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Carbonate isotope chemostratigraphy suggests revisions to the geological history of the West Finnmark Caledonides, northern Norway

T. SLAGSTAD[1], V. A. MELEZHIK[1], C. L. KIRKLAND[2], K. B. ZWAAN[1], D. ROBERTS[1], I. M. GOROKHOV[3] & A. E. FALLICK[4]

[1]*Geological Survey of Norway, 7491 Trondheim, Norway (e-mail: Trond.Slagstad@ngu.no)*

[2]*Department of Geology, University College Dublin, Belfield, Dublin 4, Ireland*

[3]*Institute of Precambrian Geology and Geochronology, nab. Makarova, 2, 199034 St. Petersburg, Russia*

[4]*Scottish Universities Environmental Research Centre, East Kilbride, Glasgow G75 0QF, UK*

Abstract: Strontium and carbon isotopic data from amphibolite-facies marbles of the Falkenes formation, Sørøy succession (structurally upper Kalak Nappe Complex) in West Finnmark, northern Norway, indicate that the marbles were deposited between 760 and 710 Ma. Marbles of similar age have previously been identified only in the Uppermost Allochthon in north–central Norway, where they are considered to have a Laurentian ancestry. A similar origin and tectonostratigraphic position appears likely for the Falkenes formation. In contrast, structurally lower units within the Kalak Nappe Complex appear to have Baltican affinities. This dichotomy requires that commonly held ideas regarding the tectonostratigraphy of the West Finnmark Caledonides be revised. Combined with recent U–Pb dating of zircon and monazite from rocks associated with the marbles, the isotopic data suggest that the Sørøy succession of the Kalak Nappe Complex is not a continuous, depositional sequence as previously thought, but rather consists of a number of disparate and probably unrelated thrust-sheets, assembled during Late Silurian, Scandian orogenesis. This work shows that the West Finnmark Caledonides share a generally similar tectonometamorphic history with certain other parts of the Scandinavian Caledonides, and contributes to already existing data that may allow 'chemostratigraphic' correlation and reconstruction of the entire Caledonian belt.

Reconstructions of the tectonic evolution of orogenic belts require constraints on the ages and provenances of the various terranes that constitute these belts. Such constraints typically derive from palaeontological and radiometric investigations; however, in many areas, a prolonged and commonly complex tectonometamorphic history has obscured all fossil evidence, hampering such reconstructions. This problem is excellently exemplified in the Scandinavian Caledonides in West Finnmark, northern Norway, where rather high-tempered debates regarding the nature and timing of Caledonian orogenesis have taken place, but with few reliable data to constrain the different interpretations. Here, we use Sr and C isotope chemostratigraphy to constrain the depositional age and, by analogy with other parts of the Scandinavian Caledonides, the provenance of a regionally extensive marble or metalimestone formation. The work shows that carbonate chemostratigraphy can place constraints on the tectonostratigraphy and tectonometamorphic evolution of high-grade terranes that may be difficult, if not impossible, using other methods.

The Kalak Nappe Complex in West Finnmark, northern Norway (Fig. 1), has traditionally been interpreted to make up the Middle Allochthon of the northern Scandinavian Caledonides (e.g. Roberts 1985), and consists of a sedimentary cover unconformably overlying a basement of para- and orthogneisses of unknown age. More recent work, however, considers it to form part of the Upper Allochthon (Andréasson *et al*. 1998; Siedlecka *et al*. 2004). The cover sequence, which is the target of this study, is informally named the Sørøy succession after its type area on Sørøya in West Finnmark (Ramsay 1971*a*). The Sørøy succession consists of an extensive unit of psammite (meta-arkoses and quartzites) structurally overlain by garnetiferous mica schists, pelites and marbles, summarized in Table 1. Ramsay (1971*a*) interpreted the Sørøy succession as a continuous depositional sequence displaying a transition from an alluvial or shallow-marine environment, through shelf deposition to distal turbidites. The lack of preserved fossils in the strongly deformed, high-grade Sørøy succession hampers estimates of its depositional age, but Daly *et al*. (1991) showed that the lowermost Klubben formation was deformed prior to *c*. 800 Ma, during the proposed Porsangerhalvøyan (Roberts 2003a) event, implying an Early Neoproterozoic minimum age for deposition of the psammite and, by inference, the whole of the Sørøy succession. Traditionally, most workers in Finnmark have ascribed the main deformation, metamorphism and tectonic shuffling of the Kalak Nappe Complex (basement + Sørøy succession cover) to an Early Palaeozoic (*c*. 540–490 Ma) Finnmarkian orogenic event (e.g. Sturt *et al*. 1978).

Ramsay (1971*a*) correlated the Sørøy succession with rocks in the Nordreisa region of North Troms (Fig. 1), and described a continuous succession from Klubben formation to Hellefjord formation correlatives (see Table 1). Later, however, Binns & Gayer (1980) reported fossils from the Guolasjav'ri area in Nordreisa that constrained the age of the host calcareous schists to Late Ordovician or Early Silurian. The fossils proved that rocks previously correlated with the Sørøy succession could not be part of a continuous sequence with the Klubben formation at the base, and, indeed, a tectonic contact was found in that particular area, separating the Klubben formation from overlying units (Binns & Gayer 1980). The fossils also proved that deformation of the rocks above the contact must have taken place after Finnmarkian orogenesis. However, despite these findings, the relationships on Sørøya were not challenged until Krill &

Table 1. *The Sørøy succession as defined by Ramsay (1971*a*) and Roberts (1971), with the position of cryptic thrust contacts or tectonized unconformities proposed here*

Formation	Depositional environment	Rock types	Age constraints
Hellefjord	Distal turbidites	Medium- to fine-grained schists with load casts; interpreted as a turbidite sequence	Deposited *c*. 450 Ma. $T_{DM} = 1.2$ Ga
Cryptic thrust or tectonized unconformity?			
Åfjord	Shallow-marine, shelf environment	Pelite overlain by quartzite and graphitic, kyanite–staurolite schists	None, but contact with underlying Falkenes formation appears transitional. $T_{DM} = 2$–2.3 Ga
Falkenes	Shallow-marine, shelf environment	Marble, with calc-silicate schists dominating near base	Deposited 760–710 Ma (this study). $T_{DM} = 1.8$ Ga
Cryptic thrust or tectonized unconformity?			
Storelv	Shallow-marine, shelf environment	Mica schists, locally with garnet, and thin layers of quartzite	None, but contact with underlying Klubben psammite appears transitional. $T_{DM} = 1.8$ Ga
Klubben	Alluvial or shallow-marine deposition	Arkoses and quartzites, locally cross-bedded, interlayered with semi-pelites and schists	Deformed and metamorphosed >800 Ma (Daly *et al*. 1991). $T_{DM} = 1.7$ Ga

TDM = Sm–Nd depleted mantle model ages from Aitcheson *et al*. (1990). Age of Hellefjord formation from Kirkland *et al*. (2005).

Zwaan (1987) suggested that the Sørøy succession was not a continuous depositional sequence and that the tectonometamorphic history of the Kalak Nappe Complex involved significant deformation and metamorphism during the Scandian event (i.e. Late Silurian–Early Devonian), similar to other parts of the Scandinavian Caledonides (e.g. Roberts 2003b, and references therein). Their suggestion, however, was dismissed by other workers (Roberts 1988; Sturt & Ramsay 1988), and the idea that the Sørøy succession comprises a continuous, transgressive sequence, unconformably overlying an older Precambrian basement, both deformed during the Finnmarkian event, has not been challenged since. Thus, at present the tectonostratigraphy and tectonometamorphic history of the Kalak Nappe Complex is difficult to reconcile with other parts of the Scandinavian Caledonides.

The purpose of the work presented here was to use Sr and C isotopic data from marbles of the Falkenes formation to constrain their depositional age. In doing so, we aimed to clarify the tectonostratigraphic and metamorphic history of the Kalak Nappe Complex and, thereby, resolve the contradictions raised by previous studies. In particular, we wished to determine if the Sørøy succession really is a continuous sedimentary succession, or if it consists of units separated by tectonic or unconformable contacts. Identifying tectonic and depositional breaks in highly strained and metamorphosed rocks, such as on Sørøya, is inherently difficult based solely on field observations, and in many cases requires isotopic or fossil age constraints on the depositional age and/or tectonometamorphic history of the rocks. Recent work elsewhere in the Caledonides (Melezhik *et al*. 2000, 2001*a*, 2002*a*, *b*, 2003; Sandøy 2003) has shown that Sr and C isotopic data from high-grade marble formations can be compared with secular variations in the isotopic compositions of Neoproterozoic and Phanerozoic seawater (see review by Melezhik *et al*. 2001*b*, and references therein) to obtain a depositional age. Thus, despite a number of complicating factors (Melezhik *et al*. 2001*b*), carbonate chemostratigraphy can provide the age constraints necessary to help decipher the tectonostratigraphic make-up of areas where structural relationships are ambiguous or have been tectonically or metamorphically overprinted.

