Northern continuation of Caledonian high-pressure metamorphic rocks in central-western Spitsbergen

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Caledonian low-temperature, high-pressure metamorphic rocks, as first recognised at Motalafjella, central-western Spitsbergen, include characteristic brown dolostone and serpentinite. Similar rocks are scattered in the strandflats, along the eastern marginal fault of the Tertiary Forlandsundet Graben, and along thrust faults to the east on both sides of St. Jonsfjorden. The mineral chemistries of the constituent carbonates and oxides are diagnostic of high-pressure metamorphic rocks, containing high contents of MgO in the carbonates and Cr_2O_3 in the oxides. Based on a surface magnetic-anomaly survey and fault-plane observations, some of these rocks are considered to have been pressed up along faults produced by strike-slip faulting during an early stage of the Forlandsundet Graben formation. The distribution of these rocks indicates that the high-pressure metamorphic rocks extend as much as 50 km to the NNW from Motalafjella to Sarsøyra.

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Introduction

A Caledonian low-temperature, high-pressure metamorphic complex of subduction-zone origin, the Vestgötabreen Complex, occurs south of St. Jonsfjorden, central western Spitsbergen (Horsfield 1972; Ohta 1979; Ohta et al. 1983; Ohta et al. 1986; Hirajima et al. 1984; Hirajima et al. 1988). These rocks occur in a thrust complex and are divided into two units based on their metamorphic grade within the typical exposures in Motalafjella (Fig. 1B).

The high-grade division has chloritoid-garnet-mica schists with eclogite inclusions, glaucophane-garnet-mica schist, eclogitic metagabbros, omphacite quartzite (Kanat 1984; Hirajima et al. 1988), and micaceous, schistose marble. The protoliths are thought to be a deep-sea igneous-sedimentary succession (Ohta et al. 1983). The age of the igneous protoliths for the eclogitic metagabbros is considered to be ca. 1,100 Ma, a Sm/Nd model age, which is possibly an age of mantle derivation (Bernard-Griffiths et al. 1993).

The low-grade rocks are black phyllites with chlorite-sericite assemblages, green phyllites with local pillow and dyke swarm structures and lawsonite-pumpellyite assemblages, limestone and quartzite lenses, and green-brown dolostone with fuchsite. Small tectonic inclusions of serpentinite occur within the dolostone (Ohta 1979; Hirajima et al. 1984; Teben'kov & Korago 1992). The metamorphism is of early Caledonian age (Ohta et al. 1989, Dallmeyer et al. 1990).

Although typical high-pressure metamorphic rocks are restricted to outcrop from Motalafjella to SW Holmesletfjella, green-brown dolostone and serpentinite similar to those in the low-grade unit of the high-pressure complex are found at isolated localities in the western part of Oscar II Land, north of St. Jonsfjorden. The green-brown dolostone with fuchsite is genetically related to the hydration of ultramafic rocks (Teben'kov & Korago 1992) and is easily recognisable in the field. This rock type and associated serpentinite occur at Ankerfjellet, the eastern and southern parts of Kaffiøyra and as far north as Sarsøyra. The last locality is ca. 50 km NNW from Motalafjella. These distinctive rocks follow thrust faults in mountainous areas to the east of the Forlandsundet Graben, but most of those in the strandflat areas within the graben are isolated due to extensive cover of Tertiary and Quaternary sediments.

This paper presents mineralogical evidence to distinguish the green-brown dolostone of the

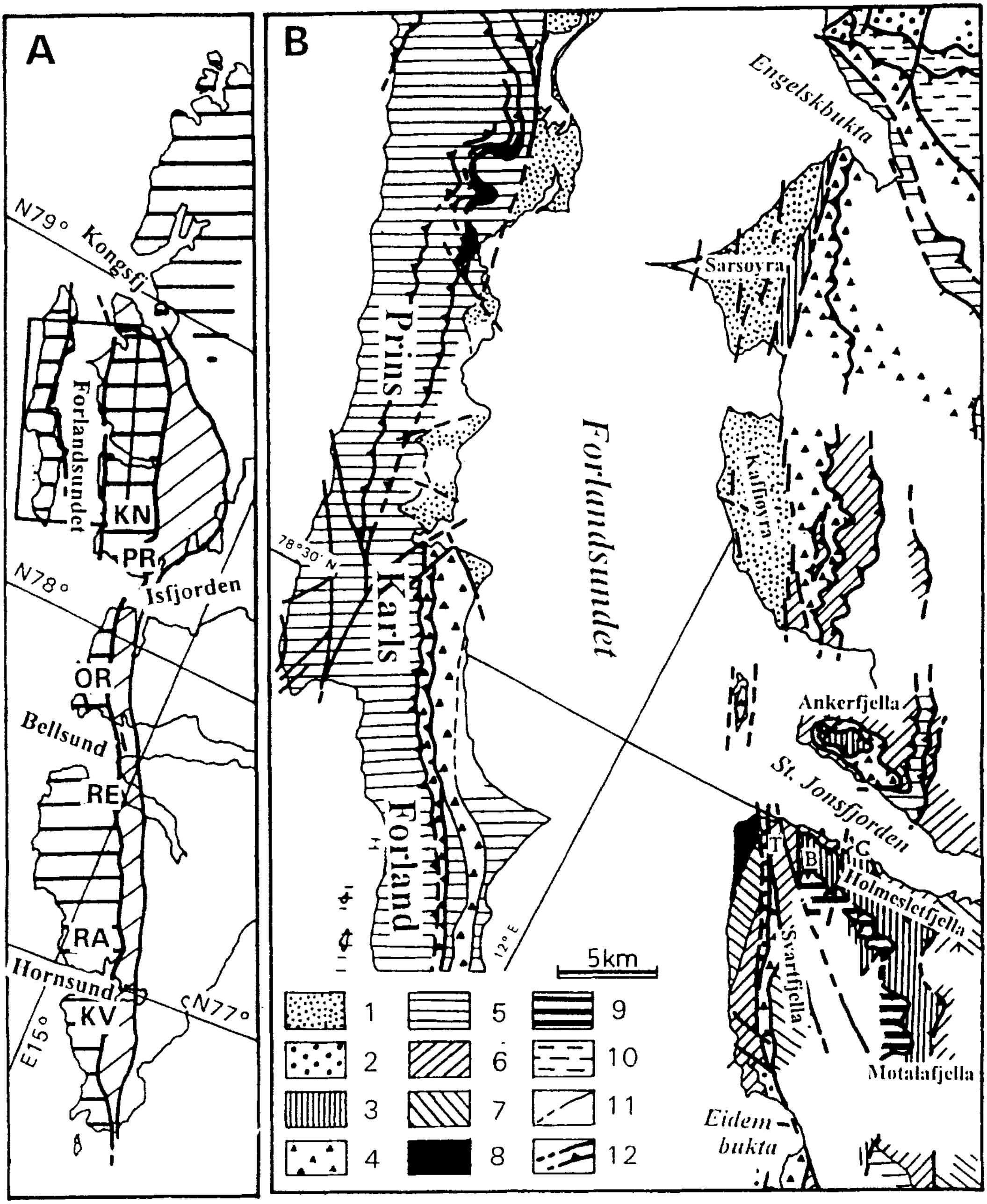


Fig. 1. Generalised geological map around Forlandsundet, from Sarsøyra to Eidembukta, with an index map.

