A common mid-Neoproterozoic chemostratigraphic depositional age of marbles and associated iron formations (Fe ± Mn ± P) in the Scandinavian Caledonides

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Carbon and strontium isotope chemostratigraphy ($178\ \delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}$, and $81\ ^{87}\text{Sr}/^{86}\text{Sr}$ analyses of carbonate components in whole-rock samples) was applied to constrain apparent depositional ages of the carbonate protoliths of amphibolite-grade, calcite marbles occurring in siliciclastic sedimentary sequences within the Upper and Uppermost Allochthons in the North–Central Norwegian Caledonides. The Sr-rich marbles hosting banded iron formations occur only in the Uppermost Allochthon. The marbles show, over a distance of 350 km, rather similar least-altered $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70645–0.70665) and $\delta^{13}\text{C}$ (+6 to +8‰) values which are all consistent with a late Tonian (800–735 Ma) age. This sets up a maximum depositional age for the overlying iron formations and somewhat younger diamictites. The apparent maximum ages of the Scandinavian iron formations suggest their contemporaneous deposition with the oldest known Neoproterozoic iron formations reported from China (Shilu Formation) and Namibia (Chuosi Formation). However, these maximum ages do not rule out the iron deposition and the diamictite accumulation in the early Cryogenian within a presumed Tonian–Cryogenian transition. Three other studied marble units in schist-marble sequences, spatially unrelated to iron formations, show different $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{13}\text{C}$ values matching younger apparent depositional ages of 685–600 Ma (the Uppermost Allochthon), and 550 or 425–410 Ma (the Upper Allochthon). The schist-marble-iron formations sequences in several areas contain extrusive meta-igneous rocks, and rare glacial diamictites. In places, all are intruded by intermediate and mafic sills. The iron formations were originally formed outside Baltica and were subsequently thrust upon the Baltoscandian margin during the Scandian orogeny. The provenance of these iron formations represents an enigma, hinting towards a passive continental margin of an unknown, apparently missing microcontinent. The accumulation of the Scandinavian iron formations within a passive continental margin or a large back-arc basin, in places glacially influenced, represents an exception to other reported clastic, sediment-dominated, Neoproterozoic (Cryogenian) iron formations which all were formed in volcanically active continental rift settings.

Keywords: North Norway, Scandinavian Caledonides, chemostratigraphy, depositional age, marbles, iron formations, Neoproterozoic

Electronic Supplement 1: Sample coordinates.

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Introduction

Dismembered stratiform iron formations (IFs) occurring over a distance of c. 550 km between latitudes 65°20' and 69°40' in the Scandinavian Caledonides of northern and

North–Central Norway, are known as the Dunderland-type deposits (e.g., Vogt, 1910; Grenne et al., 1999). In the Rana district (Fig. 1), this ore type constitutes important economic deposits which have been mined for nearly a century, whereas those in Håfjellet and farther north in Troms comprise several historical iron mines and

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Figure 1. A simplified tectonostratigraphic map of the Scandinavian Caledonides in Nordland and southern Troms.

prospects worked episodically during the last century. These IFs are mainly associated with mica schists and marbles (e.g., Bugge, 1978; Melezhik et al., 2015).

Previously suggested depositional ages range from the Late Cambrian to the Early Ordovician (e.g., Bugge, 1948) and from the Late Precambrian to the Cambro-Ordovician (e.g., Sjøvegaard et al., 1988). Radiometric constraints on the deposition of the sediment-hosted IFs in the Caledonides are absent. Apparently for this reason, the most recent compilations of Precambrian IFs did not include those in the Scandinavian Caledonides in

Norway (e.g., Trendall, 2002; Bekker et al., 2010; Cox et al., 2013).

In general, banded iron formations (BIFs) and IFs are a characteristic feature of Archaean–Palaeoproterozoic time, although they also occurred in the 800–600 Ma interval, i.e., during the Neoproterozoic (e.g., Trendall, 2002; Cox et al., 2013) when the IFs became notably enriched in phosphorus relative to older counterparts (Bekker et al., 2010). Recently published isotopic studies demonstrated that similar $\delta^{13}\text{C}$ values and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were obtained for calcite marbles in the mica schist

sequences hosting IFs in the Uppermost Allochthon in both the Håfjellet and the Dunderlandsdalen areas (Fig. 1), and linked their deposition to the late Tonian (800–730 Ma; Melezhik et al., 2015). Hence, both of the previously studied Håfjellet–Evenes and Rana stratiform IFs fit into the youngest (Neoproterozoic) time interval in the global distribution pattern.

The objects of the study area are the northernmost extension of the Dunderland-type iron deposits in the Scandinavian Caledonides of northern Norway. All are located in southern Troms and northern part of Nordland counties, north of Ofotfjorden (Fig. 2). These include mainly the IFs in the Håfjellet–Evenes, Bogen, Lavangen–Herjangen, Andørja, Salangen and Espenes–Sørreisa

Figure 2. Overview of the geology in southern Troms and northern Nordland together with the distribution of important stratiform IF deposits (black dots). The Bø quartzite is an important marker horizon.

Figure 3. A simplified tectonostratigraphic map of southern Troms and northern Nordland showing the location of the Ofoten synform and other important localities mentioned in the text. Modified after Gustavson (1974c), Zwaan et al. (1998) and Melezhik et al. (2003).

Sørreisa areas where they occur in metasedimentary successions (various mica schists and marbles) containing minor units of possible volcanic origin (e.g., amphibolites, hornblende gneisses and biotite gneisses).

The goal of the current article is: (i) to provide apparent depositional ages and depositional environments of selected marble units and associated IFs known in the area north of Ofotfjorden; and (ii) to compare/contrast them with already studied Neoproterozoic stratiform IFs elsewhere in the Scandinavian Caledonides. The

depositional environment of the IFs will be viewed through sedimentological, petrographic and geochemical studies of associated schist-marble and metavolcanic rock sequences, whereas the carbon and strontium isotope chemostratigraphy will be employed for constraining the depositional time of a carbonate mineral precursor of marbles associated with IFs. Apparent C- and Sr-isotope chemostratigraphic depositional ages will also be used for a better understanding of the tectonostratigraphy of the study area (Figs. 3 & 4).

Figure 4. A simplified tectonostratigraphic column for the Ofotfjorden area based on Gustavson (1966, 1972), Boyd et al. (1986a, b), Steltenpohl et al. (1990), Andresen & Steltenpohl (1994) and Melezhik et al. (2014).

Ages are based on: ¹Pre-kinematic Råna massif and felsic dykes (Tucker et al., 1990; Northrup, 1997); ²Tonalite from the ophiolite fragment at Harstad (Northrup, 1997); ³Tonalite from the ophiolite fragment at Gratangseidet (Augland et al., 2014); ⁴Steinsland, Ramstad, Tangen, Fuglevann and Hekkelstrand calcite marbles (Melezhik et al., 2002a, b); ⁵Liland calcite marble (Melezhik et al., 2003); ⁶Variegated (Leivset) calcite marble (Melezhik et al., 2008); ⁷Melkedalen Marble (Melezhik et al., 2014); ⁸Vassdalen marble (this study). Chemostratigraphic ages published by Melezhik et al. (2002a, b, 2003) have been modified by using up-to-date seawater reference curves (for details, see Table 5 and Fig. 25C).

Red dashed lines are thrusts or extensional faults invoked by Melezhik et al. (2002a, b, 2003) to reconcile either stratigraphic inversions or the large age differences between adjacent formations.

Tectonostratigraphic subdivision of the Caledonides in the study area

The main structure of the Scandinavian Caledonides has been described over the past few decades as a succession of four allochthons originating from different geological environments (Gee & Sturt, 1985; Roberts & Gee, 1985) thrust upon each other both prior to and during the collision between Laurentia and Baltica in Silurian–Devonian time. As a result, the bedrock geology of the study area is represented by parautochthonous, Palaeoproterozoic crystalline basement and overlying Caledonian nappes (Gustavson, 1974a, b; Bartley, 1981; Tull et al., 1985; Steltenpohl, 1987; Corfu et al., 2014).

The tectonostratigraphic subdivisions have been robustly established on either side of Ofotfjorden (Figs. 3 & 4); however, their extension farther to the north in the Salangen and Espenes–Sørreisa areas remains to be proven. Hence, the applicability of the tectonostratigraphic units described below should be considered for such areas as provisional and tentative.

The Caledonian nappes include a lowermost unit, the Abisko Nappe Complex (ANC) composed of quartz-feldspathic gneisses and granitic gneisses, overlain successively by the Narvik Nappe Complex (NNC), Evenes nappe complex (ENC), Bogen–Salangen nappe complex (BSNC) and Niingen Nappe Complex (NiiNC) (Figs. 3 & 4). The NNC was previously termed the Narvik Group by Andresen & Steltenpohl (1994), whereas the Evenes Group has been redefined as the ENC (Melezhik et al., 2002a, 2003). Based on the ages given in Fig. 4 for marbles in the Bogen Group (Melezhik et al., 2003), this group is redefined now as the Bogen–Salangen nappe complex.

In terms of the principal subdivisions of the Scandinavian Caledonides (Roberts & Gee, 1985), the Evenes, Bogen–Salangen and Niingen tectonostratigraphic units are considered to form parts of the Uppermost Allochthon (UmA), with the NNC representing the Upper Allochthon (UA), and the ANC forming part of the Middle Allochthon (MA) (Boyd & Søvegiarto, 1983; Boyd et al., 1986a, b). The main focus of our study has been on the IFs and associated marble-schist and metavolcanic rock units forming parts of the BSNC in the UmA. Some selected major marble units of the ENC in the UmA and of the NNC in the UA have also been investigated for a better understanding of the tectonostratigraphy of the study area.