Regional geology

The Finnmark Caledonides consist of four nappe complexes (Roberts 1985), described here in ascending structural order (Fig. 1). The Gaissa Nappe Complex consists of low-grade, Neoproterozoic to Early Ordovician metasedimentary rocks and represents the Lower Allochthon in the area (Sundvoll & Roberts 2003, and references therein). Overlying the Gaissa Nappe Complex is the Laksefjord Nappe Complex, consisting of greenschist- to amphibolite-facies metasedimentary rocks of inferred Late Neoproterozoic to possibly Early Cambrian age (Roberts 1985; Sundvoll & Roberts 2003). The Laksefjord Nappe Complex constitutes the lowermost unit of the Middle Allochthon and is confined to the northeastern part of the region. The Kalak Nappe Complex was previously considered to make up most of the Middle Allochthon in Finnmark, but an Upper Allochthon position is now in favour (Andréasson *et al*. 1998; Siedlecka *et al*. 2004). The Kalak Nappe Complex comprises a number of thrust-sheets or nappes formed by imbrication of the Sørøy succession and underlying basement gneisses. The latter consist of Proterozoic to Archaean complexes (Sturt *et al*. 1978; Zwaan & Roberts 1978; Ramsay *et al*. 1985*a*, *b*), locally unconformably overlain by psammites of the Klubben formation (Ramsay & Sturt 1977; Ramsay *et al*. 1979). In the structurally highest thrust-sheet, the Sørøy–Seiland Nappe, the Late Neoproterozoic Seiland Igneous Complex (Robins & Often 1996) intrudes the lowermost units (Klubben and Storelv(?) formations) of the Sørøy succession and consists of plutonic rocks mainly of ultramafic to gabbroic composition.

Except for areas on Porsangerhalvøya (Gayer *et al*. 1985, 1987), east of the study area, the tectonometamorphic evolution of the Kalak Nappe Complex is poorly constrained, and in general, the structural complexity hampers correlations between different areas. Ramsay *et al*. (1985*b*) ascribed the major structures and high-strain fabric in the Sørøy succession to two, or locally three, phases of orogenic deformation. On Sørøya, D_1 is characterized by recumbent, near-isoclinal, non-cylindrical folds and a strong fabric; the study area in SW Sørøya constitutes a large F_1 synform according to Ramsay *et al*. (1985*b*). The second phase of deformation (D_2) generated folds that vary both in scale and in symmetry. Locally, a third phase of deformation (D_3) resulted in large-scale, asymmetrical, open folds. According to Sturt *et al*. (1978) and Ramsay *et al*. (1985*b*), D_1 and D_2 were synchronous with intrusion of the Seiland Igneous Province (i.e. synorogenic magmatism) that, at the time, was dated by the Rb–Sr method at 540–490 Ma (Sturt *et al*. 1978), and interpreted to represent an early, Cambrian stage of the Caledonian Orogeny known as the Finnmarkian Orogeny. Later work by Daly *et al*. (1991) on Porsangerhalvøya, east of Sørøya, showed that the *c*. 800 Ma Litlefjord granite postdates D_1 and D_2 but predates D_3 in the Klubben formation.

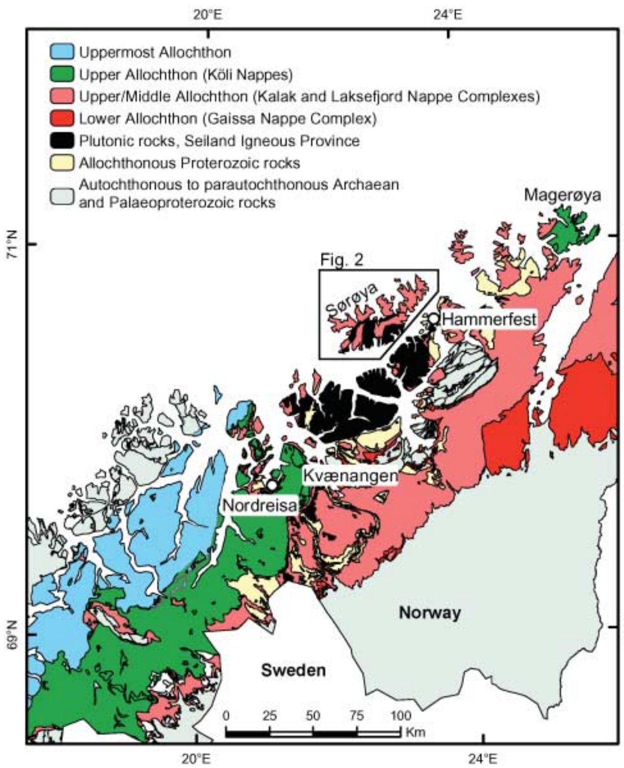

Fig. 1. Caledonian tectonostratigraphy of West Finnmark and Troms, modified after Sigmond et al. (1984).

This led Daly *et al*. (1991) to suggest an Early Neoproterozoic (>800 Ma) event in the Kalak Nappe Complex, termed the Porsangerhalvøyan Orogeny. Recent U–Pb zircon geochronology has refined the age of the Litlefjord granite to *c*. 841 Ma (Kirkland *et al*. in prep.). Geochronological data (U–Pb zircon) from gabbros of the Seiland Igneous Province yield ages between 577 and 555 Ma (Roberts *et al*. 2004); however, contrary to the interpretations of Sturt *et al*. (1978) and Ramsay *et al*. (1985*b*), most workers now agree that formation of the Seiland Igneous Province was related to continental rifting (Krill & Zwaan 1987; Reginiussen *et al*. 1995; Robins & Often 1996; Roberts *et al*. 2004) rather than to continental collision. Thus, the currently available age data suggest that a pre-Late Neoproterozoic deformational event, possibly reflecting a continuation of Grenvillian (Sveconorwegian) deformation farther south in Scandinavia (Kirkland *et al*. in prep.), affected the Klubben formation. More significantly, the data do not lend support to an Early Palaeozoic Finnmarkian event on Sørøya as originally suggested by Sturt *et al*. (1978).

Geology of Sørøya and the Sørøy succession

The geology of parts of Sørøya was described in detail by Ramsay (1971*a*, *b*), Roberts (1968, 1971) and Speedyman (1983). In the main study area in SW Sørøya, Ramsay (1971*b*) interpreted the Sørøy succession to be folded by a large recumbent to inclined F_1 syncline that varies from isoclinal to open going along the fold axis from south to north (Fig. 2). The Klubben formation forms the base of the Sørøy succession and

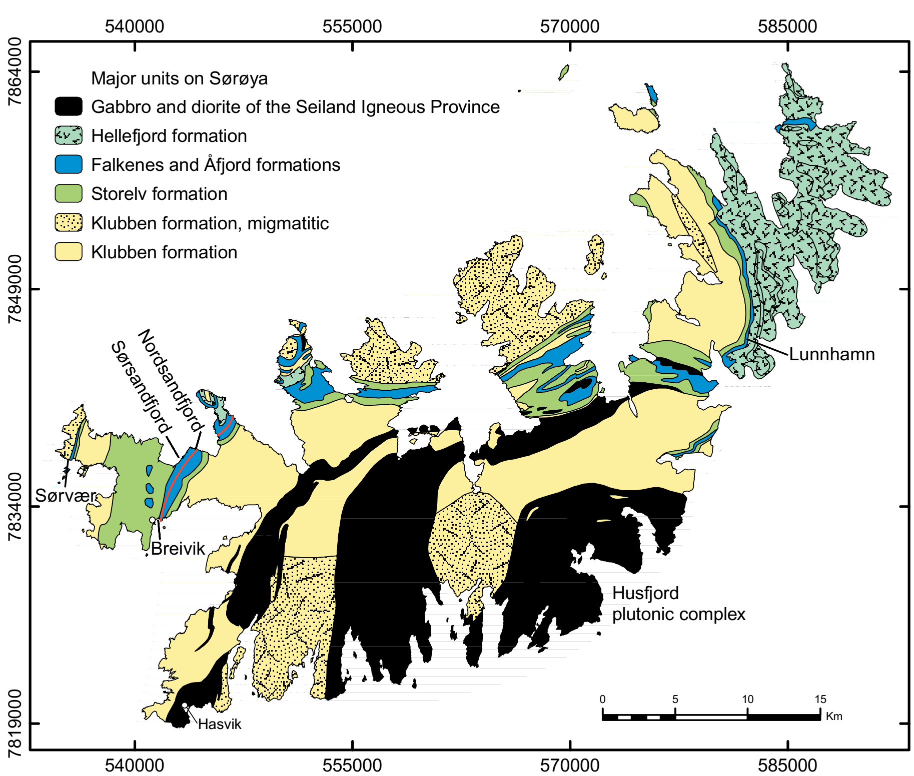

Fig. 2. Geology of Sørøya, after Roberts (1973). The locations of the investigated outcrops are indicated. The red line through the study area in SW Sørøya indicates the axial trace of a large F_1 syncline proposed by Ramsay (1971*b*). UTM zone 34, WGS84.

consists of strongly sheared, white, granoblastic meta-arkoses and quartzites. The Storelv formation comprises fine-grained biotite schist, locally with garnet. Alternating layers of schist and quartzite near the base of the Storelv formation suggest a transitional contact with the underlying Klubben formation (see also Roberts 1968), supporting the interpretation of Ramsay (1971*a*). Structurally overlying the Storelv formation is the Falkenes formation, the target of this study. The lowermost part of the Falkenes formation consists of characteristic dark green, fine-grained to microcrystalline, calc-silicate schist with thin layers of incoherent dark schist. The contact to the underlying Storelv formation is poorly exposed, and we could not confirm that this unit is transitional with the Falkenes formation, as suggested by Ramsay (1971*a*). The most complete section through the Falkenes formation in SW Sørøya is a large outcrop of vertically dipping marble and rusty pelite in Sørsandfjord (Figs 2 and 3a) that exposes the uppermost 40 m of the Falkenes formation and the lowermost part of the overlying Åfjord formation. The contact between the Åfjord formation and the underlying Falkenes formation is clearly depositional, although strongly overprinted by later deformation, and characterized by metre- to centimetre-thick, alternating layers of rusty pelite and marble in the uppermost 15 m of the Falkenes formation (Fig. 3a). This outcrop is described in more detail below. Below this transitional, upper contact, the Falkenes formation comprises white to grey, fine- to locally coarse-grained marbles, banded on a centimetre to decimetre scale (Fig. 3b). The structurally highest unit in SW Sørøya, the Åfjord formation, forms the core of the D_1 syncline, and, as described by Ramsay (1971*a*), shows a tripartite subdivision into a lower unit comprising dark grey to brown, rusty pelites that locally contain rosettes of kyanite and staurolite, overlain by a middle unit composed of white, granoblastic quartzite. The uppermost part is a graphitic pelite to coarse-grained mica schist, characterized by locally abundant coarse kyanite and staurolite porphyroblasts that may be up to several centimetres in length. The Åfjord formation is present only locally on Sørøya and in many places the Hellefjord formation, consisting of banded, turbiditic, fine-grained schists and some volcaniclastic units, directly overlies the marbles of the Falkenes formation (Fig. 3c).

