

Surface magnetic anomaly study on the eastern part of the Forlandsundet Graben

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A surface magnetic survey was carried out by use of a proton magnetometer over wide strandflats along the eastern coast of Forlandsundet, western Spitsbergen, to decipher subsurface structures and lithologies. Distinctive linear high-anomaly segments and zones were recognised on the magnetic anomaly maps. These zones coincide well with the eastern marginal fault of the Tertiary Forlandsundet Graben and associated faults north of St. Jonsfjorden, while they reflect bedrock lithologies in the south. The high-anomaly segments, which constitute the zones, are locally aligned in a left-stepping, *en echelon* arrangement within the zones, indicating a dextral transpressional stress regime on the eastern marginal fault of the graben during a certain time. Sudden termination and bends of the segments define a later transverse fault system.

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Introduction

Pronounced coastal plains have developed on the eastern coast of Forlandsundet, 1.5–6 km in width, extending N–S for approximately 75 km from Engelsbukta to the northern side of Isfjorden (Fig. 1). These plains are divided by St. Jonsfjorden and two large glaciers, Aavatsmarkbreen in the north and Eidembreen in the south. The plains are also divided into four separate strandflats: Sarsøyra (45 km²), Kaffiøyra (30 km²), Svartfjellstranda (22 km²) and Daudmannsøyra (118 km²), listed from north to south. These strandflats are slightly undulating and slope gently to the west toward Forlandsundet. Their elevation does not exceed 100 m in the piedmont areas of Oscar II Land. About 70% of the plains is covered by loose Quaternary sediments up to 10–15 m in thickness.

The geology of the area has been studied by Hjelle et al. (1979), Harland et al. (1979), Ague & Morris (1985), Kanat & Morris (1988), Krasil'sčikov & Kovaleva (1976, 1979), Wojcik (1981), Ohta et al. (1986), Ohta (1988), Teben'kov & Korago (1992), Ohta et al. (1992),

Kleinspehn & Teyssier (1992), Gabrielsen et al. (1992) and Lepvrier (1992), and various estimations of the subsurface geology have been proposed.

The areas have complex structures resulting from Caledonian thrusting which was overprinted by Tertiary tectonic disturbances. The Quaternary sediments are underlain by Precambrian volcano-sedimentary sequences, metabasic intrusive rocks and Vendian tilloids, all metamorphosed to greenschist facies (Fig. 1).

A high-pressure metamorphic complex recording a Caledonian subduction zone, including green-brown dolomites (dolomite-magnesite rocks containing fuchsite, chromite and chromian spinel) and a small amount of serpentinites (Ohta 1979; Hirajima et al. 1988; Dallmeyer et al. 1990; Teben'kov & Korago 1993), occurs in Motalafjella east of Eidembukta. Small scattered occurrences of the green-brown dolomites and serpentinites have been found in the strandflats north of St. Jonsfjorden.

Flyschoid sediments of Late Ordovician to Middle Silurian age (Scrutton et al. 1976; Ohta et al. 1984; Armstrong et al. 1986) are distributed to the east of the high-pressure complex in the St. Jonsfjorden area.

A thin, coarse-grained, unsorted conglomerate

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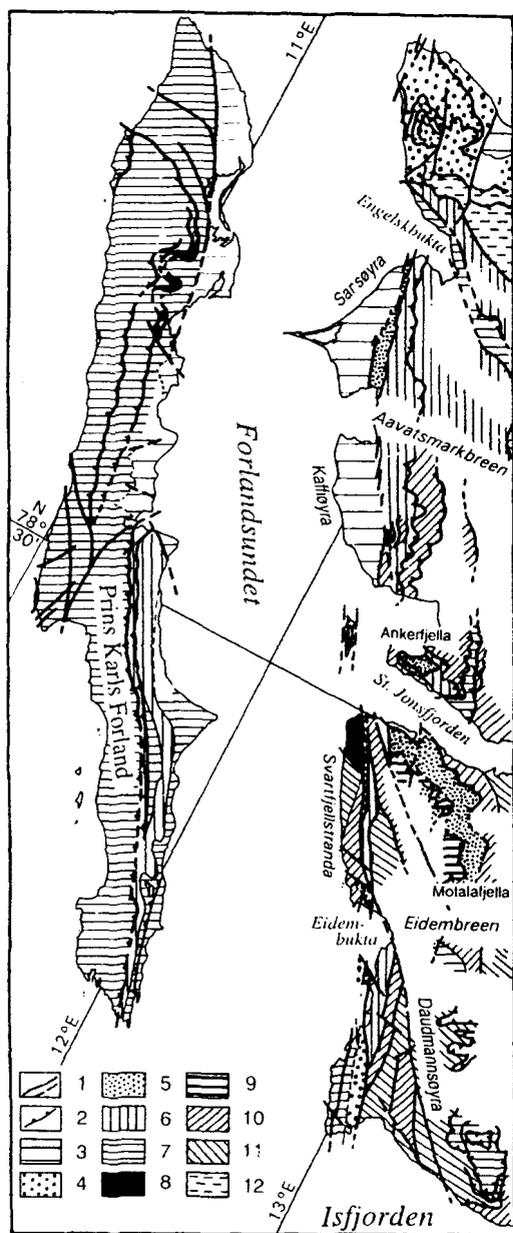


Fig. 1. Generalized geological map of the eastern margin of the Forlandsundet Tertiary Graben. Legend: 1 = steep faults, 2 = thrusts, 3 = Tertiary sediments, 4 = Carboniferous sediments, 5 = Late Ordovician–Middle Silurian sediments, 6 = Vendian tilloids, 7 = Late Proterozoic metasediments, 8 = garnet-biotite schists, 9 = high-pressure metamorphic rocks, 10 = Middle Proterozoic, calc-argillo-volcanic succession, 11 = Middle Proterozoic quartzite-sandy phyllite succession, 12 = schists and gneisses in Brøggerhalvøya.

occurs associated with a slice of serpentinite at the southeastern corner of Sarsøyra (Figs. 1 and 5a). About 1 km-thick black and green phyllites with thin carbonate and quartzite layers are distributed to the west of the conglomerate and a thick limestone-dolomite borders the Tertiary rocks to the west. Except for the serpentinite, these rocks have lithologies very similar to the flyschoids in Motalafjella. Scrutton et al. (1976) reported Paleozoic fossils from this area, and some Paleozoic microfossils have been found (A. A. Makariev, pers. comm. 1993) in the thick limestone-dolomite in the northern Sarsøyra plain. Thus, the present authors consider that this succession is of Middle Ordovician–Middle Silurian age.

Excluding the flyschoids, these rocks are involved in both early (Middle Ordovician) and late (Middle–Late Silurian) Caledonian, tightly-folded and thrust structures (Dallmeyer et al. 1990, Bernard-Griffiths et al. 1993), whereas the flyschoids were affected by the late Caledonian deformation only.

These structures were overprinted by the Tertiary deformation of the West Spitsbergen fold and thrust belt (e.g. Dallmann et al. 1993). A narrow graben containing Middle to Upper Carboniferous strata occurs along the foothills of Svartfjella to western Daudmannsøyra (Fig. 1). These rocks show a strong compressional deformation prior to the graben formation in Paleogene time (Ohta 1988; Gabrielsen et al. 1992; Lepvrier 1992).

The eastern border of the Tertiary Forlandsundet Graben roughly follows the piedmont of mountains to the east. To the west of the border a thick Paleogene succession occurs, up to 800 m in thickness and consisting mainly of sandstones and conglomerates.

