anorthosite complex and retrogressed mangerites on Langøya in Vesterålen.

Tectonics: Major Late Jurassic fault bounding the Sortlandsundet Graben (in a quarry at Rødsand). Prominent fault escarpment and tilted fault blocks controlling the landscape in southern part of Vesterålen. Drive to Evenes and flight to Oslo

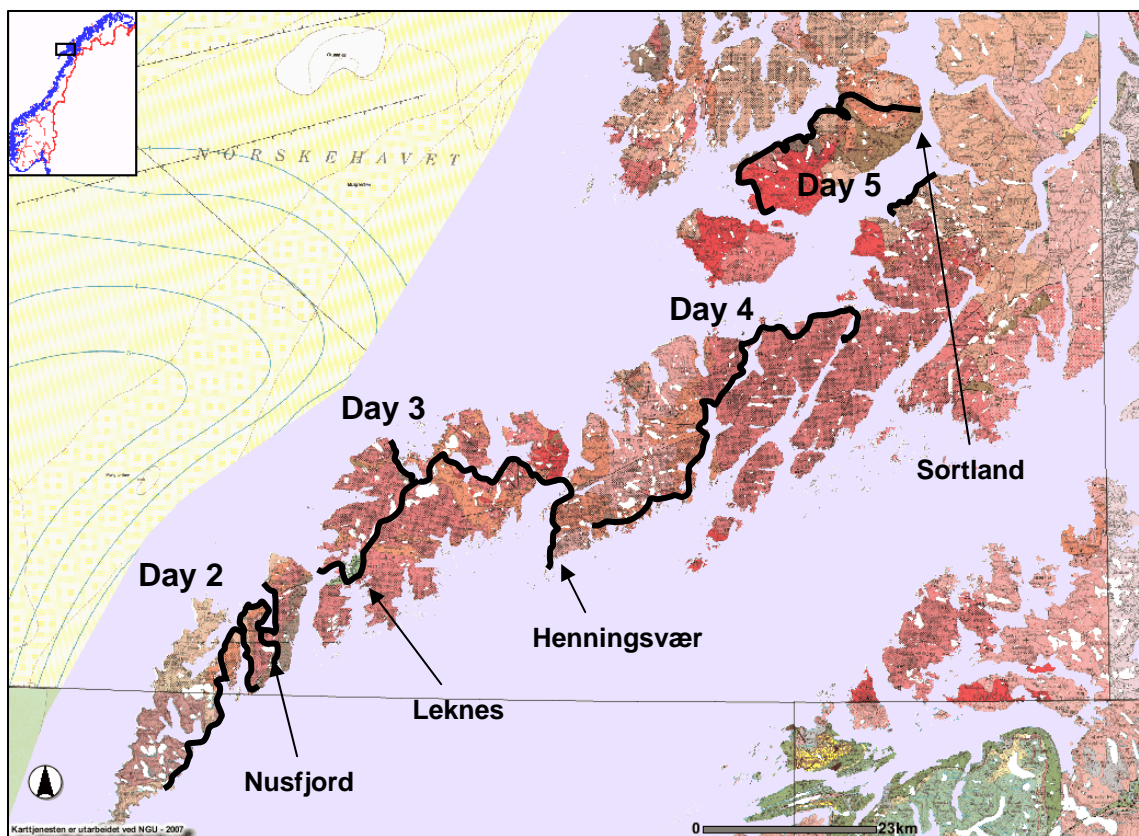


Fig. 20: Overview geological map (Tveten 1978) showing the excursion route day by day. For more detail location of separate stops, see each of the day maps.

Excursion Stops

Day 1

At the end of the IGC congress on August 14th, the participants will depart from Gardemoen airport by SAS-Braathen's flight to Bodø, with further connection on Widerøe to Leknes in Lofoten (Fig. 20). Drive from Leknes airport to Nusfjord will be by bus, arriving at Nusfjord late in the afternoon. In the evening there will be a lecture and short discussion/seminar on the introduction to the geology and tectonic evolution of Lofoten and Vesterålen.

Day 2

Except for the first two localities, the stops on Day 2 will be near the main road or along easily accessible coastal/shoreline sections. An about 1 km hike is required for stop 2.1. Before departing, be certain that you have brought along warm clothes, raingear, and good field boots.

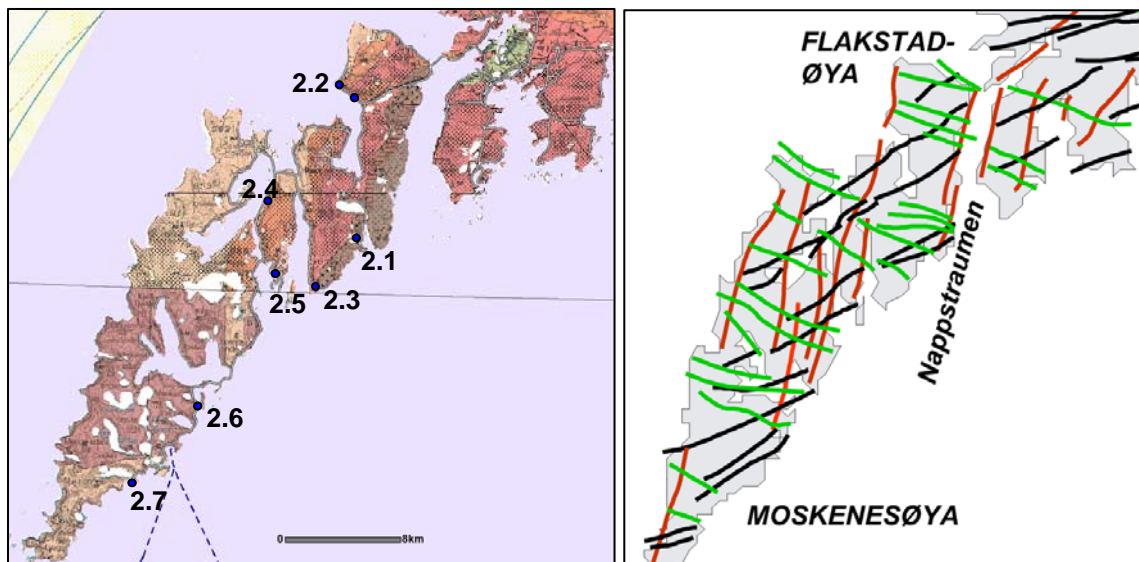


Fig. 21: Geological map with displayed localities for day 2 (left) and traces of brittle fault-fractures (right).

Day 2 is spent on the westernmost islands of Lofoten, i.e. Flakstadøya and Moskenesøya (Fig. 21). These islands are made up of weakly foliated, Palaeoproterozoic paragneisses (Green & Jorde 1971; Tveten 1978; Corfu 2004a) intruded by 1.7-1.8 Ga suites of anorthosites, the Moskenesøya anorthosite and the large Flakstadøya anorthosite, which is associated with gabbroic and troctolitic rocks (Flakstadøya Basic Complex, FBC, of Markl et al. 1998), and mangerites (the South-West Lofoten mangerite, SWLM) of Malm & Ormaasen (1978). Presumed Caledonian mylonitized shear zones comprising eclogites and Cl-rich hydrosilicates occur in the anorthosites (Kullerud 1995; 1996; Kullerud et al. 2001; Markl & Bucher 1997). We will examine magmatic and metamorphic fabrics of the plutonic rocks and contact relationships to the surrounding paragneisses, and discuss the formation of eclogitised shear zones.

The western islands of Lofoten display high-alpine topography (highest peak 1029 m) and in places a broad coastal strandflat. A number of brittle, presumed Mesozoic-Cenozoic fault-fracture sets that are easily recognizable both in satellite and aerial DEM images (Figs 14 and 17). The faults/fractures and surface elevation slopes are grouped into three main orientations and kinematic groups (Fig. 22), corresponding to the inferred age difference: NNE-SSW (S1), NE-SW (S2) and NW-SE (most frequent; S3). The structural lineaments in western Lofoten have a more WNW-ESE to NNW-SSE trend compared with areas farther east (Figs. 8 and 9). Fault scarps and rectilinear gullies are well developed in the anorthosites on Flakstadøya and in gneisses on Moskenesøya (Figs. 22 and 23). The youngest, NW-SE trending S3 lineaments delimit many composite and splayed fracture arrays including conjugate fault/fracture sets that bisect the conjugate acute angle. Dextral and sinistral motions on these conjugate arrays can be obtained in the field from local drag effects and slickenside striations, supporting a shear fracture origin with mostly dextral senses-of-shear (Fig. 22).

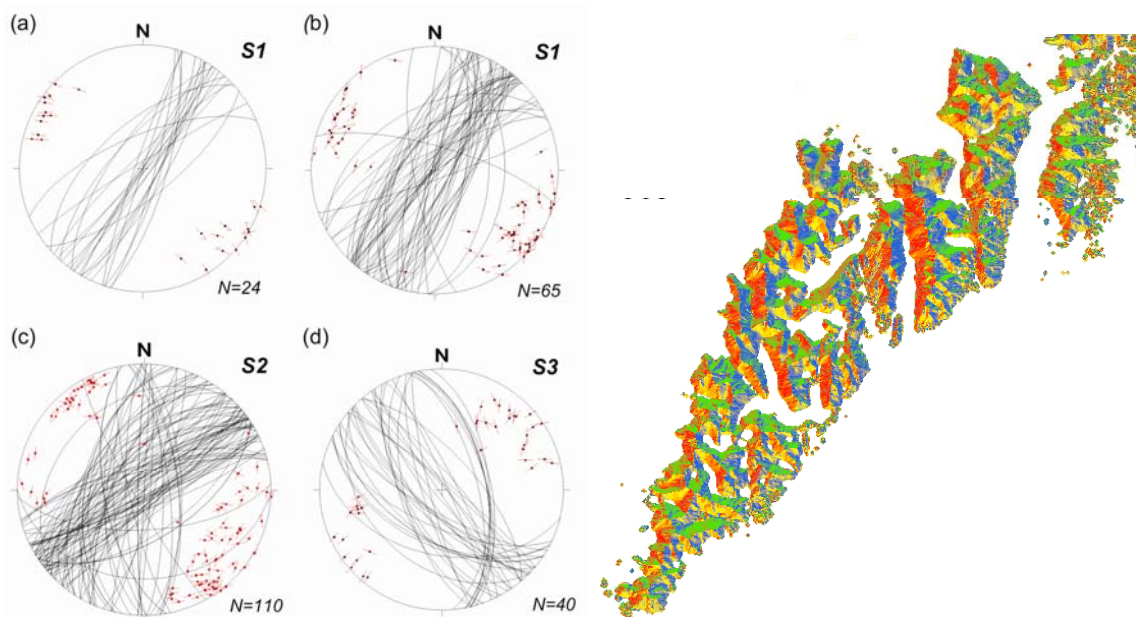


Fig. 22: Equal-area, lower hemisphere stereo net diagrams of kinematic data for brittle faults in Lofoten, including S1 faults with (a) dip-slip extensional and (b) reactivated dextral strike-slip character, (c) S2 faults and (d) S3 faults (from Bergh et al. 2007). Striated fault data are plotted as slip-linears in which the pole of the fault is representing a point with an arrow indicating the movement plane (Goldstein & Marshak 1988). Slope orientation, shown on the aspect map to the right, in Moskenesøya and Flakstadøya, to some extent overlaps with the fault-fracture groups. For colours that indicate the slope directions, see Fig. 19.

These lineaments seem to have greatly influenced topography, e.g. producing steep mountains bounded by planar surfaces, coastal cliffs, fairly straight fjords and glacial valleys, cirques and gullies of variable orientations (Fig. 17). The orientation of glacial valleys and cirques in particular follow the main, brittle fracture trends. We will study especially the NW-SE lineament set (S3), which is well developed in Moskenesøya, and discuss its relationship to the other regional scale brittle lineaments (S2-S3) and also discuss Late-Cenozoic denudation and landscape evolution.

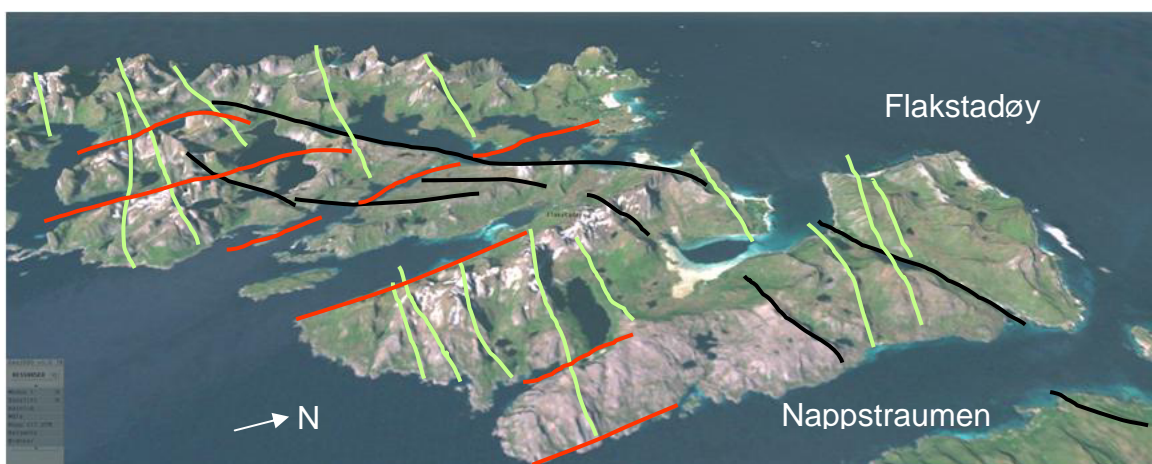


Fig. 23: 3D satellite and terrain images of western Lofoten (Flakstadøya and Moskenesøya) showing S1-lineaments (in red) along Nappstraumen, S2-lineaments (black) and S3-lineaments (light green) that obliquely truncate the former.

Stop No 2.1: Nusfjord

Location

Mørkdalen c. 1 km west of Nusfjord (446 302) and roadcuts just north of Nusfjord (481310). Map sheet Leknes 1:50000.

Introduction

The Mørkedalen locality exposes a Caledonian, eclogitized shear zone fully within anorthosites of the Flakstadøy Basic Complex. The road cuts illustrate various gabbroanorthositic and troctolitic plutonic rocks of the Flakstadøy Basic Complex, including dunitic xenoliths in anorthositic rocks.