Sampled outcrops

Sørsandfjord, SW Sørøya

The investigated outcrop in Sørsandfjord (Fig. 2) is a flat-lying, wave-washed surface consisting of *c*. 40 m of vertically dipping marble with a transitional contact towards the pelites of the overlying Åfjord formation. The transition is characterized by an increasing proportion of pelite in the uppermost 15 m of the marbles (Fig. 3a and b). The pelitic layers are typically strongly boudinaged, attesting to the high strains involved. Figure 4 presents a profile through the outcrop, indicating the positions of the 21 samples.

Nordsandjord, Breivik and Sørvær, SW Sørøya

The investigated outcrop in Nordsandfjord (Fig. 2) is located near the top of precipitous cliffs several hundred metres in height on the south side of Nordsandfjord. The marbles in this outcrop are dominantly fine-grained, with some decimetre-thick coarse-grained layers and several thin layers of pelite and calc-silicate rock. The pelitic layers are commonly calcareous. Only fine-grained marbles without visible pelitic material were sampled.

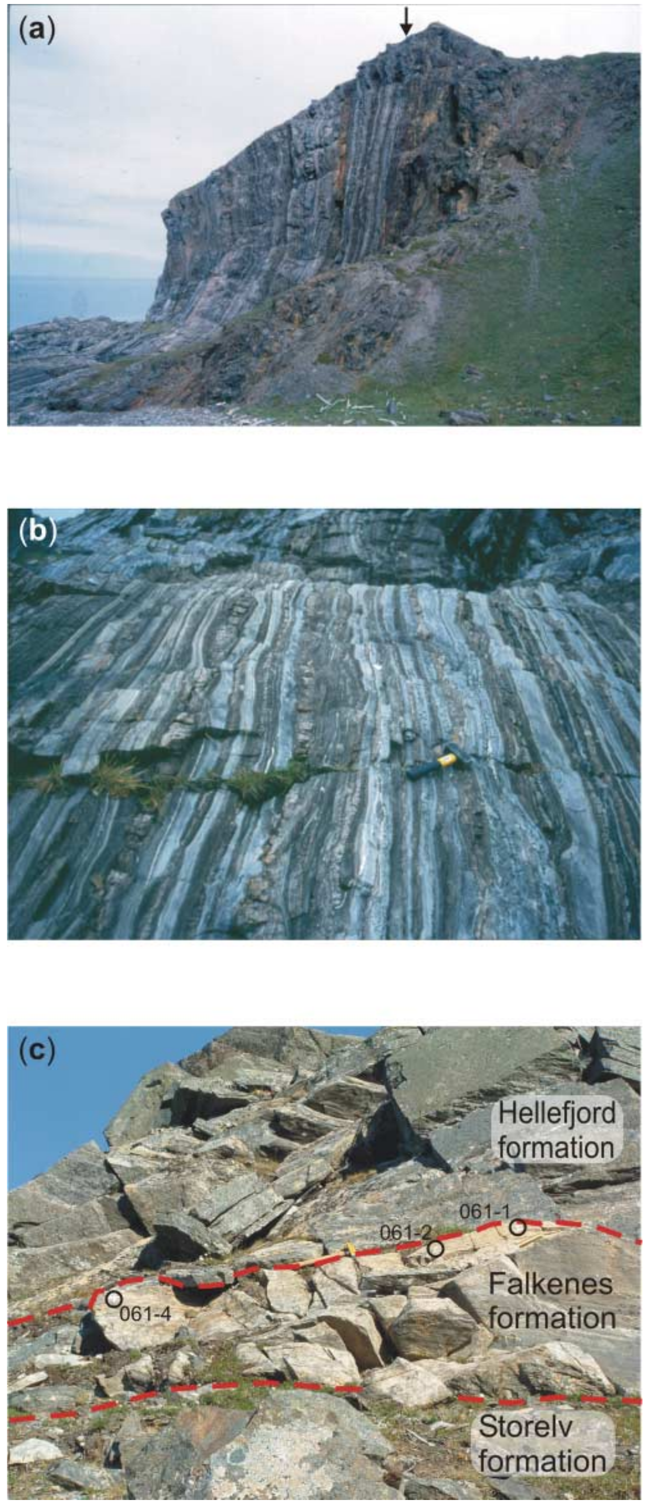

Fig. 3. (**a**) Photograph of the investigated outcrop in Sørsandfjord in SW Sørøya. The rusty-coloured rocks to the right (east) represent the base of the Åfjord formation. The arrow marks the contact between the Falkenes and Åfjord formations. (**b**) Close-up of the Falkenes formation, near the base of the Åfjord formation, characterized by interlayered marble and metapelite. The pronounced boudinage of the metapelitic layers (rusty brown), attesting to the high strains involved, should be noted. Hammer for scale is 25 cm long. (**c**) Photograph of the investigated outcrop in Lunnhamn, NE Sørøya. ○, sample sites; dashed lines indicate the contacts between the Storelv, Falkenes and Hellefjord formations.

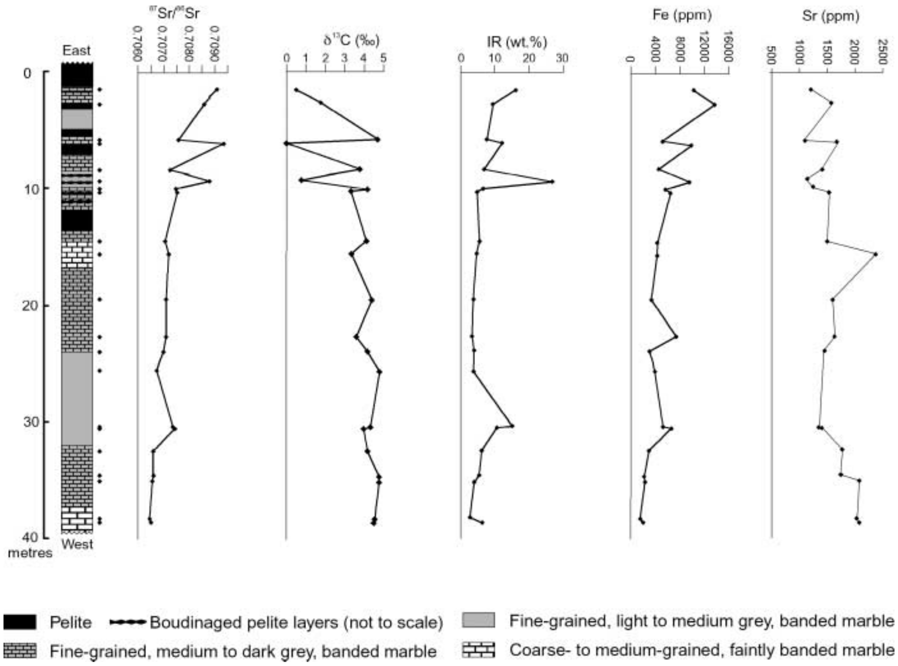

Fig. 4. Simplified lithological profile through the Sørsandfjord outcrop with sample locations, Sr and C isotopic ratios, insoluble residue, and Fe and Sr contents. The thick, metapelitic layer at the top of the profile represents the base of the overlying Åfjord formation. Interlayered metapelitic and marble layers in the uppermost 15 m of the Falkenes formation suggest that the contact between the two formations is depositional.

The investigated outcrop in Breivik (Fig. 2) is a road-cut along the road from Hasvik to Sørvær, located on the west side of the tunnel near Breivik. The outcrop is rather small and exposes the uppermost 15 m of the Falkenes formation, with a transitional contact towards the overlying Åfjord formation, characterized by interlayered marble and pelite similar to that observed in Sørsandfjord.

A thin unit of marble just west of Sørvær (Fig. 2) was sampled to compare this unit with the major Falkenes formation to the east. The marble unit near Sørvær is associated and locally interlayered with schists, pelites and quartzite. Only one sample of good quality could be obtained from this unit because of its limited thickness and contamination by siliciclastic material.