A. Index map, western part of Spitsbergen. Explanation: Obliquely lined, Tertiary fold-thrust zone; horizontally lined, basement rocks. Place names: KN, Kinnefjellet; PR, Protektorfjellet; OR, Orustdalen; RE, Recherchefjorden; RA, Raudfjellet; KV, Kviveodden. The square indicates the area of the map at right.

B. Geological map. Explanation: 1, Tertiary; 2, Carboniferous; 3, Upper Ordovician-Middle Silurian; 4, Vendian tilloids; 5, Late Proterozoic successions, excluding the Vendian tilloids; 6 and 7, St. Jonsfjorden Group; 6, Calc-argillaceous phyllites (Alkhornet Formation); 7, Quartzite and phyllites (Løvliebreen Formation); 8, garnet-biotite schists (the Müllernesset Formation in SW St. Jonsfjorden and the Pinkie Formation at Boureefjellet in Prins Karls Forland); 9, high-pressure metamorphic complex around Motalafjella; 10, schists and gneisses in Brøggerhalvøya; 11, lithological boundary; 12, fault and thrust. The white areas are covered by glaciers. B = Bulltinden, C = Copper Camp, T = Thorkelsenfjellet.

high-pressure metamorphic complex from other carbonate rocks. Their distribution can be correlated with high magnetic-anomaly zones along the eastern margin of the Forlandsundet Graben; these zones reflect the Tertiary fault pattern, which is examined kinematically with respect to the fault-plane observations.

Distribution of the green-brown dolostone and serpentinite

The high-grade unit of high-pressure metamorphic rocks in Motalafjella occurs as a thrust sheet above the low-grade unit, and the latter is unconformably covered by the Late Ordovician-Middle Silurian flyschoids. The low-grade unit and the flyschoids together form an upper limb of an overturned syncline, therefore, the low-grade unit structurally overlies the flyschoid strata (Ohta et al. 1983).

A green-brown dolostone in Motalafjella occurs in the lowest structural position of the low-grade unit, with a thickness of 50–80 m (Hirajima et al. 1984; Teben'kov & Korago 1992), directly in contact with structurally underlying, but younger basal conglomerate, 0–5 m in thickness, of the flyschoid sediments, which contains subangular clasts of the green-brown dolostone and Ordovician gastropods in the matrix (Ohta et al. 1983). A grey limestone occurs structurally below (stratigraphically above) the basal conglomerate, and a thick conglomerate even below this limestone contains boulders of the green-brown dolostone. Some grey limestones form olistostromes in this conglomerate and include Late Ordovician to Middle Silurian corals and gastropods (Scrutton et al. 1976) and conodonts (Armstrong et al. 1986). These rocks and the stratigraphically overlying sandstone-shale succession (Table 1) have been termed the Bulltinden Group and are of flysch origin (Harland et al. 1979). The high-pressure metamorphism has been dated ca. 475 Ma by the $^{40}Ar/^{39}Ar$ and Rb/Sr mica-whole rock methods (Dallmeyer et al. 1990) and is older than the unconformity. This geological relationship is exposed in the two ridges to the north of Motalafjella and southernmost part of Bulltinden (Fig. 1B). The unconformity has locally been disturbed by thrusts.

The overturned syncline of the Late Ordovician to Middle Silurian Bulltinden Group, which occurs to the east of the high-pressure metamorphic rocks, has a moderately west-dipping axial surface. Along the lower limb of this syncline, a thin green-brown dolostone and some black phyllites occur below the grey limestone of the Bulltinden Group on the south-eastern ridge of Holmesletfjella and crop out discontinuously along a thrust on the cliffs from middle-north to north-western Holmesletfjella to Copper Camp (Fig. 1B). The dolostone is thrust over the Alkhornet Formation (areno-argillaceous phyllites and marble layers) of the St. Jonsfjorden Group (Harland et al. 1979; Hjelle et al. 1979; Berg et al. 1993) of probably Middle Proterozoic age. The thrust surfaces have moderate westerly dips at eastern Holmesletfjella and Motalafjella.

Similarly discontinuous outcrops of the green-brown dolostone are found from the northern foothill of Bulltinden to the flat area between Thorkelsenfjellet and Bulltinden, ca. 200 m from the southern shore of St. Jonsfjorden, and their cleavages are almost horizontal (Fig. 1B). On the middle slopes of Ankerfjella on the northern side of St. Jonsfjorden, thin and discontinuous lenses of green-brown dolostone occur along roughly horizontal thrusts on both the southern and northern sides of the mountain, bounding the Vendian tilloids and the St. Jonsfjoden Group below and the conglomerate and shale-sandstone successions of the Bulltinden Group above.

Table 1. Lithostratigraphy in Oscar II Land (modified from Berg et al. 1993).

Paleogene	sandstones, conglomerates
Middle Carboniferous	sandstones, carbonates
Early Devonian	conglomerates
Late Ordvician-Middle Silurian	Bulltinden Group sandstone-shales grey limestones conglomerates
Vendian	Comfortlessbreen Group diamictites (tilloids)
Late Proterozoic	Daudmannsodden Group pelitic phyllites carbonates
Middle proterozoic	Vestgötabreen high-pressure metamorphic complex St. Jonsfjorden Group Alkhornet Formation (carbonate-phyllite succ.) Løvliebreen Formation (quartzite-phyllite succ.)