The Narvik Nappe Complex

The NNC has a tectonic contact with the ANC, and it is separated from the overlying ENC by an ophiolite fragment (Boyd, 1983) which, together with the overlying

Elvenes Conglomerate, was termed the Bjerkvik Nappe (Fig. 4). The C- and Sr-isotope chemostratigraphy suggests that the latter is separated from both the NNC and the ENC by tectonic contacts (Melezhik et al., 2002a, b).

The lithologies of the NNC include amphibolite-facies garnet-mica schists, calcareous mica schists, monotonous biotite schists with subordinate amphibolites, meta-keratophyres, pillowed metabasalts, and sheared mafic and ultramafic rocks (e.g., Hodges, 1985). In the structurally lower part of the nappe complex, there is a distinct calcite marble unit, tentatively termed here the Vassdalen marble (Fig. 4). The lithologies become more diverse in the structurally upper part of the nappe (Fig. 4). Here, apart from mica schists and a calcite marble formation (Melkedalen Marble), the sequence contains several thin units of IF, quartzite and graphite schist. One of these, viz the Balsnes graphite schist, hosts the Bjørkåsen massive sulphide deposit (cf., Foslie, 1946, 1949). The Sjøfjell–Narvik zone of phosphorous IFs can be traced from the western side of Håfjellet along the Ofotfjorden to Narvik, for a distance of more than 60 km (Fig. 2). It reaches a maximum thickness of 20 m at Sjøfjellet where it occurs associated with units of apparent, yet to be studied, diamictites. Another IF zone in the NNC, apparently without enrichment of phosphorus, is present at Gratangseidet to the north of the Ofotfjorden (Fig. 2). This is also associated with mica schists and may be situated in the same tectonostratigraphic level as the Sjøfjell–Narvik IF.

The NNC is cut by at least three generations of Caledonian felsic intrusions (Steltenpohl et al., 2003). However, the schists occurring above the IF are not intruded by felsic material (Foslie, 1946). In contrast, the schists occurring below the IF are injected by granitic material in the form of dykes, veins and lenses, and represent a complex of migmatized rocks (e.g., Foslie, 1946; Hodges, 1985). The dykes, veins and lenses are most abundant and thickly developed along the contacts of the Melkedalen Marble, reaching several metres in thickness.

Exact depositional ages of the schist and marble units of the NNC remain unknown, but they predate the emplacement of both the pre-Scandian Råna massif (Figs. 2 & 4) and felsic dykes constrained at 437 ± 1 Ma (U–Pb zircon; Tucker et al., 1990; Northrup, 1997). The ophiolite fragments of the Bjerkvik Nappe have been correlated with the Lyngen Magmatic Complex (Andresen & Steltenpohl, 1994), a metatonalite which has been dated to 469 ± 5 Ma (Oliver & Krogh, 1995). Metatonalites in the Bjerkvik Nappe in the Ofotfjorden region have yielded ages of 479 ± 1 Ma and 474 ± 1 Ma (U–Pb on zircon; Northrup, 1997 and Augland et al., 2014, respectively). The C- and Sr-isotope chemostratigraphy applied to the Melkedalen Marble is consistent with a seawater composition in the time interval 610–590 Ma (mid Ediacaran) and provides the first insight into

the time of deposition of the sedimentary rock column occurring in the structural upper part of the NNC (Melezhik et al., 2014).

The Evenes nappe complex

The ENC is composed of several discrete units of different age which were tectonically emplaced in a non-stratigraphic order (Melezhik et al., 2002a, 2003). In ascending structural order, these are the Steinsland, Langmark, Ramstad, Evenestangen and Tangen thrust sheets (Fig. 4). The Langmark tectonostratigraphic unit has uncertain relative and absolute age and its contact relationships with adjacent units remain unknown. It could belong to either the Steinsland or the Ramstad thrust sheets. The Steinsland, Ramstad and Evenestangen thrust sheets and the Langmark schist, collectively, correspond to the Evenes Marble of Gustavson (1966) and Steltenpohl et al. (1990).

Lithologically the ENC consists of heterogeneous calcite and dolomite marbles intercalated with various crystalline schists. The structurally lowermost calcite marbles comprising the Steinsland thrust sheet are dark grey and banded and contain several layers of graphite schists and thin amphibolite bodies scattered throughout the unit, either subconcordantly interlayered with the marbles or transecting the banding.

The Ramstad thrust sheet is composed of diverse marbles which are separated from the Steinsland thrust sheet by a thin unit of the Langmark schist (Fig. 4). The marbles are calcitic in composition, pale grey, thinly banded or massive. Fine-grained, banded or massive dolomite marbles are also present. The pale grey, thinly banded, calcite marbles contain thin intervals of highly sulphidic, garnet-bearing black schists. The massive calcite marbles form prominent lenses, several tens of metres thick with limited lateral extent, hence resembling build-ups of reefal origin (Melezhik et al., 2003).

The Evenestangen thrust sheet consists of two, very different, lithological varieties of calcite marble (Fig. 5A, B): dark grey, thinly banded marbles and structurally overlying variegated, and banded, schistose marbles (known in Norway as the Leivset Marble; for details see Melezhik et al., 2008). The latter are also associated with a significant volume of dolomite marbles. The variegated marbles are commonly mylonitised and contain abundant amphibolite boudins, whereas the dark grey marbles lack such features. The dark grey/variegated paired unit is developed discontinuously over a distance of 450 km. It has been documented in several places in northern Norway and shown to serve as a prominent marker unit in the Scandinavian Caledonides of North-Central Norway (Melezhik et al., 2008). The Evenestangen thrust sheet is also known to contain Mississippi Valley Type deposits with dolomite-hosted

sulphide-cemented collapse-breccias (e.g., Melezhik et al., 2000). Finally, the Evenestangen thrust sheet contains distinctive diamictites (Fig. 5C) which were used by Tull et al. (1985), Steltenpohl et al. (1990) and Andresen & Steltenpohl (1994) as one of the lithostratigraphic markers for long-distance correlations.

The Tangen thrust sheet, according to Steltenpohl et al. (1990), contains an approximately 50 m-thick bed of dark, either massive or banded, calcite marble occurring at the structural base. The marble is rich in pyrite and mica. In places it has a spotty appearance caused by the development of white lensoidal inclusions of coarsely crystalline calcite.

Precise depositional ages of the schist and marble units of the ENC remain unknown. In the Ofotfjorden area, apparent depositional ages of several marble formations of the ENC have been constrained by means of carbon and strontium isotope chemostratigraphy (Melezhik et al., 2002a, b, 2003, 2008). The least altered $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{13}\text{C}$ values of the lowermost and the uppermost marble formations of the ENC (the Steinsland and the Tangen thrust sheets, respectively) are consistent with Late Neoproterozoic seawater. The C- and Sr-isotope values of the carbonate precursor of the Ramstad marbles suggest a Cambrian age (Melezhik et al., 2002a, b, 2003), whereas those of the dark grey marbles and limestones of the Evenestangen thrust sheet (elsewhere fossiliferous) are consistent with a Llandovery age (for details see, Melezhik et al., 2008). The Llandovery-age carbonate unit lies structurally below the variegated Leivset marble whose extremely ^{13}C -depleted primary nature ($\delta^{13}\text{C} = -7.9 \pm 1.2\text{‰}$ on average, $n = 93$) makes this marble regionally unique. Such low $\delta^{13}\text{C}$ values combined with a high Sr content (up to 8740 ppm) that buffered $^{87}\text{Sr}/^{86}\text{Sr}$ ratios between 0.70802 and 0.70872 (Melezhik et al., 2008), suggest that it was deposited during the 600–550 Ma worldwide Shuram–Wonoka isotopic event (reviewed in Melezhik et al., 2008).

The Bogen–Salangen nappe complex

The contact of the ENC with the structurally overlying BSNC has been defined as a thrust (the Bogen thrust of Andresen & Steltenpohl, 1994) whose precise tectonostratigraphic position remains unclear. Originally, it was placed structurally above the marble of the Tangen Sequence (Steltenpohl & Bartley, 1984; Steltenpohl, 1987). Later, the thrust was redefined to occur at the structural base of the Bø Quartzite (Steltenpohl et al., 1990; Andresen & Steltenpohl, 1994). However, a detailed mapping (Melezhik et al., 2003) has shown that a thrust and associated retrograde metamorphism have been developed structurally above the Tangen marble (Fig. 4).

The current lithostratigraphy of the BSNC established for the Ofotfjorden area includes a variety of amphibolite-

Figure 5. Lithological features of the dark grey-variegated, paired marker-unit of calcite marbles (A, B) and a diamictite (C, D) from the Evenestangen thrust sheet of the Evenes nappe complex. (A) Dark grey marble with preserved thick sedimentary bedding. (B) Variegated marble with orange-pink colour and tectonically modified, composite, marble-calcareous schist rhythmic layering; unique $\delta^{13}\text{C}_{\text{carb}}$ values (-11‰ to -7‰), unusual colour and wide lateral distribution in the UmA of the Scandinavian Caledonides make this marble a very distinctive marker. (C) Dark grey, silty metagreywacke with a massive appearance (metadiamictite), containing a thinly laminated, varve-like bed, and rounded, unsorted fragments of white and pale grey dolostones as well as extremely attenuated plates of yellowish dolostones. The scale-bar in all photographs is 10 cm.

facies mica schists (Lower, Middle and Upper mica schists), quartzites (the Bø Quartzite), and several marble formations (Foslie, 1946; Gustavson, 1966; Steltenpohl, 1987; Steltenpohl et al., 1990). The Bø Quartzite

represents one of the most prominent lithostratigraphic markers because it has a persistent thickness and a considerable lateral extent throughout southern Troms and northern Nordland (Gustavson, 1974c). Especially in

the Håfjellet–Evenes, Bogen, Lavangen–Herjangen and Salangen areas it carries hanging-wall sequences with IFs (Fig. 2).