Lunnhamn, NE Sørøya

At Lunnhamn in NE Sørøya (Fig. 2), we sampled a relatively clean marble bed within a *c.* 5 m thick sequence of the Falkenes formation dipping at *c.* 50° SE. The unit was sampled at 1 m intervals along the same bed (Fig. 3c). Pelitic schist of the Hellefjord formation overlies the marble, and the contact, unlike the transitional contact between the Falkenes and Åfjord formations observed in SW Sørøya, is sharp and concordant with the foliation in the rocks. The contact between the Falkenes formation and the underlying Storelv formation is also sharp and foliation parallel.

Analytical methods

Major and trace elements were analysed by XRF at the Geological Survey of Norway (NGU) using a Philips PW 1480 X-ray spectrometer. The precision (1σ) is typically around 2% of the major oxide present. Acid-soluble Fe, Ca, Mg, Mn and Sr were analysed by inductively coupled plasma atomic emission spectrometry (ICP-AES) at NGU using a Thermo Jarell Ash ICP 61 instrument, with detection limits of 5, 200, 100, 0.2 and 2 ppm, respectively. The precision (1σ), including element extraction, is ±10%.

Carbon and oxygen isotopes were analysed at the Scottish Universities Environmental Research Centre in Glasgow, using the phosphoric acid method of McCrea (1950) as modified by Rosenbaum & Sheppard (1986) for operation at 100 °C. Carbon and oxygen isotope ratios in carbonate constituents of the whole-rock samples were measured on a VG SIRA 10 mass spectrometer calibrated to international reference material NBS 19. The precision for both isotope ratios is better than ±0.2‰. The $\delta^{13}C$ data are reported in ‰ relative to V-PDB and the $\delta^{18}O$ data in ‰ relative to V-SMOW.

Rb and Sr isotope analyses of samples from SW Sørøya were carried out on carbonate constituents in whole-rock samples at the Institute of Precambrian Geology and Geochronology of the Russian Academy of Sciences in St. Petersburg, as described by Gorokhov *et al.* (1995), except that no preanalytical leaching was used. Rb and Sr concentrations were determined by isotope dilution. Rb isotopic composition was measured on an MI 1320 mass spectrometer; Sr isotope analyses were performed on a multi-collector Finnigan MAT-261 mass spectrometer in static mode. All $^{87}Sr/^{86}Sr$ ratios were normalized to an $^{86}Sr/^{88}Sr$ ratio of 0.1194, to correct for the effects of any fractionation of Sr isotopes during the analysis. Measurements of the NIST SRM-987 run with every batch averaged 0.71025 ± 1 ($2\sigma_{mean}$, $n = 19$). During the course of the study, the value obtained for the $^{86}Sr/^{88}Sr$ ratio of the USGS EN-1 standard was measured at 0.70921 ± 2 ($2\sigma_{mean}$, $n = 11$).

Geochemical data

Forty-three marble samples from the Falkenes formation were analysed for major and trace element and isotopic compositions by XRF, ICP-AES and mass spectrometry. Elemental and isotopic data are presented in Tables 2 and 3.

Major and trace elements

The calcite marbles are characterized by low Mg concentrations, ranging from 0.15 to 1.7 wt% (average 0.69 wt%), and low Mg/Ca ratios ranging from 0.004 to 0.05 (average 0.02), indicating that the marbles were not affected by dolomitization. Most samples have total organic carbon (TOC) below the detection limit of 0.1 wt%. Samples with TOC above the detection limit

Table 2. *Chemical, carbon and oxygen isotope composition of marbles from the Falkenes formation on Sørøya*

Sample	SiO_2 (wt%)	Al_2O_3 (wt%)	Na_2O (wt%)	K_2O (wt%)	P_2O_5 (wt%)	S (wt%)	C_{org} (wt%)	Mg (wt%)	Ca (wt%)	Fe (ppm)	Mn (ppm)	Sr (ppm)	Mn/Sr	Mg/Ca	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)
Sørsandfjord; 543171E, 7837294N UTM zone 34, WGS84																
45-2	15.4	2.0	b.d.	0.24	0.05	0.03	0.22	1.51	28.4	10200	237	1200	0.198	0.053	0.5	18.7
45-3	9.1	1.3	0.14	0.10	0.10	0.05	0.19	0.80	32.2	13600	408	1590	0.257	0.025	1.7	18.1
45-7	6.4	0.8	0.33	0.03	0.06	b.d.	b.d.	0.66	33.9	5150	150	1080	0.139	0.020	4.7	19.0
45-8	12.7	2.3	b.d.	0.38	0.05	0.04	0.19	0.60	30.2	9840	518	1690	0.307	0.020	0.0	18.5
45-10	5.8	0.7	0.14	0.03	0.04	b.d.	b.d.	0.86	34.1	4510	102	1400	0.073	0.025	3.8	19.2
45-12	21.0	4.6	0.15	0.85	0.06	0.15	0.27	0.85	26.6	9510	230	1110	0.207	0.032	0.8	18.5
45-13	5.2	1.3	b.d.	0.26	0.03	0.03	b.d.	0.50	34.7	5650	187	1260	0.148	0.014	4.2	18.4
45-14	6.4	1.3	0.17	0.22	0.03	b.d.	b.d.	0.49	33.3	6440	216	1530	0.141	0.015	3.3	16.6
45-17	5.0	0.9	0.24	0.06	0.04	b.d.	b.d.	0.67	34.9	4250	160	1500	0.107	0.019	4.1	18.0
45-20	4.2	0.4	b.d.	0.05	0.02	b.d.	0.11	1.71	32.5	4260	56	2370	0.024	0.053	3.3	16.6
45-22	6.4	0.8	0.27	0.03	0.03	0.02	b.d.	0.89	33.6	3290	66	1600	0.041	0.027	4.4	18.1
45-23	4.5	0.7	b.d.	0.10	0.06	0.01	0.12	1.15	33.7	7340	348	1630	0.213	0.034	3.6	18.5
45-24	3.2	0.5	0.13	0.05	0.03	0.02	0.10	0.76	34.9	3010	96	1430	0.067	0.022	4.2	18.0
45-25	3.7	0.5	0.19	0.04	0.03	b.d.	b.d.	0.66	34.7	3890	106	1420	0.075	0.019	4.8	17.9
45-27	12.9	2.3	0.43	0.41	0.05	0.01	b.d.	0.88	29.9	5190	178	1360	0.131	0.030	4.3	18.8
45-28	11.6	2.1	0.32	0.51	0.05	b.d.	b.d.	1.35	29.9	6560	307	1400	0.219	0.045	4.0	20.1
45-29	7.4	1.2	0.25	0.14	0.04	0.02	b.d.	0.81	32.9	2940	135	1780	0.076	0.025	4.2	18.0
45-30	4.4	0.5	b.d.	0.07	0.03	b.d.	b.d.	0.69	34.2	2130	114	1730	0.066	0.020	4.8	17.6
45-31	3.5	0.3	b.d.	0.06	0.01	b.d.	b.d.	0.63	34.5	2310	96	2080	0.046	0.018	4.8	17.3
45-33	5.0	0.4	0.13	0.01	0.02	b.d.	b.d.	0.84	34.1	1500	52	2040	0.025	0.025	4.5	18.4
45-34	6.0	0.4	b.d.	0.11	0.02	b.d.	b.d.	1.33	33.4	1960	51	2050	0.025	0.040	4.5	18.1
Nordsandfjord; 544807E, 7837472N UTM zone 34, WGS84																
22-3	4.3	1.0	0.14	0.22	0.07	0.02	b.d.	0.34	35.0	2870	56.6	1420	0.040	0.010	3.1	19.9
22-4	5.8	1.3	0.17	0.31	0.07	0.03	0.11	0.33	34.1	3680	76.7	1480	0.052	0.010	3.3	20.8
22-5	4.5	1.1	0.10	0.27	0.07	b.d.	b.d.	0.32	35.1	2630	50.6	1430	0.035	0.009	3.1	18.8
22-8	5.7	1.2	b.d.	0.23	0.07	0.01	b.d.	0.38	34.3	3600	97.2	1710	0.057	0.011	3.2	19.6
Breivik; 541800E, 7833400N UTM zone 34, WGS84																
2807-1A	12.6	0.9	0.23	0.04	0.05	n.a	.b.d.	0.40	29.8	1530	101	1160	0.087	0.013	1.3	20.0
2807-1B	4.0	0.5	0.11	0.09	0.01	n.a	.b.d.	0.51	32.2	885	46	1630	0.028	0.016	3.9	17.4
2807-2A	6.3	0.9	0.16	0.18	0.02	n.a	.b.d.	0.56	31.4	1650	114	1370	0.083	0.018	5.5	17.9
2807-2C	6.3	0.8	0.15	0.18	0.02	n.a	.b.d.	0.52	31.4	1510	105	1380	0.076	0.016	5.1	20.5
58-1	5.6	1.0	0.12	0.21	0.03	0.10	0.14	0.77	33.9	3980	96	1760	0.054	0.023	n.a.	n.a.
58-2	2.8	0.5	0.14	0.07	0.02	b.d.	0.12	0.52	35.2	4990	379	2150	0.176	0.015	n.a.	n.a.
58-3	6.6	1.5	0.22	0.26	0.05	0.06	0.16	0.62	32.5	5270	420	1440	0.292	0.019	n.a.	n.a.
Sørvær; 535655E, 7837296N UTM zone 34, WGS84																
56-2	3.7	1.1	b.d.	0.23	0.03	0.02	0.11	0.24	35.1	3670	105	1880	0.056	0.007	n.a.	n.a.
Lunnhamn; 581968E, 7845055N UTM zone 34, WGS84																
061-1	6.4	1.5	b.d.	0.37	0.06	0.02	0.35	0.16	34.2	3630	103	1830	0.056	0.005	6.9	16.9
061-2	7.5	2.0	b.d.	0.38	0.07	0.01	0.25	0.28	33.3	3410	168	1830	0.092	0.008	7.0	17.6
061-4	8.9	1.4	b.d.	0.33	0.07	b.d.	0.23	0.15	33.5	3200	128	1410	0.091	0.004	6.6	17.3