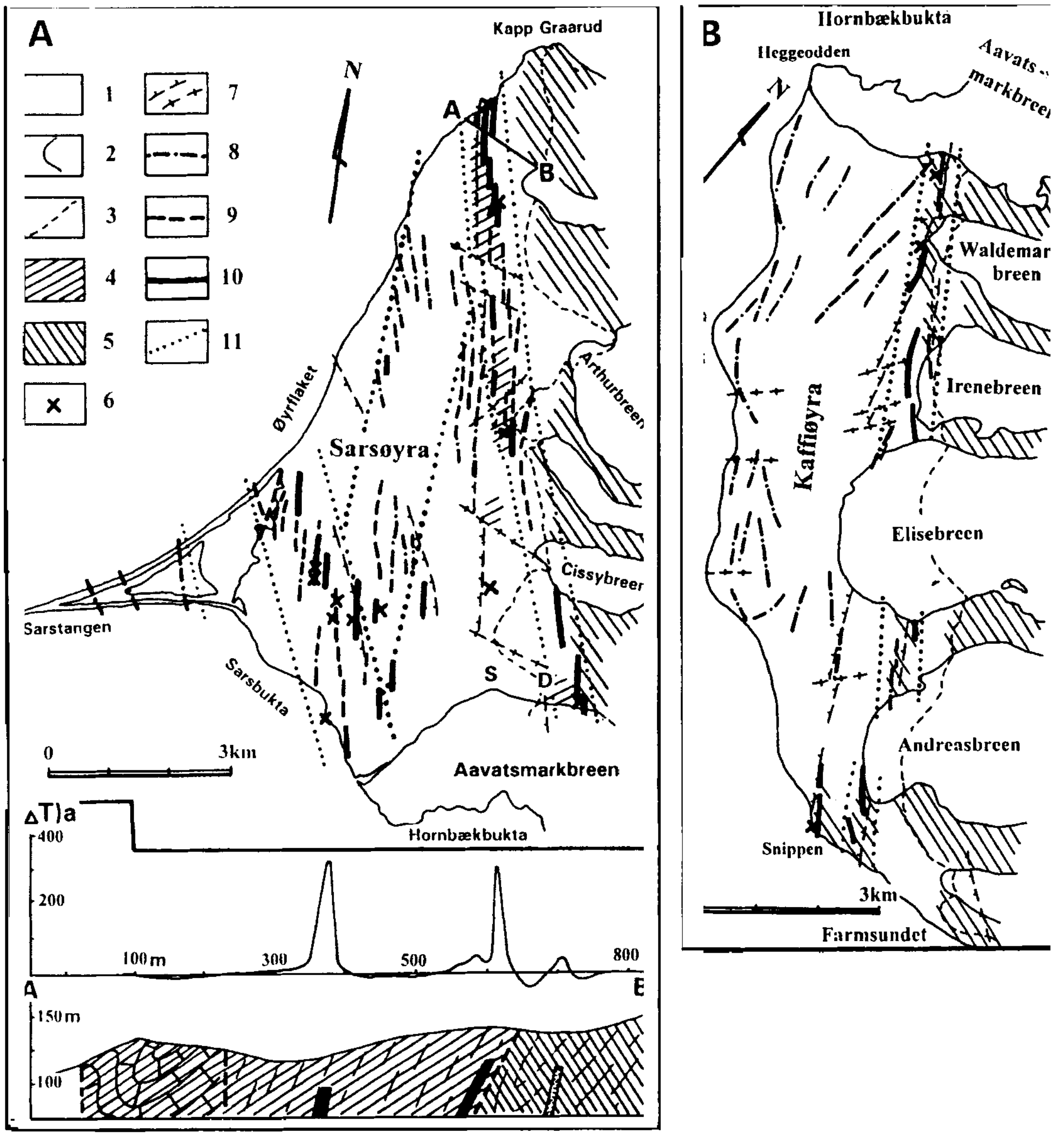


Fig. 2. High magnetic-anomaly segments and zones (simplified from Krasil'ščikov et al. 1995). A. Sarsøyra, with the profile A–B (lower figure), showing calculated magnetic-causative rock bodies: black = serpentinites, dotted = metabasic rock. S and D, refer to Fig. 5.

At Snippen, on the southern coast of Kaffiøyra (Fig. 2B), narrow serpentinite lenses are interbedded with green and purple phyllites within a sheared zone of ca. 100 m width, which bounds the Tertiary sediment to the west. A similar serpentinite and green phyllite assemblage occurs discontinuously along the northeastern foothills of Kaffiøyra. Scattered outcrops of the basement rocks within the Forlandsundet Graben in eastern Kaffiøyra have dips of more than 30° to the east or west with NNW strikes. This structure is distinctly different from complex thrust duplexes which lie to the east of the graben margin fault.

A ca. 1–3 m thick, strongly sheared serpentinite with talc-rich slip planes occurs with a 3 m wide sheared conglomerate adjacent to the east along a river within the northern moraine of Aavatsmarkbreen at the foothills of southeastern Sarsøyra (Fig. 2A). The conglomerate has undeformed quartzite clasts in a greenish brown, weakly phyllitic sandy matrix and is similar to the conglomerates of the Bulltinden Group. To the east of the conglomerate are green phyllites, possibly a member of the Vendian tilloid succession, bounded by a shear zone. To the west of the serpentine are black and green, shaly-sandy phyllites with thin intraformational conglomerate, quartzite and grey limestone layers, the Aavatsmarkbreen Formation of Waddams (1983) and Harland et al. (1993). They considered this formation the uppermost formation of the Vendian tilloid succession, but it is better correlated with the sandstone-shale succession of the upper part of the Bulltinden Group, based on Paleozoic microfossils recently found in massive limestones near northernmost Sarsøyra (Makarjev, pers. comm. 1992). Scrutton et al. (1976) also reported Paleozoic fossils from southern Sarsøyra. The cleavages in these metasediments are steep, 40–70° to the east and west, and many tight folds are expected.

Similar occurrences of serpentinite associated with brown-weathered dolostone lenses have been found along the foothills in eastern Sarsøyra. In addition, seven localities of brown dolostone with green fuchsite clots occur in the middle part of Sarsøyra (Fig. 2A). These green-brown dolostones and serpentinites are considered to be members of the low-grade, high-pressure metamorphic complex, as discussed later.

The thrust sheets comprising the high-pressure metamorphic rocks have moderate west dips in the eastern localities at southeastern Holmesletfjella and Motalafjella, but northwest of Bulltinden and around Ankerfjella they are almost horizontal with gentle open synform structures. These structural features and scattered occurrences of serpentinite and green-brown dolostone in the strandflats suggest that the thrust sheets, including the high-pressure metamorphic rocks, occur in the subsurface of Kaffiøyra and Sarsøyra to the north. The moderate-steep structures of the basement rocks near the foothills were formed by later Tertiary deformations.

Diagnostic minerals of the green-brown dolostone

The green-brown dolostone at Motalafjella is white to grey on fresh surfaces, and is mostly massive with many local thin quartz veins in an irregular network; it has mm-to-cm scale irregular green clots with diffuse margins and scattered opaque grains. Schistose structure, marked by fine-grained layers, is present locally and the cleavages are partly marked by green colour. Local sulphide and ankerite-siderite mineralisations are also seen. Serpentinite bodies of metres to tens of metres size are included in the phyllites and dolostone, commonly enclosed by conformable slip-cleavages.

The dolostone has 10–23 wt% CaO only within or near sheared zones; massive parts have less than 5 wt% CaO (commonly 1–2 wt%) and 23–36 wt% of MgO (Table 2). Thus, this carbonate rock is primarily magnesite-stone that has been modified along the sheared zones into dolostone. Total FeO averages 5 wt%, but locally in the sheared zones this increases to 7% (Teben'kov & Korago 1992).

Table 2. Chemical compositions of rocks and constituent minerals of the green-brown dolostones from various localities.

	ROCK		MINERAL				
	1	2	3	4	5	6	7
SiO_2	12.15	32.80	—	0.03	0.00	0.02	0.25
TiO_2	0.06	—	—	0.02	0.02	0.00	0.04
Al_2O_3	2.51	1.48	3.76	0.01	0.00	0.01	0.01
FeO*	4.34	6.08	—	4.25	4.57	3.66	3.88
MnO	0.14	0.17	—	0.11	0.21	0.04	0.02
MgO	14.86	36.36	44.41	17.61	18.00	46.31	45.23
CaO	26.33	3.16	0.18	30.48	30.50	0.02	0.88
Na_2O	0.72	0.18	—	0.01	0.00	0.00	0.00
K_2O	0.25	0.11	—	0.02	0.01	0.00	0.00
Cr_2O_3	—	—	—	0.08	0.00	0.00	0.00
NiO	—	—	—	0.00	0.00	0.24	0.00
Total	61.36	80.34	48.35	52.62	53.31	50.30	50.31

1, 2 Representative dolostone and magnesite-stone, both from Motalafjella (Teben'kov & Korago 1992).
3–7 New mineral analyses by EMPA; 3, magnesite from Motalafjella; 4 and 5, dolomites from Ankerfjella; 6 and 7, magnesites from Sarsøyra.