The present study has been conducted to decipher subsurface structures beneath the strandflat areas widely covered by Quaternary sediments. Field measurements were performed by a Spitsbergen party of the Polar Marine Geological Expedition, St. Petersburg, on Sarsøyra in 1984, Daudmannsøyra in 1988 and 1989, and Kaffiøyra–Svartfjellstranda in 1990 (Internal Reports of Polar Marine Geological Expedition, Lomonosov, 1984, 1988, 1989 and 1990). Present magnetic measurements covered all strandflats, extending ca. 4 km east of the graben margin in Daudmannsøyra. The total survey area covers 224 km² at a map scale of 1:25,000.

Survey methods

The magnetic profiles crossing the strandflats from the piedmont to the coast in an E–W direction were placed every 250 m and tie lines (N–S directed) were spaced every 1 km. The measurements were carried out every 25 m on the lines. Proton magnetometers were used. The precision of the measurements is ± 2.6 – 3.5 nT.

Temporal variations were measured in comparison with the measurements made by the base-stationed magnetometer. The variations of 100–200 nT were recorded during 80% of the working days. Synchrony of the measurements with the base- and field magnetometers was determined every day and necessary corrections of the field measurements were made by a graphic method.

Processing the surface measurement data included, besides the correcting of temporal variations, the unification of relative level, the construction of anomalous magnetic field graphs, and the tying of the observations of 1988 and 1989, which were based on the repeated measurements.

The construction of the graphs and isolines was carried out automatically with the aid of processing programmes for aero-geographical data modified for surface magnetic survey on a computer ES-1036 (Srebnij et al. 1985). The programme includes correction for the normal field, field interpretation into uniform net nodes by calculation of the average-weighted value, and field-tying by the method of filtrating different parameters. Original maps of graphs and isolines were constructed at the scale of 1:25,000 in the Gauss-Kryuger projection. The contour interval is 10 nT, locally 1, 3 or 5 nT in Sarsøyra. An evaluation of the error of map construction was made on the matrix points, the coordinates of which coincide with the observation points and are equal to 1.2 nT.

Magnetic property of the rocks

In order to determine the density and magnetic properties of the rocks, measurements of rock magnetic susceptibility were performed for 270 samples and at more than 2,000 outcrops.

Six rock types have been recognised in the measured samples:

- 1) Mesozoic dolerites, 28 samples;
- 2) serpentinites, 17;
- 3) metabasic rocks, chlorite- and chlorite-car-

- bonate phyllites and metasomatic rocks (e.g. green-brown dolomites) together, 102;
- 4) quartz-sericite phyllites and other psammopelitic phyllites, 30;
- 5) carbonate rocks, 56;
- 6) quartzites, sandstones and conglomerates, 37.

Fig. 2 shows the correlation of density (d) and magnetic susceptibility (χ) of the samples. The samples generally plot in two fields: a “non-magnetic” field with as much as 10×10^{-6} SI and a “magnetic” field exhibiting 40 – $1,000 \times 10^{-6}$ SI fields. Some rocks plot in the intermediate field, 10 – 40×10^{-6} SI. The rocks of types 1 and 2 are in the “magnetic” field. The rocks of type 3 plot widely over all fields. The reason is that the metasomatic rocks of type 3, i.e., green-brown dolomites (listvenites of Teben'kov & Korago 1992), identified in the field are not all metasomatic green-brown dolomites, but actually common sedimentary dolomites which have lower magnetic susceptibilities. Those having more than 50×10^{-6} SI in type 3 are rich in magnetite.

All rocks of types 4, 5 and 6 fall in the “non-magnetic” field.

Among the rocks of anomalously high magnetic susceptibility, more than 70×10^{-6} SI, the dolerites of type 1 have high densities (2.95 – 3.10 g/cm³), whereas type 2 serpentinites have low densities (2.50 – 2.70 g/cm³). The metabasic rocks and metasomatic rocks of type 3 have intermediate densities between dolerites and serpentinites. The magnetic susceptibility of serpentinites of type 2 (17 samples) varies from 45×10^{-6} SI to more than $1,000 \times 10^{-6}$ SI, indicating a wide variation of lithology.

Three types of rocks in this area can potentially cause a high magnetic anomaly: (1) Mesozoic dolerites, (2) serpentinites and (3) green rocks including magnetite-bearing chlorite phyllites and chlorite-carbonate phyllites, metabasic rocks and metasomatic green-brown dolomites. It is noteworthy that the magnetic susceptibilities of the high-pressure metamorphic rocks such as glaucophane schists and eclogites of Motalafjella, which are not shown in Fig. 2, generally have low values, i.e., 4 – 8×10^{-6} SI.

Modelling of magnetic source body

The depth of the magnetic source has been estimated using a variety of methods (Volk et al. 1973; Logačev & Zacharov 1980). The main

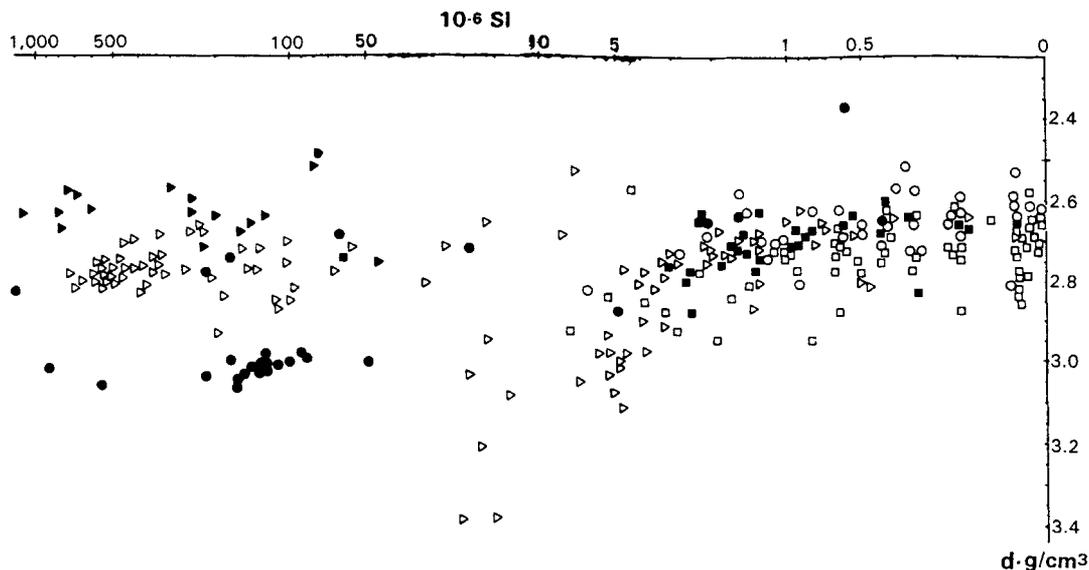


Fig. 2. Plot of magnetic susceptibility (χ) and density (d) of the basement rocks, younger clastic sedimentary rocks and Mesozoic dolerites. Legend: solid circles = Mesozoic dolerites (type 1), solid triangles = serpentine (type 2), open triangles = metabasic rocks, chlorite- and chlorite-carbonate phyllites and metasomatic rocks (e.g. green-brown dolomites, type 3), solid squares = quartz-sericite phyllites and other psammo-pelitic phyllites (type 4), open squares = carbonate rocks (type 5), open circles = quartzites, sandstones and conglomerates (type 6).

method is known as the "half-slope" method of Peters (1949), based on assumption that the anomalies can be modelled by an isolated simple body of uniform magnetisation. Another method widely used in the Arctic (e.g. Åm 1975; Kovacs & Vogt 1982) assumes that a source is either a two-dimensional dyke or the edge of a body. Model calculations of the magnetic sources and parameters of the causative magnetic bodies were performed for some selected profiles.