In the BSNC there are three thick marble formations distributed evenly through the sequence dominated by diverse schists (Fig. 4). The structurally lower calcite marble unit is the up to 250 m-thick Fuglevann Marble (Gustavson, 1966) consisting of dark grey, medium-crystalline, thickly banded, calcite marble with thin interbeds of calcareous, garnet-mica schists and graphite schists. This marble-schist sequence hosts generally Mn-rich IFs (Foslie, 1949).

The marble occurring in the middle part of the group is known as the Hekkelstrand Marble (Fig. 4; Gustavson, 1966). The unit consists of pale grey and grey, coarsely crystalline, impure calcite marbles and white, massive and banded dolomite marbles.

The structurally uppermost marble formation is the Liland marble (Fig. 4) which has been introduced informally to describe a thin marble unit occurring in a series of second-order, closed synforms in the core of the Ofoten Synform on the northern coast of Ofotfjorden (Melezhik et al., 2003). The Liland marble is more than 25 m thick and lies below the NiiNC, from which it is separated by a thrust (Steltenpohl & Bartley, 1987; Andresen & Steltenpohl, 1994). The marble is pale grey and dark grey, massive, thin- to thick-banded, and occurs in contact with IFs (Gustavson, 1974b). The marble contains abundant boudins of amphibolites and is cut by numerous veins and dykes of felsic igneous rocks. Felsic dykes are also abundant in other schist and marble intervals of the BSNC, which contrasts it strongly with the subjacent ENC: the latter lacks such intrusions (Steltenpohl, 1987; Steltenpohl & Bartley, 1987).

Similarly to other sedimentary tectonic units, precise depositional ages of supracrustal rocks of the BSNC remain unknown. In the Ofotfjorden area, the C- and Sr-isotopic signatures of carbonate precursors of marbles, occurring in the Fuglevann, Hekkelstrand and Liland tectonostratigraphic units, are consistent with the composition of Neoproterozoic seawater (Melezhik et al., 2002a, b, 2003).

The Niingen Nappe Complex

The uppermost structural unit is the NiiNC. It is separated from the BSNC by a prominent thrust (Steltenpohl & Bartley, 1987; Karlsen, 1988; Andresen & Steltenpohl, 1994). The NiiNC comprises migmatitic schists and gneisses with ultramafic lenses, metamorphosed at kyanite grade. The metasedimentary rocks which appear to be devoid of any IFs are cut by numerous veins and dykes of felsic igneous rocks.

Metamorphism and deformation

All of the bedrock units in the NNC, ENC, BSNC and NiiNC have been affected by polyphase, Caledonian, orogenic deformation (Gustavson, 1972; Tull et al., 1985; Steltenpohl, 1987), and are deformed into the Ofoten Synform, a major, late-Scandian structure in the Ofotfjorden area (Fig. 3; Gustavson, 1972; Steltenpohl, 1987). This NE–SW-trending synform is asymmetrical and plunges mainly to the northeast. It deforms the regional schistosity and all lithostratigraphic units and thrust contacts in the region. The asymmetry is reflected in changes in structural thickness of the NNC and the ENC. The structural thickness of the former gradually decreases from >8 km in the eastern limb to 2 km in the western limb. The ENC shows the opposite asymmetry (Fig. 3); its visible structural thickness gradually decreases from >12 km in the western limb north of Ofotfjorden to 3 km south of Ofotfjorden, thinning down to 1.5 km along the eastern limb and becoming highly attenuated on the northern side of Ofotfjorden (Fig. 3). The thickening of the western limb is caused by the presence of thick units of Cambrian, Ediacaran and Llandovery age marbles (Melezhik et al., 2008) deformed into a large recumbent fold. Such a fold structure and Cambrian, Ediacaran and Llandovery age marbles are absent in the eastern limb of the synform. The overall differential changes in structural thickness were largely caused by a tectonic thinning and folding that pre-dated the formation of the Ofoten Synform (Melezhik et al., 2003). This is supported by the studies of Melezhik et al. (2002a) and Roberts et al. (2002) showing that the complex tectonic imbrication of the ENC is likely to have resulted from both Taconian and Scandian orogenic deformation.

Similarly to the ENC, the NNC may contain several internal thrust sheets. These may have variable metamorphic grade (Hodges, 1985; Barker, 1986). The age of the peak metamorphism of kyanite grade (e.g., Steltenpohl & Bartley, 1987) has been dated to c. 432 Ma (U–Pb on monazite and zircon; Tucker et al., 1990; Northrup, 1997), thus during the Scandian orogeny. A Rb–Sr isochron age of 427 Ma obtained from a granite cutting nappe boundaries represents the best available constraint on the timing of the NNC assembly (Steltenpohl et al., 2003).

Peak metamorphic temperatures in the ENC and BSNC have been estimated to 540°C (e.g., Steltenpohl & Bartley, 1984). The cooling history of the rocks in the study area has been constrained by $^{40}\text{Ar}/^{39}\text{Ar}$ ages on hornblende (500°C) and muscovite (350°C) to 425–394 and 400–373 Ma, respectively (Coker et al., 1995). The differential changes in structural thickness, noted above, pre-dated the formation of the Ofoten Synform. The severe polyphase deformation and metamorphism make it impossible to assess the character of any original,

syndepositional, lithological thickness variations (Melezhik et al., 2002a, b, 2003; Roberts et al., 2002).

The IFs in southern Troms and northern Nordland

Geological outline

The Dunderland-type IFs in the Scandinavian Caledonides occur, with few exceptions, within the UmA in Norway. This is also the case for those in the study area where most of the IFs are situated in the BSNC of the UmA. IFs at lower tectonostratigraphic levels,

including the Fe–P deposits in the Sjøfjell–Narvik ore zone, are much less abundant. The IFs vary in thickness from a few centimetres up to 30 metres. However, most of them are in the range 5–10 metres when measured outside areas with isoclinal hinge zones where the ore horizons may become multiplied in thickness. They are often found at several closely spaced tectonostratigraphic levels that may represent primary stratigraphical features in combination with tectonic repetitions. The closely spaced IFs separated by various types of micaceous schists and gneisses define together an ore zone. Detailed bedrock mapping is necessary in order to understand the composition and structural complexity of the individual ore zones. However, these zones are easily recognised on aeromagnetic maps where they can be followed for long distances as linear units with small breaks (Fig. 6). The

Figure 6. Aeromagnetic map covering the northern part of the studied area (after Stampolidis & Ofstad, 2015; Ofstad, 2016). Note the strong, extensive anomalies caused by the magnetite-rich IFs in the Lavangen–Herjanger ore zone and the dismembered IFs in the Bogen area. Mines and prospects are marked by black dots.

IFs structurally above the Bø Quartzite in the Ofoten synform can be traced from Salangen southwards to the hinge zone at Håfjellet and back to Rolla in the north over a distance of 140 km (Fig. 2). The breaks in the individual IFs and ore zones are probably due to reduction or quiescence in the primary deposition of iron oxides or tectonic displacements, respectively. In areas like Sørreisa and Bogen the IFs are strongly dismembered in association with isoclinal folding and shearing along their limbs that may in areas generate 10 km-long trains of small, elliptical, atoll-shaped ore bodies distributed in an *en echelon* way.

The mineralogy and ore fabric of the IFs show small variations along the length of the Caledonides in northern Norway. However, in regard to the wall rocks, the ore horizons in the southern part of the study area occur mainly interlayered with various types of metasedimentary rocks like mica schists and marbles. The latter comprise calcite and dolomite marbles which are commonly situated in close proximity to the ore horizons. However, only in rare cases do the IFs occur in direct contact with marbles. Usually the marble and IF are separated by a thin zone of various types of mica schists, most commonly calcareous biotite-amphibole schists. Where IFs do occur in direct contact with competent units such as dolomite marble, the contact is commonly tectonic in contrast to the conformable nature of the contacts towards calcareous schists, calcite marbles and diamictites (Fig. 7; for details, see Melezhik et al., 2015). The IFs occurring in the Andørja, Salangen and Espenes-Sørreisa areas are in addition characterised by the presence of abundant interlayered homogeneous units of fine- to medium-grained amphibolites, amphibole gneisses and biotite gneisses assumed to represent intrusive and extrusive rocks (Fig. 7). Diamictites analogous to those occurring in contact with IFs in Dunderlandsdalen in the Rana area (Figs. 7 & 8; Melezhik et al., 2015) are yet to be confirmed and potential candidates have so far only been found in association with the Sjøfjell deposit in the NNC (UA).

