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Journal of Structural Geology 27 (2005) 859–870

JOURNAL OF STRUCTURAL GEOLOGY

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Quantification of neotectonic stress orientations and magnitudes from field observations in Finnmark, northern Norway

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Received 9 December 2003; received in revised form 4 January 2005; accepted 20 January 2005
Available online 26 April 2005

Abstract

Fieldwork was conducted in Finnmark, northern Norway, with the purpose of detecting and measuring stress-relief features, induced by quarrying and road works, and to derive from them valuable information on the shallow-crustal stress orientations and magnitudes. Two kinds of stress-relief features were considered in this study. The first consists of drillhole offsets that were found along blasted road-cuts and which were triggered by the sudden rock unloading following the actual blasting. Vertical axial fractures found in the concave remains of boreholes represent the second kind of stress-relief feature. The axial fractures are tension fractures produced by gas overpressure inside the drillhole when the blast occurs. As such, their strike reflects the orientation of the ambient maximum horizontal stress axis. The borehole offsets show mostly reverse-slip displacements to the E–SE and the axial fractures trend NW–SE on average, in agreement with NW–SE compression induced by North Atlantic ridge-push forces. Mechanical considerations of the slip planes offsetting some of the drillholes lead to the conclusion that the magnitude of the maximum horizontal stress at the surface is in the range ~0.1–~1 MPa. This range of magnitudes is 1–2 orders less than the horizontal stress magnitudes measured at the surface in other post-glacial environments (e.g. Canada). It is suggested that this difference is related to the marked decline in stress that followed the tremendous post-glacial burst of earthquake activity that affected Fennoscandia but apparently not the Canadian Shield.

Keywords: Stress relief; Borehole offsets; Axial fractures; Ridge push; Post-glacial rebound; Fennoscandia

1. Introduction

In the last four decades it has become increasingly apparent that the present-day Baltic Shield is not such a quiet, stable continental area as previously thought. The first indications of instability came from the discovery in Finland (Kujansuu, 1964) and, later, in Sweden (Lundquist and Lagerbäck, 1976; Lagerbäck, 1979) and Norway (Olesen, 1988; Dehls et al., 2000; Anda et al., 2002; Olesen et al., 2004), of impressive ground-surface offsets related to post-glacial reverse faulting. The increasing quantity and quality of recordings in the Fennoscandian earthquake catalogue also showed that seismic activity, although low compared with other continental areas, could hardly be regarded as negligible (Gregersen et al., 1991). In connection with civil engineering works, a regular recording of crustal stress measurements in Fennoscandia started in the late 1950s (Hast, 1958). A growing database of stress measurements was set up (Stephansson et al., 1986) and later included in the compilation of the World Stress Map (Zoback, 1992; Reinecker et al., 2004).

Despite these advances, neotectonic stress orientations in the northernmost and less populated areas of the Baltic Shield, like Finnmark, northern Norway, are still poorly constrained. A few in-situ stress measurements were made in Finnmark (a county larger in area than Denmark), in connection with mining activities in large and deep open pits, but the determined stress orientations were strongly influenced by the geometries of the excavations (e.g. Myrvang et al., 1993). Moreover, most of the permanent seismic stations in Fennoscandia are south of the Arctic

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0191-8141/$ - see front matter © 2005 Published by Elsevier Ltd.
doi:10.1016/j.jsg.2005.01.011

Circle and, thus, in most cases, preclude the use of microseismicity to determine stress axis orientations in the northernmost regions.

The first step in filling the stress-orientation gap in Finnmark was made by Roberts (1991, 2000), who applied a methodology developed and validated by Bell in Canada (Bell, 1985; Bell and Eisbacher, 1996). This approach involves the detection and measurement of stress-relief features induced by road construction or mining and quarrying activities, such as borehole offsets or axial fractures in drillholes. Borehole offsets are relatively common along rock faces in Canada. They are assumed to have been triggered by the sudden removal of a rock mass and consequent unloading, following the blasting of the road or quarry walls. The slip direction associated with borehole offsets was found to be strongly controlled by the stress orientations acting on the rock mass (Bell, 1985). Axial fractures, present in the concave remains of boreholes are vertical to near-vertical tension fractures produced by gas overpressure inside the drillhole when the blast occurs. As such, their strike reflects the orientation of the ambient maximum horizontal stress axis (Bell and Eisbacher, 1996). In Norway, in central Finnmark (i.e. in the Porsangerfjord and Laksefjord areas, Fig. 1), Roberts (2000) measured six reverse-slip borehole offsets and ~40 axial fractures. In his preliminary study, Roberts showed that the measured stress-relief features were consistent with NW–SE compression. In the present contribution we complement Roberts' work in applying a similar approach to western and eastern Finnmark, and also in reporting new observations from central Finnmark. In addition, based upon simple considerations of the frictional properties of some of the observed fault planes (i.e. planes offsetting boreholes), we have calculated the maximum horizontal stress at one key locality in central Finnmark.

2. Geological context

Fieldwork was carried out mainly in the Caledonides of Finnmark (Fig. 1) where the most suitable exposure conditions for this type of investigation are encountered. The thin-skinned Caledonides of this part of Scandinavia involve three principal allochthonous complexes, the Lower, Middle and Upper Allochthons (Roberts and Gee, 1985), which show stretching lineations indicative of SE–E thrust transport onto Archaean and Palaeoproterozoic crystalline rocks of the Fennoscandian Shield. Rocks composing the diverse thrust sheets consist mainly of thick, Neoproterozoic to Lower Palaeozoic, metasedimentary assemblages that show evidence of polyphase folding with associated axial planar schistosities or cleavages, depending on the metamorphic grade attained (Roberts, 1985).