Observed outcrops of the three possible causative rocks around the present area are not more than 50 m in width which indicates that they are small bodies. The average size of the magnetic rock bodies, estimated from local anomalies of the present area, corresponds roughly to the observed outcrop sizes. In Sarsøyra, actual magnetic sources were approximated by near vertical or steep dipping, plate-shaped magnetic bodies of various thicknesses (Fig. 3). All anomaly sources inferred from the model calculations are near the surface with their tops at approximately 30 m depth and their bottoms in a range of up to 100 m depth. Only bottoms of two estimated sources in Svartfjellstranda reach 120–130 m below the surface.

Results of magnetic anomaly measurement

All strandflats from Engelskbukta to Isfjorden generally have slightly positive or quasi-normal magnetic anomalies (Fig. 4a–d). The distinctive features superimposed on this background are N–S to NNW–SSE trending, high-gradient linear anomalies of predominantly positive nature. These linear anomalies persist across the entire measured area, though local differences are also distinguished in each strandflat. The specific nature of the magnetic anomaly patterns is described below from north to south, with reference to the mapped bedrock geology. To avoid repetition, the discussion and interpretation are arranged in separate chapters with references to each of the strandflat areas.

Sarsøyra (Figs. 4a and 5a)

Magnetic characteristics. – The background of the magnetic anomaly in Sarsøyra consists of gentle anomalies from +20 to –20 nT and of scattered small highs of up to 40 nT, interrupted by N–S to NNW–SSE elongated wide oval zones, 700–900 m

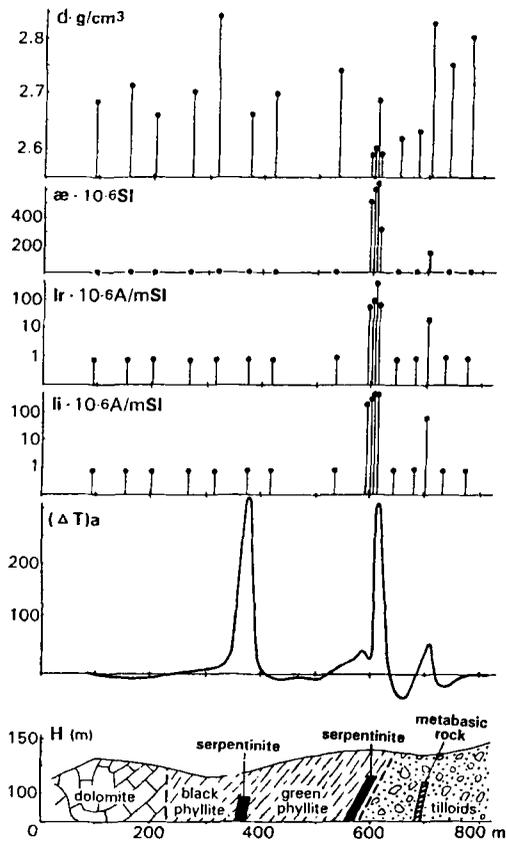


Fig. 3. Measured data and a calculated profile of source rock bodies along the measurement line in northern Sarsøyra (location A–A' shown in Fig. 4a). Ir = remnant magnetisation; Ii = induced magnetisation.

wide and 2 km long, displaying positive anomalies of 80–120 nT.

The most characteristic features are a distinctly high gradient, up to 60 nT/m, and N–S and NNW–SSE trending positive segments of 25–200 m width with 100–1, 150 nT (the highest is local and not shown in Fig. 4a). These segments comprise wide zones.

A 200–500 m wide zone is recognised along the eastern piedmont for ca. 10 km, in a 340° direction (eastern high anomaly zone: EHAZ in Fig. 5a). This zone consists of many high positive anomaly segments with steep gradients. The segments form a double alignment to the west of Arthurbreen. Narrow negative anomaly segments separate the positive anomaly segments in the northern and southern parts of the double alignment. The high anomaly segments show a left-stepping *en echelon* alignment in the west of Arthurbreen to unnamed

glacier A, and a similar tendency can be seen in the west of Dahltoppen. A possible sinistral fault displacement between the segments can not be excluded at the latter locality.

Distinct terminations of the high anomaly segments occur in front of the unnamed glacier B along a NE–SW line. Similar, but less distinct discontinuity along an E–W line occurs to the west of the unnamed glacier A.

A large, gentle, open high anomaly area occurs to the west of Arthurbreen (Fig. 4a), west of the EHAZ, elongated parallel to the EHAZ, and its eastern side is marked by a steep anomaly gradient.

A less distinct, high anomaly zone is recognised in the middle of Sarsøyra with a 345° direction (middle high anomaly zone: MHAZ in Fig. 5a) and consists of 2 or 3 high-anomaly segments in its northern and southern parts. A large, open, gentle high anomaly area occurs in the middle of the MHAZ (Fig. 4a) and its eastern margin has a relatively steep anomaly gradient. This margin trends parallel to the MHAZ, though it shows a left-stepping alignment. The southern end of this zone is abruptly terminated, and a sudden bend occurs at one of the high anomaly segments.

Another high anomaly zone occurs in the western part of Sarsøyra with a 330° direction (western high anomaly zone: WHAZ in Fig. 5a) and includes more than 15 high anomaly segments. Some segments show sudden bends or terminations NE of Sarsbukta along an ENE–WSW trending line which seems to be continuous to the southern termination of the MHAZ.

Some linear high anomalies may be deduced across the lagoon at Sarstangen (Fig. 4a), but these are not certain due to the limited number of measurement lines. A high anomaly enclosed by a curved negative anomaly segment occurs at SE Sarsbukta. Since it is located on the coast, its trend is unknown.

Geological evidence. – Surface geological maps show that almost all observed rocks of high magnetic susceptibility occur in the high anomaly zones. The western margin of the EHAZ generally coincides with the Tertiary-basement boundary in its northern half. In the south, the EHAZ extends into the basement rocks and follows the eastern boundary fault of the Late Ordovician to Mid-Silurian succession. A thin serpentinite and a conglomerate occur along the boundary fault within the southernmost high

anomaly segment. The Tertiary-basement boundary, which has not been determined as either a fault or an unconformity, is located approximately 1 km west of the southern part of the EHAZ, and no magnetic expression of the boundary has been obtained.

In the MHAZ, occurrences of two green phyllites and a green-brown dolomite fit with the high anomaly segments in its southern part, but no

basement exposure has been found in the north. Tertiary sandstones occur along the coast in the north and the change of bedding trends suggest a fault around the northernmost part of the MHAZ.

Two isolated exposures of green phyllite and a green-brown dolomite are located in the middle part of the WHAZ. An isolate green-brown dolomite occurs at the high anomaly location of SE Sarsbukta.