Abbreviations: b.d., below detection limit (0.1 wt.% for SiO_2, Na_2O and C_{org}; 0.01 wt% for S); n.a., not analysed. Mg, Ca, Fe, Mn and Sr are acid-soluble concentrations determined by ICP-AES.

also have high insoluble residues ($r_{TOC-IR} = 0.93$ at >99.9% level, n = 12), and high SiO_2 and Al_2O_3 concentrations ($r_{TOC-SiO_2} \pm 0.98$, $r_{TOC-Al_2O_3} \pm 0.96$ at >99.9% level, n = 12), suggesting that TOC is positively correlated with the amount of siliciclastic material in the samples. Statistical analysis of the data, such as correlation coefficients and confidence limits, is presented as a tool to quantitatively determine whether or not elemental and/or isotopic compositions are correlated. In some cases, clustering of the data and/or outliers make the statistical treatment difficult, but, nevertheless, useful for identifying trends in the dataset that may yield information about alteration processes.

Strontium concentrations range from 1080 to 2370 ppm (average 1600 ppm). Observations from the Sørsandfjord outcrop suggest that the Sr concentration is inversely correlated with stratigraphic level, whereas insoluble residue and Fe concentrations increase going from lower to higher stratigraphic levels (Fig. 4). Manganese concentrations range from 46 to 518 ppm (average 161 ppm) and Mn/Sr ratios from 0.02 to 0.31 (average 0.11). Manganese concentrations and Mn/Sr ratios are positively correlated with Fe ($r_{Mn-Fe} = 0.76$, $r_{Mn/Sr-Fe} = 0.81$, >99.9% level, $n = 35$).

Strontium, carbon and oxygen isotopes

$^{87}Sr/^{86}Sr$ ratios range from 0.70645 to 0.70935 and increase upward in the stratigraphy at Sørsandfjord (Fig. 4), accompanied by increased insoluble residue, Fe and Mn concentrations, and Mn/Sr ratios (Fig. 5a–c).

$\delta^{13}C$ values range from 0 to 5.5‰ and decrease upward in the stratigraphy at Sørsandfjord (Fig. 4). $\delta^{13}C$ is negatively correlated with $^{87}Sr/^{86}Sr$ ratios and Fe ($r_{\delta^{13}C-^{87}Sr/^{86}Sr} = -0.66$, $r_{\delta^{13}C-Fe} = -0.61$ at >99.9% level, $n = 31$) (Fig. 5e). Four samples with $\delta^{13}C$ values <1.8‰, corresponding to the four outliers with high $^{87}Sr/^{86}Sr$ ratios noted above, have >0.19 wt% TOC, whereas the other samples have $\delta^{13}C$ >3.1 and <0.12 wt% TOC.

$\delta^{18}O$ values range from 17.3 to 20.8‰ and do not vary

Table 3. *Insoluble residue (IR) contents and minerals, Rb and Sr concentrations and isotopic ratios of marbles from the Falkenes formation on Sørøya*

Sample	IR (wt%)	Minerals in IR	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$ measured	$^{87}Sr/^{86}Sr$ initial
Sørsandfjord; 543171E, 7837294N UTM zone 34, WGS84							
45-2	16.0	n.a.	0.28	1450	0.0006	0.70909	0.70908
45-3	9.4	n.a.	0.97	1705	0.0017	0.70859	0.70857
45-7	7.6	n.a.	0.07	1185	0.0002	0.70758	0.70758
45-8	12.1	n.a.	0.94	1980	0.0014	0.70935	0.70934
45-10	6.8	Qu (Fsp)	0.07	1560	0.0001	0.70725	0.70725
45-12	26.8	n.a.	0.80	1395	0.0017	0.70879	0.70877
45-13	6.5	n.a.	0.36	1420	0.0007	0.70748	0.70747
45-14	4.7	n.a.	0.57	1745	0.0010	0.70753	0.70752
45-17	5.5	n.a.	0.07	1625	0.0001	0.70705	0.70705
45-20	4.6	Qu (Fsp)	1.09	2700	0.0012	0.70719	0.70718
45-22	3.7	Qu (Fsp)	0.09	1730	0.0002	0.70709	0.70709
45-23	3.3	n.a.	1.20	1700	0.0021	0.70709	0.70707
45-24	3.8	Qu (Fsp)	0.12	1500	0.0002	0.70698	0.70698
45-25	3.7	Qu (Fsp)	0.10	1490	0.0002	0.70672	0.70672
45-27	15.0	n.a.	0.28	1655	0.0005	0.70735	0.70734
45-28	10.5	Qu, Fsp	2.36	1610	0.0043	0.70743	0.70739
45-29	6.1	Qu, Fsp	0.30	1940	0.0005	0.70659	0.70658
45-30	5.3	Qu (Fsp)	0.37	1910	0.0006	0.70660	0.70659
45-31	3.9	n.a.	0.10	2330	0.0001	0.70655	0.70655
45-33	2.6	Qu (Fsp)	0.09	2190	0.0001	0.70645	0.70645
45-34	6.2	Qu (Fsp, Ms)	1.87	2270	0.0024	0.70650	0.70647
Nordsandfjord; 544807E, 7837472N UTM zone 34, WGS84							
22-3	5.0	Qu (Ms, Fsp)	2.50	1560	0.0047	0.70673	0.70668
22-4	7.1	Qu, Fsp	2.05	1645	0.0036	0.70676	0.70672
22-5	5.7	Qu, Fsp	1.89	1540	0.0036	0.70670	0.70666
22-8	5.2	Qu, Fsp	4.06	1895	0.0063	0.70674	0.70667
Breivik; 541800E, 7833400N UTM zone 34, WGS84							
2807-1A	13.7	Qu, (Chl, Am, Fsp)	1.88	2050	0.0027	0.70711	0.70708
2807-1B	4.7	Qu, Ms, (Fsp)	1.23	2240	0.0016	0.70648	0.70646
2807-2A	7.7	Qu, (Fsp)	2.04	1920	0.0031	0.70645	0.70642
2807-2C	7.0	Qu, (Fsp)	2.23	1900	0.0034	0.70653	0.70649
58-1	4.5	Qu (Ms)	5.11	1785	0.0084	0.70692	0.70683
58-2	2.8	Qu	1.13	2325	0.0014	0.70728	0.70727
58-3	7.1	Qu, Fsp	3.32	1640	0.0059	0.70745	0.70739
Sørvær; 535655E, 7837296N UTM zone 34, WGS84							
56-2	4.4	Qu, Fsp	0.31	1945	0.0005	0.70692	0.70691
Lunnhamn; 581968E, 7845055N UTM zone 34, WGS84							
061-1	7.9	n.a.	n.a.	n.a.	n.a.	0.70707	n.a.
061-2	9.4	n.a.	n.a.	n.a.	n.a.	0.70713	n.a.
061-4	10.3	n.a.	n.a.	n.a.	n.a.	0.70772	n.a.

Abbreviations: IR, insoluble residue; n.a., not analysed; Qu, quartz; Fsp, feldspar (K-feldspar and plagioclase); Chl, chlorite; Am, amphibole. Rb and Sr concentrations were determined by standard isotope dilution and solid-source mass spectrometry.

systematically with stratigraphy, elemental, or any other isotopic ratios.

Geochemical screening: stratigraphic v. alteration trends

The observed variations in Sr and C isotopic composition, Fe and Mn concentrations, TOC and insoluble residue could be related to either primary stratigraphic variation or post-depositional alteration. Identifying alteration trends requires a relatively extensive database such as that presented above, with at least a few tens of samples, whereas distinguishing primary stratigraphic trends requires comparison of several distant sections.