Description

In Mørkdalen, a 2 m-thick mylonitic shear zone occurs near the contact between gabbroanorthosite on the east and mangeritic rocks on the west, but entirely within the former. The shear zone comprises an outer amphibole-bearing and a central eclogitic part with relics of omphacite in addition to garnet (Kullerud 1995, 1996; Kullerud & Erambert 1999; Kullerud et al. 2001; Markl & Bucher 1997, 1998). The central eclogitic zone is texturally late and overprints parts of the amphibole-bearing zone (Cl-bearing amphiboles are found as relicts within eclogitic garnets). The shear zone can be traced for about 2 km. The contact between shear zone and host rocks is sharp. The undeformed gabbroanorthosite contains coarse-grained (1 to 2 cm) dark-grey plagioclase, clinopyroxene, minor orthopyroxene and Fe-Ti oxides. Except for very few Cl-free biotite flakes, there are no signs of a metamorphic overprint. The mangerite also has a grain-size on the order of 1 cm, but it frequently contains biotite and amphibole and the bleached white feldspars indicate significant metamorphic overprint. The amphibole-bearing part of the shear zone contains large relicts of pyroxene in a fine-grained matrix of amphibole, garnet and plagioclase. The mineral textures demonstrate that the Cl-rich amphiboles and biotites in the shear zone developed after the granulite facies metamorphic event by reaction of the anhydrous granulite-facies mineral assemblage with an externally derived fluid. As it is common that shear zones act as fluid conduits in the middle and lower crust, especially during the retrogression of granulites (e. g. Austrheim 1987; Jamtveit et al. 1990), the observed geologic relations strongly argue for the involvement of a metamorphic fluid during Cl-mineral formation in this shear zone.

Roadcuts about 1-2 km north of Nusfjord comprise fresh outcrops of anorthosite of the Flakstadøy Basic Complex, leucotroctolite and some blocks of mangerite; furthermore, in an old gravel quarry on the east side of the road, nice corona textures in metamorphosed anorthositic rocks.

Stop No 2.2: Vareid-Vikten

Location

Stop at two localities (a, b) along the shoreline between Vareid (562 308) and Hestneset (585 293) southwest of Vikten. Map sheet Leknes 1:50000

Introduction

Both localities expose basement rocks of the South-West Lofoten mangerite, which covers most of the northern and eastern part of Flakstadøy. In addition, near Hestneset, the contact between homogenous mangerites and quartz-feldspathic paragneisses can be seen.

Description

The SWLM intrudes the anorthositic rocks of the Flakstadøya Basic Complex to the east and Palaeoproterozoic paragneisses to the northwest. The mangerites near Vareid in places show porphyritic textures consisting of mesoperthite megacrysts (up to 4 cm) in a matrix of about 1 cm diameter grains. The gneisses display complex banding which is folded (steep/subvertical axes) and sheared, likely during the Svecofennian orogeny.

Along the shore at Vareid, steep, localized brittle fault/fracture zones (S2 set of Bergh et al. 2007) can be seen in the homogenous mangerite. The main fault/fractures strike on average NE-SW and dip steeply to the NW and appear to follow a regional onshore-offshore system that bounds the northern margin of the Lofoten Ridge, i.e. parallel with the West Lofoten Border Fault (Figs. 4, 9). Prominent seaward dipping coastal escarpments can be observed along strike to the southwest (Fig. 24). They correspond to similar and presumed linked fault systems further northeast, at Eggum (Fig. 8). Complex internal geometries and kinematic indicators of the brittle fault/fracture zones, such as sigmoidal structures, imbricated and lensoidal shaped fracture surfaces and possible brittle duplex structures will be demonstrated. These brittle fault zones reveal partly conflicting shear-senses and various interpretations may be discussed.



Fig. 24: Major fault escarpment of western Lofoten, parallel to the West Lofoten Border Fault. View is to the southwest.



Fig. 25: Outcrop view of NE-SW striking S2 fault/fractures at Vareid showing lensoidal and duplex-like geometries.

Stop No 2.3: Nesland

Location

Road cut and shoreline exposures near the village of Nesland (442277). Map sheet Leknes.

Introduction

This locality demonstrates the characteristics and contact relationships of the South-West Lofoten Mangerite and the Flakstadøy Basic Complex (FBC). The latter is divided into three parts, an eastern anorthosite, a middle troctolite and a western gabbro (Romey 1971). The contacts between the troctolitic and the gabbroic rocks are gradational whereas the relations between anorthosite and troctolite are less clear. When observed the contacts between these two units appear to be sharp. The occurrence of a troctolite xenolith with sharp contacts towards the surrounding anorthosite suggests that the anorthosite postdates the troctolitic-gabbroic portions of the intrusion.

The average grain size of the rocks from the FBC varies between 1 and 4 cm, but may reach 35 cm in pegmatitic pods. Fresh plagioclase in all units of the FBC is always black in color; plagioclase in the eastern anorthosite part, however, commonly shows white recrystallized rims. Pods and lenses of massive Fe-Ti oxides and nearly pure dunitic rocks are common in the troctolite but are not found elsewhere. Along the contact to the mangerite the gabbro is generally porphyritic in contrast to all other anorthositic rocks of the FBC.

Description

The contact relations between anorthosites and the troctolites are best exposed at its southern end near Nesland near the contact to the mangerite. Along about 300 m of coastal outcrops the anorthositic and gabbroic rocks are intruded by veins and large lenses of mangerite, some containing large xenocrysts of anorthositic plagioclase. Mafic minerals are pyroxenes and Fe-Ti oxides, and in the metamorphosed varieties, garnet, biotite and amphibole. The rocks lacking pyroxene or olivine are relatively easy to recognize; the feldspars are white in contrast to the golden-brownish to greenish feldspars in the unmetamorphosed varieties.

Stop No 2.4: Selfjorden-Straumsnes-Kakeren

Location

Several hundred meters long road cuts in the cliffs along the eastern shore of the NNE-striking Selfjorden sound (502 243) and Kakeren (462242). Map sheet Moskenesøy

Introduction

In a road cut and a little quarry near Kåkern, just east of the bridge between Moskenesøy and Flakstadøy, the host rock is composed of greyish-greenish andesitic gneisses with nice pegmatitic pods containing plenty of orthopyroxene and mesoperthite.

Description

Both localities expose Mesozoic-Cenozoic brittle fault-fracture surfaces with NNE-SSW, NE-SW to ENE-WSW and NW-SE strikes (Eig et al. 2008). Slickenlined fault planes are common and often covered by films and fibres of iron oxide or epidote. Orientations and cross-cut relations of the fractures indicate that the NNE-SSW striking sets are the oldest, and

they are reoriented into and cut by a new, favourable ENE-WSW striking fracture set. These localities are interesting for their abundant and consistent slip striae that yield important kinematic information. NNE-SSW striking fractures are subvertical, with slip striae indicating dip-slip or oblique-down-to-SW normal motion (Fig. 22a). These NNE-SSW striking faults are truncated by NE-SW to ENE-WSW striking faults/fractures with steep dip. Slip striae are mainly horizontal to very gently plunging and indicate strike-slip movement (Fig. 22c). A few dip-slip striae also occur. The youngest fracture set is steep and strikes NW-SE and consistently cut all other sets. Striae on this latest set show dip-slip or down-to-the NE and SW normal motion; the latter indicates a left-hand shear component (Fig. 22d). Although the relative age of NNE-SSW and NE-SW to ENE-WSW striking faults is generally well constrained, local temporal overlap is inferred where the two sets are linked by a “hinge” (Fig. 13b). Such linkage may be indicative of a progressive rotation of the strain field. Where present at these localities, foliation in the andesitic gneisses is generally weak. Its dip varies, but a consistent strike suggests that it is folded around a ~N-S axis. It seems to have had less influence on the fracture development, but is well visible as a controlling element of the landscape in Moskenesøy.

Comparison of these local fracture patterns with those of the entire Lofoten and offshore (Fig. 10; Bergh et al. 2007, Eig et al. 2008) indicates that the NNE-SSW set is the oldest (Permian - Jurassic), the NE-SW to ENE-WSW sets of intermediate age (Early to Late Cretaceous), and the NW-SE-striking sets the latest (Late Cretaceous to Early Palaeocene). In this tectonic model, the ~NW-SE sets are thought to have developed in between the regionally oblique dextral (ENE-WSW) strike-slip sets (see above).

Stop No 2.5: Sund

Location

Outcrops near and in the village of Sund (450250). Map sheet Moskenesøy.

Introduction

The Sund-Ølkona Mangerite (SØM) extends from the western part of Flakstadøy to the eastern part of Moskenesøy. This mangerite contrasts sharply with the SWLM as it contains bluish quartz aggregates and schlieren. The SØM is typically fresh and shows only minor metamorphic mineral growth.

Description

The best exposures of the SØM are west of Sund. The rocks consist of fresh charnockite with bluish quartz and in parts with interesting, probably granulite-facies textures (only visible in thin section). The SØM exhibits intrusive contacts and apophyses into the surrounding gneisses. These often contain anatectic schlieren-like veins of mesoperthite with ortho- and clinopyroxene.

Stop No 2.6: Reine

Location

Viewpoint from the main road just south of the village of Reine (361197)

Introduction

The dominant rock type of the area is Palaeoproterozoic paragneisses with a variably developed and oriented metamorphic fabric. The village of Reine is famous for its spectacular high-alpine landscape and steep cliffs and a lot of geomorphological phenomena can be seen, notably, steep fractured cliffs, escarpments, rectilinear gorges, gently dipping planar slopes or surfaces, U- and V-shaped glacially eroded valleys, valley cirques, and various glacial sediment deposits (Fig. 17). This variability in glacial geomorphology seems to be controlled by both the pre-existing basement fabrics (i.e. foliation in the gneisses and weak magmatic layering in the mangerites) and the frequency and spatial orientation of the three dominant Mesozoic-Cenozoic fault/fracture sets (trending NNE-SSW, NE-SW and NW-SE). The U-shaped valleys and bounding escarpments and gorges are thought to have originated by Late-Cenozoic carving in domains between the dominant fault/fracture trends.

NW

SE



Fig. 25: Panorama view of the village Reine on Moskenesøya. Note the variable and steep fracture sets outlined by topographic escarpments, valleys and ridges.

Description

This stop offers a view of the village of Reine and its surrounding mountain ridges and cliffs and narrow sounds with variable trends (Fig. 25). Slopes defined by gently SE-dipping flat-top summit remnants (Figs. 15 and 26) may reflect Mesozoic-Cenozoic fault block tilting or Late-Cenozoic palaeosurfaces (the Paleic surface?). A significant system of shoreline fault escarpments is visible to the northeast. These are aligned parallel to the major East Lofoten Border Fault that bounds the entire Lofoten ridge islands against the Vestfjorden basin offshore (Fig. 9). The fabric of the basement paragneisses is not well defined, but when present it is steep to subvertical and strikes on average N-S with subvertical dip. Further south, this metamorphic fabric varies from gently SE-dipping to subhorizontal, and seems to have minor influence on landscape topography.



Fig. 26: NE view of the village of Reine showing SE-dipping palaeosurfaces (to the right).



Fig. 27: Landscape scenarios near Reine.

Stop No 2.7: Å in Moskenes

Location

Stop near the shore at the dead end of the main road west of the village of Å (304148). Map sheet Lofotodden.

Introduction

A shoreline transect in the Moskenes area of westernmost Lofoten (Fig. 21) displays spectacular outcrop fracture sets with varying geometries both at local and outcrop scales. The dominant fractures form part of a WNW-ESE to NNW-SSE striking lineament set (S3) distributed throughout western Lofoten, and thought to be Late-Cretaceous to Early Cenozoic in age (Bergh et al. 2007, Eig et al. 2008). On a regional scale, fault scarps and gorges in the Moskenes area's steep mountains, as well as trends of fjords, sounds and valleys, follow the same, roughly NW-SE orientations and are likely fault controlled. In addition, lineaments trending NE-SW (S2) are well displayed on aerial images (Fig. 28), and in outcrop view, they make up pronounced cliff escarpments dipping moderately to steeply to the SE, parallel to the East Lofoten Border Fault.

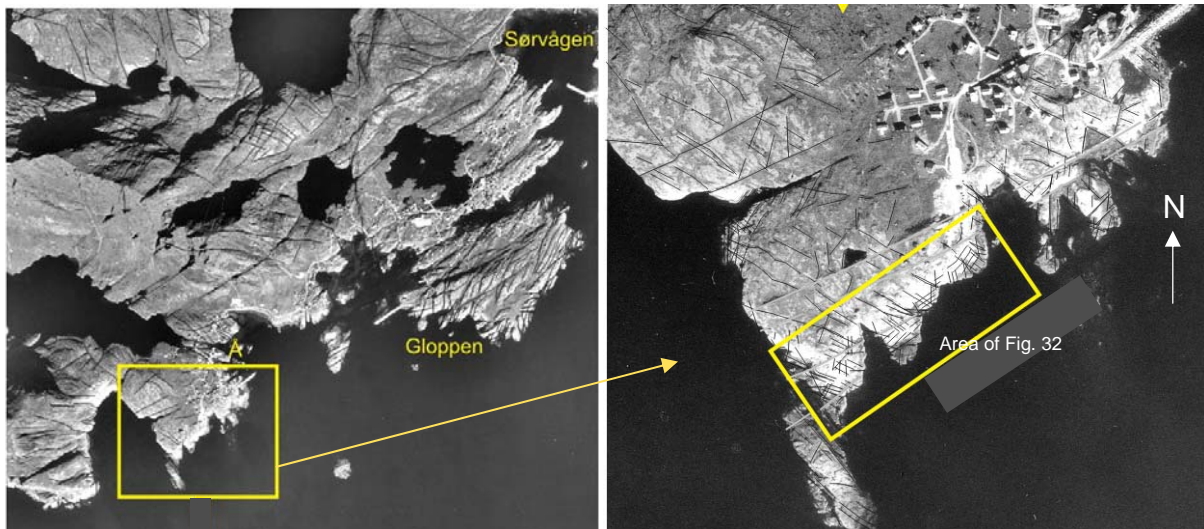


Fig. 28: Aerial images of the Moskenes area illustrating brittle fault/fracture patterns of the area. Note that NNE-SSW striking sets are confined and bent right-hand by NE-SW striking sets on the Gloppen peninsula, and the NW-SE striking sets. Also note the ENE-WSW striking pegmatite dykes (straight grey lines) in picture to the right.



Fig. 29: 3D terrain image of the Moskenes area. Arrow shows excursion locality 28.