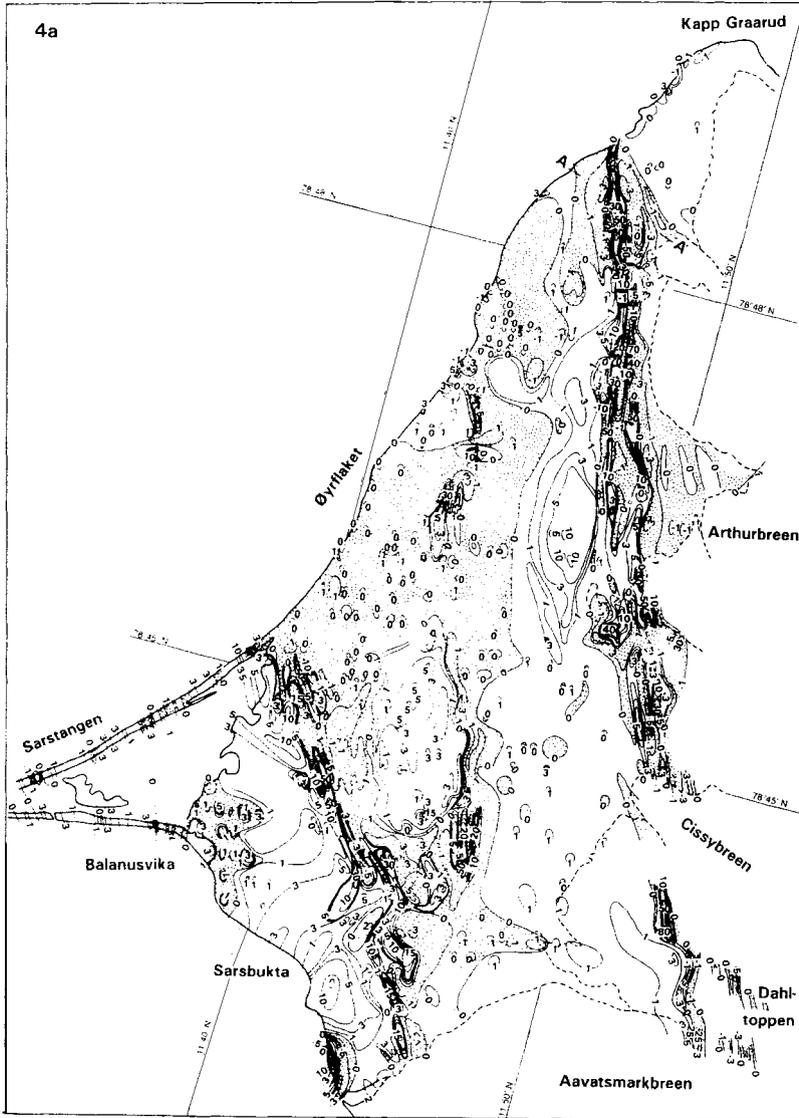
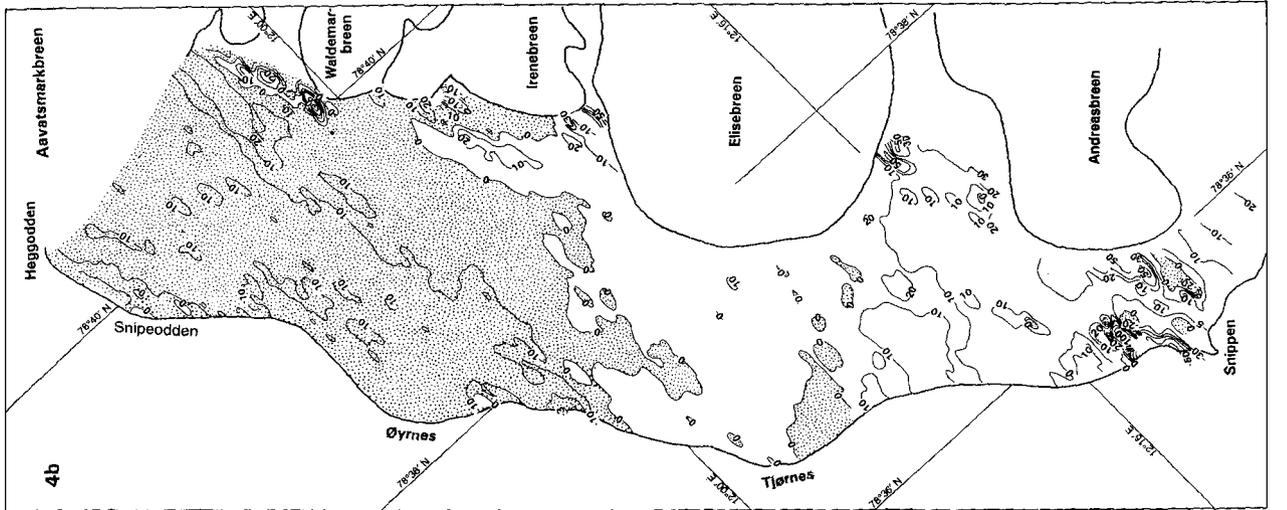
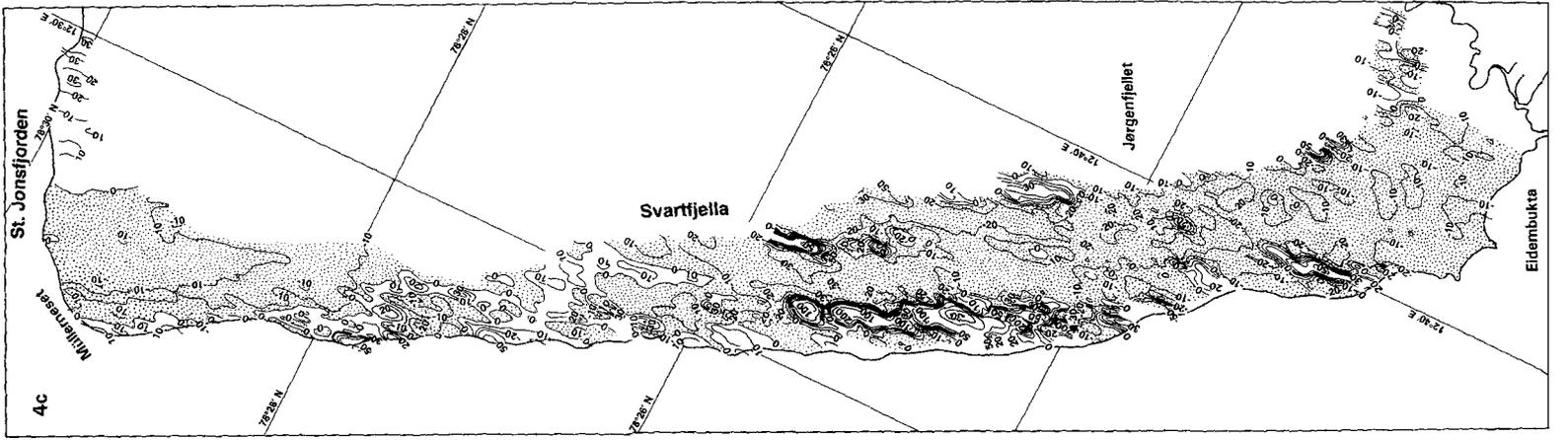
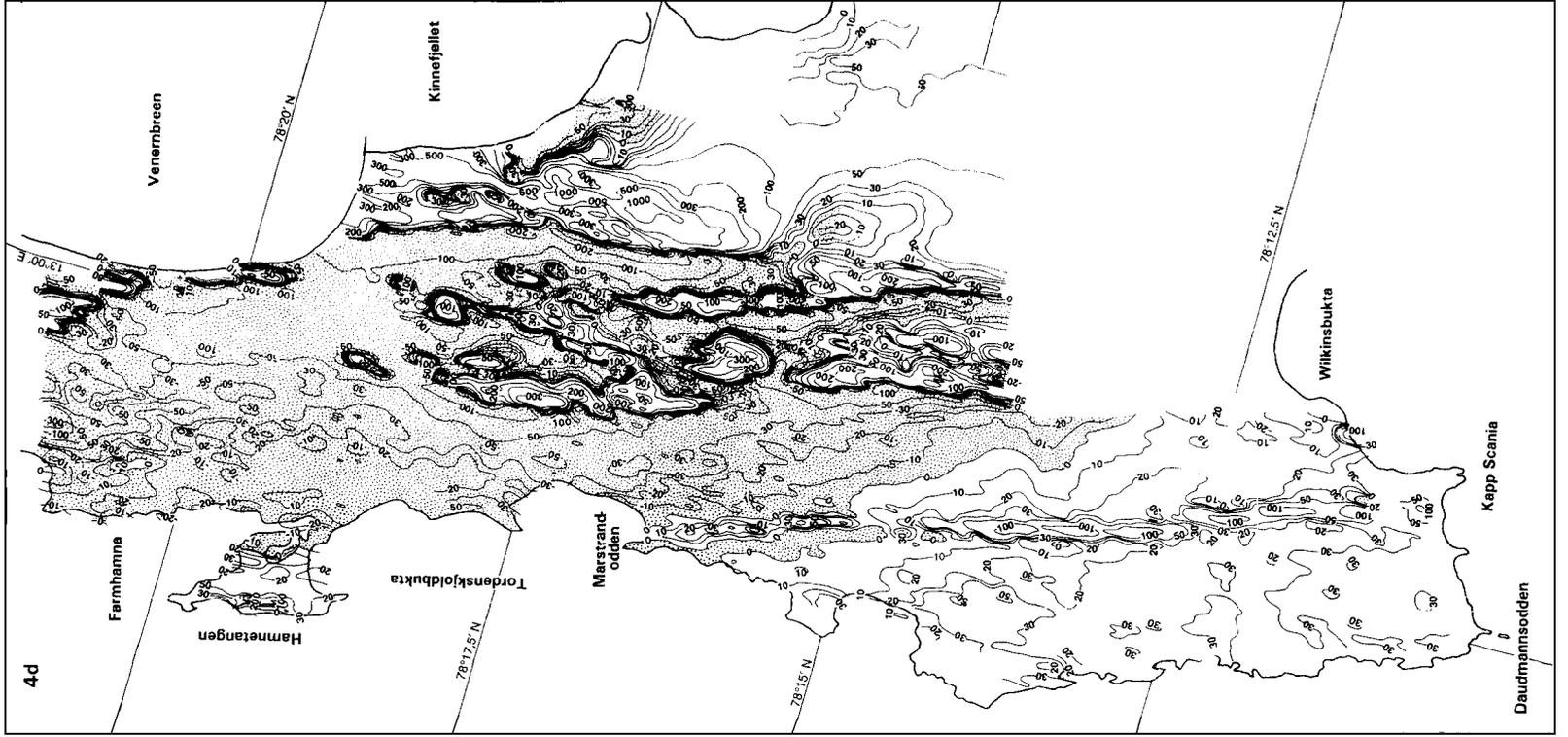