There is a significant negative correlation between $^{87}Sr/^{86}Sr$ and $\delta^{13}C$. The significant positive correlation between $^{87}Sr/^{86}Sr$ and insoluble residue, TOC, Fe, Mn, SiO_2 and Al_2O_3, and a negative correlation for $\delta^{13}C$, indicate that post-depositional resetting of the Sr and C isotopic systems is proportional to the amount of organic-rich siliciclastic (pelitic) material in the marbles. Pelitic material is commonly enriched in Rb and ^{87}Sr and, in addition, tends to increase the permeability of carbonates, thus allowing easier access for externally derived, ^{87}Sr-rich fluids. Carbon isotopes are strongly buffered by the high C concentrations in calcite relative to the fluid (Banner & Hanson 1990; Jacobsen & Kaufman 1999) and, consequently, infiltration of externally derived fluids is likely to have a relatively greater effect on Sr isotopes. However, the high Sr concentrations in the Falkenes formation marbles probably provided a relatively strong buffer for the Sr isotope system as well (Fig. 5d), although this is impossible to quantify. The preservation of high Sr concentrations and generally low Mg concentrations indicates an original aragonite precursor that underwent diagenesis primarily within a marine environment. The available geochemical data suggest that siliciclastic material affected the Sr isotope system of the investigated marbles by isotopic exchange with Rb-bearing silicates such as mica and feldspar (Fig. 5a; Table

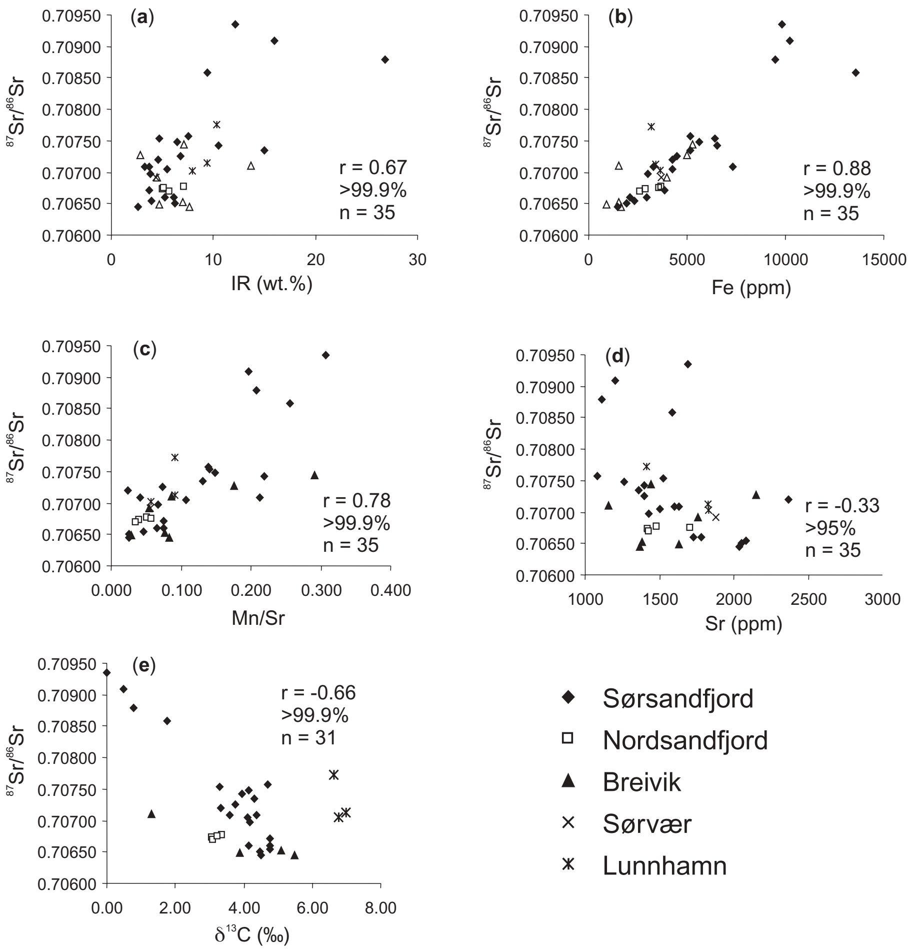

Fig. 5. Bivariate plots showing the variation in Sr isotopic composition with insoluble residue (IR), Fe and Sr concentrations, and Mn/Sr and δ^{13}C ratios. These diagrams were integral to determining the least altered Sr isotopic ratio of the Falkenes formation marbles.

3), thereby increasing the ^{87}Sr/^{86}Sr ratio of the marble. The positive correlation between insoluble residue and TOC suggests that the former contains a significant proportion of organic matter. Oxidation of organic matter produces ^{12}C-rich fluids that may be incorporated into newly formed carbonate, thus reducing the δ^{13}C value of the marble. Such a process is consistent with the observations from the Falkenes formation marbles. Finally, the increase in insoluble residue, TOC, Fe and Mn concentrations, and concomitant increase in Mn/Sr and ^{87}Sr/^{86}Sr ratios, and decrease in δ^{13}C ratios, with increasing stratigraphic level, is consistent with increasing amount of siliciclastic material upwards towards the overlying organic-rich pelites of the Åfjord formation (Fig. 4). We therefore conclude that the isotopic variations observed in the Falkenes marbles are a secondary effect related to a stratigraphically controlled increase in the amount of organic-rich siliciclastic material, and do not reflect variations in the isotopic composition of seawater during deposition.

Here, we consider that the least altered samples in terms of ^{87}Sr/^{86}Sr ratios are those with the highest Sr contents and δ^{13}C ratios, and lowest Mn/Sr ratios, Fe contents and insoluble residues. From the bivariate plots in Figure 5, we take a value of 0.70645 to represent the least altered ^{87}Sr/^{86}Sr ratio of the Falkenes formation marbles. The least altered samples have δ^{13}C ratios ranging from 3.9 to 5.5‰. There are no systematic differences between the Falkenes formation marbles in SW Sørøya as compared with the marbles in NE Sørøya.

Constraints on depositional age

Strontium isotope ratios of seawater display a general increase from *c.* 850 to 500 Ma (Fig. 6), and are, therefore, well suited for indirect dating of Neoproterozoic to Early Palaeozoic carbonate rocks. Another favourable factor is the long residence time of Sr in the oceans (*c.* 5 million years) relative to the inter-ocean mixing time (*c.* 1500 years) (Banner 2004), leading to a very high degree of homogeneity in the oceans' Sr isotopic composition at any given time (e.g. Veizer *et al*. 1997).

The least altered ^{87}Sr/^{86}Sr ratio of 0.70645 in the Falkenes formation marbles intercepts the seawater reference curve at 760–710 and 630 Ma (Fig. 6). The majority of samples yield δ^{13}C values between 3.9 and 5.5‰, suggesting that deposition at 630 Ma is unlikely (Fig. 7). Depositional ages of 760–710 Ma are all possible, judging from the published C isotope variation curves. Thus, based on the available Sr and C isotopic data, we interpret deposition of the Falkenes formation marble to have taken place between 760 and 710 Ma.

Tectonostratigraphic implications

The Sørøy succession: a Scandian thrust assemblage

The isotopic data from the Falkenes formation suggest that it was deposited >80 Ma after deformation and metamorphism of the underlying Klubben formation, the latter taking place at or

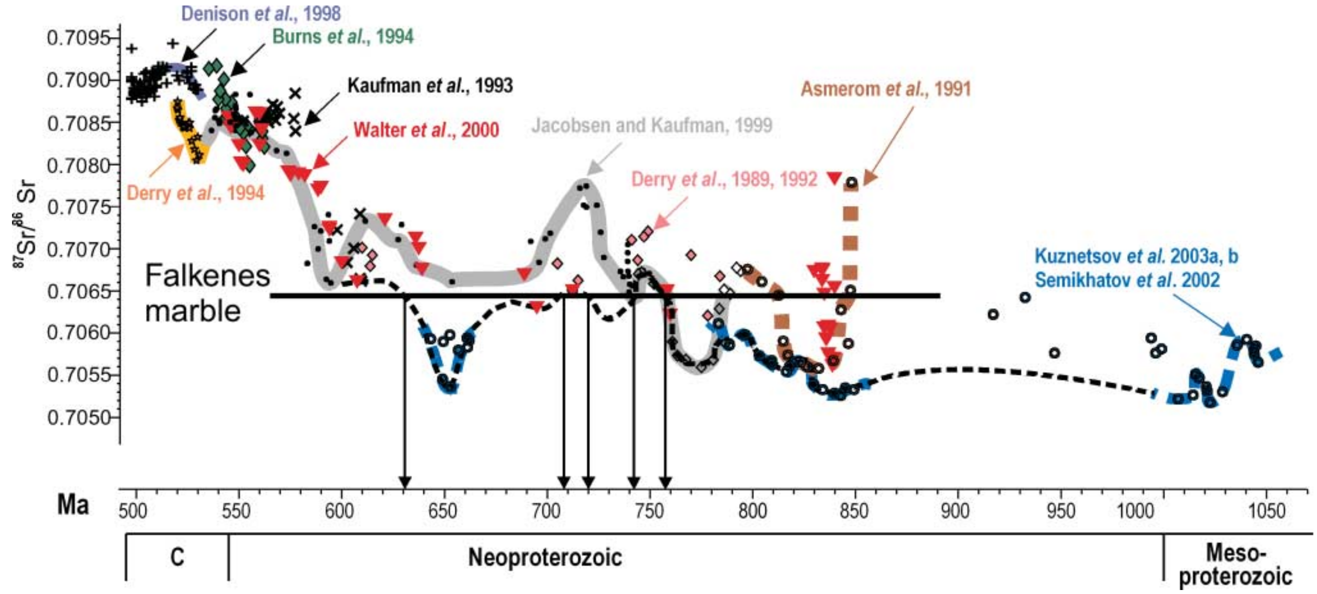

Fig. 6. Temporal trends of $^{87}Sr/^{86}Sr$ in seawater and apparent depositional ages of the Falkenes formation marbles. The least altered $^{87}Sr/^{86}Sr$ is represented by a horizontal line. Its intersection with $^{87}Sr/^{86}Sr$-age reference curve reported in the literature gives the apparent depositional age of the marbles, as indicated by vertical, dashed lines. Data sources: Derry *et al*. 1989, 1992, 1994; Asmerom *et al*. 1991; Kaufman *et al*. 1993; Burns *et al*. 1994; Denison *et al*. 1998; Jacobsen & Kaufman 1999; Walter *et al*. 2000; Semikhatov *et al*. 2002; Kuznetsov *et al*. 2003*a*, *b*.