Ore types

The IFs comprise texturally two major ore types: disseminated and banded ores. The dissemination occurs commonly in quartz-rich or calcareous biotite and/or hornblende schists where the Fe-oxides occur impregnated in several-metre-thick zones, in narrow diffusely delineated bands, in parallel stringers and/or in widely distributed grains and aggregates. The banded iron ores are commonly fine grained (<1 mm) and show a composite banding represented by semi-massive to massive Fe-oxide bands alternating with gangue mineral-dominated bands on a mm- to m-scale. The IFs are generally poor in sulphides which occur mainly as scattered grains, aggregates and veinlets of pyrite,

pyrrhotite and/or chalcopyrite. When an IF is composed of both hematite and magnetite the minerals commonly constitute separate layers. The iron ores north of Bogen normally carry magnetite as the sole Fe-oxide.

The banded structure is assumed to represent the primary compositional layering that was metamorphosed to variable ratios of fine-grained (<1 mm) intergrowth of magnetite, hematite, quartz, amphibole (e.g., hornblende and grunerite), almandine, spessartine, apatite, augite, epidote, carbonates, and/or biotite in order of decreasing abundance. Depending on the dominant gangue minerals in the bands, the IF can be subdivided into quartz-, amphibole- (grunerite-) and garnet-banded ores which are the most common types. These ore types may occur at different levels in the individual IF horizons as well as showing changing composition along strike. The garnet-banded ores are composed of either Fe-rich (almandine) or Mn-rich garnet (spessartine). The Mn-rich subunits may, besides spessartine, also contain locally abundant rhodochrosite, Mn-grunerite (dannemorite) and/or pyroxmangite as in the Håfjellet ore zone (Foslie, 1949). Apatite is invariably present in the ores from accessory amounts up to more than 10 wt.% in the Fe-P ores. Although apatite is found in most types of mineral bands with the exception of spessartine-rich bands, it appears preferentially in quartz- and amphibole-banded magnetite ores.

The prograde and retrograde metamorphic transformation of the sedimentary layering has resulted in the development of gradational contacts between the individual bands, local hydrothermal mobilisation of iron into Fe-oxide veinlets and aggregates, as well as silica being deposited as layer-parallel quartz veinlets.

High-grade banded IF is commonly surrounded by massive, carbonate-bearing, amphibole-biotite schists and gneisses (calcareous schists/gneisses) containing low-grade disseminated ores over a distance of 1–5 m away from the border of the ore zone. In cases where the banded IFs are in contact with assumed metavolcanic rocks like amphibolites there is commonly a gradation from high-grade amphibole-banded magnetite ores via amphibolites with strong magnetite dissemination to amphibolites with only scattered magnetite grains. It is possible that this type of gradational border may indicate simultaneous deposition of Fe-oxides and volcanic material e.g., pyroclastics and volcanoclastics, which ought to be considered when sampling for lithochemical studies.

Altogether 240 samples of iron ores in southern Troms and northern Nordland have been analysed for major and trace elements by the standard XRF method (see Chapter: Analytical methods below). Based on their iron, manganese and phosphorus contents which are largely dependent on the relative amount of Fe-oxides, metamorphic Mn-silicates and apatite, respectively,

Figure 7. Generalised lithostratigraphic columns of main studied sections containing IFs. Geographical and geological positions of all sections studied in southern Troms and northern Nordland are shown in Fig. 11. The Rana section is modified from Melezhik et al. (2015); the Håfjellet, Bogen and Herjangen sections are modified from Melezhik et al. (2003).

Figure 8. Sedimentological features of diamictites associated with iron ore in the Ørtfjellet–Kvannvatnet area in the Rana district. (A) A massive diamictite composed of dolostone clasts embedded in a calcareous, mica schist matrix. (B) A wall of an open pit exposing bedding-perpendicular surface of massive diamictite with numerous, nonsorted clasts of white dolostone. (C) A diamictite composed of unsorted clasts of brown-stained, white dolostone irregularly scattered in a massive, calcareous, mica schist matrix. The scale-bar is 10 cm.

Table 1. Fe, Mn and P contents in different iron ore types.

Ore type	Fe ₂ O ₃ , wt. %	MnO, wt. %	P ₂ O ₅ , wt. %	Notes
Fe banded ores	>20	<2.5	<1.0	
Fe–Mn banded ores	>10	>2.5	<1.0	incl. Fe + Mn > 20 wt. %
Fe–P banded ores	>20	n.d.	>1.0	
Fe disseminated ores	<20	n.d.	n.d.	
Fe–Mn disseminated ores	>10	>2.5	n.d.	
Fe–P disseminated ores	>10	n.d.	>0.3	

Abbreviation: n.d. – not determined.

the ores can be subdivided into different geochemical types (Table 1). The division between massive and disseminated Fe ores is defined at 20 wt.% Fe₂O₃ with those at 10 to 20 wt.% Fe₂O₃ representing disseminated types. Fe–Mn ores are those which have more than 2.5 wt.% MnO and 20 wt.% Fe₂O₃ + MnO. Ores with more than 1% P₂O₅ are classified as Fe–P ores. These are characteristically low in manganese (<0.1 wt.% MnO). Most of the banded ores contain 20–35 wt.% Fe, <0.5 wt.% TiO₂ and normally much less than 0.5 wt.% MnO as well as variable concentrations of P₂O₅.

According to Bugge (1978), the Dunderland-type IFs can be subdivided into low-P and high-P ores. The former, which is the ore type presently being exploited in the Rana area, contains less than 0.9 wt.% P₂O₅. The high-P ores commonly contain 1–3 wt.% P₂O₅ which may reach 5 wt.%, i.e., nearly 12% normative apatite in the ores of the Sjøfjell–Narvik zone. Fe and P are commonly more evenly distributed across the IFs in contrast to Mn which appears in most cases to be concentrated in spessartine-rich subunits occurring along one of the margins of the IFs. Since the full width of the IFs is rarely exposed, including its potentially Mn-rich margins, the distinction between IFs composed solely of Fe ores and those with marginal Fe + Mn ores is difficult. The marginal Mn-silicate subunits, which may exceed 20 wt.% MnO as in the Salangen area, carry locally Fe-oxides which rarely contain more than 1 wt.% MnO.

The distribution of the different ore types in the IFs of the study area is shown in Fig. 9. It shows that most of the areas have ores of most (if not all) types. However, there are some differences. The most apatite-rich deposits are found in the Espenes–Sørreisa, Andørja and Sjøfjell–Narvik areas whereas those of the Lavangen–Herjanger area comprise both Fe–P and Fe–Mn ores. The latter are, in contrast, dominant in the Håfjellet–Evenes, Rolla, Bogen and Salangen areas (Fig. 2)

Brief description of IFs associated with sampled marbles

The geological descriptions of IFs occurring proximal to marbles that were sampled for chemostratigraphic studies and age determinations are given below. The IFs in the individual areas are described in order from south to north (Fig. 7). They include, for comparison, a short summary of the geology of the IFs in the Rana and Håfjellet–Evenes areas which were previously investigated by Melezhik et al. (2015).

The Rana area

Mining operations in the Rana area started more than 100 years ago. Until 1999 iron ore was mined only by open-pit methods. Today, Rana Gruber AS operates an underground mine as well as several open pits. Currently, 1.73 million tons of hematite concentrates and more than 100,000 tons of magnetite concentrates are produced annually from low-P ores (in 2015).

The amphibolite-facies IFs in the Rana area are confined to the Dunderland formation in the Rödingsfjället Nappe Complex in the UmA. The formation represents a complexly folded and imbricated marble-schist succession locally containing bodies of amphibolite of assumed intrusive origin (Bugge, 1948). The calcite and dolomite marbles occur commonly either in close proximity to or at the contact with the IFs. Other lithologies hosting the IFs are calcareous schists and diamictites (Figs. 7 & 8).

The banded IFs with low-P ores, some with Mn-silicate rich margins, occur as a series of densely spaced segments representing one or several tectonically dismembered stratigraphic intervals. The IFs reach 4 km in length and occur both as up to 30 m-thick linear units and as detached ore bodies doubled to tripled in thickness in the hinge of isoclinal folds.

The low-P ore is commonly the most iron-rich type comprising both hematite and magnetite ores that usually occur as separate horizons within the individual IFs. According to Bugge (1978) they contain an average

Figure 9. A simplified geological map of the studied area showing the distribution different chemical ore types and sample locations.

of about 34 wt.% Fe_{tot} , 0.31 wt.% MnO and 0.49 wt.% P_2O_5 . The high-P magnetite (Fe-P) ores contain more than 0.9 wt.% P_2O_5 and less than 0.2 wt.% MnO. They are commonly hosted by calcareous hornblende-bearing mica schists, although Fe-P ores hosted by a diamictite have also been recorded (Melezhik et al., 2015).

Bugge (1948) and other earlier workers inferred the original deposition of various ore types in one

continuous horizon which was subsequently affected by tectonic dismembering, duplication and triplication during the course of multiphase deformations. Although currently available geological information does not suggest any obvious stratigraphic separation between the different ore types, Melezhik et al. (2015) speculated that lithostratigraphic relationships of the different segments of Fe, Fe-Mn and Fe-P iron ores indicate original deposition in several, closely spaced, stratigraphic levels.

The Håfjellet–Evenes area

Two horizons of IF occurring associated with the thick Fuglevann marble in the Håfjellet–Evenes ore zone south of Ofotfjorden were studied by Melezhik et al. (2015) (Figs. 2 & 4). The IFs are intercalated with thin layers of mica schist within the marble (Fig. 7), which in turn is folded in the large Håfjellet synform structure. The ore zone and its host rocks are members of the BSNC in the UmA (Fig. 4).