In some areas, banded volcanosedimentary Svecofennian rocks of Palaeoproterozoic age, first deformed during the

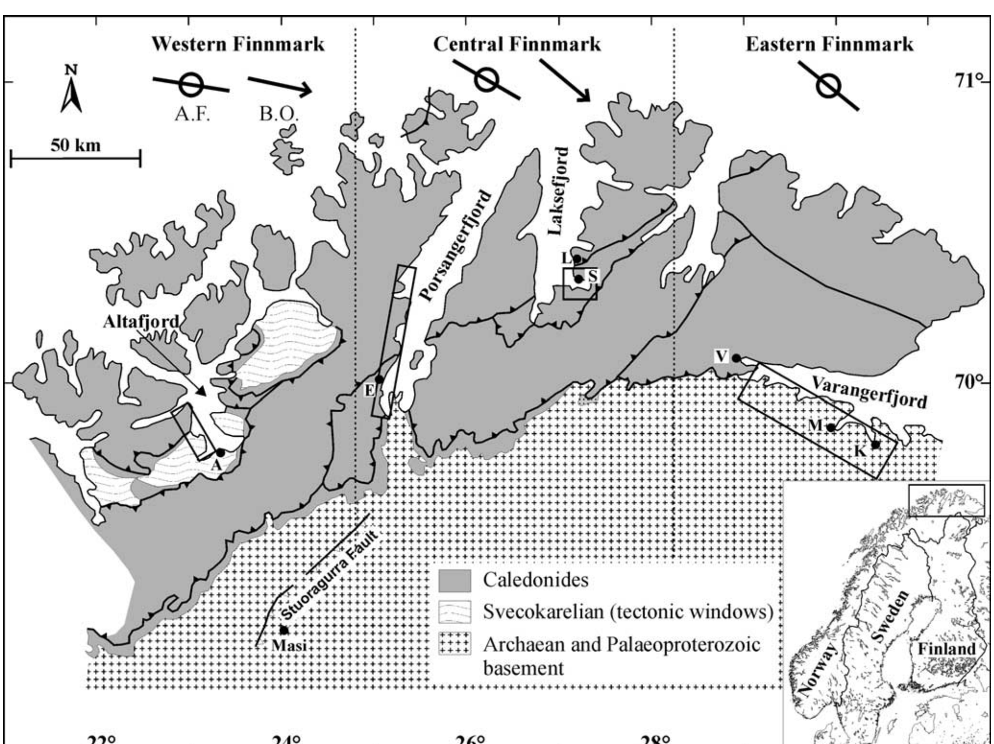

Fig. 1. Simplified geological map of Finnmark. The boxes show the locations where stress-relief fractures were found to be most abundant. The mean (i.e. median or central value) azimuths for axial fractures (A.F.) and for slip vectors associated with borehole offsets (B.O.) are also shown for each studied area (i.e. western, central and eastern Finnmark). A, Alta; E, Elvenes; K, Kirkenes; L, Lebesby; M, Munkelv; S, Skogvika; V, Varangerbotn.

c 1.9–1.8 Ga Svecokarelian orogeny, are also involved, to varying degrees, in the Caledonian thrust deformation (Gayer et al., 1987; Olesen et al., 1990). One such area is that of the Alta-Kvænangen tectonic window of western Finnmark (Fig. 1), the easternmost part of which was visited during this field study. Elsewhere in western and central Finnmark, older crystalline basement rocks are also represented in some thrust sheets.

In eastern Finnmark, south of Varangerfjord, high-grade metamorphic and intrusive rocks of Late Archaean age form the autochthonous crystalline bedrock (Dobrzhinetskaya et al., 1995; Koistinen et al., 2001), and can be followed southeastwards into the Kola Peninsula of NW Russia. These, generally massive, orthogneissic complexes show no visible signs of Caledonian deformation, but are transected by many NW–SE and c N–S-trending, multiply reactivated lineaments and shear zones (Karpuz et al., 1995; Roberts et al., 1997). During the field study reported here, traverses were undertaken along prominent road-sections in this easternmost part of Finnmark.

3. Field observations and stress orientations

3.1. Method of investigation

The method applied in the present study requires visiting a relatively large number of artificial outcrops. In the present case, more than 100 long road-cuts and quarry walls were examined throughout Finnmark, but valuable stress-relief fractures were found at only ~30 sites. In order to be diagnostic of far-field tectonic stresses, measurements have to be made as far as possible from local stress sources, such as regions with pronounced topography. Except for the area west of Altafjord (Fig. 1), Finnmark presents a comparatively gentle topography.

Axial fractures are seen as subvertical fractures parallel to the axes of boreholes (Fig. 2a–c; Bell and Eisbacher, 1996). These fractures are, in general, ~10 cm to ~1 m in length and can penetrate up to ~20 cm into the bedrock. In detail, they comprise anastomosing and branching cracks whose respective azimuths present limited variations with respect to the average strike of the axial fracture (i.e. $<10°$ divergence). However, the development of axial fractures can be strongly influenced by the pre-existing rock fabric. Careful examination of the outcrop is therefore essential and rocks that are sufficiently homogeneous in structure and texture are preferred targets for axial fracture measurements.

Borehole offsets (e.g. Fig. 2d and e; Bell, 1985) are considered to be related to stress relief if the following requirements are met. (1) The faulting associated with the offset shows a reverse-slip component. If the faulting is normal, the associated mechanism is merely a gravitational collapse of the rock mass. It is noteworthy that only two occurrences of borehole normal offset were detected during this study. (2) The measured slip vectors present consistent strikes and show no dependence on the orientation of the rock faces. (3) The outcrops are relatively fresh, and wide, open fractures are not detected in the vicinity of the drillhole offsets. This latter condition is crucial in cold areas, like Finnmark, where open fractures can host ice during the long winter months, and where frost–thaw cycles can induce rock motions. Because frost action is usually limited to within 1 m of the ground surface in Finnmark, borehole offsets are preferentially measured in the lowermost parts of the sections, a few metres below the top of the outcrop. This ensures that the database is not contaminated by features related to frost action which acted prior to the blasting of the road or quarry sections.

3.2. Western Finnmark

In western Finnmark, convincing stress-relief features were observed only in the area of SW Altafjord (Fig. 1), along a c 50-km stretch of road trending roughly NNW–SSE with abundant road-cuts. From south to north, this road cuts through the Svecokarelian greenstones and metasedimentary rocks of the Alta-Kvaenangen tectonic window, and metasedimentary rocks and gneisses of the Caledonian nappes. Bedrock crops out almost everywhere along the road section where rock faces from a few metres to tens of metres high are exposed. The road section has been reworked in places at various times since World War II and the remains of drillholes are easy to find.