Description

At this locality the dominant basement rock is Palaeoproterozoic paragneiss intruded by a number of granitoid pegmatite dikes. The weak foliation of the basement gneisses is subhorizontal. The pegmatite dykes trend consistently NE-SW and can be easily traced for several kilometres both on air photos and in outcrop (Figs. 28 and 30). A similar pegmatite, collected at Djupfjord further north in Moskenes yields a U-Pb zircon age of 410 ± 3 Ma (Corfu 2004b), showing that they are the product of late Caledonian extension and enhanced fluid activity.



Fig. 30: Granitic pegmatite dykes at Moskenes having a rectilinear trace.

The main NW-SE striking fractures (termed S3) in the shore transect exhibit a variety of geometries and orientations and seem to be both spatially and temporally distributed along the shore transect (Eig & Bergh 2008). They include: (i) distinctly conjugate fracture sets (Fig. 31) with bisecting axes striking mainly NW-SE, (ii) localized zones of undulating fractures that form duplex-like shear zones, from a few centimetres to tens of meters wide, and related relay and/or *en-echelon* stepped fractures, and (iii) narrowly spaced, subvertical, parallel fractures (Fig. 2.11) that form complex horizontal and vertical relayed patterns, often with breached transition zones. Some of the parallel fractures are observed to mutually intersect with the parallel fracture sets striking NE-SW, suggesting largely synchronous formation. The geometry and kinematics and relative timing of the various fracture sets will be studied and discussed more closely. One tentative conclusion is that the different patterns highlight fracture geometry examples along a spatially and temporally partitioned continuum from precursory tensile and conjugate shear fractures into more advanced stages of shear zone-related fracture sets.



Fig. 31: Conjugate and parallel fracture sets at Moskenes.

According to the regional model, the major NE-SW to ENE-WSW trending faults that bound the Lofoten Ridge are considered as transtensional normal faults with a significant dextral strike-slip component. In this context, the NW-SE faults-fracture set at Moskenes may have formed as a regional subsidiary set, or Riedel shears, in response to the dextral shearing and overall NW-SE transtensional plate setting (Bergh et al. 2007).

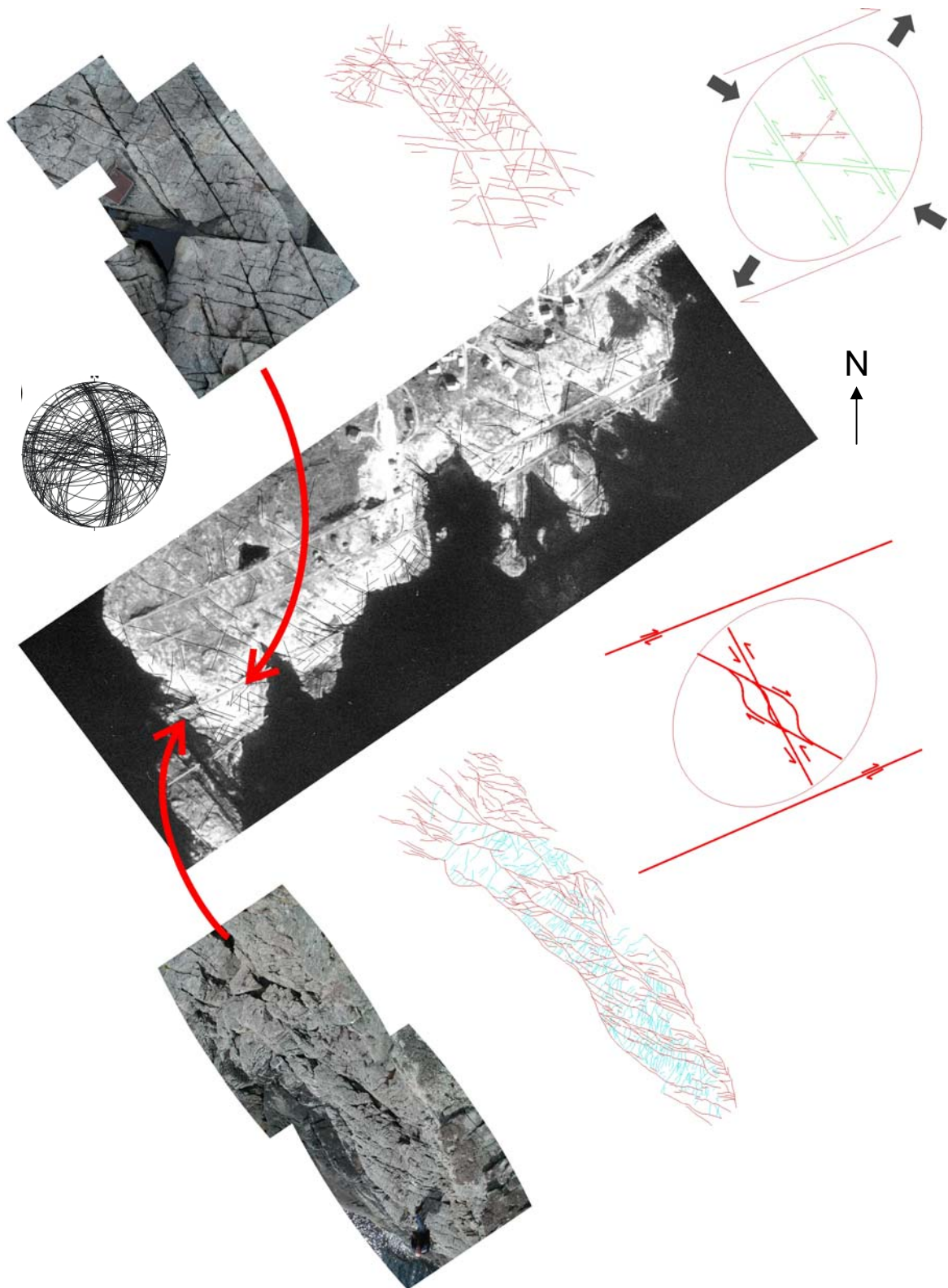


Fig. 32: Aerial image and details of the NW-SE fracture sets (S3) in outcrop at Moskenes: The upper part shows image and line drawing of a representative conjugate fracture set with a second-order conjugate set in between. The lower part shows an undulating fracture zone interpreted as a strike-slip duplex with ribs of minor Riedel shears. Strain ellipses indicate the local strain field and mechanism of fracture formation as Riedel shears between right-lateral ENE-WSW striking major faults (after Eig et al. 2008, Eig & Bergh 2008).

Day 3

Day 3 we leave Nusfjord heading for Nappstraumen and Vestvågøy and spend most of the day in this central island (Fig. 33). At the first stops we will explore basement rocks and rocks belonging to the Caledonian Leknes Group and discuss brittle faults/fractures and landscapes in this central part of Lofoten. A lot of nice scenery and historic places are located along today's route, e.g. the Viking Museum LOFOTR near the village of Borg, and the famous fishing village of Henningsvær. Lunch will be eaten at the LOFOTR museum, followed by a short guided tour. All localities are close to the road and along coastal/shoreline sections. Before departing, be certain that you have brought along all your personal belongings, including clothes, raingear, and good field boots. We will arrive in Henningsvær late in the afternoon, eat dinner and stay overnight there.

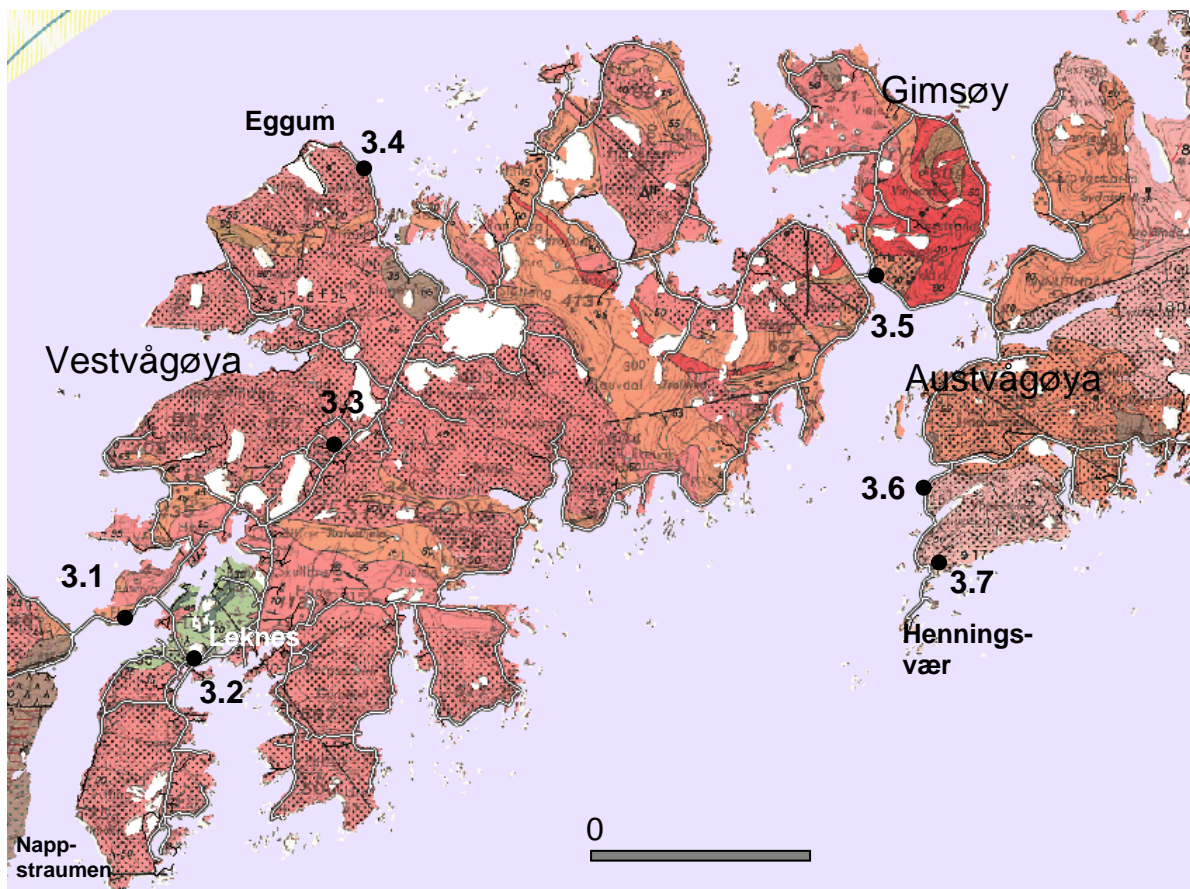


Fig. 33: Geological map (Tveten 1978) with localities for day 3.

Vestvågøy and western Austvågøy (Fig. 33) are dominated by 1.7-1.8 Ga plutonic rocks, i.e. mangeritic to quartz mangeritic and charnockitic intrusives and their hydrated equivalents (Tveten 1978; Corfu 2004a). The largest pluton is the South-West Lofoten Mangerite, which covers almost the entire Vestvågøy. The Hopen Mangerite Complex occupies the southwestern part of Austvågøy (Figs. 2, 33). In addition, there are up to km-wide NW-SE trending belts of Palaeoproterozoic paragneisses consisting of andesitic metavolcanics, amphibolites, leucogneisses, marbles, metapelitic rocks and banded iron formations (e.g. Krogh 1977). They underwent granulite- to upper amphibolite-facies metamorphism and multiple deformation events. We will examine the magmatic rocks and their fabrics and discuss their crystallization, metamorphic and reactivation history, relative to shear zone and metamorphic fabrics of the surrounding paragneisses.

The central islands of Lofoten display a complex network of brittle faults/fractures (Fig. 34) that form part of the three regional populations, S1-S3 (Bergh et al. 2007), trending NNE-SSW (S1), ENE-WSW to E-W (S2) and NW-SE (S3). In this part of the archipelago, the NW-SE-striking S3 lineaments appear to have affected the S1 and S2 lineaments causing large-scale curving and kinematic reactivation. An illustrative example is observed in the 3D simulator, where the interaction of two valley- and- ridge sets trending ENE-WSW parallel to the Olderfjorden lineament (S2) and NW-SE (S3), respectively, created a curved valley-ridge landscape pattern (Fig. 34). Conceivably, the S3 lineament trends may have been dextrally bent into a new and dominant NW-SE trend, which is otherwise marked by straight faults and fractures (Fig. 34).

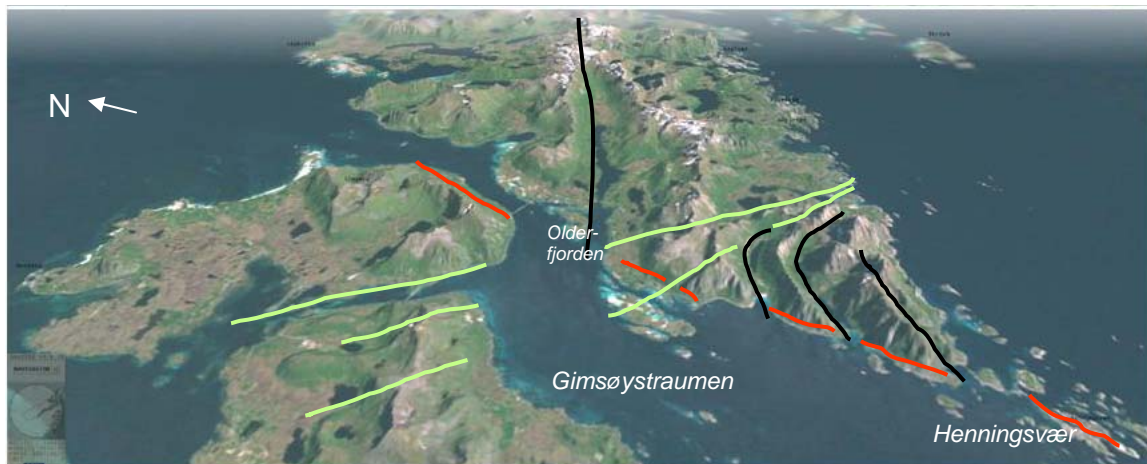


Fig. 34: 3D satellite and terrain images outlining S1-lineaments (in red) along Gimsøyfjorden, S2-lineaments (black) along Olderfjorden and S3-lineaments (light green) that obliquely truncate the former. Note prominent bends of S2 into S3 north of Henningsvær (locality 3.7).

Stop No 3.1: Offersøy-Karifloget

Location

This locality is an about 20 m high road-cut on Offersøy (602377) east of the subsea tunnel beneath the sound of Nappstraumen. Map sheet Leknes 1:50000.