The IF horizons are generally very thin and rarely reach a thickness of more than 6 m. Because of the restricted thickness, the ores have never been mined despite extensive exploration. The most common ore type is quartz-banded on a centimetre scale. The ores vary from magnetite- to hematite-dominated, generally in separate layers (Foslie, 1949). The IF is characterised by the presence of Mn-rich subunits composed mainly of spessartine.

The IFs at Håfjellet continue north across Ofotfjorden to the Evenes area, where similar ores are present in several deposits in which there are hematite- and magnetite-rich layers, as well as manganese-rich subunits. The IFs generally yield ores with 22.9–44.3 wt.% Fe_{tot} , 1.0–6.4 wt.% MnO and 0.5–0.9 wt.% P_2O_5 .

The Bogen area

Mining of iron in the the Ofotfjorden region was almost exclusively carried out in the Bogen area, intermittently between 1906 and 1939, by several companies. The Bergvik, Øvre and Nedre Kleven deposits produced about 1.63 Mt of hand-cobbed iron ore (26 wt.% as magnetite and 5 wt.% as hematite) and about 408,600 t of Fe-oxide concentrates.

The geology of the Bogen area is dominated by different types of mica schist, calcite marble and calcareous quartz-biotite-muscovite schist (calcareous schist) containing subordinate carbonate, clinoamphibole and garnet. Quartzitic schist, dolomite marble, hornblende schist and amphibolite occur as subordinate units. The mineral parageneses of the individual lithologies indicate low to middle amphibolite-facies metamorphism.

Most of the IFs are situated at the contact between calcite marble and calcareous schist, but a few are also located within the major units of calcareous schist. As many as 15 different units of IF have been identified in the central part of the Bogen area (Fig. 10) where they exceed 1 km in length and 20 m in width.

The ore-bearing sequences are deformed into a number of large-scale tight to isoclinal folds (Fig. 10). The strong deformation and tectonic dismembering of the ore layers is probably the main reason for the multitude of ore horizons in the area.

Figure 10. A simplified geological map of the central part of the Bogen area showing the distribution of dismembered IF ore zones.

The IF horizons consist predominantly of rich disseminations to massive bands of iron oxides (mainly magnetite) that alternate with bands of calcareous schists and/or amphibole-rich schists. Quartz- and amphibole-banded IF ores are common and a number of these carry marginal Mn-rich subunits.

The Bergvik–Kleven zone is the most important mining field in the Bogen area. Here, IFs are mainly concentrated at the western (the Bergvik deposit) and eastern (Øvre and Nedre Kleven deposits) flanks of a large antiform (Fig. 10). The Orli–Røssali and Bufallmyr zones 1–3 km to the east of the Kleven mines are likely a continuation of the Bergvik–Kleven IF.

The Gruvli–Gorsjoka Fe–P ore zone differs from the other IFs in the Bogen area by being enclosed by calcareous schists (Fig. 10). The IF at Gruvli is up to 10 m in thickness and comprises quartz-banded magnetite-apatite ores (>2 wt.% P_2O_5) with zones rich in grunerite. The Gorsjoka phosphorus IF (1–2 wt.% P_2O_5) with an overall thickness of 2–6 m consists of several 0.1–0.5 m-thick bands of fine-grained quartz- and amphibole-banded magnetite ores, locally showing almandine banding. The calcareous schist in contact with the IF zone contains a weak magnetite dissemination which extends 50 m away from the IF.

The Lavangen–Herjangen area

The Lavangen–Herjangen area comprises an extensive ore zone that can be traced as a strong anomaly on the aeromagnetic map for a distance of nearly 60 km along strike from Salangen in the north to Herjangen in the south (Fig. 6).

The aeromagnetic survey shows that the IFs developed partly as two distinct zones in the southern part of the studied area (Fig. 6). The upper zone is enriched in apatite ($P_2O_5 > 2$ wt.%), while the lower zone commonly has a thick manganese-rich subunit. The composition of the Lavangen–Herjangen IF varies along strike in the northern part of the zone where both P-rich (up to 3.51 wt.% P_2O_5) and Mn-enriched (up to 28.6 wt.% MnO) ores are found. The IF is hosted by a mica schist that becomes carbonate-bearing in the Gratangen area (Fig. 3) and garnetiferous in the Lavangen area where it is situated in close proximity to marble horizons. Magnetite is the only Fe-oxide and occurs in thin massive bands or as disseminations showing a development of diffuse banding. Major constituents are quartz and amphibole (hornblende or grunerite) whereas biotite, epidote and carbonate occur in subordinate amounts. Garnet-banded IFs are common, being dominated either by almandine or spessartine in the different deposits. The Lavangen–Herjangen IF has not been exploited and only minor trenching and test drilling have been carried out.

The Andørja area

The phosphorous IFs at Andørja are situated in the axial part of the Ofoten Synform in its northern extension (Figs. 2, 3 & 11). They are situated structurally far above the assumed northern extension of the Bø Quartzite. The Andørja ore zone, which is rimmed by marbles, occurs engulfed in a sea of various types of mica schists. The ore zone has a strike length of about 5 km and according to Geis (1967) comprises a 70–180 m-thick sequence of amphibolites hosting several units of IF. Estimated reserves are 94 Mt with 11.1–22.1 wt.% Fe_{mag} and 1.9–2.7 wt.% P_2O_5 . The fluorocarbonate apatite with 0.23 wt.% Cl is too high in chlorine to represent a potential by-product for fertilizer production (Lindahl & Priesemann, 1999). The separate ore bodies shown in Fig. 7 comprise several closely spaced IF units dipping at 15° – 25° E to NE. Re-logging of DDH 29 (Fig. 7) has, however, shown that the amphibolite sequence hosting the ore bodies comprises thin and rather homogeneous units (0.5–13.1 m thick) of fine-grained amphibolite, biotite-amphibole gneiss and quartz-feldspathic biotite gneiss assumed to represent metavolcanites. These gneisses contain numerous units of banded IF ranging in thickness from 0.10 m to 1.95 m with the exception of three units measuring 4.70 m, 6.05 m and 21.90 m. They show banding on a cm scale and comprise quartz- and/or hornblende-banded ores containing randomly distributed grains and aggregates of apatite. The banded units commonly grade on one side into thicker units (3–10 m) of hornblende and/or biotite schist which are, in comparison with the feldspar-bearing orthogneisses, characterised by high amounts of quartz and disseminations and thin banding-parallel stringers of magnetite. The ore-bearing gneiss succession is terminated downwards by a narrow unit (0.6 m) of grey calcite marble. In its structurally uppermost part it carries bands (0.02–0.35 m thick) of pink marble and at a somewhat lower level a 13 m-thick sequence of intercalated light grey calcite marble and greenish banded calc-silicate gneiss.

The Salangen area

The IFs in the Salangen area (Fig. 2) occur in a sequence of mica schist and marble dipping 10° – 30° north and forming a number of recumbent folds with close to 10 km amplitudes (see Fig. 11). The IFs with dominantly magnetite ores cluster at three different structural levels.

The lowermost level starts approximately 30 m structurally above the assumed northern extension of the Bø Quartzite (Fig. 7). It includes a lower unit of banded Fe ores and a 15 m-thick upper unit of disseminated Fe–P ores in calcareous quartz-biotite schists. The former unit comprises a 4 m-thick horizon of quartz- and/or hornblende-banded magnetite ore that is separated

Figure 11. A simplified geological map of southern Troms and northern Nordland (modified after Gustavson, 1974c; Zwaan et al., 1998; Melezhik et al., 2003) with emphasis on marble formations. The map shows locations of the sampled sections and their names (in red) and locations of sampled localities and their names or sample numbers (in black).

by a narrow shear zone of phyllonitic muscovite schist from an underlying unit of grey calcite marble (6 m thick). The IF is terminated upwards by a metre thick zone of magnetite-banded quartz-biotite-hornblende schist towards the transitional contact with an overlying unmineralised sequence of garnetiferous biotite gneiss.

The lowermost structural level of IFs does not show Mn enrichment, thus contrasting with the garnetiferous Mn-rich IFs situated immediately above the Bø Quartzite in the Lavangen–Herjangen and Håfjellet profiles. In the Salangen area such Mn enrichment is found in the middle and upper structural levels (Fig. 7). The middle structural level is recognised and characterised by the appearance of a succession of dolomite marbles that alternate with units of amphibolites. The IFs at this level are hosted by fine-grained, homogeneous, biotite-hornblende gneisses of dacitic composition. Most of them occur in up to 30 m-wide ore zones consisting of several 2–5 m-thick IF units separated by up to a few metre thick units of magnetite-disseminated and barren hornblende-biotite gneisses as well as fine-grained plagioclase-porphyritic metadolerites. The most common ore type represents quartz-hornblende-banded magnetite ores that carry apatite in the uppermost unit. The margins of these IFs may carry Fe–Mn ores associated with garnet-banded zones rich in MnO (2–23 wt.%). Characteristic for the middle structural level is the presence of an up to 30 m-thick unit of nearly monomineralic reddish garnet fels containing up to 23.29 wt.% MnO (6.93 wt.% Fe_2O_3).

In the upper level, the 20 m-wide IF zone carries abundant gneiss interlayers and Mn-rich garnetiferous subunits due to isoclinal folding and tectonic imbrication. These are comparable to the garnet-banded ores in the middle level with the exception that some of them are high in hornblende instead of grunerite and carbonates.