Although most of the exposures visited are strongly affected by frost weathering, five examples of borehole offsets potentially induced by stress relief were measured in recently reworked parts of the road section (Figs. 2d and 3a; Table 1). These offsets occur along pre-existing shallow-dipping planes in the rocks (i.e. mostly cleavage surfaces). The associated faulting is reverse, and on average, the slip is directed towards E–ESE. In these cases, the boreholes are offset by 1–5 cm. Numerous axial fractures can be seen in several road-cuts in different parts of the road section; however, a careful investigation revealed that the orientations of most of them were influenced and diverted by a well-pronounced vertical jointing in the rocks. Only four axial fractures (e.g. Fig. 2a) were considered to be reliable present-day stress indicators and are orientated, on average, N099°E (Fig. 3a).

3.3. Central Finnmark

A similar study of stress-relief features has been carried out in central Finnmark, in the Porsangerfjord and Laksefjord areas (Fig. 1), by Roberts (2000). In the present paper we supplement Roberts' observations and summarise the results in Fig. 3b.

In SW Porsangerfjord, two additional borehole offsets were observed along a fresh NE–SW road section near the small settlement of Elvenes. Strongly folded

Fig. 2. Examples of axial fractures observed in the concave remains of boreholes along road-cuts and quarries in Finnmark: (a) western Finnmark (SW Altafjord); the strike of the axial fracture is N113°E; (b) central Finnmark (SE Laksefjord); the strike of the axial fracture is N140°E; (c) eastern Finnmark (near Kirkenes), the strike of the axial fracture is N130°E. Examples of borehole offsets found along road-cuts: (d) western Finnmark (SW Altafjord); the offset here is ~1 cm towards N119°E along a plane orientated at N037°E 14°W; (e) central Finnmark (SW Porangerfjord), the offset is ~1.5 cm towards N128°E along a plane orientated at N134°E 58°S.

metasandstones crop out at this locality. One of the borehole offsets is reverse with a small sinistral strike-slip component; the slip vector is towards N098°E (Table 1). The offset, with a few mm of displacement, occurs along a shallow SW-dipping bedding plane. The second observed drillhole offset occurs along a pre-existing fracture striking NW–SE and dipping at about 60° to the SW (Fig. 2e; Table 1). The drillhole is offset by 1 cm in a sinistral sense. The associated slip vector is directed to the SE. This particular drillhole offset represents the only observation where a relatively steep, pre-existing fracture, and not a shallow-dipping cleavage or bedding plane, is reactivated.

The locality encountered along the Skogvika–Lebesby road in SE Laksefjord (Fig. 1) displays an abundant number of very well exposed stress-relief structures and represents a key locality for the present study. This locality is located ~100 m west of the one where Roberts (1991) observed the first drillhole offset in Finnmark and, to our knowledge, in Fennoscandia. Phyllites of the Friarfjord Formation of the Laksefjord Nappe Complex are exposed along this road

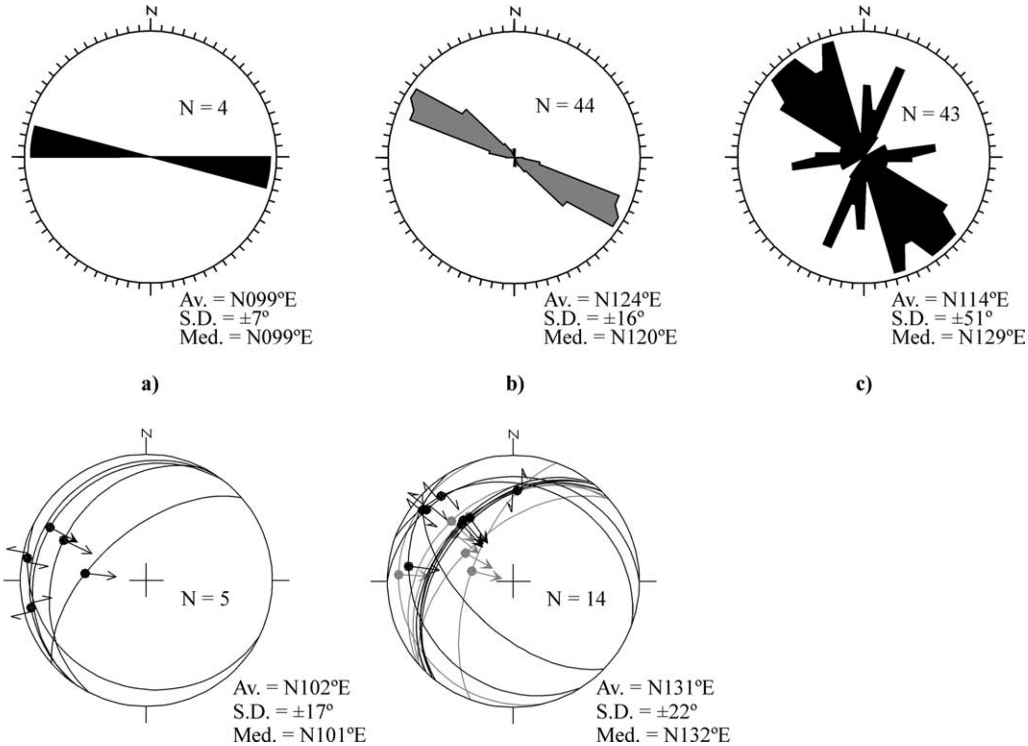

Fig. 3. Azimuth distributions of axial fractures and fault planes offsetting boreholes, represented on the lower hemisphere of Schmidt nets, in (a) western, (b) central and (c) eastern Finnmark. The results of the statistical analyses are shown (Av, average, SD, standard deviation, Med., median or central value). Note that because the strike of the axial fractures in eastern Finnmark shows a multimodal distribution, the median value is more representative in this particular case. Grey: data from Roberts (2000). Black: this study.

section. The phyllites show a slaty cleavage striking NE–SW and dipping at 40° to the NW, and a penetrative stretching lineation striking NW–SE can be observed. Some of the cleavage surfaces show quartz steps and normal to dextral slickenside lineations, indicating that the planes had previously been reactivated subsequent to the Caledonian folding and metamorphism. This also indicates that these discrete surfaces of slaty cleavage are prone to reactivation. The studied outcrop is ~15 m long and ~5 m high, and can be divided into two sectors: a western sector corresponding to an artificial E–W road-cut, and an eastern sector comprising a natural scarp dipping at 30° to the southeast (i.e. oblique to the road).