Table 3. Chemical composition of fuchsites, new data by EMPA.

	1	2	3	4	5	6
SiO_2	48.42	46.92	48.96	48.04	46.89	46.22
TiO_2	0.05	0.03	0.12	0.11	0.08	0.07
Al_2O_3	27.46	26.12	32.09	30.88	25.39	24.92
FeO*	0.46	0.41	0.53	0.53	0.15	0.27
MnO	0.02	0.02	0.02	0.00	0.00	0.00
MgO	1.61	2.31	1.61	1.69	1.24	1.39
CaO	0.10	0.03	0.05	0.07	—	—
Na_2O	0.18	0.22	0.21	0.23	0.39	0.32
K_2O	7.94	8.03	9.27	9.65	8.58	9.20
Cr_2O_3	9.29	9.06	2.40	2.82	11.81	11.12
NiO	0.15	0.76	0.05	0.01	—	—
Total	95.68	93.91	95.31	94.03	94.53	93.51

1 and 2, from Motalafjella; 3 and 4, from Ankerfjella; 5 and 6, from Sarsøyra.

The analyses of carbonate minerals from massive dolostone of Motalafjella also show pure magnesite with less than 0.2 wt% CaO and 44 wt% MgO (Table 2).

The green mineral is the chromium-bearing, (ca 10 wt% Cr_2O_3) white mica, fuchsite (Table 3). The chromium contents are higher than that of some metamorphic rocks, which have commonly 2–5 wt% of Cr_2O_3, and this is indicative of a close genetic relationship of the fuchsite with an ultramafic rock.

The opaque minerals are chromite, some with more than 48 wt% Cr_2O_3, and chromian spinel (Table 4). The analysed chromites from Motalafjella contain variable amounts of ZnO, 3–18 wt%, especially around the margins of grains. As much as 3 wt% ZnO has been reported from sagvandite in northern Norway (Donath 1931), but 13–18 wt% in the present minerals are exceedingly high. The low Al_2O_3 contents in these minerals show that the Zn is not in the form of spinel or gahnite, but possibly in the form of oxides or sulphides (S has not been analysed). Later sulphide mineralisation in the sheared zones may have partly modified the marginal parts of the chromite. The chromian spinels from Sarsøyra also contain some amounts of ZnO (Table 4). Their host dolostones are from sheared parts with later sulphide mineralisation.

Fuchsite and chromium-bearing minerals, together with magnesite, provide critical evidence for an ultramafic affinity of the dolostone (O'Hara 1967), and they discriminate these rocks from other carbonate rocks of sedimentary origin present in the area.

Carbonate minerals of similar dolostones from Ankerfjella and Sarsøyra have been analysed by an EMPA as shown in Tables 2, 3 and 4. They also have magnesite composition and are associated with chromium-bearing minerals demonstrating that these rocks, scattered as far north as northern Sarsøyra, belong to the high-presure metamorphic complex. The extent of the high-pressure metamorphic rocks is, therefore, about 50 km in a NNW–SSE direction.

Table 4. Chemical compositions of chromites and chromian spinels, new data by EMPA.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	0.50	0.50	0.50	0.50	0.08	0.08	0.59	0.79	0.00	0.03	—	—	—	—
TiO_2	—	—	—	—	0.03	0.04	0.21	0.18	0.04	0.04	—	—	—	—
Al_2O_3	8.06	10.58	9.44	9.06	31.21	29.58	3.09	4.10	28.55	28.95	32.04	28.38	30.94	30.17
FeO*	14.80	29.44	21.93	21.46	14.34	20.25	44.08	43.68	14.36	14.15	14.13	28.03	19.92	20.62
MnO	0.00	0.00	0.00	0.00	0.11	0.28	0.21	0.14	0.12	0.13	—	—	—	—
MgO	0.58	1.72	0.87	0.80	14.60	8.11	0.30	0.30	14.84	15.10	15.81	2.19	9.60	8.19
CaO	—	—	—	—	0.01	0.00	0.04	0.00	0.00	0.00	—	—	—	—
Na_2O	0.00	0.00	0.00	0.00	0.04	0.14	0.14	0.09	0.01	0.00	—	—	—	—
K_2O	0.00	0.00	0.00	0.00	0.03	0.04	0.02	0.02	0.00	0.00	—	—	—	—
Cr_2O_3	53.20	47.96	48.89	51.00	36.99	34.73	44.63	42.35	41.18	41.54	38.87	34.88	36.25	36.20
NiO	0.00	0.00	0.00	0.03	0.09	0.08	0.33	0.51	0.04	0.23	0.24	0.19	0.14	0.00
ZnO	17.96	2.86	13.51	12.94	—	—	—	—	—	—	0.11	6.03	3.55	4.59
Total	94.60	92.56	94.64	95.29	97.53	93.33	93.64	92.16	99.14	100.17	101.20	99.70	100.40	99.77

1–4 from Motalafjella: 1 = rim of chromite; 2 = core of 1; 3 and 4 = homogeneous chromites; 5 and 6, chromian spinels from Ankerfjella.

7–14 from Sarsøyra; 7 and 8 = chromites; 9, 10 and 11 = chromian spinels; 12, 13 and 14 = Zn-rich chromian spinels.

Table 5. Chemical composition of chloritoids (new analyses by EMPA) from a Tertiary gritty sandstone on the river bed in the northern moraine of Aavatsmarkbreen. Mg/Fe: Mg/Fe* + Mg (Fe* = total Fe as Fe^{+2}).

	1	2	3	4	5	6	7	8	9	10
SiO_2	24.32	24.57	24.52	24.58	24.43	24.66	24.50	24.68	24.38	24.71
Al_2O_3	39.09	38.78	38.46	39.94	39.93	40.57	40.32	40.23	39.99	40.21
FeO*	25.49	26.07	25.57	26.94	25.88	23.81	23.87	23.83	24.14	23.97
MnO	0.47	0.59	0.51	0.25	0.19	0.77	0.84	0.85	0.89	0.83
MgO	2.00	2.18	2.28	1.01	1.03	1.87	1.59	1.74	1.42	1.63
Total	91.37	92.19	91.34	92.72	91.46	91.68	91.12	91.33	90.82	91.35
Mg/Fe	12.30	14.60	13.70	6.40	6.60	12.30	10.60	11.50	9.50	10.80

Detrital chloritoid grains

A Tertiary conglomeratic sandstone exposing on the river bed along the northern side of Aavatsmarkbreen moraine contains detrital chloritoid grains in its matrix, as much as 0.2 volume percent. The chloritoid grains are fresh and angular in shape, indicating a short transport distance. It is assumed that the weathering was of short duration and that the grains were moved as stream bed load. This rock also contains cm-size clasts of limestone with fragments of Late Paleozoic fossils. Because Carboniferous rocks are assumed to occur widely in this area before the development of Tertiary graben (Gabrielsen et al. 1992), the sources of the sandstone materials are considered to be local. The chloritoid may have been supplied from the low-pressure metamorphic rocks exposed together with the serpentinite in the foothills of southeastern Sarsøyra.