The Salangsverket mine working the structural uppermost IF in the area produced 427,000 tonnes of crude iron ore in the period 1909–1912 from quartz- and/or amphibole-banded ores. The ore reserves prior to mining were estimated to 25 Mt of magnetite ore with about 30 wt.% Fe, 0.1–0.5 wt.% Mn, 0.25 wt.% P and 0.1 wt.% S (Vogt, 1910).

The Espenes–Sørreisa area

The IFs in this area constitute a linear ore zone that starts at Espenes and continues northeastwards for about 7.5 km before it wedges out when entering the mining field at Sørreisa, where the IFs occur at higher structural levels affected by strong isoclinal folding and the generation of thickened ore zones (see Fig. 11).

The Espenes ore zone is considered to have the best ore potential due to the presence of three closely spaced and

parallel ore zones caused by a detached isoclinal dragfold with subhorizontal plunge parallel to the strike of the ore zone. Each zone is 10–20 m thick and 500–1300 m long and shows variable dips in the range 30°–70° SE. The zones comprise several parallel IFs consisting of both disseminated and banded magnetite ores. These are separated by partly garnetiferous and calcareous biotite-hornblende gneisses and schists containing a number of 0.5–2 m-thick calcite marbles and locally thin lens-shaped amphibolites (Fig. 7). Both the marbles and the IFs show pinch-and-swell structures and may split into several thinner units along strike. The upper part of the ore zone comprises quartz-hornblende Fe ores, grading into quartz-garnet-banded Fe–Mn ores that together are 2–20 m thick. The hanging-wall IF is separated by a metre-thick gneiss zone from an overlying 25 m-thick unit of calcite marbles. Below the banded ores in the lower part of the ore zone occur several 5–15 m-thick units of quartz-rich hornblende-biotite schists with disseminated Fe–P ores (Fig. 7). The three ore zones at Espenes contain, according to Brandval (1964), a total of 35 Mt with 34–40% magnetite and variable, but generally low, contents of P_2O_5 .

The ore zones in the Sørreisa mining field are dominated by banded Fe–P ores that rarely contain Mn-rich garnetiferous subunits. The IFs are 2–15 m thick and vary between ankerite-bearing quartz-hornblende-banded and quartz-grunerite-banded ores grading into siliceous biotite-hornblende schists with disseminated magnetite and apatite. The IFs are hosted by calcareous and partly garnetiferous biotite and biotite-hornblende schists which locally contain thin units of amphibolites and hornblende-biotite gneisses. The IFs in Sørreisa are strongly deformed and detached along the sheared limbs of isoclinal folds leading to the formation of up to kilometre-long, augen-shaped, synformal fold closures showing an *en echelon* distribution along strike. Their structural pattern is in many aspects similar to that in the Bogen area (Fig. 10).

Test mining has taken place in some areas in Sørreisa where the hinge zones comprise multiple parasitic folds giving an increased thickness of the ore zone plunging moderately towards the south or southeast (15°–30°). The atoll-shaped IF units normally show ore reserves in the order of 1 Mt. Their small size has been the main obstacle to their exploitation, although some ores in thickened hinge zones have been mined.

Igneous rocks associated with the IFs

Scattered lens-shaped bodies and more extensive zones of amphibolites occur proximal to the IFs in most of the studied areas (Fig. 7). According to their grain size, textures and contact relationships,

these can be subdivided into: 1) medium- to coarse-grained metadolerites and metagabbros with intrusive contacts cutting the banding of the marbles; and 2) fine- to medium-grained metavolcanic amphibolites forming conformable zones in the banded marble-schist sequence. The coarse-grained and more than one meter-thick metadolerite at Espenes appears to be of intrusive origin (Fig. 7). This is also the case for the fine- to medium-grained, plagioclase-porphyritic, gabbroic lenses at the middle structural level in Salangen, where their borders cut the foliation and mineral banding of the wall rocks. The origin of the conformable units of fine- to medium-grained amphibolites in the Håfjellet, Bogen and Salangen (middle level) areas (Fig. 7) is difficult to assess due to widespread deep weathering. However, contacts parallel to the banding of the marbles in the wall rocks suggest a volcanic origin. This is also the case for the fine-grained amphibolites in the footwall of the uppermost IF in the Sørreisa area. The magnetite-disseminated amphibolites associated with the Fe–P ores at Andørja may represent periods of active volcanism with deposition of basaltic ash-fall tuffs.

Some of the areas including Andørja, Salangen and Espenes are also characterised by the presence of conformable units of intermediate to felsic, hornblende-biotite gneisses and biotite gneisses, respectively (Fig. 7). They are generally fine- to medium-grained (0.5–2 mm) and show in most cases a semi-penetrative foliation, but locally also a well-developed lineation. The grey hornblende-biotite gneisses are commonly found as units a few metres thick in the calcareous mica and biotite-amphibole schists (4 in the legend of Fig. 7). A thicker unit occurs in the Salangen area where it is composed of a lower section with wide-spread magnetite bands, stringers and dissemination succeeded by an upper section of very homogeneous hornblende-biotite gneiss. Although unequivocal evidence for a volcanic vs. sedimentary origin is difficult to recognise in the highly deformed marble-schist sequences, the lack of banding in the upper section suggests that it may be of volcanic origin. This is also the case for the homogeneous unit of light grey biotite gneisses in the hanging-wall of the calcite marble structurally overlying the Espenes ore zone. The gneisses in the Andørja ore zone differ from the other areas by being banded on a dm to metre scale by variations in the amount of mafic minerals and locally the presence of bands rich in calc-silicates. The latter type of band suggests a sedimentary origin. Only the structurally lowermost part of the ore zone (226–244 m depth in DDH 29; Fig. 7) shows homogeneous unbanded hornblende-biotite gneisses, 1–3 m thick, which may represent intermediate metavolcanites. However, since these units are similar in composition to many of the bands in the banded gneisses found in the upper part of the ore zone, it may be possible that the gneisses in the ore zone constitute a mixture of volcanoclastic sediments and intermediate volcanites.

The IFs and the described units of metavolcanites are invariably cut by scattered dykes and sills of pegmatitic granites and medium-grained granites. They are commonly only a few metres wide and rarely exceed 10 m in width. They are generally only weakly deformed and appear to have been formed at the termination of the Caledonian tectonothermal activity.

Lithological features of the marble formations in the study area

In the study area, the marbles are present in the UA and UmA. In the former, the marbles constitute a small part of the NNC, whereas in the UmA the marbles make up an essential portion of the ENC and BSNC (Figs. 5 & 11). However, only in the BSNC do the marbles show a close association with the IFs (e.g., the Fuglevann and Liland marbles or their stratigraphic equivalents). Both the marbles associated with the IFs and those exposed in the structurally underlying tectonostratigraphic units, are briefly considered here because they are utilised in the current research for indirect, chemostratigraphic dating. In all cases, the marble underwent an amphibolite-grade metamorphic alteration which, with very few exceptions, obliterated primary depositional features and resulted in the development of a composite banding (Fig. 12). When primary structures are preserved, the marbles show rhythmic bedding and a gradational contact with neighbouring calcareous schists (Fig. 12B). In places, marbles exhibit a parallel bedding and clastic structure. Such well preserved beds may intercalate with intervals showing isoclinal folding. At the Vasskardammen, near Strømslia (Fig. 11), garnet-mica schists hosting a marble unit also contain a c. 20 m-thick section of carbonate-cemented, shale-supported breccias with cross-bedded intervals of calcareous sandstone and small-scale channels filled with a dark grey calcite marble, originally a calcarenite.

Overall, the marbles constitute an essential part of banded and/or rhythmically-banded, carbonate-schist successions. In most cases, such successions are characterised by a significant thickness and a great lateral extent.

Analytical methods

Major and trace elements in carbonate and metavolcanic rocks were analysed by X-ray fluorescence spectrometry (XRF) at the Geological Survey of Norway (NGU), Trondheim, using a PANalytical Axios at 4 kW X-ray spectrometer. The precision (1σ) is typically around 2% of the major oxide present. In carbonate rocks, acid-

Figure 12. Sedimentological features of the Elvenes (A–C) and Vassdalen (D) marbles. (A) A grey, thickly bedded, calcite marble exposed in a road-cut at Laberget, Salangen (sample IM-74; Table 3). (B) A thinly bedded, impure, partially dolomitised, calcite marble passing upwards into calcareous mica schist. An exposure at Flåget road, Salangen. (C) A pale grey, bedded, calcite marble exposed in a road-cut at Flåget, Salangen (sample IM-60; Table 3). (D) A road-cut exposing an over 40 m-thick section of dark grey calcite marble near the E6–E10 road junction (samples IM-118 – M-127; Table 3). The scale-bar in photographs A–C is 10 cm.

soluble Fe, Ca, Mg and Mn extracted with 10% cold HCl acid were analysed by ICP–AES at NGU using a Thermo Jarrell Ash ICP 61 instrument. Detection limits for Fe, Mg, Ca and Mn are 5 ppm, 100 ppm, 200 ppm and 0.2 ppm, respectively. The total analytical uncertainty including element extraction (1σ) is $\pm 10\%$ relative.

Stable carbon and oxygen isotope analyses in carbonate rocks were performed at the Scottish Universities Environmental Research Centre (SUERC) in Glasgow and at the Geological Institute of the Russian Academy of Sciences in Moscow. Approximately 1 mg powder was reacted overnight with phosphoric acid at 70°C. Ratios were measured on PRISM III, AP2003 and DELTA V mass spectrometers. Repeat analyses of NBS-19 and

internal calcite standards are generally better than $\pm 0.2\%$ for carbon and $\pm 0.3\%$ for oxygen at 1σ , and interlaboratory differences are within these ranges. Carbon and oxygen isotopic values are reported and discussed in the conventional delta notation relative to V–PDB and V–SMOW, respectively.