Fig. 4. Magnetic anomaly maps of the strandflats. Legend: numbers on contours = nT, dotted areas = negative anomaly areas, dashed lines = margins of glaciers, moraines and 100 m contours. 4a: Sarsøyra. A-A'; profile line of Fig. 3. 4b: Kaffiøyra. 4c: Svartfjellstranda. 4d: Daudmannsøyra.



The base of the Tertiary sediments at Sarstangen is ca. 800 m below the surface. The Quaternary deposits on the strandflat are estimated to be several metres in thickness, deduced from the coastal exposures, and are probably underlain by Tertiary sediments in the middle and western parts of the strandflat.

Interpretations. – The coincidence of the high magnetic anomaly segments and observed localities of the rocks with high magnetic susceptibility on the strandflat supports that these rocks are solid exposures, but not glacial erratics.

Superposition of the EHAZ and observed faults along the piedmont indicates that the high anomaly zones are magnetic expressions of faults underlying the Quaternary cover. Relatively ductile green phyllites, serpentinites and sheared green-brown dolomites are supposed to be squeezed up along the faults.

The estimated magnetic source bodies shown in Fig. 3 are in accordance with this interpretation. The shapes of the calculated bodies are 60–80° W-dipping plates, 10–60 m thick, their tops at 0–30 m and their bottoms at 18–100 m depth. Estimated efficient magnetisations, $300\text{--}850 \times 10^{-6}$ SI, are in the range of measured magnetic susceptibilities of the possible causative rocks.

General left-stepping *en echelon* alignment of the high anomaly segments within the EHAZ may indicate a dextral slip movement at a certain time during the complex movements along the eastern marginal fault of the Tertiary Forlandsundet Graben. The distinct bends and terminations of the high anomaly segments suggest later transverse faults which displaced the N–S and NNW–SSE trending faults.

Kaffiøyra (Figs. 4b and 5b)

Magnetic characteristics. – The magnetic field of this strandflat is quiet, near-normal, predominantly negative in the northwest and positive in the south and east.

Small segments of high positive anomaly occur along the piedmont, forming five clusters from NW to SE. Most segments tend to show roughly NS elongation.

Three segments of high anomaly, up to more than 200 nT, occurring to the west of Waldemarbreen, form a short zone (NHAZ in Fig. 5b). A high anomaly segment, up to 200 nT (local and

not shown in Fig. 4b) to the NNW of Snippen on the southern coast is associated with one or two negative anomaly segments with steep gradients. These can be assigned as a short zone (SHAZ in Fig. 5b). The minimum magnetic susceptibility estimated for the causative rocks is ca. 360×10^{-6} SI which is conformable with the measured susceptibility of more than 500×10^{-6} SI from the rock samples of green phyllites of this area.

The other clusters of high anomaly within the area from W of Irenebreen to SW of Andreasbreen are isolated and their relations are uncertain, but they could be included in a faint high anomaly zone (FHAZ in Fig. 5b).

Geological evidence. – The mountains east of Kaffiøyra consist of thick tilloids in their higher parts, with a general cleavage striking NW–SE and dipping moderately SW. A succession of dominantly grey and black phyllites, with frequent intercalations of marbles, green phyllites and occasional metabasic rocks (meta-diabase and -gabbro) occurs along the piedmont, and these rocks are in contact with the Tertiary rocks to the west. The Tertiary sediments are supposed to underlie ca. two-thirds of the western part of the strandflat (Wojcik 1981). They have subparallel strikes and steep W-dips near the boundary to the basement, while they are in ENE–WSW to ESE–WNW strikes and moderate N dips along the western coast.

Several green phyllite exposures have been observed immediately east of the Tertiary-basement boundary in the west of Waldemarbreen, which coincides with the western margin of the NHAZ. A few serpentinite lenses and green and purple phyllites are incorporated in a wide shear zone along the Tertiary-basement boundary NW of Snippen, which is superposed by the SHAZ.

Many lenses of green phyllites and metabasic rocks occur at the locations of high anomaly segments along the piedmont from the west of Irenebreen to the northwest of Andreasbreen. A serpentinite locality has been reported in front of Irenebreen. In SW of Andreasbreen, some marble lenses occur along the steep magnetic anomaly slopes.

Interpretation. – The weakly negative magnetic field in the western half of the strandflat can be explained by a thick Tertiary cover consisting of rocks with low magnetic susceptibility.