Introduction

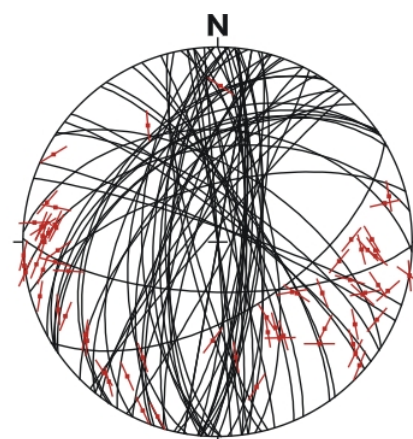
This small peninsula (island) exposes rocks of a WNW-ESE trending metasupracrustal gneiss belt surrounded by plutonic rocks of Vestvågøy. This locality is also at the junction of a major through-shaped NE-SW trending Caledonian basement depression in central Vestvågøy, and the NNE-SSW trending Nappstraumen sound.



Fig. 35: Overview of the island of Offersøy and locality 3.1 (arrow). Note the steep basement fabric foliation (visible in cliff to the left), gently SE-dipping palaeosurface and steep NW-dipping escarpment.

Description

Distinctly light-coloured and weakly foliated quartz-feldspathic paragneisses display high-frequency and notably curved fracture sets (Fig. 36). These sets are steep and NNE-SSW striking and parallel with the sound of Nappstraumen, inferred to be a major S1 fault zone (Fig. 11; Hendriks et al. 2005; Bergh et al. 2007). The main S1 fracture set is curved and made up of fan-shaped fractures that splay into different orientations and terminate in apparently younger, planar and NW-dipping fractures (S2). Associated minor faults emerge from the larger ones producing a complex distributional and linked fracture system. The various fault sets are distinguished by secondary mineral growth (hematite, chlorite) and/or they are open-spaced, with numerous striations, while some larger sets develop cataclastic fault rocks. An evolution model suggests an origin of S1 fractures by extensional (tensile) modes and that these were subsequently reactivated as shear-induced strike-slip fracture sets (Bergh et al. 2007; Eig et al. 2008).



Fractures with slip striae, N=67

Fig. 36: Road cut approximately 20 m high showing curved S1 fracture (centre left of picture) that merge into steep planar fracture sets (S2). Orientation data are shown in stereo net to the right (Eig et al. 2008).

Stop No 3.2: Leknes

Location

Small quarry ca. 1 km southwest of the city of Leknes (578408). Map sheet Leknes 1:50000.

Introduction

The metasedimentary rocks of the Leknes Group (Fig. 33, green colour) occur within a trough-shaped basement depression, the latter trending NE-SW along the entire length of Vestvågøy. Zircon work on metasedimentary rocks of the Leknes Group indicates the presence of a detrital component with ages in the 1600-1000 Ma range, which elsewhere is also found in the Seve-Kalak Nappes of the Middle and Upper Caledonian Allochthons. It is suspected here that the previously obtained Sveconorwegian Rb/Sr whole rock ages (Taylor 1974) may reflect an inherited signature, or mixing, as they are too old with respect to the actual age of deformation and metamorphism. In fact, the main fabric forming event in the Leknes Group is now constrained by U-Pb zircon and titanite data to a Middle Ordovician age (Corfu 2004b). Based on the structural interpretation given by Klein & Steltenpohl (1999) and Klein et al. (1999), this age dates the eastward translation of the Group onto the Lofoten basement. A younger, Silurian event that caused some partial resetting and renewed growth of zircon, titanite and rutile probably reflects the west-vergent extensional phase already recorded by Ar-Ar data (Hames & Andresen 1996) and also corresponding to the formation of the 410 ± 3 Ma pegmatites in Moskenesøy (Fig. 30).

Description

The Leknes group consists mainly of amphibolites and quartz-rich schists, with some quartzite, calc-silicate gneiss and local marble, metamorphosed at amphibolite facies and affected by multiple (Caledonian) deformation events (Tull 1977). These rocks are inferred to be part of several internal imbricated fold-thrust nappes (Klein 1997) bounded by slivers of mylonitic augen-gneisses along the traces of thrust faults. The contact between the Leknes Group and the basement is vaguely defined by tectonized zones of mylonitic gneisses and schists.

Stop No 3.3: Rise

Location

Near cross-road, east of the little village of Rise (666456). Map sheet Leknes 1:50000.

Description

This is a short stop to demonstrate, in panorama view, a variety of landscape phenomena in the central portion of the Lofoten islands. To the southwest there is a characteristic low-relief depression (underlain by the Leknes Group Caledonian thrust sheet) which appears to be bounded by NW- and SE-dipping Mesozoic normal fault escarpments and gently tilted palaeosurfaces (Figs. 35 and 37). These surfaces, in combination with the adjacent normal faults, resemble rotated fault blocks related to the main S2 lineament trend of central Lofoten (Figs. 13 and 15). The interaction between the basement-seated Leknes Group thrust sheet and the Mesozoic fault systems and subsequent, Late-Cenozoic uplift and erosion created this pronounced U-shaped valley-ridge landscape and linear escarpments and cliff faces, much smoother than, and contrary to the high-alpine geomorphology further west.



Fig. 37: SE-dipping low-relief paleosurfaces bounded by presumed steep fault escarpments resembling tilted and rotated fault blocks in the central Lofoten area, north of Leknes.

Stop No 3.4: Eggum

Location

Panorama view from a small road just south of Eggum and outcrop in the cliff, c. 150 m above sea level (767468). Map sheet Eggum 1:50000.

Introduction

The peninsula near the village of Eggum (Fig. 33) marks the outermost onshore exposure relative to the Cretaceous West Lofoten Border Fault, a regionally important offshore bounding normal fault system of the Lofoten ridge (Fig. 9). The steep shore cliffs define a regional onshore fracture array (S2) that coincides with the main topographic depressions and scarps along the dominant NE- to ENE-WSW trend of the Lofoten archipelago (Fig. 10). A well-exposed S2 fault system crops out in coastal cliffs south and west of Eggum and may be directly traced up along strike with the offshore West Lofoten Border Fault.



Fig. 38: 3D satellite and terrain image of the peninsula of Eggum, showing the trace of faults parallel to the West Lofoten Border Fault (lines). A zone of paragneiss is marked as foliation.

Description

When driving towards Eggum, there is a nice view of the mountains between Eggum and Unstad. These are composed of dominantly mangeritic plutonic rocks and a narrow metasupracrustal zone with rusty weathered, foliated banded iron formations and quartzites,

traceable all across the peninsula (Fig. 33). A weak foliation in the mangerites dips gently to the N and is itself cut by a network of brittle fault/fractures dipping on average c. 60° to the NNW. In the cliff exposures just south of Eggum, a semi-brittle fault zone (c. 10 m wide) is composed of sinusoidal lenses of the host rock gneisses surrounded by undulating listric, normal faults that locally consist of cataclastic fault rocks (Fig. 39). Kinematic indicators of down-to-the NNW normal motion are evidenced by local bending of the adjacent, gently dipping foliation toward the brittle S2 faults that characterise the outcrop. Also very clearly seen is merging of the steeper brittle faults into the gently dipping foliation, thus indicating the local effect of favourable foliation attitudes (Fig. 39).

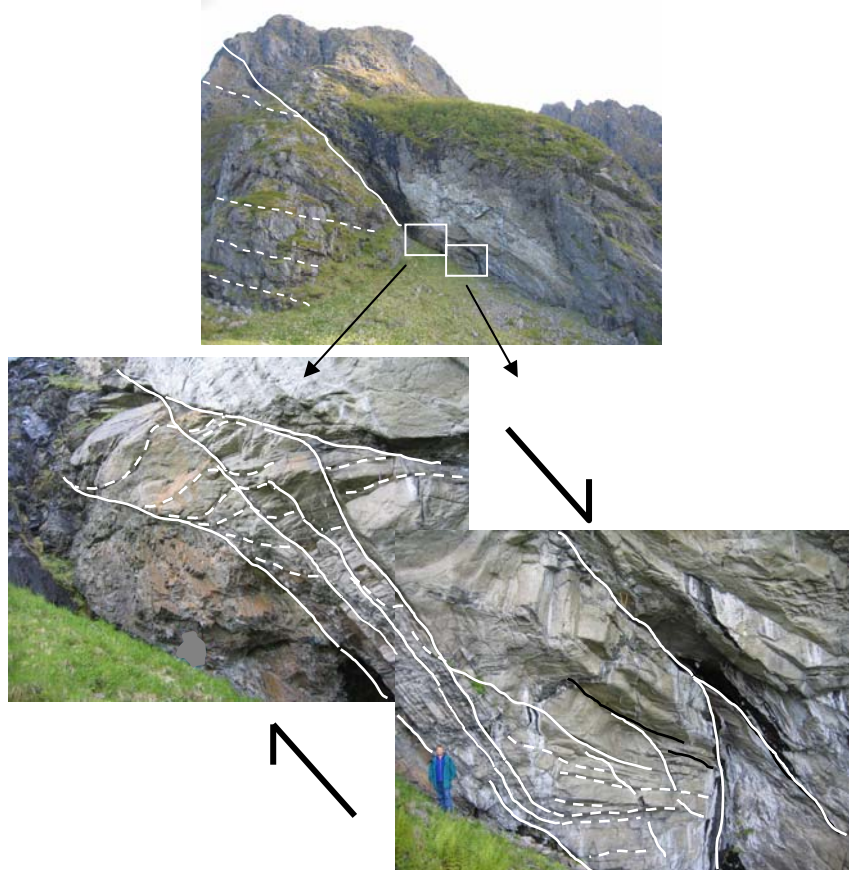


Fig. 39: S2 normal fault systems exposed in a cliff section near Eggum. The S2 faults have similar strike but a steeper dip angle than the main gneissic foliation. Note also local curving and internal reorientation of the brittle faults adjacent to the foliation.

Stop No 3.5: West side of Gimsøy

Location

Shoreline outcrop on Gimsøy, immediately east of the bridge to Vestvågøy (730655). Map sheet Gimsøy 1:50000.

Introduction

The host rock of the island of Gimsøy comprises various mangeritic and monzonitic gneisses with coarse-grained augen textures. Lenses of marbles and calc-silicate schists occur as dismembered fragments within the gneisses. Glassley (1975) studied the metamorphic petrology of zoned carbonate lenses across the transition from the amphibolite to the granulite facies zone. These carbonate bodies are meters to tens of meters in size and typically zoned,

with a carbonate core separated by a pyroxenite mantle rocks from the surrounding felsic gneisses. The zoning has been interpreted to reflect metasomatic exchange between the carbonate and the surrounding silicate gneisses. Glassley indicated that the internal mineralogical variation of the bodies was strongly dependent on the composition of the fluids. He used the dominant mineral assemblages in the core of each carbonate body to outline a regional transition from an Eastern zone with hornblende + calcite + dolomite, over a Central zone with diopside + spinel + dolomite, to a Western zone with forsterite + calcite + spinel.

Description

One of the calc-silicate lenses investigated by Glassley (1975) is from the locality on western Gimsøy. At this location the carbonate bodies occur as small boudins, up to 1-2 m in size, stretched out along one horizon within a heterogeneous assemblage of amphibolites, melanocratic biotite schists, fine-grained gneisses and augengneisses, the latter probably sheared megacrystic mangerites. Pegmatitic dykelets are common. Glassley (1975) describes the mineral assemblage in the core of the pod as consisting of Fo + Sp + Cc + Do with a rim of Fo + Phl + Cc + Do. The assemblage is characteristic for the highest grade Western metamorphic zone in Lofoten (Fig. 2).

Stop No 3.6: Rørvika north of Henningsvær

Location

Coastal exposures c. 4 km north of Henningsvær (652676). Map sheet Stamsund 1:50000.



Fig. 40: 3D terrain image viewed toward north (left) and panorama of the mountain Presten, viewed toward south (right) near locality 3.6.

Introduction

The coastal shoreline between Henningsvær and Rørvika (see Fig. 34) consists of magmatic rocks belonging to the Hopen Mangerite Complex (Ormaasen 1977). At Rørvika, the rock is weakly foliated with a general E-W strike and steep dip, and cut by minor mafic dykes with approximately the same trend. The boundary to Archaean migmatites is present c. 1 km further north and in the south near Geitvika (next stop). A great variety of brittle, Mesozoic-Cenozoic fractures and faults (Bergh et al. 2007; Eig et al. 2008) can be studied in the shore section and adjacent cliffs. Notably, this locality is close to the junction between a regional, curved U-shaped valley-fill landscape (Fig. 34) which is thought to be controlled by the interaction of two lineament sets, trending NNE-SSW (S1) and ENE-WSW-trending (S2). In particular, S1-related features (geometries and kinematics) can be studied closely. Hill-side

fault escarpments can be seen in the west sides of the mountain Presten (Fig. 40), which also happens to be an excellent site for rock climbing.

Description

Spectacular fault-fracture sets (S1) crop out along the shore west and south of the mountain ridge near Rørvika, in the form of scarps and gorges (Fig. 41). The dominant fault-fractures strike c. NNE-SSW and dips steeply to the east (Fig. 41). They are heterogeneously distributed both in map and outcrop view, e.g. as zones of intense parallel fracturing alternating with zones of more moderate fracturing and non-fractured rocks. They developed in opposite dips as a conjugate pattern in vertical view and dip angles are approximately 60° and steeper (Fig. 42a). These isolated conjugate fractures (termed S1a) form, in combination, an undulating pattern, where individual fractures replace each other and/or terminate in a splayed relay or en echelon pattern. Many of the fractures define duplexes (Fig. 42b) with undulating splays that truncate or are truncated mutually (termed S1b sets). Intermediate, NE-SW striking splay faults may split or terminate into en echelon- or horsetail patterns (Fig. 42b). Another steep, rectilinear fracture set (S2) strikes NE-SW and is usually expressed as zones that truncate the complex S1 sets (Fig. 42d, e) and develop minor scarps in the terrain.



Fig. 41: S1 fracture sets in Hopen mangerite along the shore of Rørvika. View is due north.

Kinematic information can be obtained from a number of geometric relationships (Eig et al. 2008). First, the overall and consistent dips (c. 60°) of the NNE-SSW sets (S1a), and widespread conjugate patterns are an indication of conjugate normal faulting due to WNW-ESE extension. Second, the en echelon faults that branch from S1 faults, including horse-tail fan termination relay zones (S1b), suggest a superimposed, dextral strike-slip component or a strike-slip reactivation. These superimposed strike-slip elements are all consistent with formation in a dextral strain field relative to the NNE-SSW master faults (Fig. 42). The youngest S2-fractures are thought to reflect a further rotation of the strain field to a local NW-SE long-axis orientation (Fig. 42, strain ellipses).