Five major drillhole offsets were measured in the western sector (Fig. 4; Table 1); two of them have already been documented by Roberts (2000). The offsets occur along the cleavage planes in a reverse dip-slip sense, directed towards the SE and in the order of a few centimetres. A closer look to the outcrop reveals that two of the drillhole offsets are associated with the displacement, by 1–1.5 cm, of a large block of rock coming out of the face of the road-cut (Fig. 4a–d). The block is bounded at its base by a cleavage plane and is limited laterally by two major joints striking N–S and WNW–ESE, respectively. The outcrop length of the block is ~4 m. No clear upper boundary was observed. Examination of the top of the hill above the road-cut revealed a similar offset to the SE of the actual ground surface (Fig. 4g).

In the eastern sector, the natural scarp, nicely rounded by Pleistocene glacial erosion, appears to be affected by a step of 2 cm to the SE (Fig. 5). The step is parallel to the trace of the cleavage and continues over ~6 m along the scarp. It cannot be followed to the east, where the outcrop disappears below vegetation, or to the west, where the scarp obliquely transects the near-vertical road-cut. The occurrence of identical lithologies above and below the step suggests that the observed step is also a stress-relief feature and not merely due to differential erosion. Previous observations of similar structures in the vicinity of blasted road-sections in Canada (Adams, 1989) corroborate this interpretation.

Additional reverse borehole offsets were measured in SE Laksefjord (Table 1) and are plotted in Fig. 3b. All the encountered offsets show a notable consistency with reverse-slip displacements of a few centimetres to the SE. The measured senses of slip are also consistent with the NW–SE orientation of axial fractures from boreholes in central Finnmark reported by Roberts (2000) (see also Fig. 3a). Note that other minor, reverse borehole offsets (i.e. ~1–2 mm) with a sense of slip roughly to the SE have also been observed.

3.4. Eastern Finnmark

In eastern Finnmark, suitable good-quality road sections were encountered only to the south of Varangerfjord (Fig. 1).

Table 1
Measured borehole offsets in Finnmark

Fault plane	Slip azimuth	Regime	Offset (cm)	Locality	Ref. Map. (1:50,000)	UTM coord.	Comments
Eastern Finnmark							
N049°E 58°N	N097°E	RD	1	Vengbergan (Alt.)	Talvik	EC795694	This study
N037°E 14°N	N119°E	R	1	Smedvik (Alt.)	–	EC768694	–
N033°E 10°W	N077°E	RD	4.5	Gjermundby (Alt.)	–	EC755800	–
N117°E 16°S	N101°E	RS	2.5	Storvik (Alt.)	Alta	EC801650	–
N027°E 28°W	N117°E	R	2.0	Tangnesland (Kv.)	Kvaenangen	EC427391	–
Central Finnmark							
N166°E 10°W	N093°E	RS	1.5	Elvenes (Por.)	Lakselv	MT223931	Roberts (2000)
N020°E 62°W	N104°E	R	0.8	Storbukta (Por.)	Billávuotna	MU300992	–
N148°E 22°W	N098°E	RS	0.2	Elvenes (Por.)	Lakselv	MT223931	This study
N134°E 58°S	N128°E	RS	1.5	–	–	MT225934	–
N045°E 40°W	N128°E	R	5.8	Skogvika (Lak.)	Lebesby	NU004227	Roberts (1991)
N050°E 32°N	N134°E	R	4.0	–	–	NU000227	Roberts (2000)
N048°E 38°N	N146°E	R	3.5	–	–	–	–
N040°E 42°W	N182°E	RS	0.7	–	–	–	This study
N044°E 39°W	N138°E	R	1.3	–	–	–	–
N038°E 38°W	N140°E	R	2[a]	–	–	–	–
N040°E 40°W	N146°E	R	2[b]	–	–	–	–
N049°E 55°N	N120°E	R	4.1	Friarfjord (Lak.)	Adamsfjord	MU977189	Roberts (2000)
N090°E 18°N	N130°E	RD	1.5	Ifjord (Lak.)	Ifjordfjellet	NU029167	This study
N110°E 24°N	N140°E	RD	0.3	Ifjord (Lak.)	–	NU037186	–

R, reverse-slip (no or negligible strike-slip), RD, reverse dextral, RS, reverse sinistral, Alt., (southwestern) Altafjord, Kv., (eastern) Kvænangen, Por., (western) Porsangerfjord and Lak., (southeastern) Laksefjord.
[a] Natural scarp offset (Fig. 5).
[b] Offset of the top of the outcrop (Fig. 4g).

No convincing examples of borehole offsets related to stress relief were found there. However, the rocks of the Archaean crystalline basement exposed there are, in general, more isotropic and less affected by pervasive cleavages than the Caledonian and Svecokarelian rocks of western and central Finnmark. Hence, the orientation of potential axial fractures was expected to be controlled largely by the orientation of the ambient stress axes. A series of 43 convincing axial fractures was measured in variably orientated road-cuts along the E6 road from Varangerbotn to Kirkenes (Fig. 1). Statistical analysis of the dataset shows that ~NW–SE axial fracture azimuths dominate (Fig. 3c). The two second-order trends (i.e. NE–SW and E–W) are attributed to controls on axial fracture development by pre-existing rock structures not detected in the field, but stress axis rotations due to local changes in rock rheology (e.g. Pascal and Gabrielsen, 2001) cannot be excluded.