The Mg/Mg + Fe* ratios (Fe* = total Fe as Fe^{+2}) of the detrital chloritoid grains (Table 5) are similar to those of the chloritoid rims in the chloritoid-bearing schists of the high-pressure metamorphic complex (Ohta 1979; Hirajima et al. 1988), but not to those occurring on Prins Karls Forland (Manby 1983) (Fig. 3). It is not likely that the chloritoid grains were transported from Prins Karls Forland across the graben. Given the angularity of the grains and their amount, and the lack of this mineral in the Tertiary sediments in Kaffiøyra, it is unlikely that these chloritoid grains had been transported from the Motalafjella area for ca. 50 km along the eastern margin of the Forlandsundet Graben basin.

Possible southern continuation of the high-pressure metamorphic rocks

The extent of the high-pressure metamorphic rocks to the south of Motalafjella is not known. However, a metabasic rock lense on the northwestern slope of Kinnefjellet, ca. 5 km south of Motalafjella (Fig. 1A), has amphiboles with a winchite core and actinolite margin (Ohta et al. 1992); winchite is an indicator of high-pressure metamorphism of moderate temperature range (Hirajima et al. 1988). Other metabasic rocks on the northern slope of Protektorfjellet (Fig. 1A),

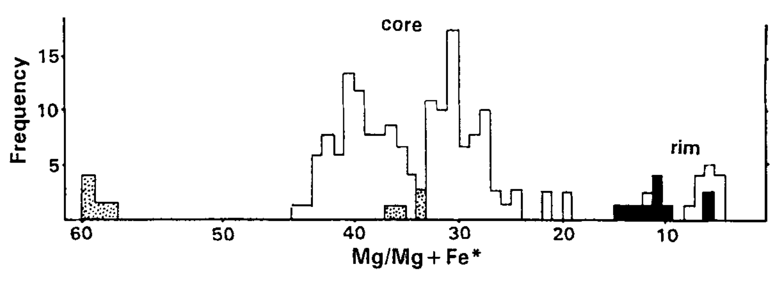


Fig. 3. Comparison of the Mg/Fe* + Mg ratios of the chloritoids. White, from Motalafjella (Ohta 1979 and Hirajima et al. 1988); dotted, from Prins Karls Forland (Manby 1983a); black, detrial chloritoid grains in a Tertiary conglomeratic sandstone, southern Sarsøyra (new analyses by EMPA). Fe* = total Fe as Fe^{+2}.

ca. 20 km SSE of Motalafjella, have a pumpellyite-prehnite-chlorite-epidote assemblage (Ohta et al. 1992). A brown dolostone, with a small amount of fuchsite with 1.7 wt% Cr_2O_3 has been reported by Hjelle (1962) from NE of Liknausen in Orustdalen (Fig. 1A) in southern Nordenskiöld Land, between Isfjorden and Bellsund, ca. 50 km south of Motalafjella. If these rocks represent signs of the high-pressure metamorphism, the distribution of high-pressure metamorphic rocks becomes roughly 100 km in length.

Farther to the south at Asbestodden, west of Recherchefjorden (Fig. 1A) on the southern side of Bellsund, a serpentinite with asbestos veins occurs in a limestone-rich phyllite succession of Late Proterozoic age (Dallmann et al. 1990). Sulphide and ankerite-siderite mineralisations, characteristic along some thrust zones around Motalafjella (Teben'kov & Korago 1992), have also been described from Raudfjellet (Fig. 1A) in northwest Hornsund and Kviveodden (Fig. 1A) on the southern coast of Hornsund (Czerny et al. 1992a, b) with some sulphides. These mineralisation zones could be an extension of the thrust-dominated zone (senso lato) involving sheets of the high-pressure metamorphic rocks, although these rocks are not exposed on the present surface.

Reference to the surface magnetic anomaly patterns

The scattered distribution of very small, green-brown dolostone and serpentinite outcrops in Sarsøyra were considered by some geologists to possibly be Quaternary glacial erratics. However, a recent surface magnetic-anomaly survey over the area (Krasil'ščikov et al. 1995) shows that distinctly high, positive-anomaly zones coincide exactly with the localities of these rocks (Fig. 2A). Examinations of magnetic susceptibility on various rock samples showed that the green-brown dolomites, serpentinites, some magnetite-bearing green phyllites and Mesozoic dolerites in the strandflat areas are the causative rocks of these high, positive-anomalies. This correlation indicates that the small scattered outcrops are bedrock exposures.

The results of the magnetic survey show that distinctive high-anomaly segments are concentrated in narrow zones. The segments are less than a few hundred metres wide, and they extend roughly in a N–S direction for approximately 1–4 km in Sarsøyra (Fig. 2A).

A distinctive easternmost high-anomaly zone along the foothills of Sarsøyra, which coincides with the eastern marginal fault of the Tertiary Forlandsundet Graben, has a NNW trend and consists locally of a left-stepping *en echelon* arrangement of the high-anomaly segments within the zone (Figs. 2A and 4). Another high-anomaly zone in the western part also has similar trend and *en echelon* arrangement of the high-anomaly segments, while NNE–SSW trending discontinuous zones in the middle part of Sarsøyra shows a right-stepping *en echelon* segments in its northern part. These three high-anomaly zones separate Sarsøyra into two subareas: NW and SE (Fig. 4). The NW subarea has an acute edge to the south and the SE subarea shows pointing edge to the north. This subarea pattern infers a sinistral strike-slip or transpressional movement which formed these subareas near the eastern margin of the Forlandsundet Graben. If this is the case, the NNW trending high-anomaly zones to the east and west of Sarsøyra consisted of left-stepping segments, can be explained as dextral strike-slip or transpressional fault zones with antithetic faults (Lowell 1972; Wilcox et al. 1973). The small angles between the high-anomaly segments and the zones can be interpreted by a flattening of

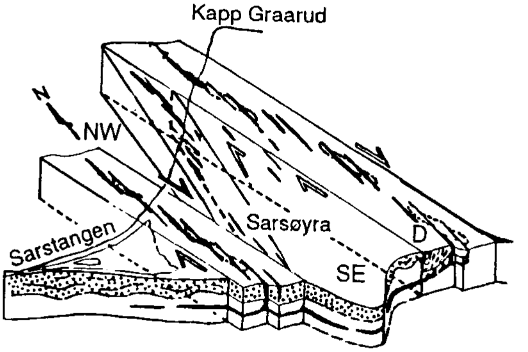


Fig. 4. Schematic interpretation of the fault movements along the high magnetic-anomaly zones in Sarsøyra. Explanation of the profile: Dotted area, Tertiary sediments; broken hatched area, Late Ordovician-Middle Silurian; white, Precambrian; black, the green-brown dolostone and serpentinite; broken line, fault. Surface of the profile: solid lines indicate boundaries of high-anomaly zones; open arrows, inferred movement sense. Displacement by supposed strike-slip movements are schematically shown by strain ellipsoids.

the zones to rotate the segments by later near orthogonal compression, as mentioned later.

These explanations of the sense of fault movement can be debated; however, the present data do not allow any more solid conclusion, due to very poor exposures around the high-anomaly segments. It will be safe to state that the *en echelon* arrangements of the segments within the high-anomaly zones indicate a strike-slip movement along the eastern marginal fault of the Forlandsundet Graben.