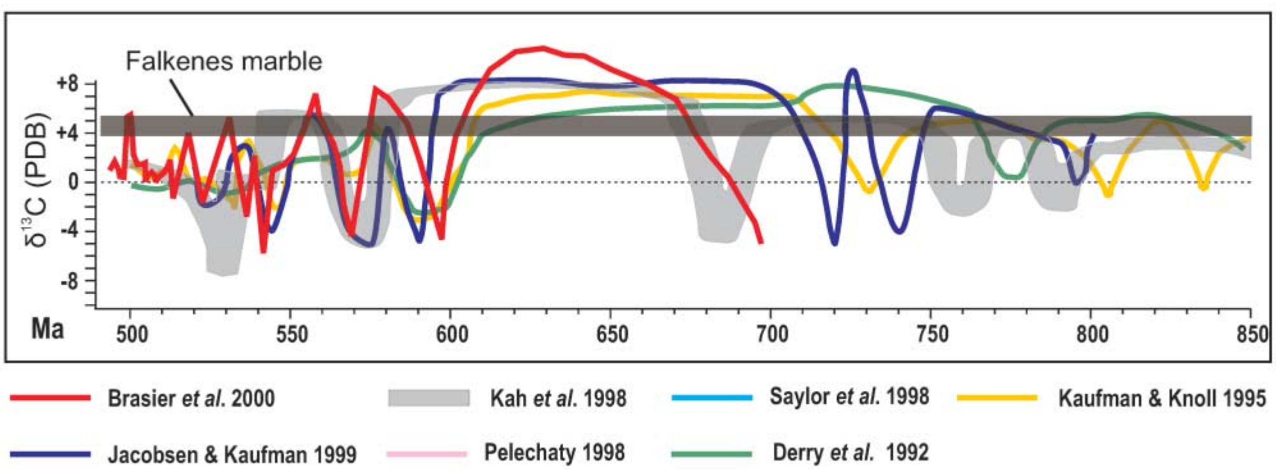

Fig. 7. Temporal trends of $\delta^{13}C$ in seawater (after Melezhik *et al*. 2001*b*). A grey horizontal box shows the range of least altered $\delta^{13}C$ values from the Falkenes formation marbles.) Data sources: Derry *et al*. 1992; Kaufman & Knoll 1995; Kah *et al*. 1998; Pelechaty 1998; Saylor *et al*. 1998; Jacobsen & Kaufman 1999; Brasier *et al*. 2000.

before *c*. 841 Ma (Kirkland *et al*. in prep). Obviously, the minimum (i.e. 'least altered') $^{87}Sr/^{86}Sr$ ratio of the Falkenes formation marbles presented above represents a maximum estimate of the original value; thus, the true depositional age could be older. However, if the Falkenes formation is conformable with the underlying units (i.e. older than 841 Ma), the 'least altered' $^{87}Sr/^{86}Sr$ ratio would have to be reduced to *c*. 0.7053. The geochemical data presented above, i.e. low Mn/Sr (<0.1), SiO_2 and Al_2O_3 (<5 and 0.5 wt%, respectively), insoluble residue (<5 wt%) and high Sr contents (>2000 ppm) in particular (see Melezhik *et al*. 2003), indicate that the $^{87}Sr/^{86}Sr$ values are near minimum, seawater values. Thus, it is very unlikely that the Falkenes formation marbles were deposited significantly earlier than *c*. 760 Ma. A major implication of this new age constraint is that the commonly held conception of the Sørøy succession (Table 1) as a continuous, transgressive sequence (e.g. Ramsay 1971*a*) is incorrect, and that the contacts between units need not be conformable but could represent tectonically reworked and metamorphically overprinted, unconformable and/or thrust contacts (Table 1). This interpretation is supported by field observations; in particular, mafic dykes, probably genetically and temporally related to the Seiland Igneous Province (see Reginiussen *et al*. 1995), are abundant in the Klubben formation but absent in higher structural units (Roberts 1968; Krill & Zwaan 1987). This observation, in turn, suggests that there was a significant geographical separation between the Klubben

(+ Storelv?) formation and higher formations prior to *c*. 555 Ma. Sigmond (1996) reached a similar conclusion based on the geological map of Sørøya (Roberts 1973), placing an inferred tectonic contact between the gabbro-intruded Klubben formation and overlying units. These observations, together with isotopic data constraining the age of the bulk of the Seiland Igneous Province and associated mafic dykes to 577–555 Ma, and the apparent depositional age of the Falkenes formation marbles at 760–710 Ma, suggest that the Falkenes formation is separated from the Klubben (+ Storelv) formation by a thrust contact, active after *c*. 555 Ma. As a note of caution, however, Speedyman (1983) identified rafts of the complete Sørøy succession, except for the uppermost Hellefjord formation, in the Husfjord plutonic complex in SE Sørøya (Fig. 2). Although undated, the Husfjord plutonic complex is probably genetically and temporally related to the Seiland Igneous Complex, which, if correct, implies that the Falkenes, Storelv and Klubben formations were juxtaposed prior to *c*. 577 Ma. A corollary of this idea is that the contact between the Falkenes formation and underlying units is a reworked unconformity or a pre-577 Ma thrust. The latter possibility implies a hitherto unrecognized tectonic event that is not corroborated by existing geochronological data. Thus, although interpretations regarding the nature and timing of juxtaposition between the Falkenes and underlying formations must be regarded as preliminary, we consider a post-555 Ma thrust contact most likely.

Aitcheson (1990) first identified a sharp break in Nd isotope model ages (T_{DM}) between the Hellefjord formation and underlying units of the Sørøy succession. She interpreted this observation to suggest deposition of the Sørøy succession on crust juxtaposed with a terrane of significantly younger crustal extraction age than that found in the northern Baltic Shield (see Krill *et al*. 1985). This interpretation, however, relied on the assumption that the Sørøy succession represented a continuous depositional sequence. Recognizing that the contacts between the formations of the Sørøy succession need not be conformable calls for a reinterpretation of the T_{DM} data presented by Aitcheson (1990). We consider it more likely that the sharp break in T_{DM} ages between the Hellefjord formation and underlying units of the Sørøy succession (Table 1) signifies the presence of a cryptic thrust, or alternatively a tectonized unconformable contact, beneath the Hellefjord formation. Recent U–Pb zircon dating yielding a Llandovery age for a volcaniclastic unit within the Hellefjord formation (Kirkland *et al*. 2005) lends strong support to this interpretation. The new age data from the Hellefjord formation suggest that it may be correlated with the Ankerlia formation of the Øksfjord group in the Kvænangen area (Lindahl *et al*. 2005), south of the study area (Fig. 1).

A major conclusion of this study is that the Sørøy succession probably constitutes a thrust assemblage consisting of at least three distinct tectonic units separated by cryptic thrust contacts beneath the Falkenes and Hellefjord formations (Table 1). Stacking of the Sørøy succession took place after *c*. 760–710 Ma, the apparent depositional age of the Falkenes formation, and is probably younger than *c*. 555 Ma. Chemical dating of monazite (see Montel *et al*. 1996) from kyanite- and staurolite-bearing pelite and schist of the Åfjord formation, conformably overlying the Falkenes formation in SW Sørøya, yields ages close to *c*. 415 Ma, interpreted to reflect the time of high-grade metamorphism (T. Slagstad, unpubl. data). This observation, therefore, suggests that stacking of the Sørøy tectonostratigraphic succession took place during the Scandian phase of the Caledonian Orogeny, supporting the interpretation of Krill & Zwaan (1987) that many of the structures and fabrics observed on Sørøya are of Scandian age. More work is needed, however, to determine the possible pre-Scandian tectonometamorphic histories of the various formations that constitute the Sørøy succession.

Regional correlation

The new ideas presented here imply that the West Finnmark Caledonides do not differ significantly in terms of style and timing of orogenesis from what has been observed and described elsewhere in the Scandinavian Caledonides (e.g. Roberts 2003b, and references therein). This allows for some discussion of the significance of the Falkenes formation in an orogenic context by comparing the data obtained from the Falkenes marbles with those for marble units elsewhere in the Scandinavian Caledonides, and in other parts of the Caledonian orogenic belt.