The NHAZ and the SHAZ are explained as

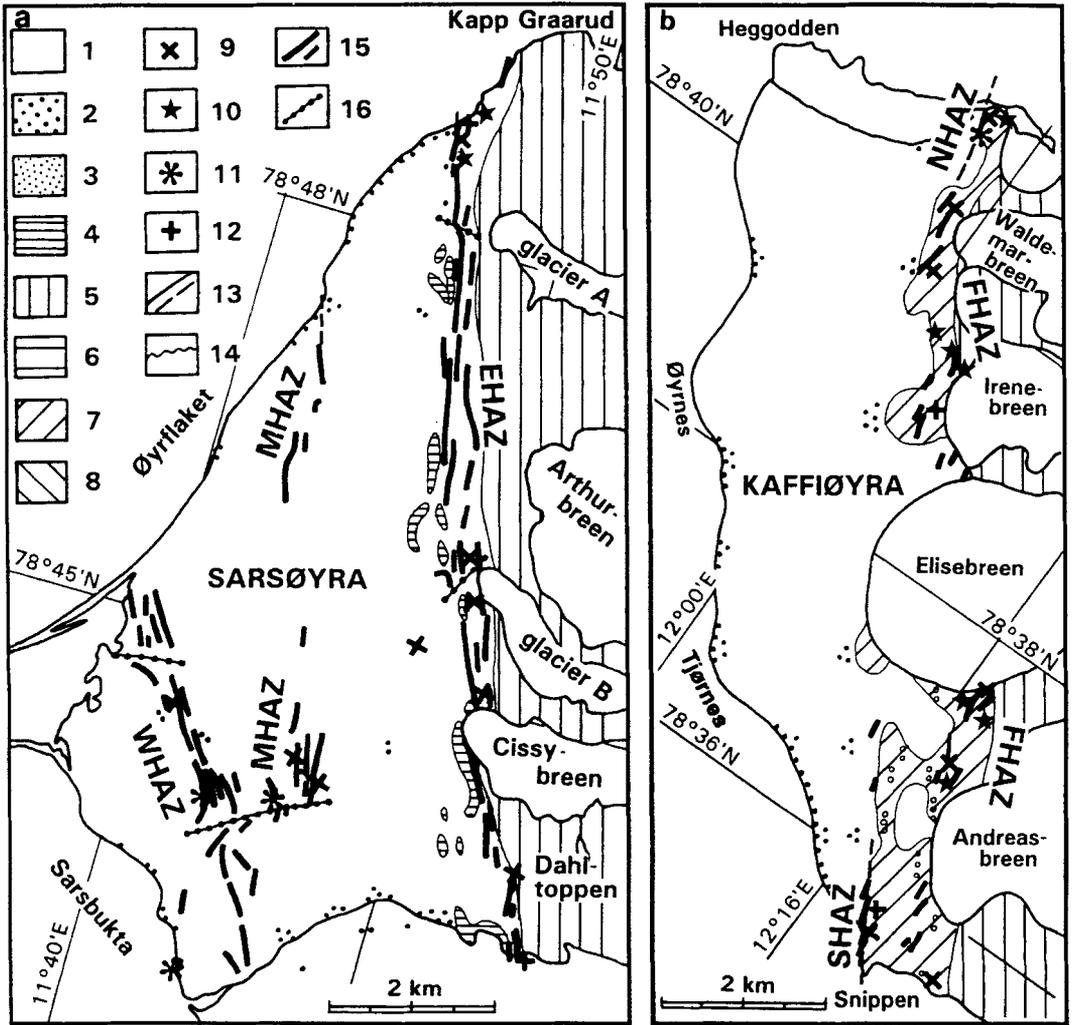
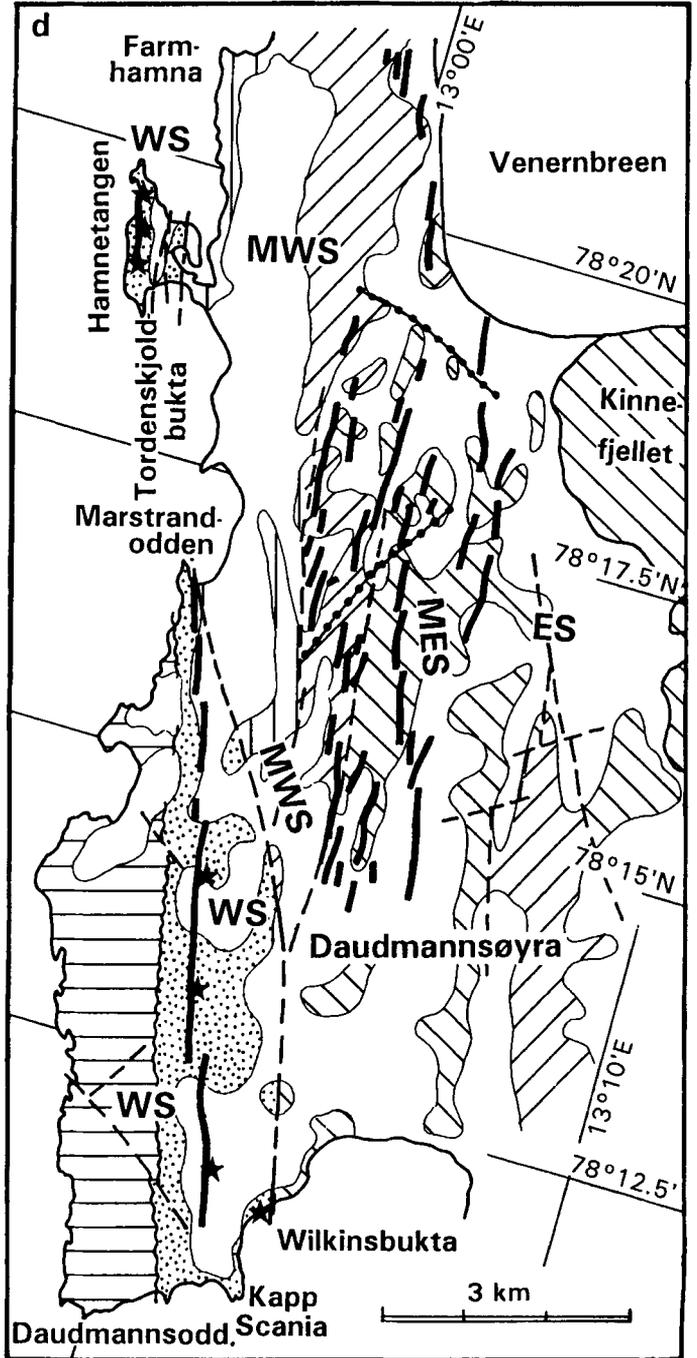
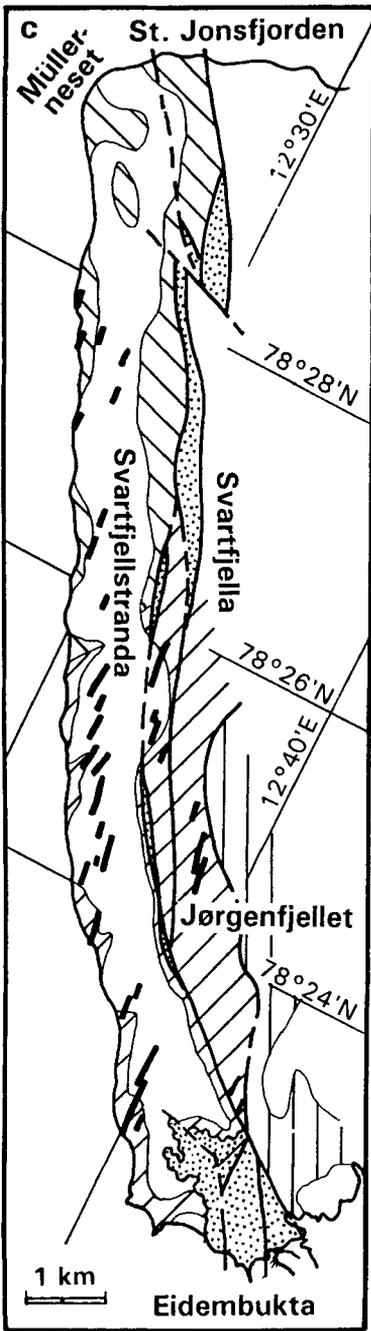


Fig. 5. High magnetic anomaly segments and zones. Legend: 1 = Quaternary cover of the strandflats, 2 = Tertiary exposures, 3 = Carboniferous rocks, 4 = Late Ordovician–Middle Silurian succession, 5 = Vendian tilloids, 6 = Late Proterozoic succession, 7 = marble–phyllite succession, 8 = quartzite–phyllite succession, 9–12 = isolate localities of rocks with high magnetic susceptibility, 9 = green phyllites, 10 = Mesozoic dolerites, 11 = green-brown dolomites, 12 = serpentinites, 13 = observed and estimated faults, 14 = unconformities, 15 = high positive anomaly segments, 16 = later transverse faults deduced from the bends and sudden terminations of high anomaly segments.