The occurrences of serpentinite and green-brown dolostone coincide with the high-anomaly segments. The green-brown dolostone is very solid in thick layers, but it is strongly brecciated and sheared together with phyllites at all occurrences in the strandflats. Thus, this rock is supposed to be pressed up, together with incompetent serpentinite, along the antithetic faults.

The high magnetic anomalies can be modelled to be narrow, steeply west-dipping plates reaching as deep as ca. 50 m. (Krasil'ščikov et al. 1995) (Fig. 2A, lower figure, and Fig. 4). It seems that the steep inclinations of the causative rocks result in the high, positive-anomaly segments. But in other places the same rocks have an almost horizontal, thin sheet structure at ca. 50 or more metres depth; there they do not show any distinctive high-anomaly, but apparently smooth, near normal magnetic fields, due to their small vertical thicknesses.

A weak, but similar, pattern of the high magnetic-anomaly segments and zones is recognisable in the eastern margins of Kaffiøyra (Fig. 2B). An indistinct left-stepping *en echelon* arrangement of high-anomaly segments can be seen in this zone, which coincides with the eastern marginal fault of Forlandsundet Graben. Scattered exposures of the green-brown dolostones, serpentinites and some other magnetite-bearing phyllites occur along this zone and a short, N–S trending zone around Snippen.

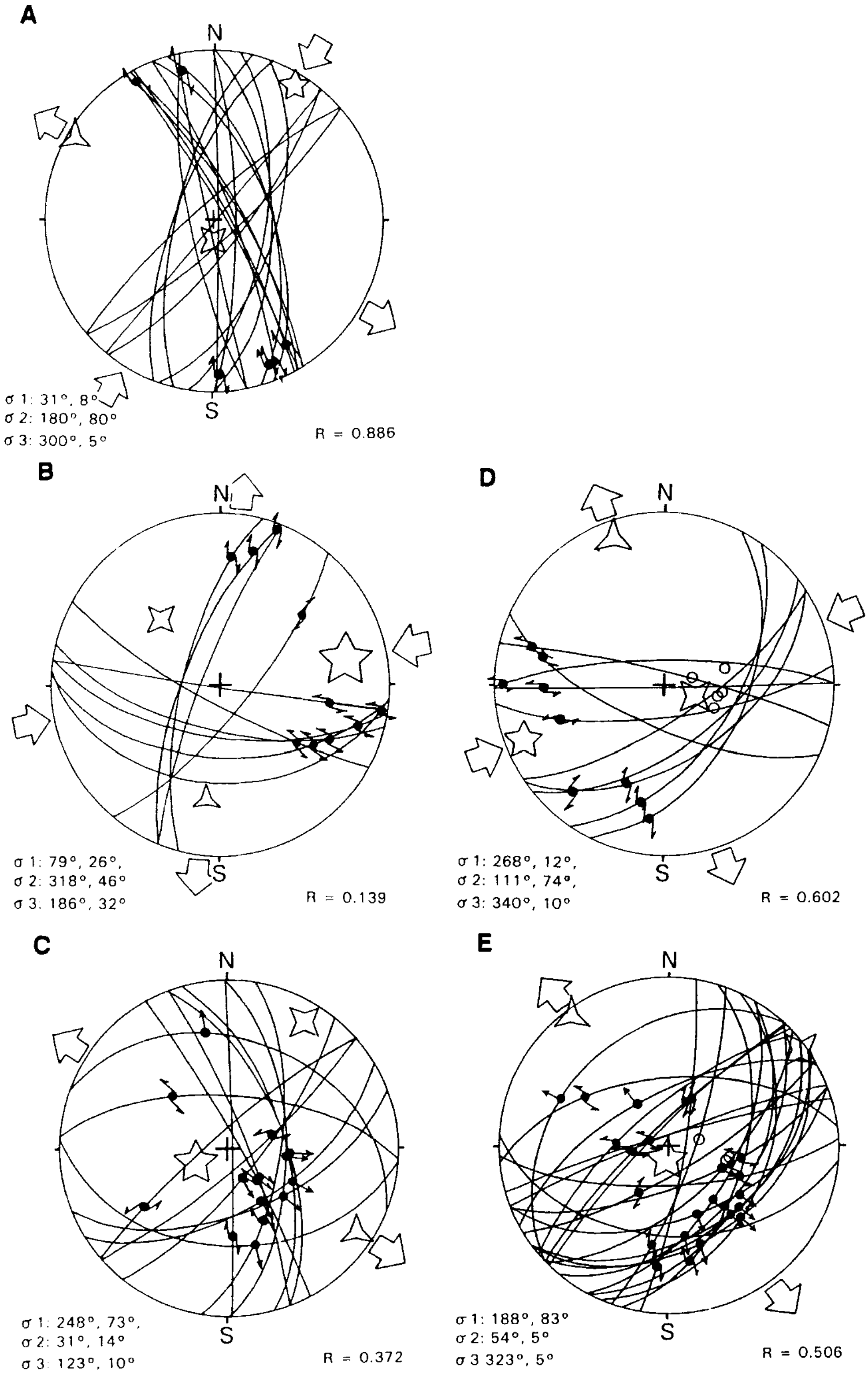
In western Kaffiøyra, the magnetic high-anomaly segments are not as distinctive as in the middle part of Sarsøyra, possibly due to thicker Tertiary cover as in the westernmost part of Sarsøyra. However, the general similarity of the high-anomaly patterns in Kaffiøyra and Sarsøyra implies similar underlying magnetic causative rocks, including the green-brown dolostone and serpentinite of the high-pressure metamorphic complex.

Fault plane observations and Tertiary movements

The eastern margin of Forlandsundet Tertiary Graben is bounded by steeply dipping, 320–360°-striking fault segments. The tectonic development of this basin comprises several episodes of post-depositional brittle deformation, also revealed by the paleostress state evolution in the Tertiary strata (Lepvrier & Geyssant 1985; Lepvrier 1990; Gabrielsen et al. 1992; Kleinspehn & Teyssier 1992). The graben-like aspect is due to a late phase of extension/transtension and has developed in early Oligocene in relation with the plate-tectonic reorganisation which occurred at that time. Prior to this late event, the basin had suffered a phase of near-orthogonal compression during Eocene time (Lepvrier 1990; Gabrielsen et al. 1992), and the marginal faults are cross-cut and offset by a conjugate set of the WNW–ESE and WSW–ENE striking strike-slip faults (Fig. 1B). A still older strike-slip or transpressional phase can be proposed as suggested by the existence of a first set of structures (Lepvrier 1990; Gabrielsen et al. 1992) and by the interpretation of the high magnetic-anomaly segments and zones. A similar three-stage structural evolution, including successively dextral transpression, contraction and extension/transtension, is observed for the kinematics of Tertiary deformation in the West-Spitsbergen fold-and-thrust belt (Braathen & Bergh 1995).

Based mainly on the regional plate-tectonic setting, it has been suggested that the Forlandsundet Tertiary basin developed initially as a transtensional zone between right-stepping dextral wrench faults in a general regime of transpression (Lowell 1972; Steel et al. 1985; Ohta 1982, 1988; Lepvrier 1988; Gabrielsen et al. 1992). This pull-apart model for the Forlandsundet Graben is consistent with sedimentological observations (Rye-Larsen 1982) and the interpretation of the magnetic-anomaly patterns (Krasil'ščikov et al. 1995), but structural kinematic indicators for strike-slip movement are rare.