The dominance of the NW–SE axial fracture trend was clearly demonstrated in one particular road section. This road-cut is located ~40 km northwest of Kirkenes north of the village of Munkelv (Fig. 1) and cuts through massive, almost non-jointed granitic gneisses. The road section is of recent construction, and consequently the remains of boreholes are very well preserved. The road section itself swings in orientation from N020°E to NW–SE. Along the NNE–SSW-trending part of the section 94 boreholes and 10 axial fractures were counted (i.e. the ratio, R, between observed axial fractures and exposed boreholes, is ~11%). In contrast, only one axial fracture was found along the NW–SE-trending part of the section, even though no fewer than 48 boreholes were exposed (i.e. $R\sim 2\%$). These observations, made in the context of very good field-exposure conditions confirm the tendency for the vertical axial fractures to develop preferentially along a NW–SE trend in the area south of Varangerfjord.

4. Quantification of stress magnitudes

A tentative quantification of the maximum horizontal stress (i.e. σ_1, in the present case) was carried out on the basis of the observations made at the key outcrop along the road section from Skogvika to Lebesby, central Finnmark (Figs. 1 and 4). As noted above, borehole offsets occur there along fault planes with similar strike and dip and show reverse dip-slip motions with negligible strike-slip components (Table 1). This particular situation is expected to occur only in two cases: (1) where the dip direction of the fault planes and σ_1 are parallel, or (2) where horizontal stresses are equal. In this latter case, the motion would be reverse dip-slip whatever the orientation of the fault plane (e.g. Pascal and Angelier, 2003, and references therein). The pronounced strike-slip components of motion along fault planes associated with some drillhole offsets from nearby

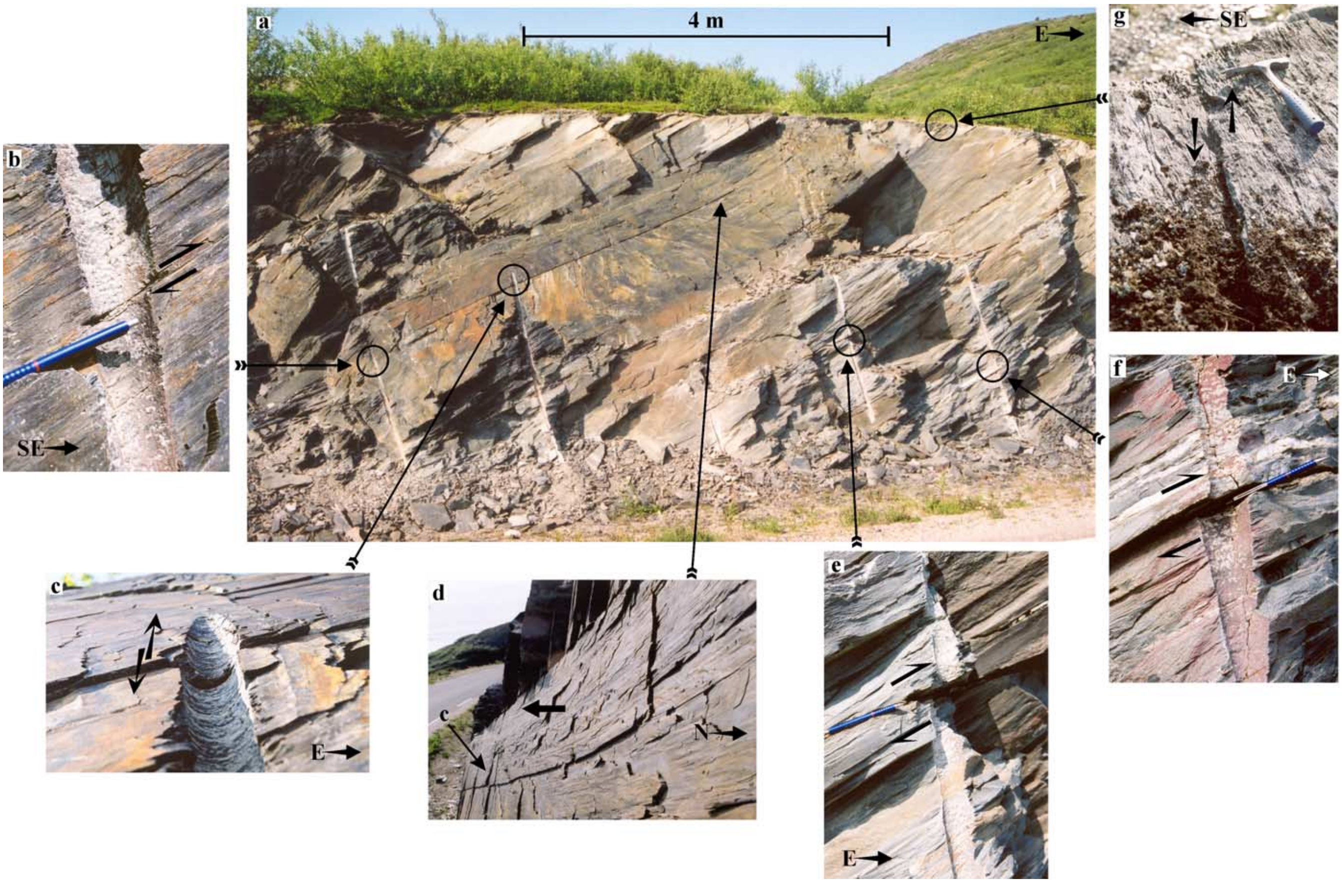

Fig. 4. (a) Western sector of the key outcrop along the Skogvika–Lebesby road section in SE Laksefjord, central Finnmark. (b) and (c) Drillhole offsets by 1–2 cm to the SE associated with the motion out of the road-cut face of the rock block shown in (d). (e) and (f) Drillhole offsets to the SE, by 2–3 cm. The offset in (e) was previously documented by Roberts (2000). (g) The natural rock surface on top of the section is also offset to the SE. Minor (i.e. ~mm-scale) drillhole offsets are also observed along the section.

localities in central Finnmark, together with the very consistent NW–SE strike found for the axial fractures (Fig. 3b), rules out the possibility of the two orthogonal horizontal stresses being equal. Thus, the fault planes observed at our key locality appear to be optimally orientated with respect to the stress field. In this particular case, a simple 2-D mechanical approach involving the applied stress and the dip and friction of the fault plane can be safely conducted.