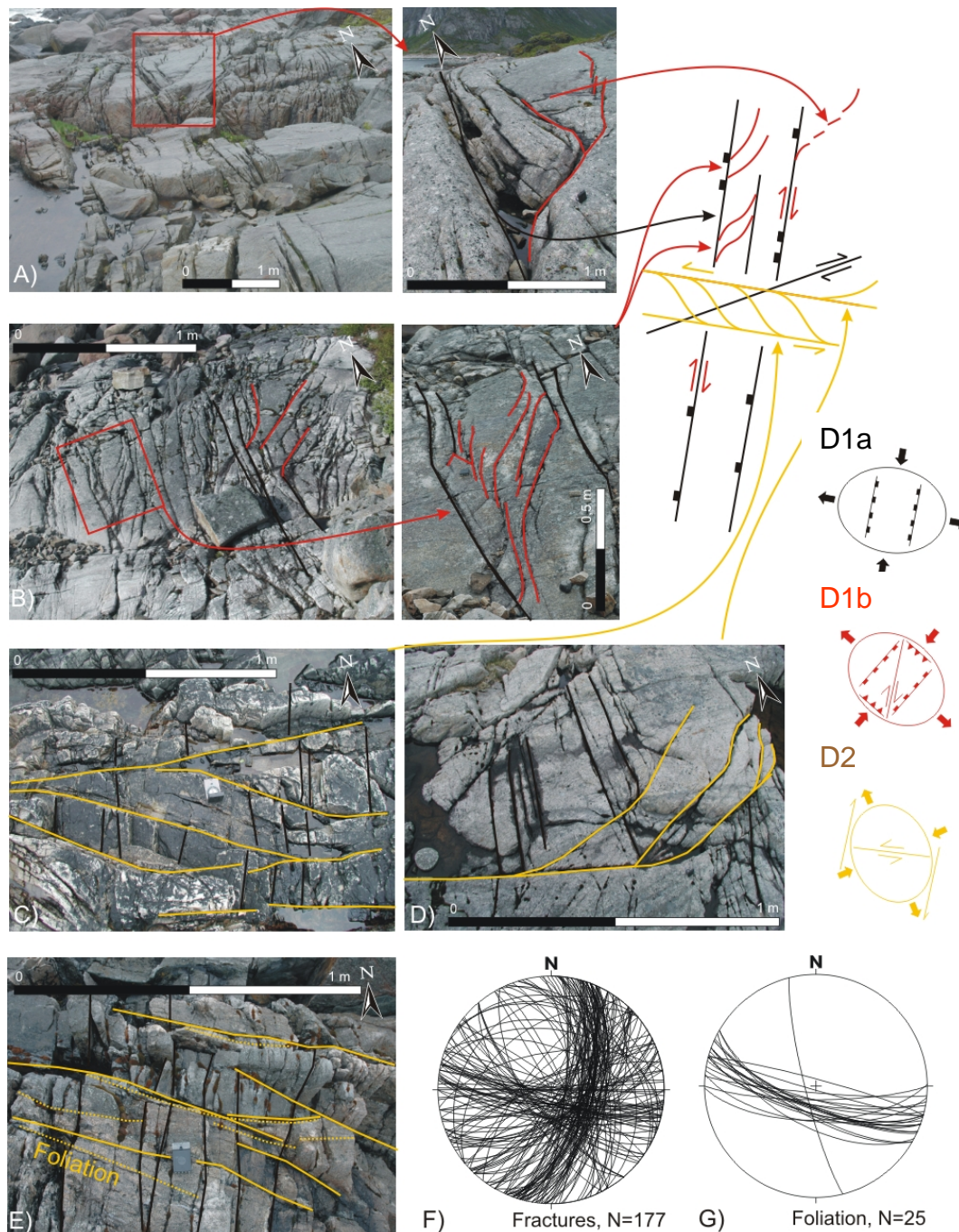


Fig. 42: Images illustrating fracture geometries at Rørvika. (a-b) Examples of NNE-SSW striking fractures (S1a, black) dipping 50° - 80° E and indicating normal slip, and splay fractures (S1b, red) indicating lateral reactivation. (c-e) Examples of E-W striking S2 fractures (f) and local foliation (g) measured at the locality. Data are from Eig et al. (2008).

Stop No 3.7: Geitvika north of Henningsvær

Location

Geitvika bay is situated just north of the bridge to Henningsvær (620679). Map sheet Stamsund 1:50000

Introduction

At this locality we will: (i) study in detail the Hopen Mangerite Complex (HMI), and (ii) view and discuss various interactions of S1 and S2 brittle fault sets and landscape features. The Hopen mangerite is unique, because it is a completely exposed mangerite body, from its floor against Archean migmatites (Fig. 43) to the roof where it forms apophyses in Proterozoic supracrustal gneisses. It exhibits a continuous fractionation sequence ranging in composition from mangerite to quartz mangerite and finally to charnockite (Ormaasen, 1977). The true total thickness of the intrusion is about 3.5 km. In vertical cross-section, the pluton is zoned, with the most silica-poor rocks in the southwest, at the floor of the intrusion, evolving to charnockites in the north and northeast, near the roof. In the northeastern part of the intrusion, charnockitic pegmatites with coarse-grained (up to 10 cm) quartz and nearly pure hedenbergite occur. In the lower part of the HMI there are structures suggesting that Fe-rich gabbroic magma intruded into the magma chamber when the charnockitic magmas were still liquid and mingled with the host magma, producing features similar to those described by Wiebe (1988). The Hopen mangerites have been investigated using Rb-Sr whole-rock systematics by Griffin et al. (1978) and subsequently by Wade (1985). They reported ages of 1790 ± 50 Ma and 1811 ± 33 Ma, respectively. More recent U-Pb zircon dating of a charnockite yields an age of 1860 ± 5 Ma and a mangerite 1864 ± 5 Ma (Corfu 2004a), indicating that this pluton is some 60-70 m.y. older than the rest of the mangeritic suite.

E



Fig. 43: Panorama view of the cliffs north of Henningsvær (bridge in foreground). Note gently W-dipping magmatic layering in the mangeritic rocks.



Fig. 44: Boundary between layered mangeritic rocks of the Hopen Pluton and migmatitic gneisses west of Geitvika.

Description

In the section from Geitvika and eastward, the layered series forming the lowermost 50-150 m of the HMI can be traced for about 800 m. This series resides on migmatitic basement gneisses to the south and seems to be continuous with massive mangerite to the north. Strike and dip of the layering contour the shape of the overall complex. The best outcrops are in the bay of Geitvika itself. Gabbros and fine-grained pillows and pillow-like lenses of about 0.2-2 m size occur within the layered bottom series at Geitvika. The layering itself shows the typical, but here very spectacular features of rhythmic layering with normal and inverse gradation, of troughs and of pod holes. The layers are between 5 and 50 cm thick. The gabbroic pillows occur in both mafic and leucocratic layers and seem to be xenoliths fallen from above into the still mushy cumulate pile. They have the typical rounded shapes with a small edge at the bottom. By falling into the mush they seem to have squeezed out some leucocratic liquid from the cumulate and they clearly disturbed the layering. They are interpreted as resulting from a later injection into already cooler mangeritic magma above, where they were chilled and from where they fell down into the cumulates.

The migmatites to the west of Geitvika (Figs. 43 and 44) have been interpreted to have undergone migmatization during the Archean (Griffin et al., 1978; Wade, 1985). They contain many basic and acid dikes. The acid dikes are coarse grained to pegmatitic and contain two feldspars in addition to two pyroxenes, indicating a relation to the mangerites. Similar mangeritic pegmatites are also found in the layered series. Here, they occur in the center of ductile shear zones, which deform the magmatic layering. It is evident that this deformation had nothing to do with later metamorphic overprints, but that it occurred at very high temperatures, when the cumulates were still ductile. In fact, the mangeritic veins are thought to be interstitial residual liquid that was pressed out during compaction of the cumulate and escaped. It thereby acted as a lubricant and caused deformation of the still hot and not yet completely solidified cumulates (Markl & Corfu 2004).

The mountains north of Geitvika show well the interaction of the two main fracture sets of the region, NNE-SSW striking S1 fracture sets can be seen as distributed, high-frequency sets in E-W sections, while prominent, SE-dipping shoreline cliffs and escarpments (S2 faults) defined by steep mountain slopes exist in the south and east (Fig. 43). A weak magmatic layering is also visible in the rocks, dipping gently, c. 30 °, to the WNW.



Fig. 45: Steeply east-dipping S1 fracture sets viewed from Henningsvær harbor.

Day 4

On day 4 we leave Henningsvær and drive eastward along the main road to Svolvær, the capital of Lofoten (population c. 7000) and the famous narrow sound, Raftsundet (Fig. 46). Lunch will be eaten outside, today. All localities are close to the road, mostly road cuts and distance viewed sceneries. Before departing, be certain that you have brought along all you personal belongings, including clothes, raingear, and good field boots.

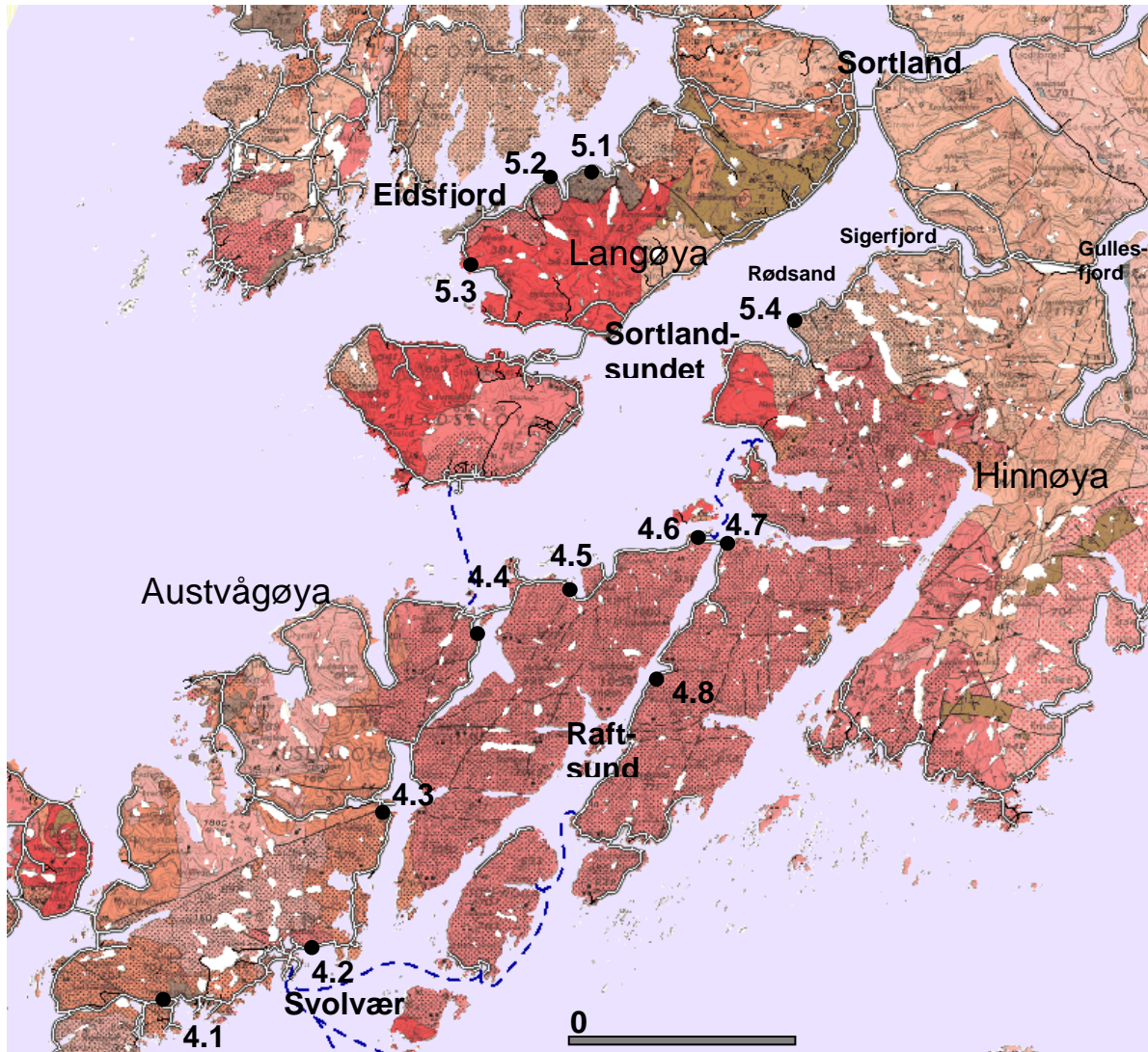


Fig. 46: Geological map (Tveten 1978) with localities for days 4 and 5.

Austvågøya, the eastern portion of the Lofoten islands, is dominated by the Raftsundet Mangerite Complex, which covers more than 1000 km² (Fig. 2), and thus is the largest mangeritic body on the Lofoten Islands (Griffin et al. 1974). It extends from the island of Austvågøya to Hinnøya in the east and Hamarøy in the southeast. Today's plan is to examine host rock fabrics and discuss the petrology of the Raftsundet Mangerite Complex and to, specifically, study internal ductile shear zones of the mangerites. In addition, widespread brittle faults/fracture sets, their geometry and kinematics, relative age constraints, and notable brittle faults with pseudotachylites will be addressed. Finally, the changing landscape styles compared to the central islands of Lofoten will be commented. On the way to Sortland, we will drive along the new LOFAST road connection (opened Dec. 2007), that links the Lofoten islands with the main road network in Northern Norway. A lot of new road cuts have been exposed, and if time permits, we may do some quick stops, especially when crossing the

boundary between the Raftsundet mangerite and its adjacent Archaean gneisses. The city of Sortland (population c. 5000) will be the location for the last overnight stay.

Stop No 4.1 Ørsvåg

Location

Stop on the main road near Ørsvåg (668750). Map sheet Svolvær 1:50000

Introduction

This stop is a supplement to understanding gabbroic components of the Hopen Mangerite Complex (cf. yesterday). Generally, there are four types of gabbro occurrences in and beneath the Hopen Mangerite Complex. First, medium-grained gabbro forms an about 50 m thick crosscutting dike in the charnockitic upper unit. Then there are very fine-grained pillows and pillow-like lenses of about 0.2-2 m size within the layered bottom series at Geitvika (cf. stop 3.7 yesterday). Similar, but even finer grained are typical pillows in a charnockitic apophyse of the HMI that is exposed near Ørsvåg. Finally, a medium grain-sized gabbro body crops out in a small quarry on the island immediately south of the HMI, about 200 m from the contact.