Rb–Sr analyses in carbonate rocks were carried out at the Institute of Precambrian Geology and Geochronology of the Russian Academy of Sciences, St. Petersburg, as specified in Gorokhov et al. (1995). The Rb and Sr concentrations were determined by isotope dilution with reproducibility better than $\pm 0.5\%$. Rb isotopic composition was measured on a multicollector Finnigan MAT-261 mass spectrometer. Strontium isotope analyses

were performed in static mode on a multicollector Triton TI mass spectrometer. All $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were normalised to an $^{86}\text{Sr}/^{88}\text{Sr}$ ratio of 0.1194 and measurements of the NIST SRM-987 run with every batch averaged 0.710256 ± 0.000009 ($2\sigma_{\text{mean}}$, $n = 19$). During the course of the study, the value obtained for the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the U.S.G.S. EN-1 standard was measured at 0.709197 ± 0.000010 ($2\sigma_{\text{mean}}$, $n = 11$).

Samples of iron mineralisation in southern Troms and northern Nordland have been analysed for major and trace elements including REE by the accredited ACME laboratories in Vancouver, Canada (now Bureau Veritas Minerals).

Geochemical features of igneous rocks associated with the IFs

The UA and UmA in the study area between Ofotfjorden and Sørreisa comprise dominantly metasedimentary rocks (marbles and various schists), whereas amphibolites and orthogneisses occur subordinately. Major and trace element XRF analyses have been carried out on 23 samples of amphibolites of inferred volcanic origin. Representative analyses of the metavolcanites are given in Table 2. Metavolcanites that are not associated with both IFs and sampled marbles, i.e., from the Sjøfjellet and Gratangseidet areas, are also included in order to obtain a better understanding of the paleotectonic setting of the studied area.

The igneous rocks from the different areas have rather similar chemistry. The spider diagrams (Fig. 13A–D) demonstrate with few exceptions enrichment of the incompatible large ion lithophile (LIL) elements K, Rb, Ba, Th and depletion of the high-field-strength (HFS) elements Ti and Y compared to MORB. Furthermore, Nb is also depleted compared to Ce. This pattern is typical for calc-alkaline and within-plate igneous rocks, which is also consistent with the discrimination diagrams (Fig. 13E, F).

Major and trace element geochemistry, carbon, oxygen and strontium isotope ratios of the marble formations in southern Troms and northern Nordland

The studied and sampled carbonate formations of southern Troms and northern Nordland are composed mainly of calcitic varieties (Table 3; Fig. 7) having an average Mg/Ca ratio of 0.03 ± 0.08 ($n = 179$) with the majority of samples showing a Mg/Ca ratio <0.02 (Fig. 14A). However, in the Salangen section, several units of

Table 2. Representative analyses of amphibolites. (Major elements in wt.% and trace elements in ppm).

Sample Area	obs.pkt.44 Bogen	DDH23, 117,16 m Andørja	WP 84 Salangen
SiO ₂	49.6	52.4	49.4
Al ₂ O ₃	15.0	8.5	14.1
Fe ₂ O ₃	12.2	19.4	12.9
TiO ₂	1.4	0.7	2.0
MgO	8.3	4.8	6.5
CaO	8.0	8.8	11.1
Na ₂ O	2.3	1.2	3.2
K ₂ O	1.4	1.7	0.4
MnO	0.2	0.1	0.2
P ₂ O ₅	0.1	1.0	0.2
LOI	1.1	0.4	0.5
Total	99.4	99.0	100.0
Ba	233	371	47
Cr	356	64.6	247
Ni	65.0	24.8	45.2
Co	44	14	40
Cu	46	49	35
Pb	7	8	2
Zn	130	56	76
Rb	60	42	6
Sr	138	250	171
Zr	63	158	135
Y	19	27	34
Nb	6	13	4
V	218	80	313
La	10	25	10
Ce	10	73	23
Nd	13	26	17
Ga	15	11	18
Mo	1	<3	1
Sc	34	10	42
Th	2	7	2
U	<2	<5	<2

dolomite marble have been documented, and one thin bed has been observed in the Herjangen section (Fig. 7). In Salangen, the dolomite marbles occur intercalated with units of amphibolites and garnet-mica schists.

The analysed samples are characterised by a moderate content of SiO₂ (6.9 ± 0.9 , $n = 171$, with 8 samples below the detection limit of <0.5 wt.%) and Al₂O₃ (1.0 ± 1.0 , $n = 177$, with 2 samples below the detection limit of <0.5 wt.%). A significant positive correlation between these two components (Fig. 14B) suggests their presence mainly in the form of aluminosilicates with

Figure 13. Whole-rock geochemistry of amphibolites from various iron-ore districts in southern Troms and northern Nordland. (A–D) Spider diagrams; MORB data for normalisation are from Pearce (1983). (E) A Ti–Zr–Y diagram based on Pearce & Cann (1977). (F) A Zr/Y–Zr diagram based on Pearce & Norry (1979).

very few exceptions having quartz as a dominant clastic component.

The ranges in Sr and Mn contents are large (Fig. 14C); however, the majority of non-dolomitised calcite marbles are characterised by a high Sr content ranging between 600 and 5560 $\mu\text{g}\cdot\text{g}^{-1}$ (1910 on average, $n = 173$), and a moderate

Mn content fluctuating between 12 and 500 $\mu\text{g}\cdot\text{g}^{-1}$ (133 on average, $n = 173$). The Fe concentration varies between 27 and 10200 $\mu\text{g}\cdot\text{g}^{-1}$. Interestingly, in the marbles associated with the IFs, Fe correlates with the content of Mn ($r = +0.52$, $n = 95$, $>99.9\%$; Fig. 14D), whereas such correlation is less significant in marbles from other stratigraphic intervals ($r = +0.25$, $n = 74$, $<95\%$).

Figure 14. Various cross-plots illustrating geochemical characteristics of the studied marbles.

Both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values ($n = 178$) exhibit a large range (from -1.7 to $+9.4\text{‰}$, and from 13.4 to 26.4‰ , respectively) and show a significant positive correlation (Fig. 14E). However, despite the large variation, the average of the $\delta^{13}\text{C}$ values ($+4.0 \pm 2.2\text{‰}$) remains positive and the $\delta^{18}\text{O}$ ratios are rather high ($21.5 \pm 2.8\text{‰}$). Similar to the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios measured on the calcite marbles ($n = 81$) are also characterised by a large fluctuation ($0.70647\text{--}0.70899$), and exhibit no significant correlation with the Mn/Sr ratio (Fig. 14F).

The marbles from different tectonostratigraphic intervals share similar $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ isotopic ratios and cannot

be distinguished by these geochemical features alone. However, they show a clear difference in $^{87}\text{Sr}/^{86}\text{Sr}$ values. The marbles from the NNC have the most radiogenic values, those from the BSNC (e.g., the Fuglevann and Liland marbles or their stratigraphic equivalents) are characterised by the least radiogenic ratios, whereas the marbles from the ENC (e.g., the Tangen thrust sheet) are placed in between the two (Fig. 14F). The combination of $\delta^{13}\text{C}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ values may offer the next step of discrimination. Subject to the geochemical screening for a post-depositional resetting, such combination will be used for assessing apparent depositional ages of various marble formations in the following sections.

Geochemical screening of post-depositional resetting of the C and Rb–Sr isotope systems: a general consideration

‘Extraction’ of the ‘least altered’ C- and Sr-isotopic values for the purpose of isotope chemostratigraphy requires the geochemical assessment of post-depositional resetting of the above-mentioned isotope systems during diagenetic and metamorphic processes. The geochemical assessment of meteoric diagenesis of Phanerozoic carbonates and their carbon, oxygen and Rb–Sr systems is mainly based on the Mn/Sr, Fe/Sr, Ca/Sr and Rb/Sr ratios and on the relative abundance of Mn, Fe, Rb and Sr (e.g., Brand & Veizer, 1980). Such an approach has been also adopted for Neoproterozoic (e.g., Jacobsen & Kaufman, 1999) and Palaeoproterozoic (e.g., Melezhik et al., 1999) carbonates. However, in some cases precaution needs to be taken into consideration when assessing the effect of meteoric diagenesis in Paleoproterozoic carbonates, which may have formed in an anoxic water enriched in Fe^{2+} and Mn^{2+} (e.g., Veizer et al., 1992; Bekker et al., 2001).

Melezhik et al. (2003) have refined such a geochemical assessment for high-grade marbles. Based on a decade of empirical experience they have suggested that the level of screening criteria implemented for high-grade marbles should be significantly higher than that used for non-metamorphosed rocks. For identifying the least altered syndeositional Sr-isotopic ratio in marbles with a Sr content $>1000 \mu\text{g}\cdot\text{g}^{-1}$, they have suggested the use of both Mn/Sr and $\text{Mg}/\text{Ca} \leq 0.02$, and low abundances of SiO_2 ($<5 \text{ wt.}\%$) and Al_2O_3 ($<1 \text{ wt.}\%$). However, in all cases the choice of the elemental ratios and, in particular, their values is empirical, and to some extent arbitrary, and may vary depending on the diagenetic and tectono-metamorphic history of the studied rocks (e.g., Melezhik et al., 2001, 2003). In some instances, neither of the above-mentioned criteria works. In such cases, the highest $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ and lowest $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are the best choice to be considered as the least altered and to represent the proxy to seawater composition.