For the analysis, let us consider an applied stress state, with σ_1 horizontal and σ_3 vertical (i.e. a reverse-slip regime), with $\sigma_1 \geqq \sigma_3$ and pressures being positive. As

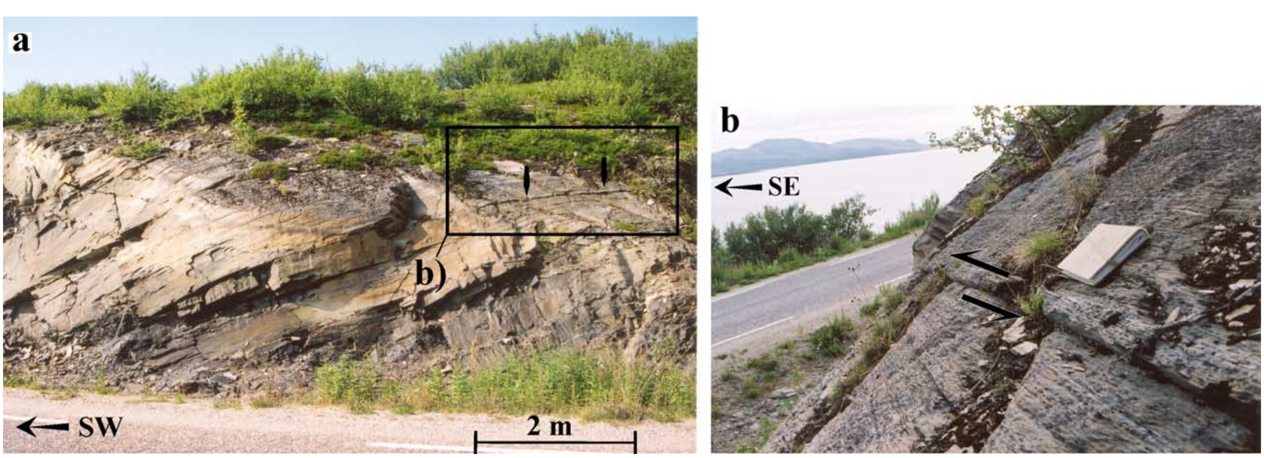

Fig. 5. Eastern sector of key outcrop along the Skogvika–Lebesby road section in SE Laksefjord, central Finnmark. The reverse-slip offset of the natural scarp, by 2 cm, is towards the southeast.

stated above, σ_1 is parallel to the dip direction of the plane, hence only the dip of the plane (hereafter p) is needed to characterise its orientation with respect to the stress axes.

The normal and shear stress absolute values (i.e. σ_n and τ, respectively) are derived as functions of σ_1, σ_3 and p (e.g. Jaeger and Cook, 1969):

$$\sigma_n = \frac{\sigma_1 + \sigma_3}{2} - \frac{\sigma_1 - \sigma_3}{2}\cos(2p) \quad (1)$$

$$\tau = \frac{\sigma_1 - \sigma_3}{2}\sin(2p) \quad (2)$$

where p is bounded by 0 and 90°.

Faulting occurs along the fault plane when the following general condition is met (e.g. Ranalli, 1995):

$$\tau \geq c_0 + \mu(\sigma_n - P_0) \quad (3)$$

where c_0 and μ are, respectively, the cohesion and the friction static coefficient of the fault plane and P_0 is the ambient pore pressure.

Following Byerlee (1978), we neglect fault cohesion at shallow depths. In addition, the slates of the Friarfjord Formation present negligible porosity and as the rocks are exposed along the sides of a small hill, fluids are likely to have been drained out from potential hydraulic conductors existing in the rock mass (i.e. fractures or cleavage planes). Consequently, c_0 and P_0 are taken to be zero in Eq. (3):

$$\tau \geq \mu\sigma_n \quad (4)$$

Combining Eqs. (1), (2) and (4), we write the minimum σ_1 value needed to reactivate the fault plane as a function of σ_3, μ and p:

$$\sigma_1 \geq \frac{\sin(2p) + \mu(1 + \cos(2p))}{\sin(2p) - \mu(1 - \cos(2p))}\sigma_3 \quad (5)$$

Note that Eq. (5) is valid for reverse regimes, where $\sigma_3 \geq 0$, for $p > 0$ and for:

$$\sin(2p) - \mu(1 - \cos(2p)) > 0 \quad (6)$$

This latter condition can be rewritten as:

$$p < \tan^{-1}(\mu^{-1}) \quad (7)$$

and Eq. (7) thus gives the fault dip angle above which reactivation cannot occur.

In the following, Eq. (5) is used to explore the range of σ_1 minimum values that comply with the reactivation of the slaty cleavage planes as dip-slip reverse faults. The dips of the planes, p, were measured in the field and found to be ~37° to the NW, on average. According to Eq. (5), σ_1 is relatively sensitive to p. Consequently, we will consider an uncertainty in the measurement of the cleavage dip value in excess of ±7° (i.e. the interval that contains all the measured dip values). In the present case, the value taken by σ_3 does not notably influence σ_1. We write

$$\sigma_3 = \rho g H \quad (8)$$

where $\rho = 2800\ \mathrm{kg\ m^{-3}}$ is the average density for slates, $g = 10\ \mathrm{m\ s^{-2}}$, the gravitational acceleration, and $H \sim 4$ m the maximum height of the outcrop above the observed borehole offsets.