A growing database of Sr and C isotopic data from the Scandinavian Caledonides shows that marble units of different isotopic composition and age exist (Table 4). There is a predominance of marbles in the Uppermost Allochthon of the Scandinavian Caledonides, and consequently most of the investigated units are found at this tectonostratigraphic level. In a reconnaissance study, Trønnes & Sundvoll (1995) presented C, O and Sr isotopic data from the Helgeland Nappe Complex of the Uppermost Allochthon in Nordland, and Seve- and Köli-equivalent nappes of the underlying Upper Allochthon. They showed that marbles from the Helgeland Nappe Complex have $\delta^{13}C$ values and $^{87}Sr/^{86}Sr$ ratios ranging from +3.6 to +6.8 and 0.7067 to 0.7076, respectively, whereas marbles from nappes in the Upper Allochthon have lower $\delta^{13}C$ values, ranging mainly from −0.5 to +2, and higher $^{87}Sr/^{86}Sr$ ratios ranging from 0.7075 to 0.7090. Later, more detailed investigations in the Uppermost Allochthon have revealed a more complex picture, and show that in many areas, carbonates of different composition and age were tectonically stacked during Caledonian orogenesis (Melezhik *et al*. 2001*a*, 2002*a*, *b*, 2003; Roberts *et al*. 2002; Sandøy 2003). The Falkenes marbles have isotopic compositions that are comparable with those of several units in the Uppermost Allochthon to the south; in particular, the Hekkelstrand, Fuglevann, Liland, Evenes and Saus marble units (Table 4). In contrast, the limited sampling of marbles from the Upper Allochthon suggests that these units have significantly higher $^{87}Sr/^{86}Sr$ ratios (Trønnes & Sundvoll 1995), distinct from those of the Falkenes formation marbles. This suggests that the Falkenes formation may be correlated with some of the marbles in the Uppermost Allochthon farther south, opposing the traditionally held view that this unit forms part of either the Middle or the Upper Allochthon. The provenance of marbles in the Uppermost Allochthon is generally believed to be the Laurentian continental margin (e.g. Melezhik *et al*. 2002*a*; Roberts *et al*. 2002). This interpretation is based on the following: (1) considerations of palaeogeographical reconstructions of Laurentia and Baltica at the time of deposition (assuming that carbonates generally form only at relatively low latitudes) (Melezhik *et al*. 2002*a*); (2) geological and geochronological data that constrain the provenance and geological history of associated rock units; (3) basinal configuration in one area where the platform is situated to the NW; (4) early NW- to west-vergent thrusting, which is considered to be Taconian in age (Roberts *et al*. 2002). The first point may seem straightforward; however, two main factors make interpretations based on palaeogeography uncertain. The first and most direct factor is that seawater Sr and C isotope curves are under constant revision, thus, the interpreted depositional age of a marble is liable to change. A similar ‘problem’

Table 4. *Summary of apparent depositional ages of carbonate formations from the Scandinavian Caledonides determined by Sr and C isotope chemostratigraphy*

Unit	Tectonostratigraphic affinity	$\delta^{13}C$ (‰)	$^{87}Sr/^{86}Sr$	Age (Ma)	Reference
Helgeland nappe complex	Uppermost Allochthon	+3.6 to +6.8	0.7067–0.7076	750–600	Trønnes & Sundvoll (1995)
Hekkelstrand Marble	Bogen Gp, Uppermost Allochthon	5	0.70615	710–700, 660	Melezhik *et al*. (2002*a*)
Tangen sequence marble	Evenes nappe complex, Uppermost Allochthon	8	0.70720	620–610	Melezhik *et al*. (2002*b*)
Fuglevann Marble	Bogen Gp, Uppermost Allochthon	6.5	0.70669	650–595	Melezhik *et al*. (2002*a*)
Saus carbonates	Helgeland nappe complex, Uppermost Allochthon	+5.8 to +6.0	0.70673–0.70678	650–590	Sandøy (2003)
Sokumfjell Group marbles	Beiarn nappe complex, Uppermost Allochthon	8.4	0.70642	635–600	Melezhik *et al*. (2001*a*)
Liland Marble	Bogen Gp, Uppermost Allochthon	6.5	0.70655	650–595	Melezhik *et al*. (2003)
Evenes Marble, Fm I	Evenes nappe complex, Uppermost Allochthon	5	0.70663	650–595	Melezhik *et al*. (2002*b*)
Steinsland thrust sheet marble		6	0.70677	650–595	Melezhik *et al*. (2003)
Evenes Marble, Fm II	Evenes nappe complex, Uppermost Allochthon	+2.2	0.70878	550–500	Melezhik *et al*. (2002*b*)
Ramstad thrust sheet marble		0.2	0.70920	515	Melezhik *et al*. (2003)
Seve–Köli equivalent nappes	Upper Allochthon	−0.8 to +6.4	0.7074–0.7090	560–470	Trønnes & Sundvoll (1995)
Hillstadfjellet carbonates	Helgeland nappe complex, Uppermost Allochthon	+0.5 to +1.5	0.70904–0.70905	530–480	Sandøy (2003)
Evenes Marble, Fm III	Evenes nappe complex, Uppermost Allochthon	5	0.70826	440–438	Melezhik *et al*. (2002*b*)
Evenestangen thrust sheet marble (Dark marble)		6	0.70821	440–438	Melezhik *et al*. (2003)
Evenestangen thrust sheet marble (Variegated marble)	Evenes nappe complex, Uppermost Allochthon	−8.3	0.70824	440–438	Melezhik *et al*. (2003)
Evenestangen thrust sheet marble (White marble)	Evenes nappe complex, Uppermost Allochthon	−5.9	0.70870	*c*. 437	Melezhik *et al*. (2003)
Sagelvvatn area, Mosberg Fm, Sandvika Member		4.3	0.70829	443–428	Melezhik *et al*. (2002*b*)
Falkenes formation	Uppermost Allochthon?	+3.9 to +5.5	0.70645	760–710	This study

exists for palaeogeographical reconstructions, which tend to change (sometimes dramatically) as new data become available or old data are reinterpreted. If the Falkenes formation was deposited at some time between 760 and 710 Ma, as indicated by the isotopic data, the recent palaeogeographical reconstruction by Hartz & Torsvik (2002) suggests that both Baltica and Laurentia were located close to the equator; thus the carbonates may have been deposited on both continents. The same is true for the marbles in the Uppermost Allochthon farther south, with similar compositions to the Falkenes marbles. Thus, although carbonate chemostratigraphy can be used to compare and correlate units over great distances, it does not yield unambiguous information about the provenance of the Falkenes marbles and correlative units to the south.

Geological and geochronological data from the Uppermost Allochthon, in particular from the Helgeland Nappe Complex, point to an early phase of magmatic and orogenic activity at this tectonostratigraphic level, concentrated between *c*. 477 and 445 Ma and accompanied by west-vergent thrusting (Nordgulen *et al*. 1993; Yoshinobu *et al*. 2002). Farther north, the tectonothermal record points to deformation and metamorphism during the period *c*. 465–450 Ma (Selbekk *et al*. 2000; Corfu *et al*. 2003). This Mid- to early Late Ordovician event, which has not been identified in underlying units with Baltican affinities (but see Brueckner *et al*. 2004), is generally accepted to relate to the Taconian orogenic event along the Laurentian margin (Roberts *et al*. 2001). Together with the sedimentary evidence of basin polarity, this suggests that marble units in the Uppermost Allochthon were deposited along the Laurentian continental margin. The observation that the Falkenes marble is isotopically similar to several marble units in the Uppermost Allochthon could suggest a similar provenance; recent U–Pb zircon dating yielding a *c*. 440 Ma magmatic age for parts of the overlying Hellefjord formation (Kirkland *et al*. 2005) supports this interpretation.

In contrast to the new interpretations of the suggested provenance of the Falkenes and Hellefjord formations, fluvial palaeocurrent data from medium-grade, structurally low levels of the Kalak Nappe Complex over wide areas indicate derivation of the Klubben formation arkoses and quartzites from a southerly (present-day coordinates) source, probably Baltica (Williams 1974; Roberts & Andersen 1985; D. Roberts, unpubl. data). The combined data thus suggest that the Kalak Nappe Complex may contain both Baltican and Laurentian elements, amalgamated and stacked during Scandian orogenesis.

Correlating the Falkenes marbles and other marble units in the Scandinavian Caledonides with similar rocks elsewhere in the Caledonian orogenic belt is probably premature in the absence of a more extensive database. A few points of interest can, nevertheless, be considered. Recent work by Thomas *et al*. (2004) in the Dalradian Supergroup of Scotland and Ireland showed that some of the marble units there have Sr isotopic compositions (e.g. Appin Group, $^{87}Sr/^{86}Sr$ ratios from 0.70665 to 0.70690) comparable with those of the Falkenes formation. Furthermore, carbonate formations in the East Greenland Caledonides also have Sr and C isotopic compositions (d^{13}C ranging from +4.3 to +7.4 and an $^{87}Sr/^{86}Sr$ ratio around 0.70635; Fairchild *et al*. 2000) that are similar to those of the Falkenes marbles and other marble occurrences in the Uppermost Allochthon of the Scandinavian Caledonides (Melezhik *et al*. 2002*a*). These observations support the conclusion reached above, that the Falkenes marbles may have a Laurentian affinity, and hold some promise that a growing database of Sr and C isotopic compositions from marbles in the Caledonides belt will have an impact on future reconstructions of the pre-, syn- and rift-/drift history of the Caledonian orogenic belt.

Conclusions

The main conclusions from this study of Sr and C isotopic compositions of marbles from the Falkenes formation of the Sørøy succession of West Finnmark are that: (1) the carbonate sedimentation took place some time between 760 and 710 Ma, i.e. >80 Ma after deformation of the underlying Klubben formation; (2) the Sørøy succession is not a continuous depositional sequence as previously thought, but probably a thrust assemblage consisting of unrelated tectonic units assembled during Scandian orogenesis, although a succession containing units separated by reworked unconformable contacts cannot be ruled out; (3) the Falkenes formation marbles can be correlated chemostratigraphically with marble units in the Uppermost Allochthon to the south, and the tectonostratigraphy of the West Finnmark Caledonides is probably comparable with that observed elsewhere in the Scandinavian Caledonides, in contrast to previously held conceptions; (4) carbonate chemostratigraphy appears to be a powerful tool for identifying cryptic tectonic and/or stratigraphic breaks in strongly deformed, high-grade metamorphic complexes, and for facilitating the correlation of far-separated units.

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