5a. Sarsøyra. EHAZ = eastern high anomaly zone; MHAZ = middle high anomaly zone; WHAZ = western high anomaly zone. 5b. Kaffiøyra. NHAZ = northern high anomaly zone, three segments of high anomaly, up to more than 200 nT, occurring to the west of Waldemarbreen and forming a short zone.

SHAZ = southern high anomaly zone, negative anomaly segments with steep gradients assigned as a short zone and associated with a high anomaly segment, up to 200 nT (local and not shown in Fig. 4b) to the north–northwest of Snippen on the southern coast.

FHAZ = a faint high anomaly zone, which includes other isolated clusters of high anomaly within the area from west of Irenebreen to south-west of Andreasbreen. Small circles: metaconglomerates.



5c. Svartfjellstranda.

5d. Daudmannsøyra. WS = western subarea. MWS = middle-western subarea. MES = middle-eastern subarea. ES = eastern subarea.

magnetic expressions of the Tertiary-basement boundary shear zones. Both show a left-stepping alignment of the high and low anomaly segments within the zones. Their continuation in the middle part of the strandflat is not clear, but a weak alignment of small high and low anomalies for ca. 5 km NW from Snippen and the 0 anomaly contour line to the west of Irenebreen (Fig. 4b) are supposed to reflect the position of boundary on the surface.

Discontinuous, high anomaly segments along the piedmont in the FHAZ, are caused by magnetite-bearing green phyllites and metabasic rocks in the marble-phyllite succession. The FHAZ indicates the distribution of this succession. A serpentinite occurrence west of Irenebreen may indicate a fault. A NW–SE trending, narrow quiet area occurs between the SHAZ and the FHAZ, to the west of Andreasbreen. Several impersistent meta-conglomerates have been observed in this area together with marbles. This conglomerate-bearing part seems to have no rocks of high magnetic susceptibility and has been considered as the Late Ordovician–Middle Silurian succession by some geologists (A. Hjelle, pers. comm. 1995). Discontinuities between the clusters of high anomaly segments within the FHAZ may indicate the positions of transverse faults similar to those suggested by Wojcik (1981).

A distinct N–S trend shown by the -10 nT contour in the magnetically negative area of the northwestern part of the strandflat (Fig. 4b) may indicate the general structural trend of the underlying basement.

Svartfjellstranda (Figs. 4c and 5c)

Magnetic characteristics. – Short and narrow anomalies up to 50 nT are scattered in a relatively quiet magnetic field in the northern half of this strandflat, north of ca. N78°26'. In contrast, in the southern half, distinct high-anomaly segments, up to 200 nT, are aligned in a left-stepping *en echelon* zone at 335° direction along the western coast. The minimum magnetic susceptibility estimated from the most intense anomaly of this strandflat does not exceed 100×10^{-6} SI. The low intensity anomalies in this area give deeper calculated bottoms of magnetic source bodies, 120–130 m beneath the surface, than those of Sarsøyra and Kafføyra.

A NW–SE alignment of three N–S striking, high-anomaly segments occurs in the east along

the piedmont between N78°25' and 26'. Two clusters of high anomaly segments occur further east south of N78°25'.

Geological evidence. – A narrow graben with Carboniferous quartzites, shales and limestones, which is considered to be the eastern margin of the Tertiary Forlandsundet Graben, occurs along the western slope of Svartfjella to the strandflat southwest of Jørgenfjellet, keeping a 1.3–1.5 km distance from the coast (Ohta 1988). The Carboniferous rocks occur as a half-graben in the northern coast of Eidembukta, showing an unconformity in the west and a steep fault in the east. The basal conglomerate locally has a hematite matrix.

To the west of the graben occur low-grade metamorphic rocks, observed at scattered exposures along streams under marine terrace deposits and along the western coast (Berg et al. 1993). Psammo-pelitic phyllites and quartzites occur in the northern part, striking ca. 330° and dipping moderately to steeply, showing repetitions by folding. These rocks have a garnet-biotite assemblage within the northernmost 3 km from Müllerneset (Ague & Morris 1985).

To the south of N78°25', similar phyllites and quartzites are exposed along the coast and are associated with some marbles and green phyllites, showing roughly N–S strike.

The area between two margin faults of the Carboniferous rock graben between N78°24' and 26' consists of a marble-bearing phyllite succession with steep to vertical dips. The same succession occurs to the east of the graben as south as N78°23' with subvertical dips, suggesting repetition by folding. South of N78°23' occur phyllitic tilloids, meta-sandstones and some marble lenses.

Interpretations. – Intense high magnetic anomaly segments in the southern half, to the west of the Carboniferous rock graben, are thought to have been caused by frequent occurrences of green phyllites with magnetite in a marble-quartzite-phyllite succession. The boundary between this succession and the northern quartzite-phyllite succession without green phyllites could not be drawn by surface mapping due to poor exposure, but the magnetic pattern gives its approximate position at around N78°26'.

The elongation trend of the high anomaly segments along the coast in the southern half is

subparallel with the observed fold axes, weakly oblique to the trend of the alignment in a 330° direction. This may represent refolded green phyllites in the marble-quartzite-phyllite succession. An older steep fold limb striking 330° was folded into younger folds with a N-S axial trend.

The high anomaly segments between the faults bounding the Carboniferous rock graben show a left stepping arrangement which may suggest folds with a N-S axial trend, produced by a sinistral transpressive component of the fault movements.

The marble-phyllite succession to the east of the graben has some high anomaly clusters caused by green phyllites. The tilloid succession in the southeast shows a relatively quiet magnetic field.

The western marginal fault of the Carboniferous rock graben can locally be recognised as the terminations of high anomaly clusters in the east between $78^\circ 25'$ and $78^\circ 26'$, but it has no magnetic expression along large parts of its surface trace. The basal conglomerate of the Carboniferous succession with a hematite matrix also shows no magnetic anomaly.

Daudmannsøyra (Figs. 4d and 5d)

Magnetic characteristics. – Four subareas are recognized on the magnetic anomaly map of Daudmannsøyra. The western subarea (WS in Fig. 5d), west of the Wilkinsbukta–Marstrandodden line and Hamnetangen, is characterised by gentle positive anomaly gradients, having a narrow, straight high anomaly zone, ca. 200 m wide, with more than 30 nT (local max. 350 nT, not shown in Fig. 4d).

The middle-western subarea (MWS in Fig. 5d) extends for ca. 2 km from the east of Farmhamna to the south and wedges out to the NW of Wilkinsbukta. It shows negative anomalies with gentle gradients.