The coefficient of friction, μ, is kept as a degree of freedom in Eq. (5) and varied between extreme limits represented by $\mu = 0$ and $\mu = 0.85$ (i.e. Byerlee's (1978) value for maximum friction at shallow depths). The value is considered to be an upper limit in the case of the slaty cleavage planes of the Friarfjord Formation. As these planes are developed as smooth surfaces with very few asperities, it is reasonable to assume that their associated coefficient of friction would be lower than the standard value proposed by Byerlee. Also, as pointed out in Section 3.3, field observations indicate that these cleavage planes had already accommodated components of faulting in earlier geological times. In addition, rock-mass dilatation, arising from the blasting, is expected to have weakened the contact surfaces between the slate lithons, resulting in a lowering of their static friction coefficient (μ) and triggering the faulting.

The results of the analysis are presented in Fig. 6. As expected, the minimum σ_1 value required for faulting to occur decreases with a decreasing friction coefficient but increases with the dip of the plane. The analysis shows that, in general, values required to reactivate the slaty cleavage planes remain relatively low and are in the order of ~0.1 up to ~1 MPa.

5. Discussion

Close to 90 axial fractures and ~20 reverse to strike-slip borehole offsets have been measured in different parts of eastern, central and western Finnmark (Fig. 3; Table 1). Both kinds of stress-relief structures are consistent with a regional horizontal σ_1 trending NW–SE, on average, and confirm the preliminary study made by Roberts (2000) in central Finnmark. In detail, stress orientations are better constrained in central and eastern Finnmark, where

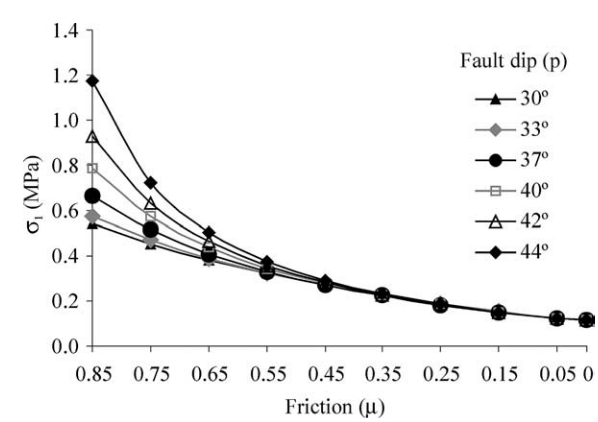

Fig. 6. Magnitude of σ_1 vs. friction coefficient (μ). The analysis was carried out on optimally orientated, reverse-slip, borehole offsets present at the key-outcrop of the Skogvika–Lebesby road-section (Fig. 4, Table 1).

exposure conditions were more favourable to the approach used in this study (i.e. relatively fresh road or quarry sections and low topography) than in western Finnmark, where heavily jointed and weathered road sections were commonly exposed. Furthermore, the relatively high and rugged mountains west of Altafjord may have caused local distortions of the regional stress field. Nevertheless, the few data that could be extracted from this latter area are in reasonable agreement with a regional NW–SE-trending maximum horizontal stress.

The NW–SE trend found for σ_1 in this study appears to be in contradiction to the more N–S one derived from three in situ stress measurements in Finnmark (Myrvang, 1993) and from studies on borehole breakouts in the adjacent western Barents Sea (Gölke and Brudy, 1996). Although the quality of borehole breakout measurements in the Barents Sea is low (in general ranked C to D in the World Stress Map; Reinecker et al., 2004), it has been proposed that the apparent N–S reorientation of the maximum stress axis offshore reflects a local perturbation due to the pronounced elevation of the western Barents Sea margin with respect to the adjacent oceanic basins (e.g. Fejerskov and Lindholm, 2000). Concerning Finnmark and according to Reinecker et al. (2004), the three in situ measurements present a very poor record of the orientation of the regional stress field (i.e. two measurements are ranked D and the remaining one is ranked E in the World Stress Map).

The only reliable stress-orientation determination in Finnmark comes from the analysis of five earthquake focal mechanisms associated with the Stuoragurra Fault (Bungum and Lindholm, 1997; Hicks et al., 2000), near Masi (Fig. 1). According to Hicks et al. (2000), the result of the inversion of the nodal planes was found to be relatively unstable with the σ_1 azimuth ranging between NNW–SSE and E–W. However, the NW–SE mean value found for the σ_1 is in good agreement both with field observations on the post-glacial Stuoragurra Fault (Olesen, 1988; Roberts et al., 1997; Dehls et al., 2000) and with our own results.

NW–SE compression has been reported from regions of Fennoscandia south of the Arctic Circle, by in situ stress measurements (e.g. Stephansson, 1989; Fejerskov et al., 1995), borehole breakout measurements (e.g. Spann et al., 1991; Gölke et al., 1995) and inversion of earthquake focal mechanisms (e.g. Bungum et al., 1991; Gregersen et al., 1991; Arvidsson and Kulhanek, 1994; Hicks et al., 2000; Uski et al., 2003). This trend for the maximum horizontal stress axis is traditionally associated with the North Atlantic distributed ridge-push force that is the main source of lithospheric stresses acting on Northwest Europe (Gölke and Coblentz, 1996; Reinecker et al., 2004). A second-order stress-generating mechanism specific to Fennoscandia is post-glacial rebound, also known as glacial unloading (Stein et al., 1989; Fjeldskaar, 1997; Fejerskov and Lindholm, 2000). In particular, post-glacial rebound should induce radial stresses with respect to the rebound centre located in the Gulf of Bothnia. In the case of Finnmark, this should result in superposition of the N–S rebound stress component upon the NW–SE regional stress pattern and deviation of the latter (Muir Wood, 2000). We can speculate that if ridge-push and rebound stresses were equal in magnitude the resultant stress orientation would be rotated about 22° from NW. Such a rotation cannot be detected in our data, which show a clear NW–SE signal, and in particular in areas where we have a reasonably good data coverage (i.e. central and eastern Finnmark; Fig. 3). This suggests that rebound stresses play a minor role in Finnmark and that the stress field is dominated by ridge-push forces.