Within the Tertiary deposits cropping out near the eastern margin of the basin, observed fault striae on small-scale fault planes are related only to the episodes of compression and final extension/transtension. These can be seen along the northwestern coast of Sarsøyra, in the Paleogene Sarsbukta Formation, north of Aavatsmarkbreen (locality S in Fig. 2A) and around


A
N
S
σ 1: 31°, 8°
σ 2: 180°, 80°
σ 3: 300°, 5°
R = 0.886
B
N
S
σ 1: 79°, 26°,
σ 2: 318°, 46°
σ 3: 186°, 32°
R = 0.139
D
N
S
σ 1: 268°, 12°,
σ 2: 111°, 74°,
σ 3: 340°, 10°
R = 0.602
C
N
S
σ 1: 248°, 73°,
σ 2: 31°, 14°
σ 3: 123°, 10°
R = 0.372
E
N
S
σ 1: 188°, 83°
σ 2: 54°, 5°
σ 3 323°, 5°
R = 0.506

Snippen in southern Kaffiøyra (Lepvrier 1990), where movements in relation to these two successive episodes of faulting can be seen on NE–SW and E–W to ESE–WNW striking sets of fault planes (Fig. 5D and E). The fault-planes have not been restored to their pre-folding/tilting orientations in Fig. 5D. However, the pitches of the striae are nearly similar to the dips of the beds, the poles of which are shown by small open circles in Fig. 5D. These fault striae will be roughly horizontal, when the beds are rotated to the horizontal position. The slip-movements which formed these striae took place prior to the folding/tilting during the earliest stage of the compressional event. Only the final extensional event (Fig. 5E), in part observed on the same fault-planes and marked by dip to oblique slip movements, occurred after the folding/tilting of the strata, and its rotation is assumed to be very small. Instead of pure extension, the NW–SE direction of the minimum stress axis at that location, with respect to the marginal faults, better corresponds to a regime of transtension. A variable direction of this stress axis during the latest kinematic episode has been observed over the length of the basin (Lepvrier 1990).

Near the eastern marginal fault in the basement rocks around Dahltoppen (locality D in Fig. 2A), fault activity was also multiphase, and superimposed slip striae have been observed on several NNW–SSE trending fault-planes.

Prior to the compressional (Fig. 5B) and extensional/transtensional events (Fig. 5C) similar to Fig. 5D and E, an earlier striae-set has been recognised, and they show dextral strike-slip movements on the fault planes (Fig. 5A), which is in agreement with the estimated dextral movement from the magnetic-anomaly patterns. These faults are cut by those on which the compressional striae are distinct. The NNE–SSW striking fault-set may correspond to the pseudo-conjugate sinistral fault planes (Figs. 4 and 5A). It is natural that the basement has experienced the folding/tilting that occurred in the adjacent Tertiary strata, which show less than 35° westerly dips in this part of the area. But this rotation did not modify the orientations of dextral strike-slip striae on the NNW–SSE fault-planes which would be only somewhat steeper in their pre-folding/tilting orientation. The basement under the folded Tertiary cover does not need to have been folded as block-faulting/tilting of the basement could flexure the cover sediments.

Tight fold structures have been observed in the sliver of Carboniferous rocks in Svartfjella, southwest of St. Jonsfjoden (Ohta 1988). The folds have 45–65° west-plunging axes. These structures are cut by the younger extensional faults parallel to the eastern marginal fault of the graben, and could be drag folds related to the Tertiary transpression (Lepvrier 1988, 1990).

Conclusions

The green-brown dolostone, actually a magnesite-stone, with fuchsite and accessory amounts of chromite and chromian spinel, is an important component of the low-grade, high-pressure metamorphic complex of Motalafjella and it is commonly accompanied by tectonic blocks of serpentinite. These two rock types can be used to trace the distribution of these high-pressure metamorphic rocks. Similar dolostone and serpentinite occur north of St. Jonsfjorden as far north as Sarsøyra. They follow along thrusts at Holmesletfjella and Ankerfjella, along steep faults near the eastern margin of the Tertiary Forlandsundet Graben, and as scattered outcrops on the strandflats. Mineralogical study on the diagnostic minerals in the green-brown dolostones from these areas suggests an affinity with the high-pressure metamorphic rocks and, accordingly, indicates that the complex extends ca. 50 km to the north-northwest from Motalafjella.

These rocks have high, positive magnetic susceptibility and clearly mark high magnetic-anomaly segments and zones on the strandflats. One of the high-anomaly belts coinciding with the eastern marginal fault of the Forlandsundet Graben consists of a left-stepping *en echelon* arrangement of

Fig. 5. Successive fault movements observed on fault planes. All are lower hemisphere projections. A, B and C, Dahltoppen (locality D in Fig. 2A) within the basement of southern Sarsøyra; D and E, Tertiary rocks of the Sarsbukta Formation on the river bed in the moraine north of Aavatsmarkbreen (locality S in Fig. 2A). Note that all the projections have not been restored to their primary orientations. A. Phase I, dextral transpression. B and D, Phase II, compression; C and E, Phase III, extension/transtension. Small open circles in D and E = poles of bedding plane, stars with 5, 4 and 3 projections = maximum ($\sigma 1$), intermediate ($\sigma 2$) and minimum ($\sigma 3$) principal stress axes, respectively, and their positions are given in degrees at the lower-left corner. Azimuth and plunge value ($R = \sigma 2 - \sigma 3/\sigma 1 - \sigma 3$) is shown at the lower-right corner.

segments associated with the green-brown dolostone and serpentinite. This is considered to suggest a strike-slip movement along the marginal fault. Successive fault movements have been recorded on the fault planes as superimposed striae.

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References

Armstrong, H. A., Nakrem, H. A. & Ohta, Y. 1986: Ordovician conodonts from the Bulltinden Formation, Motalafjella, central-western Spitsbergen. *Polar Res. 4*, 17–23.

Berg, S. G., Ohta, Y., Andresen, A., Maher, H. D., Braathen, A. & Dallmann, W. K. 1993: St. Jonsfjorden. Geological map of Svalbard 1:100,000, sheet B8G, Preliminary edition. Norsk Polarinstitutt, Oslo.

Bernard-Griffiths, J., Peucat, J. J. & Ohta, Y. 1993: Age and nature of protoliths in the Caledonian blueschist-eclogite complex of western Spitsbergen: a combined approach using U-Pb, Sm-Nd and REE whole-rock system. *Lithos 30*, 81–90.

Braathen, A. & Bergh, S. G. 1995: Kinematics of Tertiary deformation in the basement-involved fold-thrust complex, western Nordenskiold Land, Svalbard: tectonic implications based on fault-slip data analysis. *Tectonophysics 249*, 1–29.

Czerny, J., Lipien, G., Manecki, A. & Piestrzynski, A. 1992a: Geology and ore-mineralization of the Hecla Hoek succession (Precambrian) in front of Werenskioldbreen, south Spitsbergen. *Stud. Geol. Pol. 98*, 67–104.