Description

A small road-cut near Ørsvåg shows the nature of gabbroic and pillow-lava textures within the upper portion of the layered Hopen Mangerite Complex. Very fine-grained pillows and pillow-like textures occur in a charnockitic apophyse of the mangerite. The pillows have typical rounded shapes and are partly cracked with the cracks filled by acid liquid.

To the south, there is a panorama view of the famous mountain of Vågakallen (Fig. 47), showing a characteristic, valley-ridge topography likely formed by interaction of the two main, brittle fracture sets trending at high angle to each other (NNE-SSW and ENE-WSW).



Fig. 47: View toward west of the mountain Vågakallen, showing scarps and ridges that reflect the S1 and S2 fracture populations.

Stop No 4.2 Svolvær

Location

Coastal cliffs of the mountain Fløya, northeast of Svolvær (700830). Map sheet Svolvær 1:50000.

Description

Isolated mangeritic rocks outcrop in Svolvær. Eastward toward the airport, the contact to surrounding and well foliated metasedimentary gneisses can be seen in road cuttings. The well foliated gneisses dip gently (25°) SW and can be seen in the mountains all along the western side of Austfjorden.

The cliffs north of the city of Svolvær are outlined by a planar, several hundred metres high escarpment (Fig. 48) that may correspond with the East Lofoten Border Fault trending ENE-WSW and dipping $c. 60^\circ$ to the south (Fig. 9). The master fault is located a few kilometres further south offshore. In the hill slope, the erosion remnant of two spires, named the Svolvær Goat, is famous because fearless climbers use to jump from one spire to the other.



Fig. 48: Cliffs north of the city of Svolvær. Note fault escarpment dipping steeply to the SE. View is towards NE.

Stop No 4.3 Sildpollneset

Location

Stop at tourist view point south of Sildpollneset (877 790). Map sheet Austvågøy 1:50000.

Introduction

In the central part of the island of Austvågøy, a spectacular landscape is apparent from the road, with a straight attitude of sounds, ridges, glacially eroded valleys and lakes, and steep coastal cliffs and escarpments are aligned in a zigzag pattern that mimics the NNE-SSW (S1) and NE-SW to ENE-WSW striking (S2) brittle fault trends (Fig. 16). Notably, the NNE-SSW trending S1 lineaments define narrow valleys and ridges with consistent planar and gently eastward dipping palaeo (?) surfaces bounded by steep, $c. 60-70^\circ$ west-dipping fault scarps, resembling a series of domino-style fault blocks bounded by normal faults. This geometry is clearly visible in satellite and digital terrain images (Fig. 49a). Another common feature of this region is highly curved traces of the S1 lineaments (Fig. 49b), especially when they approach major ENE-WSW striking lineaments, the latter of which are mostly rectilinear in shape.

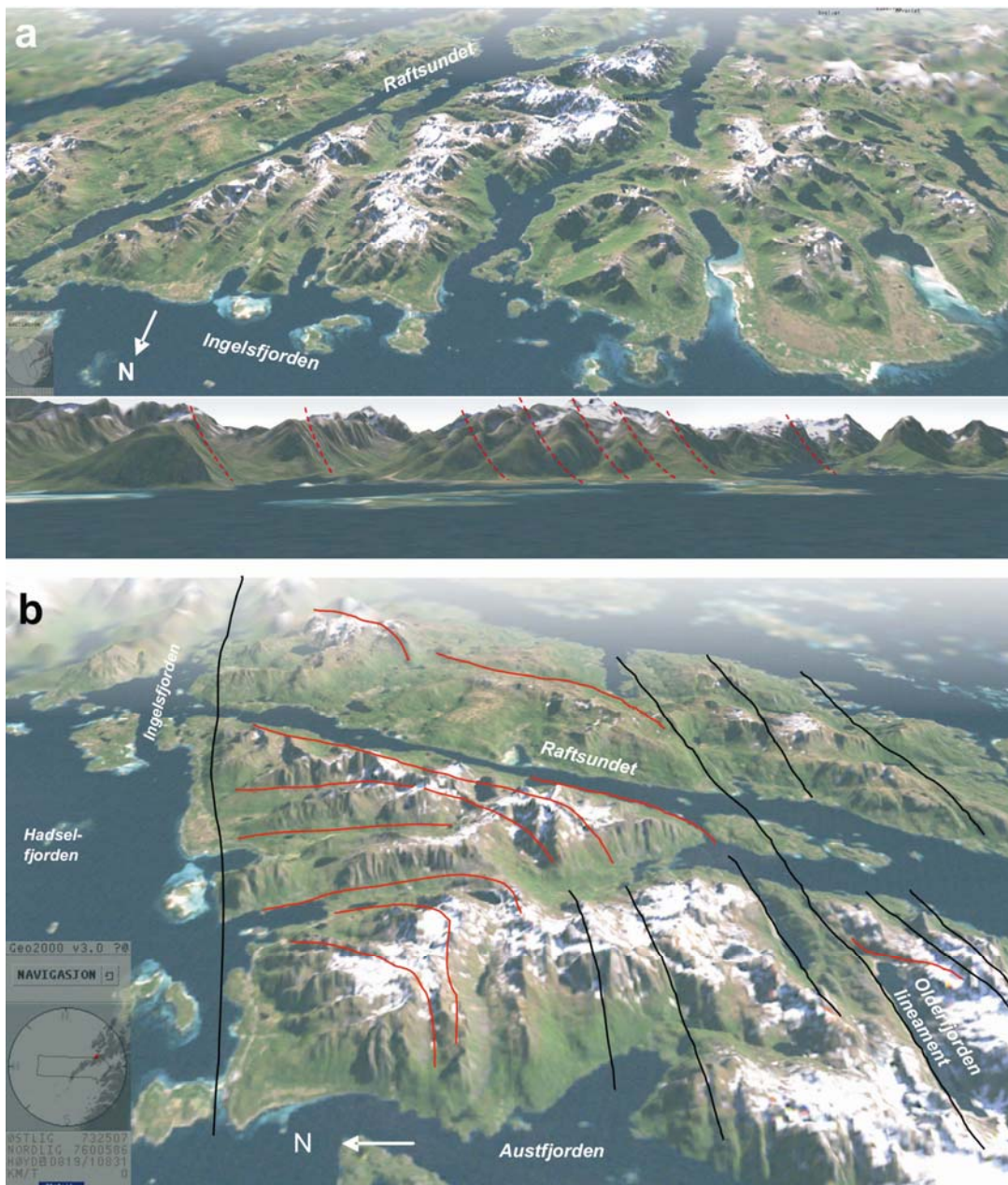


Fig. 49: 3D satellite and terrain images of the eastern islands of Lofoten: (a) Southward view from Hadsel fjorden showing narrow valleys and ridges with gently ESE-dipping and steeply WNW-dipping surfaces (S1), resembling domino-style fault blocks bounded by normal faults. (b) Eastward view of main topographic lineaments near Raftsundet, Austfjorden and Hadsel fjorden. Note the prominent curved traces of the S1 lineaments (red) and more straight attitudes of S2 lineaments (black). Data are from Bergh et al. (2007).

Description

From this tourist viewpoint, we can see a panorama of Trolltinden to the east, the highest and probably most rugged peaks of the Lofoten islands (Fig. 50). To the north, Higravtinden consists of a number of steep NNE-SSW trending brittle fractures/faults that are curved adjacent to more rectilinear, ENE-WSW regional fractures. The latter are parallel to the most impressive narrow fjord system in Lofoten, named Trollfjorden (see lower-left image on cover sheet), of which is developed along the major S2 lineament sets (Figs. 8 and 9).

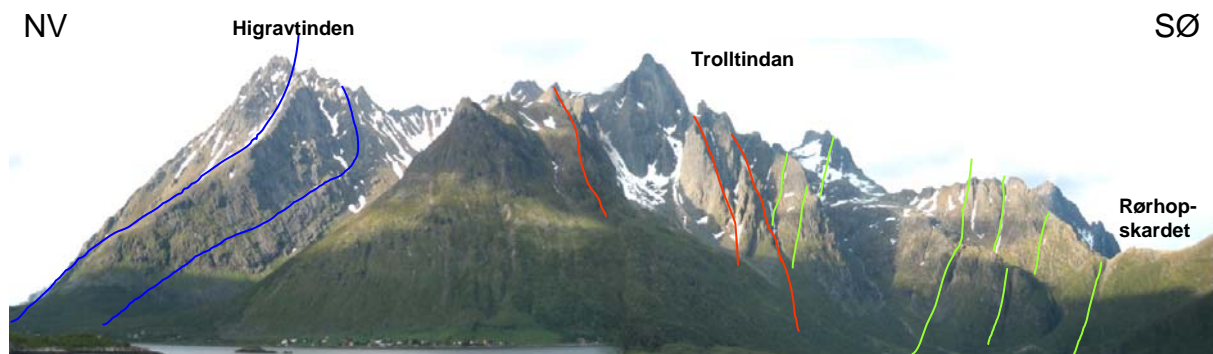


Fig. 50: Panorama view of Trolltindan with the three main fracture sets outlined by S1 (red) S2 (blue) and S3 lineaments (green).

Stop No 4.4 Hattneset, Sløverfjorden

Location

Hattneset near the mouth of Sløverfjorden (893936). Map sheet Austvågøya 1:50000.

Introduction

Along the road between the inner part of Austfjorden and Raftsundet, there are many fresh roadcuts with nice outcrops of the Raftsund Mangerite Complex, in parts with gneissic xenoliths. Griffin et al. (1974) mapped three petrographically different zones in the mangerite based on the mafic minerals: an ol+cpx zone, an ol+cpx+opx zone and an opx+cpx zone. They also described well-developed igneous layering from several localities. The layers are nearly horizontal and the intrusion appears to be a laterally extensive yet relatively thin sheet. Griffin et al. (1974) estimated the thickness to about 3 km. Contacts with adjacent basement rocks are not well exposed. The intrusive age of the Raftsundet mangerite is now well constrained to 1796 ± 2 Ma by recent U-Pb geochronology using the abundant zircon present in a charnockitic sample. This age shows that the intrusion is essentially coeval with most of the suite on these islands (Corfu 2004a), and in contrast to previous Rb-Sr isochron ages of 1700 ± 20 Ma (Griffin et al., 1974) and 1705 ± 30 Ma in Griffin et al. (1978). Interestingly, coexisting zircon and titanite in a sample of the Lødingen granite farther east (Fig. 2), yield a significantly older age of 1869 ± 4 Ma (Corfu 2004a), contrary to previous datings revealing 1400-1600 Ma. It is evident, therefore, that the Rb-Sr systems in both intrusions were variously reset, presumably during the Caledonian events. The Caledonian events also led to the partial recrystallization of titanite in the Lødingen granite, but they left no major mineralogical expression in the dated sample of the Raftsund mangerite.

Description

The host rock in this road cut is mostly homogenous, coarse-grained mangerite. It is cut by a pronounced subvertical, NNE-SSW striking brittle fault system (S1), which shows undulating attitudes in cross section and a number of upward fanning and relayed splay faults that merge into a master fault, generating a flower-structure-like geometry. Along the trace of the master fault, local cataclasites and pseudotachylites are developed.

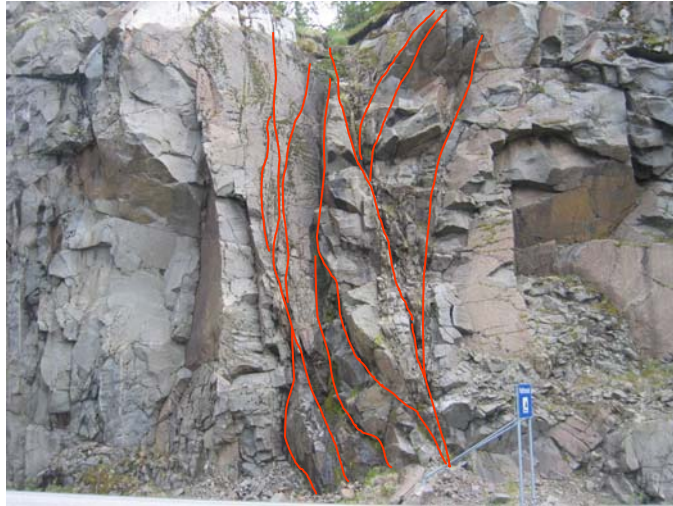


Fig. 51: Road cutting at Hattneset showing the Raftsundet mangerite with a localized brittle fracture zone (S1).

Stop No 4.5 Falkfjorden

Location

Large road cut on the main LOFAST road at the inner part of Falkfjorden (996 913). Map sheet Austvågøya 1:50000.

Introduction

This location shows magmatic and metamorphic fabrics in the inner parts of the Raftsundet Mangerite Complex. The locality also shows the outcrop-scale correspondence of NNE-SSW striking brittle fractures and the narrow V-shaped valley south of Falkfjorden, which is likely a regional fault (S1) adjacent to westward tilted fault blocks of the region (see Fig. 49a).

Description

The host rock is homogenous mangerite, locally with a weak, nearly horizontal magmatic layering. A dm-wide ductile shear zone dips moderately to the SW and truncates the magmatic layering. This shear zone shows progressively higher strain, from homogenous magmatic textures at the margin, to ultramylonitic texture in the centre of the shear zone. In addition, a nearly vertical and c. E-W trending mafic dyke cross-cuts the mangerite (Fig. 52). The age of this dyke is unknown.



Fig. 52: Raftsundet mangerite with a vertical mafic dyke and planar fractures (S2). View is to the east.

NNE-SSW striking fractures are most abundant; they contain hematite precipitates and display normal, down-to-the west sinistral sense-of shear. E-W-striking fractures truncate the former and show down-to-the-north motion, and comprise local pseudotachylites.

Stop No 4.6 Hanøyvika west of Raftsundet

Location

An almost 200 m long road cut near Hanøyvika (950 075). Map sheet Raftsundet 1:50000.

Introduction

Raftsundet is a spectacular narrow sound along the coastal route of Northern Norway. The bridge across this sound was built in 1998 during the first stage of the LOFAST road construction. In December 2007, the construction ended and now, Lofoten is connected to the main road network.

Description

The host rock of this wide road cut is variously homogenous and weakly layered mangerite. A number of brittle faults and fracture systems can be seen, and they display a variety of geometries, attitudes and interacting connections (cf. Wilson et al. 2006). Zones of localized, high-frequent fractured rocks comprise cataclastic fault rocks and gouges, including pseudotachylite on specific surfaces. The nature and relative ages of the fracture sets can be evaluated by careful examinations, but we will leave this for the next stop.

Stop No 4.7 East of Raftsundet

Location

Two localities just south of the Raftsundet bridge along the road to Digermulen (942 085 and 938 084). Map sheet Raftsundet 1:50000.