In the field, the borehole and scarp offsets give the appearance of impressive stress-relief structures involving high stresses at the surface (Figs. 4 and 5). Our analysis (Fig. 6) suggests, however, that only moderate levels for the maximum stress (i.e. in the order of 0.1–1 MPa, Fig. 6) are required to trigger the faulting in connection with the blasting of the road-cuts. This may largely relate to the fact that the reverse-slip displacements are more commonly observed in multilayered and cleaved rock successions with prominent anisotropy; thus, they are more likely to be generated in these comparatively fissile rocks, at moderate stress levels, than in massive, homogeneous, rock bodies. The maximum horizontal stress magnitudes, derived from our analysis, remain in reasonable agreement with the average value obtained (i.e. 2.8 MPa) by Stephansson (1989), on the basis of hydraulic fracturing measurements from different places and diverse rock types in Fennoscandia. Although error-bars are not mentioned in his paper, Stephansson (1989) recognised that stress magnitudes measured close to the surface show wide variations. Stress measurements carried out in Finnmark show that stress magnitudes can reach a few tens of MPa but only at several hundred metres below the ground surface (Myrvang et al., 1993; Reinecker et al., 2004). The rare occurrence of stress-relief phenomena in connection with quarrying or road works in Finnmark supports the conclusion that stress magnitudes are, in general, relatively low at the surface. Indeed, this conclusion is also applicable to the Fennoscandian region as a whole where, apart from the Tysfjord–Kobbelv region in northern Norway (Myrvang, 1999), stress-relief phenomena at the surface have rarely been reported.

This situation is in sharp contrast with the present-day stress situation documented in northeastern North America, especially in SE Canada, in another post-glacial environment. Stress-relief features are far more common there and tend to be much more impressive than those recorded in Fennoscandia. For example, following excavation, the buckling and upheaval of quarry floors by several metres have frequently been observed (Coates, 1964; Wallach et al., 1993; Adams and Fenton, 1994; Karrow and White, 2002). Furthermore, various stress estimations or in situ measurements in eastern Canada have shown that stress magnitudes can be as high as a few tens of MPa at the surface (e.g. Adams and Bell, 1991; Karrow and White, 2002).

There are also differences in the post-glacial seismic activity between Fennoscandia and northern North America. Following deglaciation (i.e. ∼10 ky BP), powerful earthquakes with estimated magnitudes up to ∼7–8 and impressive reverse faulting of the ground surface occurred in Fennoscandia (Muir Wood, 1989), whereas, related surface expressions of any similar event are either undiscovered or unclear in northern North America (Stewart et al., 2000 and references therein). Also, present-day and historical seismic activity is more pronounced in this latter region (e.g. the 1989 Ms 6.3 Ungava earthquake; Adams et al., 1991) than in Fennoscandia (Adams and Basham, 1989). All these observations suggest that the post-glacial faults of Fennoscandia relaxed most of the seismic strains which had accumulated during glacial loading (Johnston, 1989), resulting in moderate stress magnitudes at the present-day surface. It is notable that seismic observations show that the post-glacial faults are still the loci of strain relaxation (Arvidsson, 1996; Bungum and Lindholm, 1997) but their activity is minor. The crust of northeastern North America, on the other hand, has not dispersed all the accumulated strains by mega-scale faulting; and that, in turn, could explain both the high stresses observed at the surface and the greater, present-day, seismic activity.

At the present stage we cannot speculate about the geographical distribution of stress-relief features (in particular borehole offsets) in Fennoscandia. To our knowledge, only two systematic studies have so far been carried out in Fennoscandia (Roberts, 2000 and the present contribution). However, it is worth noting that Roberts (2000) mentions the occurrence of a reverse borehole offset in the Roan district, Mid Norway. Moreover, Roberts and Myrvang (2004) have recently reported five reverse-slip offsets of drillholes from the same area, and other offsets and axial fractures from the Mid Norway region. Furthermore, sporadic observations of borehole offsets have been reported, but not published, in the Oslo Graben area (R. Gabrielsen, unpublished data), as well as from parts of the counties of Nordland and Troms, northwestern Norway (D. Roberts, unpublished data). As far as Sweden and Finland are concerned, we know of no systematic studies of drillholes in road-cuts or quarry walls in these countries.

The conclusion is that stress-relief features in Fennoscandia appear to be relatively rare, but much more common than can be anticipated from the present observations. It is a fact that little attention has so far been paid to these features.

6. Conclusions

About 130 stress-relief features induced by road and quarry works (i.e. axial fractures and borehole offsets) were measured over wide areas of Finnmark, northern Norway, allowing the completion of the stress map of Fennoscandia in a region where stress-data coverage had hitherto been poorly represented. These structures were found to be consistent with a regional NW–SE compression which is commonly inferred to arise from North Atlantic ridge-push forces. No clear perturbation of the regional stress pattern from post-glacial rebound stresses was found, suggesting that this source of stress has little effect today in Finnmark. Estimation of maximum horizontal stress magnitudes leads to the conclusion that only moderate stresses (i.e. 0.1–1 MPa) are currently active at the surface in Finnmark. The rare occurrence of stress-relief features in this northernmost part of Norway, and more generally in Fennoscandia, suggests that most of the strains that accumulated during glacial loading have been relaxed by the tremendous post-glacial burst of seismic activity. Strains accumulated during glacial loading are, however, still affecting the North American crust, where such a major post-glacial seismic event has never been documented, but where surficial stress-relief phenomena and relatively large earthquakes are far more common than in Fennoscandia.

Stress-relief features in Fennoscandia appear to be relatively rare but much more common than can be anticipated from the present observations. The results presented in this paper show the great potential of their systematic study in neotectonic research. Furthermore, we suggest that, as far as axial fractures are concerned, the approach presented here is not restricted to formerly glaciated areas but might be applied to other geological enviroments.

Acknowledgements

Drs J. Adams and R. Muir-Wood are acknowledged for their constructive reviews that helped to improve this paper. C. Pascal is grateful for funding from the Dutch ISES Program and the University of Bergen, Norway, during the course of this study. Prof. A. Myrvang, NTNU, Trondheim and Dr O. Olesen, NGU, Trondheim, are kindly acknowledged for helpful comments. This is the Netherlands Research School of Sedimentary Geology (NSG) publication nr. 20041102.

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