Czerny, J., Plywacz, I. & Szubala, L. 1992b: Siderite mineralization in the Hecla Hoek succession (Precambrian) at Strypegga, south Spitsbergen. *Stud. Geol. Pol. 98*, 165–170.

Dallmann, W. K., Hjelle, A., Ohta, Y., Salvigsen, O., Bjornerud, M. G., Hauser, E. C., Maher, H. D. & Craddock, C. 1990: Geological map Svalbard 1:100,000, sheet B11G Van Keulenfjorden. *Norsk Polarinst. Temakart Nr. 15*. 58 pp.

Dallmeyer, R. D., Peucat, J. J., Hirajima, T. & Ohta, Y., 1990: Tectonothermal chronology within a blueschist-eclogite complex, west-central Spitsbergen, Svalbard: Evidence from $^{40}Ar/^{39}Ar$ and Rb-Sr mineral ages. *Lithos 24*, 291–304.

Donth, M. 1931: Zink-bearing chromite. *Am. Mineral. 16*, 484.

Gabrielsen, R. H., Kløvjan, O. S., Haugsbø, H., Midbøe, P. S., Nøttvedt, A., Rasmussen, E. & Skott, P. H. 1992: A structural outline of Forlandsundet Graben, Prins Karls Forland, Svalbard. *Norsk Geol. Tidskr. 72*, 105–127.

Harland, W. B., Hambrey, M. J. & Waddams, P. 1993: The Vendian geology of Svalbard. *Norsk Polarinst. Skr. 193*. 150 pp.

Harland, W. B., Horsfield, W. T., Manby, G. M. & Morris, A. P. 1979: An outline pre-Carboniferous stratigraphy of central western Spitsbergen. *Norsk Polarinst. Skr. 167*, 119–144.

Hirajima, T., Hiroi, Y. & Ohta, Y. 1984: Lawsonite and pumpellyite from Vestgötabreen Formation in Spitsbergen. *Norsk Geol. Tidskr. 64*, 267–274.

Hirajima, T., Banno, S., Hiroi, Y. & Ohta, Y. 1988: Phase petrology of eclogite and related rocks from the Motalafjella high-pressure metamorphic complex in Spitsbergen (Arctic Ocean) and its significance. *Lithos 22*, 75–97.

Hjelle, A. 1962: Contribution to the geology of the Hecla Hoek Formation in Nordenskiöld Land, Vestspitsbergen. *Norsk Polarinst. Årbok 1961*, 83–95.

Hjelle, A., Ohta, Y. & Winsnes, T. S. 1979: Hecla Hoek rocks of Oscar II Land and Prins Karls Forland, Svalbard. *Norsk Polarinst. Skr. 167*, 145–169.

Horsfield, W. T. 1972: Glaucophane schists of Caledonian age from Spitsbergen. *Geol. Mag. 109*, 29–36.

Kanat, L. H., 1984: Jadite from southern Oscar II Land, Spitsbergen. *Mineral. Mag. 48*, 301–303.

Kleinspehn, K. L. & Teyssier, C. 1992: Tectonics of the Paleogene Forlandsundet basin, Spitsbergen: a preliminary report. *Norsk Geol. Tidskr. 72*, 93–104.

Krasil'ščikov, A. A., Kubansky, A. P. & Ohta, Y., 1995: Surface magnetic anomaly study on the eastern side of the Forlandsundet Tertiary Graben. *Polar Res. 14(1)*, 55–68.

Lepvrier, C. 1988: Relais compressifs et distensifs entre décrochements dans la chaine tertiaire du Spitzberg. (Svalbard, Norvège). *C. R. Acad. Sci. Paris, 307, II*, 409–414.

Lepvrier, C. 1990: Early Tertiary stress history and tectonic development of the Forlandsundet basin, Svalbard, Norway. *Norsk Polarinst. Medd. 112*, 1–16.

Lepvrier, C. & Geyssant, J. 1985: L'evolution structurale de la marge occidentale du Spitsberg: coulissement et rifting tertiaires. *Bull. Soc. Geol. France 8*, 115–125.

Lowell, J. D. 1972: Spitsbergen Tertiary orogenic belt and the Spitsbergen fracture zone. *Geol. Soc. Am. Bull. 83*, 3091–3102.

Manby, G. M. 1983: A reappraisal of chloritoid-bearing phyllites in the Forland Complex rocks of Prins Karls Forland, Spitsbergen. *Mineral. Mag. 47*, 311–318.

O'Hara, M. 1967: Mineral facies in ultrabasic rocks. Pp. 7–18 in Wylie, P. J. (ed.): Ultra mafic and related rocks. Wiley, New York.

Ohta, Y. 1979: Blueschists from Motalafjella, western Spitsbergen. *Norsk Polarinst. Skr. 167*, 171–217.

Ohta, Y. 1982: Morpho-tectonic studies around Svalbard and the northernmost Atlantic. *Can. Soc. Petrol. Geol. Mem. 8*, 415–428.

Ohta, Y. 1988: Structure of Carboniferous strata at Trygghamna and along the SE margin of the Forlandsundet Graben. *Norsk Polarinst. Rapp.ser. 46*, 25–28.

Ohta, Y., Hiroi, Y. & Hirajima, T. 1983: Additional evidence of pre-Silurian high-pressure metamorphic rocks in Spitsbergen. *Polar Res. 1*, 215–218.

Ohta, Y., Hirajima, T. & Hiroi, Y. 1986: Caledonian high-pressure metamorphism in central-western Spitsbergen. *Geol. Soc. Am. Mem. 164*, 205–216.

Ohta, Y., Dallmeyer, R. D. & Peucat, J. J. 1989: Caledonian terranes in Svalbard. *Geol. Soc. Am. Spec. Pap. 230*, 1–15.

Ohta, Y., Hjelle, A., Andresen, A., Dallmann, W. K. & Salvigsen, O. 1992: Geological map Svalbard 1:100,000, sheet B9G Isfjorden. 52 pp.

Rye-Larsen, M. 1982: Forlandsundet graben (Paleogene), Svalbard. Univ. Bergen thesis. 380 pp.

Scrutton, C. T., Horsfield, W. T. & Harland, W. B. 1976: Silurian fossils from western Spitsbergen. *Geol. Mag. 113*, 519–523.

Steel, R., Gjelberg, J., Helland-Hansen, W., Kleinspehn, K., Nøttvedt, A. and Rye-Larsen, N. 1985: The Tertiary strike-slip basins and orogenic belt of Spitsbergen. In Biddle, K. T.

and Christie-Blick, N. (eds.): Strike-slip deformation, basin formation and sedimentation. *SEPM Spec. Publ. 37*, 339–359.

Teben'kov, A. M. & Korago, E. A., 1992: Osobennosti listvenitov Zapadnogo Špicbergena (Peculiarities of the olistvenites of West Spitsbergen). Vsesojuznoe mineralogičesjie obščestvo SSR. Trudy (Panunional Mineralogical Society of the USSR. Trudy). Pp. 69–83.

Waddams, P. 1983: The late Precambrian succession in northwest Oscar II Land, Spitsbergen. Pp. 232–252.

Wilcox, R. E., Harding, T. P. & Seely, D. R. 1973: Basic Wrench tectonics. *Am. Assoc. Petrol. Geol. Bull.* 57, 74–96.