Introduction

The localities at the northern termination of Raftsundet mark a domain where the two dominant fault-fracture groups (S1 and S2) in Lofoten interact to produce the characteristic zigzag or rhombic shaped pattern (Figs. 8 and 9). This pattern is outlined by the NNE-SSW trend of Raftsundet and the ENE-WSW trend of Ingelsfjord (Fig. 49), the latter of which is likely connected regionally, with the West Lofoten Border Fault offshore to the west. The LOFAST road follows this narrow fault-controlled lineament trace eastward.

Description

These two localities in homogenous mangerite spectacularly expose all the main S1-S3 brittle fault/fracture sets present in Lofoten (Bergh et al. 2007; Eig et al. 2008). In addition, the fractures show uniform and consistent cross-cutting relations and often slip striations, fault gouges and pseudotachylites on specific fault surfaces. The dominant fracture sets include: (i) NNE-SSW striking, steep fractures (S1; Fig. 53) that contain slip striations varying in plunge from subvertical to subhorizontal (Fig. 54). The strike-slip and oblique-slip striations are superimposed on the dip-slip striations, suggesting that normal movement was followed by strike-slip shearing. (ii) The second fracture set (S2), which strikes ENE-WSW and dips steeply to the north, consistently truncates the S1 sets (Fig. 53). Characteristically, the S1 fractures are bent parallel to the S2 set confirming a younger, relative age. Slip striations on the S2 fractures are horizontal to gently plunging and indicate a mainly strike-slip movement (Fig. 54). A right-hand shear sense is indicated from the bending of the preceding sets. (iii) The third, S3 fracture set (Fig. 53) is less well developed but composed of NW-SE and N-S striking surfaces, which vary in dip from steep to locally gentle and comprising subhorizontal to gently plunging slip striations (Fig. 54). Many of the steep varieties dip 45° to 60° , which indicate that they experienced a component of normal \sim NE-SW oriented slip. The low angle members of the latest, N-S striking set suggests that they are reverse faults, with up-to-the ESE-movement, and may have formed due to incremental transpression (Eig et al. 2008).

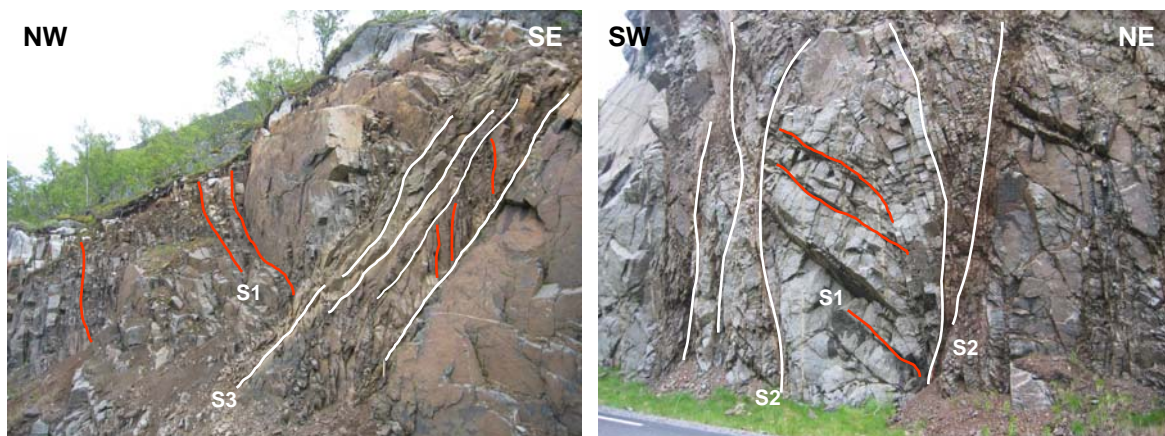


Fig. 53: Outcrops east of Raftsundet showing steep S1 fractures truncated by S2 and S3 faults (Bergh et al. 2007). Note the steep attitude and width of S2 faults comprising fragmental cataclasite and gouge breccias.

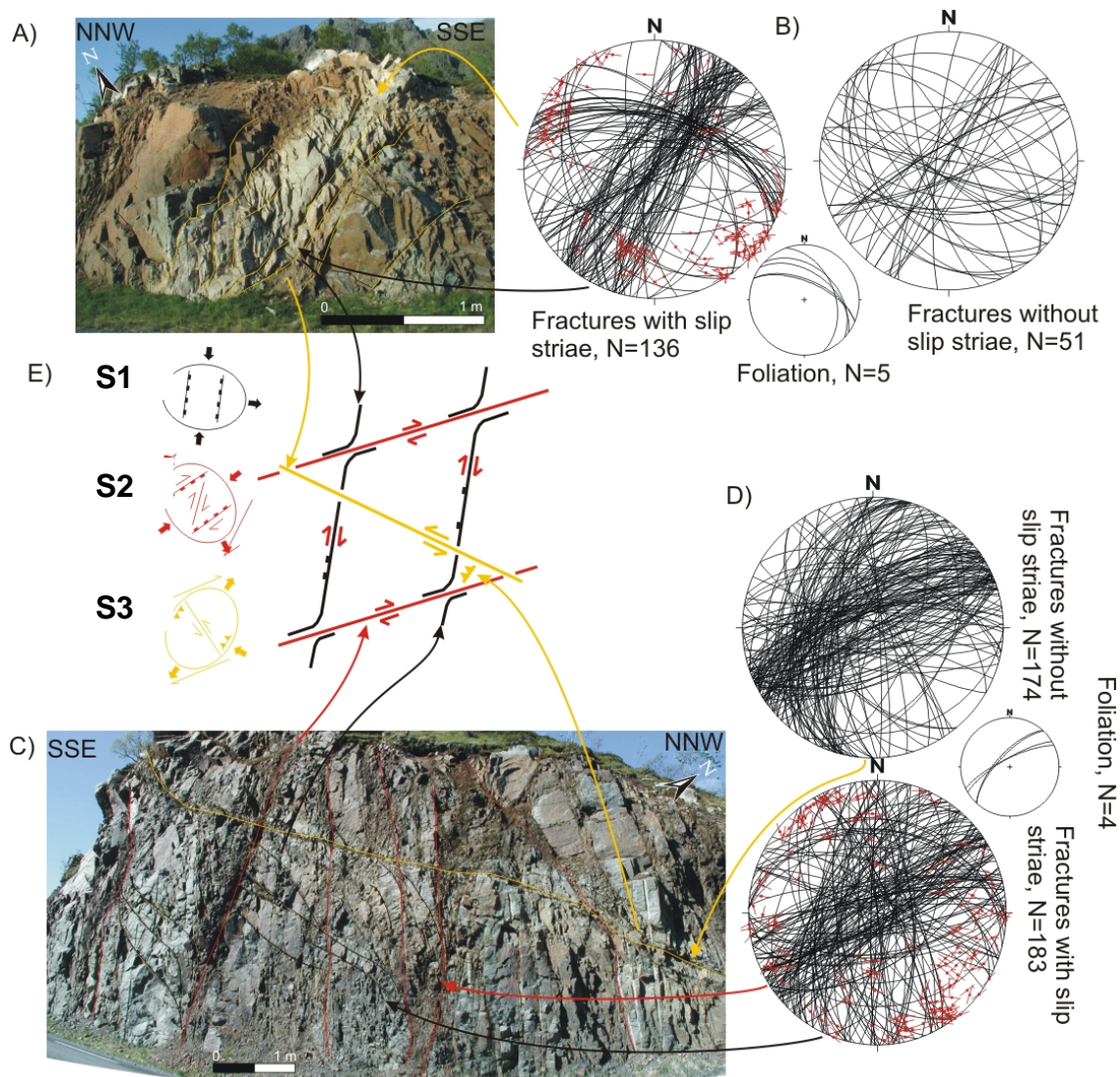


Fig. 54: Images (a, c) and orientation data (b, d) of the two main outcrops east of Raftsundet, each with several distinct fracture sets and cross-cut relations (Eig et al. 2008). Note the clear bending of S1 fractures into S2 fractures in the lower image (c). Each fracture set is colour coded (S1 black; S2 red; S3 orange) with arrows to stereo plots showing kinematic data. Red lines in the stereo nets are slip striae on fault surfaces, on points representing the respective fault plane poles. Arrows indicate hanging wall movement (Goldstein & Marshak 1988). Note the presence of both dip-slip, oblique-slip and strike-slip striations on the main fractures (b). Cross-cutting relations, curvatures, and interpreted fault movements are shown by a schematic drawing and strain ellipses depicting the development of the interpreted local strain field in chronological order (S1-S3).

Stop No 4.8 Raften

Location

View point near the small village of Raften (870 052). Map sheet Raftsundet 1:50000.

Introduction

If time allows, we will drive a few kilometers farther south along the road to Digermulen, to the small village of Raften.

Description

From this point, there is a spectacular view of the mountain massif of Trolltindan, which is entirely made up of the Raftsundet Mangerite Complex. The Trolltindan massif is the highest in Lofoten (maximum 1146m) and supports many cirque glaciers. Two dominant sets of brittle fault surfaces (S1 and S2) produced a zigzag topography, where individual fault surfaces are well displayed as steeply dipping scarps, gorges and slopes.

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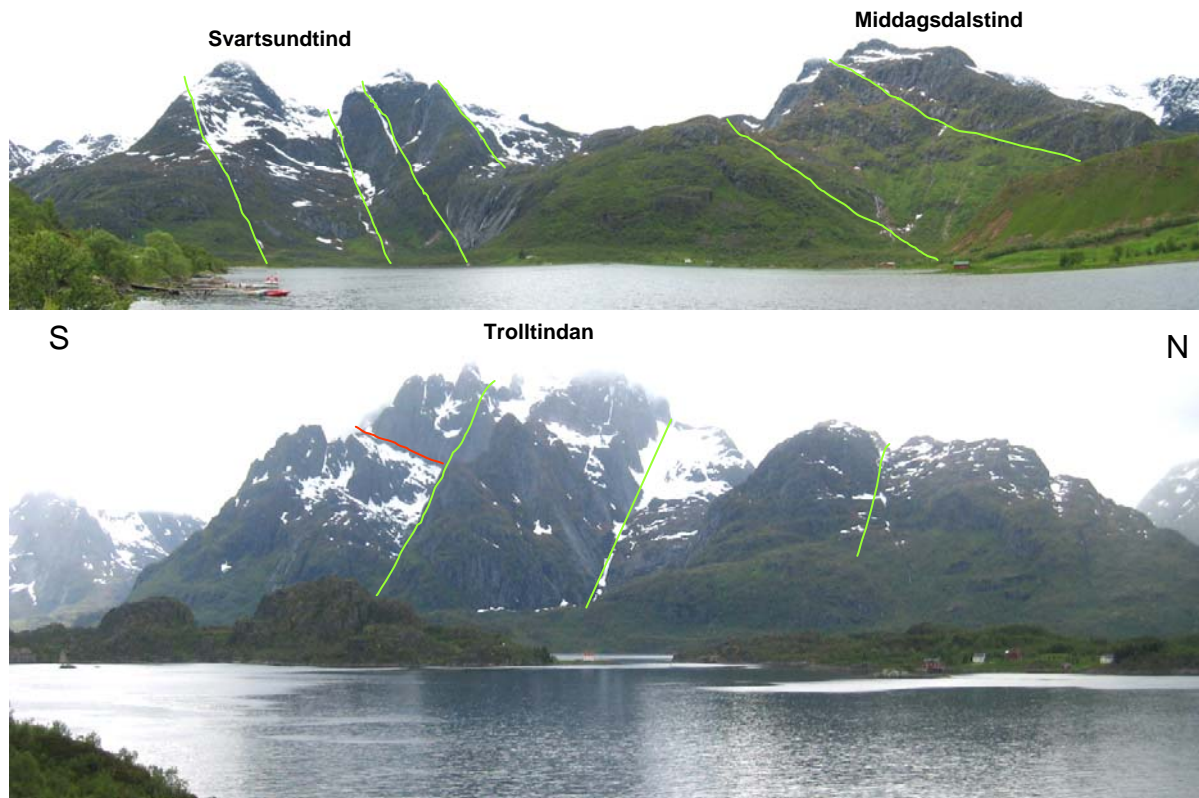


Fig. 55: Panorama views from the east side of Raftsundet toward Trolltindan in the west. Note the pronounced planar slopes and scarps outlined by S2 fractures (green) and near-perpendicular S1 sets.

Day 5

The last day of the excursion will be spent on the island of Langøya in Vesterålen and on Hinnøya, southeast of Sortlandsundet (Fig. 46). We drive north and west on Langøya visiting localities along Eidsfjord, then, head back to Sortland for lunch. After lunch, we drive southwards to Sigerfjord and turn west along the road to Kaljord, with the last stop at a large quarry near Rødsand. In the afternoon, we leave for the airport in Evenes (ca. 2 hours nonstop drive). All localities are close to the road. Before departing, be certain that you have brought along all your personal belongings, including clothes, raingear, and good field boots.

The island of Langøya was mapped by Heier (1960). He distinguished massive monzonitic rocks in the southwestern part of the island from anorthosite in the northwestern, central and eastern part. In their investigation on mangerites and charnockites from the Lofoten-Vesterålen area, Malm & Ormaasen (1978) adopted the map produced by Heier (1960), which was also followed by Tveten (1978) on his map on the geology of the Lofoten-Vesterålen

area. Markl (1998) remapped the whole anorthosite complex (Fig. 2) and tried to distinguish between anorthositic, noritic and ferrodioritic rock types, although this often proved difficult.

The main topics for today's excursion include first, the study of the Eidsfjord anorthosite Complex on the island of Langøya, which is about 11 by 2 km in extent and which comprises rocks of anorthositic, ferrodioritic, noritic and monzonitic composition. The second topic will be the Heier Zone, which represents a presumed late- to post-Caledonian regional-scale ductile shear zone that helped exhuming the crystalline and metamorphic rocks of the Lofoten-Vesterålen areas as a metamorphic core complex, likely in the Permian (Steltenpohl et al 2004; Eig. et al. in prep.). The third focus today will be to study one of the major, NW-dipping master-boundary faults of the Sortlandsundet graben (of Late Jurassic-Early Cretaceous age) which is fully exposed in a quarry at Rødsand.

Stop No 5.1 Between Indre Straumfjorden and Ytre Eidsfjord

Location

There will be some short stops along the road between Indre Straumfjord and Ytre Eidsfjord. Map sheets Sortland and Stokmarknes 1:50000.