The middle-eastern subarea (MES in Fig. 5d) is shown in the middle of Fig. 4d, and has many distinctly high anomalies more than 100 nT (local max. 2,500 nT, not shown in Fig. 4d) with steep gradients, separated by negative fields. The clusters of high anomalies abruptly terminate, or probably displace dextrally in the SW of Venernbreen, along a WNW–ESE line. Another line of discontinuity of high anomaly segments, but with a sinistral displacement, can be recognised ca. 2 km east of Marstrandodden in the middle of high-anomaly-clustered area. These

two lines are located roughly at the positions where later faults have been estimated by the surface mapping (Ohta et al. 1992).

The eastern subarea (ES in Fig. 5d) shows wide high and low anomalies with gentle gradients. A wide negative anomaly area in western Kinnefjellet (Fig. 4d) shows a steep gradient at its western margin, but the over-all shape of this has not been measured.

Geological evidence. – The eastern margin of the Tertiary Forlandsundet Graben in this area is a narrow half-graben filled by Carboniferous rocks. The west side of the half-graben is a moderately E-dipping unconformity, with a basal conglomerate having a hematite matrix. The eastern margin is a steep fault, which extends to the middle of Hamnetangen in the north (Ohta 1988).

Mesozoic dolerites are exposed within the Carboniferous rock areas, at four localities in western Daudmannsøyra and at three localities in Hamnetangen (Ohta et al. 1992).

The area west of the half-graben contains thick marbles and pelitic phyllites, showing repeated folds with steep axial surfaces with strikes of 340 – 350° . This succession has been considered Late Proterozoic (Ohta et al. 1992).

A ca. 1 km wide area in the east of Farmhamna and Tordenskjoldbukta consists of phyllitic tilloids.

To the east of the tilloids, a 1 to 3 km wide zone is composed of psammo-pelitic phyllites with many marble layers. West of Kinnefjellet and Holtedahlvarden (ca. 2 km south of Kinnefjellet), another ca. 1 km wide zone consists of phyllites with quartzite layers. This quartzite-phyllite succession has a gentle W-dipping structure and underlies widely in the eastern part of Daudmannsøyra. The lower part of the marble-phyllite succession and some parts of the quartzite-phyllite succession in the mountains to the east contain green phyllites and metabasic rocks. e.g. weakly metamorphosed gabbros.

Interpretations. – Six of the seven localities of the Mesozoic dolerites are located in the linear high anomaly zone within the half-graben containing the Carboniferous rocks. A gabbro-diorite mass occurs at the isolated magnetic high on the western coast of Wilkinsbukta, along the eastern marginal fault of the half-graben. The dolerites, having high magnetic susceptibility (Fig. 2), are the causative rocks of this high anomaly zone.

Small sinistral displacements of this high anomaly zone can be seen at ca. 3 km north of Kapp Scania and at ca. 1.5 km south of Marstrandodden. These may suggest faults formed after the emplacement of the dolerites. The basal conglomerate of the Carboniferous with a hematite matrix does not show any magnetic expression.

The Late Proterozoic phyllite-marble succession appears as a gentle positive anomaly area of the WS. The tilloids and a part of the marble-phyllite successions reveal gentle negative anomaly areas in the MWS and the MES. A relatively intense negative anomaly area in the northernmost MWS (Fig. 4d) can be explained by the presence of an open synform of thick marbles which have low magnetic susceptibility.

Distinctly high anomalies in the MES can be explained by green phyllites and metabasic rocks, having high magnetic susceptibilities of $100\text{--}500 \times 10^{-6}$ SI, intercalated with both marble-phyllite and quartzite-phyllite successions. They probably have steep fold structures. These successions are similar to those in SW Svartfjellstranda. The boundary between these two successions is not distinguishable on the magnetic anomaly map.

Open magnetic anomaly patterns with gentle gradients in the ES suggest gentle structures of the quartzite-phyllite succession, as observed in the eastern mountains. The green phyllites and metabasic rocks there have small vertical thicknesses due to gently dipping structures.

The abrupt termination and interruption of the high anomaly clusters in the MES indicate WNW-ESE and NE-SW striking faults. Faults in these strikes have been observed in the field, displacing the marginal fault of the half-graben.

Conclusions

Three types of rocks from the present area are magnetic with values higher than 40×10^{-6} SI (Fig. 2). Type 1 rocks are Mesozoic dolerites (Ohta et al. 1992), and serpentinites of type 2 and green-brown dolomite of type 3 are affinities of the high-pressure metamorphic suite (Ohta 1979; Teben'kov & Korago 1992). Green phyllites and metabasic rocks of type 3 are members of the marble-(quartzite)-phyllite succession (calcargillo-volcano formation of Hjelle et al. 1979, the Alkhornet Formation of Harland et al. 1979), some belong to the quartzite-phyllite succession

(quartzite-shale formation of Hjelle et al. 1979, the Løvliebreen Formation of Harland et al. 1979). Some are intrusive sills and stocks (Ohta 1985).

The occurrences of these highly magnetic rocks coincide well with those of the high magnetic anomaly zones.

Some subsurface structures and lithologies under the Quaternary cover on the strandflats became evident by the present magnetic survey.

Sarsøyra: Three high magnetic anomaly zones coincide with the observed faults and the occurrences of the rocks of types 2 and 3. These zones are considered magnetic anomaly expressions of subsurface faults or fault zones.

The EHAZ is superposed by the eastern marginal fault of the Tertiary Forlandsundet Graben. Some high anomaly segments in this zone show a left-stepping *en echelon* alignment which suggests a set of synthetic faults produced by a dextral transpressive movement at a certain stage of fault activities.

Some abrupt terminations and bends of the high anomaly segments may have been resulted by younger faults after the formation of the N-S and NNW-SSE trending faults.

Kaffiøyra: Probably due to a thick Tertiary cover, the middle and western parts of this strandflat show a relatively quiet magnetic field. Distinct high anomaly segments occur along the piedmont in the east. The NHAZ and SHAZ coincide with the Tertiary-basement boundary, though the boundary is magnetically very weakly expressed between these two zones in the middle of the strandflat.

The FHAZ along the eastern piedmont corresponds to the distribution area of the marble-phyllite succession containing green phyllites and metabasic rocks. A fault within the zone is suggested by an occurrence of serpentinite. A possible continuation of the NHAZ to the FHAZ can not be neglected.

Svartfjellstranda: The boundary between the marble-(quartzite)-phyllite and the quartzite-phyllite successions is roughly defined by the difference of intensity of high magnetic anomaly segments. The graben consists of Carboniferous rocks along the eastern margin of the Forlandsundet Graben are not expressed by a magnetic anomaly.

Daudmannsøyra: Mesozoic dolerites show a distinct high anomaly zone from Hamnetangen to Kapp Scania.

Both marble-phyllite and quartzite-phyllite successions contain green phyllites and metabasic rocks in this area. As these rocks are highly magnetic, the boundary of these successions cannot be recognised on the magnetic anomaly map. Late Proterozoic and the tilloid successions show relatively quiet magnetic fields. The half-graben with the Carboniferous rocks, which represents the eastern margin of the Forlandsundet Graben, does not show any specific magnetic signature.

Sudden truncations and interruptions of the high anomaly clusters suggest later faults. Faults with similar strikes were observed cutting the fault along the eastern margin of the half-graben.

Field occurrences of serpentinites and green-brown dolomites along the high-anomaly zones in Sarsøyra and Kaffiøyra suggest that these rocks underly the present surface. They are diagnostic members of the thrust sheets, which consisted mainly of the high-pressure metamorphic rocks in Motalafjella (Ohta 1979; Hirajima et al. 1988). Accordingly, the possibility of a distribution of the high-pressure metamorphic rocks as far north as Sarsøyra is suggested. This point will be presented further in a separate article (Ohta et al. in prep.).

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