Introduction

The Eidsfjord Anorthosite Complex contains various types of coarse-grained anorthosite that has orthopyroxene as the most important interstitial mafic mineral and minor amounts of clinopyroxene, magnetite and ilmenite. Megacrystic orthopyroxenes with crystal sizes up to 25 cm diameter occur locally. Heier (1960) mapped a charnockite intrusion flanking the anorthosite to the east. Crosscutting basic dikes occur at Grønning, just west of Ytre Eidsfjord. In most areas, the anorthosite is not retrogressed and only weakly deformed. There are two main rock types; a pure, blackish (fresh) or whitish (weathered), coarse-grained anorthosite and a mafic, leuconoritic to noritic rock with a significantly higher content of mafic minerals. Both rock types contain lenses and stringers of pyroxenites, but only the more mafic type contains rounded lenses composed almost exclusively of Fe-Ti oxides and Fe- and Fe-Cu-sulphides. It appears as if the mafic rocks are younger component, an inference supported by the occurrence of xenoliths of anorthosite in ferrodiorite.

Zircon data from the anorthosite yields an age of 1796 ± 2 Ma (Corfu 2004a). This age overlaps within error a zircon age of 1800 ± 3 Ma obtained for a foliated monzonite to the southwest of the complex. The latter sample also contains two generations of secondary titanite. The first one records development of the titanite at 1769 ± 11 Ma, probably during hydration of the original mangerite, whereas the second one indicates an Early Ordovician overprint presumably related to the initial phases of the Caledonian orogeny (Corfu 2004a).

Description

The mafic rocks are easily spotted in the field due to their rusty brown colour (in contrast to the whitish weathering colours of the anorthosites). The largest accumulation of mafic rocks occurs near Indre Straumsfjord, where large and abundant masses of Fe-Ti oxides and sulfides occur along the road immediately in the west of the bay of Straumfjord, another occurrence was found at the roadcut near Ytre Eidsfjord.

Stop No 5.2 Ytre Eidsfjord

Location

There will be two stops; one along the road (173983) to view the mountain Slåttnesfjellet, and a second stop at the shore near Grønningsnakken (173 980). Map sheet Stokmarknes 1:50000.

Introduction

The most prominent feature of the Eidsfjord anorthosite is that the entire complex is bounded by an underlying regional scale ductile shear zone (Fig. 56), interpreted as a thrust by Heier (1960) who thought that the Eidsfjord Anorthosite Complex was thrust over monzonites and monzonitic gneisses that crop out to the south and the northwest. New studies (Eig et al. 2007, 2008) indicate that at least a portion of this thrust was reactivated as an extensional fault in the Late-Caledonian to Devonian and can be linked to the regional onshore-offshore network of similar extensional detachments (Figs. 4 and 9). The Mesozoic basins offshore Lofoten and Vesterålen are all bounded by oppositely dipping, low-angle listric extensional detachment faults that form composite asymmetric grabens (Figs. 9, 57). These regional faults detach well within the underlying basement forming a web of undulating shear zones, likely imbricate Late Caledonian-Devonian thrust sheets and single or stacked nappes bound by thrusts (Eig et al. 2007). They are equivalent to the onshore Late/post-Caledonian Nordfjord-Sogn detachment in southwestern Norway, and the Devonian Sagfjorden and Nesna shear zones onshore central Norway (Braathen et al. 2002). These depressions formed by orogen-parallel to oblique extension, locally transpression, and accompanying Late Caledonian transtensional reactivation in the Late Permian and Mid/Late Mesozoic.



Fig. 56: Panoramic NE view of the Heier Zone in the mountain Slåttnesfjellet. Note the lack of vegetation on the grey-coloured Eidsfjord anorthosite above the shear zone contact.

Similar to the Heier Zone in Vesterålen, the island of Røst in the outermost Lofoten comprise zones of strongly sheared basement mylonites interpreted to be part of a Permian metamorphic core complex (Steltenpohl et al. 2004; Osmundsen et al. 2007b; Eig et al. 2007) rooted in a bowl-shaped Devonian detachment (Fig. 57). This detachment either plunges beneath the Lofoten Ridge or was at a higher, now eroded level during the Mesozoic-Cenozoic passive margin evolution. The new data indicate that the Mesozoic-Cenozoic extensional geometry of the Lofoten-Vesterålen continental margin was shaped by Late Caledonian/Devonian structures superimposed on older inherited fabrics (thrusts?). These basement fabrics became the template for Mesozoic-Cenozoic rifting involving extensional detachments and exhumation of metamorphic/crystalline core complexes.

Description

The viewpoint near Ytre Eidsfjord shows the ductile shear zone below the Eidsfjord anorthosite in the central part east and southeast of Slåttnesfjellet. The shear zone is recorded by a ca. 40 m thick mylonite zone (Fig. 56), which partly contains ultramylonites. This mylonite zone dips gently ($\sim 25^\circ$) to the northwest in the mountain side, but changes to a steep dip along the shore near Ytre Eidsfjord. In the central portion of the mylonite zone, the host rock is expressed as a c. 5 m thick dark, semi-brittle cataclasite superimposed on the mylonite fabric. Notably, stretching lineations in this shear zone plunge 20° to the NNW and reveal down-to-the NNW oblique-normal sense-of shear (Eig et al. 2007). The cataclasite is slightly greenish and greyish black, with rounded or stretched clasts of feldspar. Below the cataclasite, the monzonitic gneiss is mylonitic and darkened by chlorite, with small asymmetric, down-dip verging folds. Away from the Heier-zone, the gneiss becomes coarser, with some eye-shaped clasts in a foliation that is slightly darkened by chlorite. The foliation is itself folded with axes and axial plane orientations independent of the cataclastic zone, indicating that the foliation predated the development of the cataclasite zone. Although the ductile deformation was localized to this shear zone, deformation also affected the underlying monzonite, whereas the anorthosite above shows abundant, superimposed pseudotachylites (linked to the cataclasites). These small "vein-like" pseudotachylites are found throughout the anorthosite complex.

In the shoreline exposure at Grønningsnakken, the Heier zone is expressed differently; it consists of a ten meter thick zone of mylonitic anorthosite with a core zone of semi-brittle, dark cataclasite. The sheared anorthosite is folded, with axes plunging NW, indicating a lateral component of shear, or a synchronous NNW-SSE stretching and NE-SW compression. The sheared rocks are truncated by later high-frequency brittle fractures. The core of the cataclasite is greenish to greyish black, in some places homogeneous without visible grains, in other places it consists of 5 mm-sized clasts in a dark matrix. Locally, the cataclasite is foliated and parallel with the ductile mylonite.

The differences in expression of the Heier zone at the shore location relative to that of the mountain, may be that the latter covers the lower gneissic part (or the footwall) of the shear zone, while the locality at the seashore covers the upper, hanging wall, part in the anorthosite. The kinematic data from the mountainside locality indicate formation during mainly NNW-SSE extension, but the folds at the seashore indicate a NE-SW compression component, i.e. a temporal (?) or spatial strain partitioning, which is well known from Devonian detachments elsewhere (Braathen et al. 2002). As the Heier-zone dips progressively more steeply to the NNW, it may possibly be located in the footwall of a large antiform above Langøya, i.e. a detachment bounding an exhumed metamorphic/crystalline core complex (Eig et al. 2007).

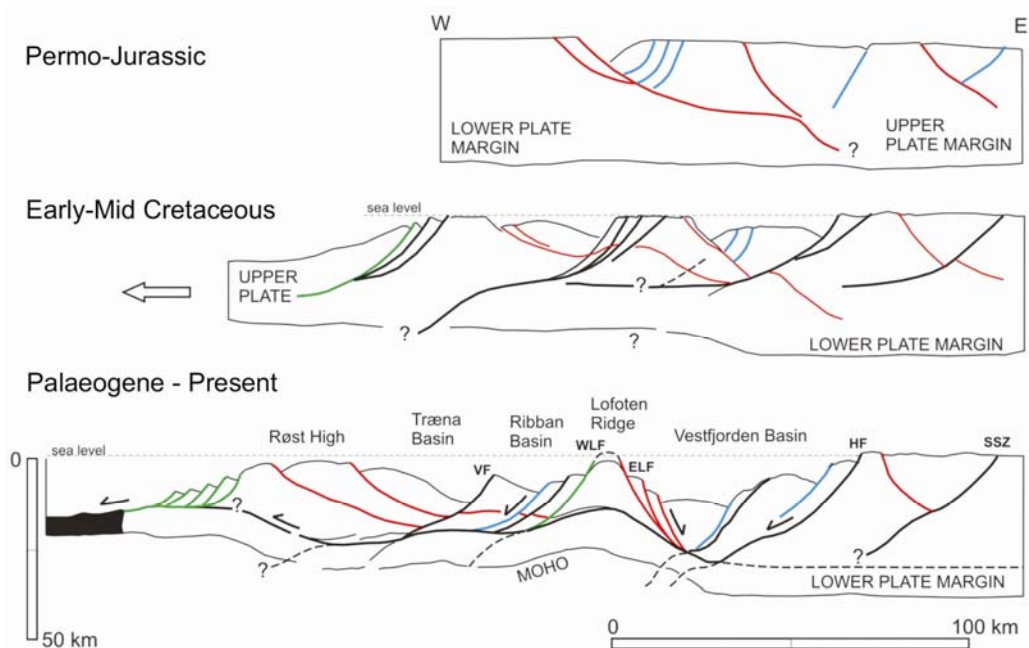


Fig. 57: Crustal-scale fault evolution model of the Lofoten-Vesterålen continental margin based on Figs. 7 and 9 (Bergh et al. 2007). Note the polarity shift between fault populations 1a-b offshore (S1 and S2 faults onshore) and a corresponding change from upper-plate to lower-plate margin characteristics (cf. Lister et al. 1986). These faults may have been responsible for exhumation of basement-seated metamorphic core complexes. The crustal sections are modified after Mosar et al. (2002), Olesen et al. (2002) and Tsikalas et al. (2005).

Stop No 5.3 Fleinnes-Varvika

Location

Coastal outcrops between Fleinnes and Varvika (135 928). Map sheet Stokmarknes 1:50000.

Introduction

The peninsula near the mouth of Eidsfjorden outlines a section from the base of the Eidsfjord Anorthosite Complex, including the Heier Zone, into the underlying mangeritic and monzonitic gneisses (Tveten 1978). The shear zone is visible in the steep cliffs, from the distance, but is not well exposed along the shore.

Description

Near Fleinnes, noritic rocks occur in a zone between two patches of anorthosites. The anorthosite, which crops out in the bay of Fleinnes, is strongly overprinted by an amphibolite-facies metamorphic assemblage, but still shows magmatic textures. These textures are unlike those found elsewhere in the complex. Specifically, large quadrangles of plagioclase up to 10 cm in size "float" in a groundmass of plagioclase of 1-2 cm size, with some mafic interstitials. It is this portion of the anorthosite that exhibits the best magmatic layering in the complex. The field appearance of the monzonitic rocks on the peninsula south of Fleinnes (Fig. 58) differs from that of the monzonitic rocks in the valley southeast of Straumfjord in that they are coarser grained (feldspars up to 4 cm in contrast to about 1 cm) and in that they contain abundant biotite rather than pyroxene.



Fig. 58: Metamorphosed and ductilely sheared monzonitic gneisses south of Fleinnes.

Stop No 5.4 Rødsand

Location

Atle Mathiassen AS, quarry near Rødsand (089 134). Map sheet Sortland 1:50000.

Introduction

The topography of the islands of Vesterålen differs somewhat from that of Lofoten, by smoother and lower topographic elevation, and distinct changes in asymmetric slopes across linear (fault) zones (Figs. 18 and 19; Olesen et al. 1997; Osmundsen et al. 2007a). On the more detailed level, a notable jump in apatite fission track ages and a marked change in the mean topographic elevation, as well as a change in landscape morphology, is observed across Sortlandsundet (Fig. 11). This jump corresponds well with the presence of a major tectonic lineament (fault) offshore that bounds a Late-Jurassic half-graben, the Sortlandsundet basin (Fig. 5; Davidsen et al. 2001). A corresponding fault is excellently exposed onshore at Rødsand. The jump in AFT age across this fault system indicates kilometre-scale fault movements (Fig. 11) that are younger than the Late Cretaceous (Redfield et al. 2005; Osmundsen et al. 2007a), e.g. similar to that of the Møre-Trøndelag Fault Complex in southern Norway. The architecture, kinematics and fault-rock distribution of such faults that caused the jumps in AFT age may provide important information on the kinematic regime and conditions of faulting in western Fennoscandia during the Mesozoic and Cenozoic.

The topography on Langøya north of Sortlandsundet has a general low elevation and is gently SE-dipping, resembling the tilted palaeosurfaces elsewhere in Lofoten. The pattern of valleys and fjords on this part of Langøya, as well, is similar to that of dendritic drainage systems that evolve around normal faults (cf. Fig. 12: Osmundsen et al. 2007a).

Description

The quarry at Rødsand exposes the bed rocks in a several 100 metres long NE-SW section. The host rock consists of heterogeneous Archaean gneisses, e.g. granitic and amphibolitic gneisses, migmatites, and banded gneisses. A variety of alteration zones and shear-induced ductile fabrics, sulphides iron oxides and retrogressed, red-coloured granites can be seen from the distance (Figs. 59-61). Where present the foliation of the gneisses dips moderately and/or steeply to the SE.

In the northern portion of the quarry, a spectacular planar surface dipping c. 50° to the NW is fully exposed (Fig. 59). Closer inspection outlines the surface of a semi-brittle fault zone developed within a chlorite/mica-rich unit of the host rock. A nearly 1 m thick zone of retrogressed and highly fragmented rock (cataclasite) occurs along the fault trace. Slickenside lineation on the fault surface is mostly down-dip (i.e. down-to-the NW normal motion), but a weak oblique set is superimposed on the former. In the hanging wall of the major fault, near-perpendicular and conjugate, presumed hk_0 -fractures developed in the zone of accommodation of critical shear stresses. A possible older fracture set strikes c. NNE-SSW (S1) and is highly curved or bent into an attitude parallel to the major NE-SW striking fault (S2).



Fig. 59: Outline of the distinct fault surface (stippled) exposed in the quarry at Rødsand. The fault is dipping c. 50 ° to the NW.



Fig. 60: Down-dip view of the fault plane in Fig. 5.4. Note the presence of meter-thick cataclastic fault rocks and accompanied, read-stained altered granite in the hanging-wall.



Fig. 61: NE-ward view along strike of the main fault plane at Rødsand. Note hillside cliffs in the distance that may be part of the same corresponding regional fault system.

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