In general, based on the sediment/water ratios of diagenetic/metamorphic systems (e.g., Banner & Hanson, 1990; Land, 1992), among the two isotopic systems utilised for the purpose of isotope chemostratigraphy, the carbon system is far more resilient during post-depositional, open-system recrystallisation (excluding organic diagenesis) because it is effectively buffered by the dissolving carbonate precursor. In contrast, the post-depositional fate of the Sr-isotopic system is largely dependent on the original abundances of Sr. With a Sr content above 1000 ppm, even high-grade, polydeformed and polymetamorphosed, calcite marbles may retain near-depositional Sr-isotopic ratios (Brasier & Shields, 2000; Melezhik et al., 2001, 2003; Thomas et al., 2004).

Diagenetic and metamorphic alterations affect carbonate material in a similar way (Nabelek, 1991). These processes usually lower $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ contents, and introduce radiogenic strontium. The Mn and Sr contents would be partially shifted towards equilibrium with the ambient diagenetic/metamorphic fluids. Hence, the common practice adopted in the exercise of ‘extracting’ the least-altered $\delta^{13}\text{C}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ values is to choose the ones that are most enriched in ^{13}C and the least enriched in ^{87}Sr , whereas other discrimination criteria briefly addressed above should provide general guidance to the degree of the preservation/alteration. In our following discrimination exercise we adopt this combined approach.

Geochemical screening for post-depositional resetting of the C and Rb–Sr isotope systems in the studied marble formations

Narvik Nappe Complex

The Vassdalen marble. The most completely studied calcite marble section located near the E6–E10 road junction is over 50 m thick and situated tectonostratigraphically in the lower part of the NNC (Figs. 4 & 11). Neither a formal nor an informal name has been designated previously for this marble formation. For the brevity of the forthcoming description and discussion, the formation is provisionally named here as the Vassdalen marble.

The Vassdalen marble has been documented in and sampled from seven road-cuts (e.g., Fig. 15A) and natural exposures located between the Strømslia tunnel in the northeast and Storvatn (Øvre Håvikdalen) in the south (all locations are listed in Table 3 and marked in Fig. 11). Forty-four samples, collected from several localities along a strike-length of over 70 km, represent the entire thickness of the marble unit. The marbles are grey, medium-crystalline, banded, with intercalations of calcareous garnet-mica schists and, in places, with intervals of sheared rocks with lenses and veins of white calcite and dolomite (Fig. 15B). The marbles have low but variable contents of SiO_2 and Al_2O_3 (Table 3). In terms of Sr, Mn, Fe concentrations, and Mn/Sr, Mg/Ca, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$, they are comparable to many marble units occurring in the BSNC (Tables 3 & 4). The only difference is their more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratios.

A limited degree of variability of $\delta^{13}\text{C}$ values seen in each single section (e.g., Fig. 15A), suggests a high preservation potential of the carbon isotope system. This is supported by the lack of correlation of $\delta^{13}\text{C}$ with $\delta^{18}\text{O}$, Sr, Fe and Mn abundances, and Mn/Sr and Mg/Ca ratios (Fig. 15C), and strongly suggests an average $\delta^{13}\text{C}$ of c. $+2\%$ as a seawater proxy.

Figure 15. The Vassdalen marble at the E6–E10 road junction. (A) A lithological column of the sampled section and geochemical and isotopic characteristics of the marbles. Note a limited degree of $\delta^{13}\text{C}$ variability. (B) Intensely sheared, grey, calcite marbles with bedding-parallel lenses and veins of white calcite and dolomite. (C) Various cross-plots illustrating alteration trends of the Sr-isotopic system indicated by red arrows. Note that $\delta^{13}\text{C}$ does not correlate with Mn/Sr or $^{87}\text{Sr}/^{86}\text{Sr}$ ratios.

Table 3. Geochemical and isotopic composition of marble formations studied in southern Troms and northern Nordland (see Electronic Supplement 1 for sample location coordinates).

Tectonostratigraphic unit, location, sample #, lithology	SiO ₂	Al ₂ O ₃	Na ₂ O	K ₂ O	P ₂ O ₅	Mg	Ca	Fe	Mn	Sr	‰				Rb	Sr	⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr	
											wt. %	δ ¹³ C	δ ¹⁸ O	μg·g ⁻¹					
The Narvik Nappe Complex																			
The Vassdalen marble																			
Late Ediacaran or Early Ordovician–Mid Silurian																			
Stromsli tunnel																			
IM–66	Grey CM	7.24	1.22	<0.1	0.38	0.07	1830	331000	460	66.2	2960	0.02	0.006	1.4	20.7	0.48	3490	0.0004	0.70874
IM–67	Grey CM	7.33	1.31	<0.1	0.39	0.08	2340	335000	597	88.2	2870	0.03	0.007	1.5	20.7	1.71	3370	0.0015	0.70873
IM–68	Grey CM	15.8	2.18	0.16	0.57	0.13	2290	294000	384	131	2750	0.05	0.008	2.6	19.0	1.84	3590	0.0015	0.70889
IM–69	Grey CM	6.28	1.13	<0.1	0.32	0.06	2770	335000	772	213	3820	0.06	0.008	2.3	21.5	1.83	4420	0.0012	0.70880
IM–70	MCM	14.9	3.09	0.26	0.81	0.10	3760	286000	2330	229	2090	0.11	0.013	1.3	18.0	n.d.	n.d.	n.d.	n.d.
IM–71	ChCM	18.6	3.33	0.32	0.75	0.12	13900	252000	3780	275	1470	0.19	0.06	1.7	16.3	n.d.	n.d.	n.d.	n.d.
Fjordbotn marka																			
IM–102	Grey CM	6.04	0.75	<0.1	0.10	0.17	2130	337000	476	131	1500	0.09	0.006	1.3	17.4	n.d.	n.d.	n.d.	n.d.
IM–103	Grey CM	5.03	0.87	<0.1	0.17	0.07	2090	340000	733	148	2880	0.05	0.006	0.9	17.9	0.41	3180	0.0004	0.70878
IM–104	Dark grey CM	4.88	0.84	<0.1	0.22	0.06	2280	346000	869	118	3240	0.04	0.007	1.5	17.2	0.90	3650	0.0007	0.70880
IM–105	Dark grey CM	7.78	1.46	0.22	0.37	0.22	9830	341000	732	81.1	759	0.11	0.03	2.5	21.5	n.d.	n.d.	n.d.	n.d.
IM–106	Dark grey CM	12.5	1.69	0.11	0.54	0.14	5020	333000	689	120	1640	0.07	0.02	0.7	21.7	n.d.	n.d.	n.d.	n.d.
Vassdalen																			
IM–107	Grey CM	7.06	1.35	<0.1	0.32	0.06	5840	347000	1310	180	4020	0.04	0.02	3.5	20.2	n.d.	n.d.	n.d.	n.d.
Kvarnemoelva																			
IM–108	Grey CM	8.32	1.72	0.14	0.35	0.08	2230	339000	1120	175	2450	0.07	0.007	1.3	19.6	n.d.	n.d.	n.d.	n.d.
IM–109	Grey CM	4.65	0.89	<0.1	0.22	0.06	4580	351000	942	216	3510	0.06	0.013	3.0	18.3	n.d.	n.d.	n.d.	n.d.
IM–110	Grey CM	9.70	1.78	<0.1	0.45	0.07	4310	318000	843	336	3240	0.10	0.014	2.2	18.2	4.69	3990	0.0034	0.70896
IM–111	Grey CM	2.17	0.37	<0.1	0.05	0.05	1210	367000	255	31.2	3470	0.009	0.003	1.9	21.5	0.45	3820	0.0003	0.70864
IM–112	Grey CM	7.36	1.55	0.18	0.47	0.08	2940	333000	607	81.9	3030	0.03	0.009	1.4	22.1	3.44	3580	0.0028	0.70881
IM–113	Grey CM	8.12	1.84	0.21	0.56	0.08	3580	318000	1100	180	2850	0.06	0.011	1.5	21.7	n.d.	n.d.	n.d.	n.d.
IM–114	Grey CM	4.93	1.27	0.12	0.35	0.07	2940	340000	730	63.0	3190	0.02	0.009	1.8	21.2	1.3	3610	0.0010	0.70874
IM–115	Grey CM	8.31	1.73	0.18	0.48	0.09	4120	327000	1060	163	2710	0.06	0.013	1.1	20.0	n.d.	n.d.	n.d.	n.d.
Liljadal																			
IM–116	Dark grey CM	13.6	1.42	<0.1	0.48	0.11	3180	301000	424	83.1	2080	0.04	0.011	1.2	19.5	1.34	2570	0.0015	0.70896
IM–117	Dark grey CM	17.9	1.80	<0.1	0.61	0.11	2460	287000	1080	83.2	1920	0.04	0.009	1.3	19.1	0.88	2560	0.0010	0.70894

Table 3. (Continued)

Tectonostratigraphic unit, location, sample #, lithology	SiO ₂	Al ₂ O ₃	Na ₂ O	K ₂ O	P ₂ O ₅	Mg	Ca	Fe	Mn	Sr	Mn/Sr	Mg/Ca	δ ¹³ C	δ ¹⁸ O	Rb	Sr	⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr	
	wt. %																	μg·g ⁻¹	μg·g ⁻¹
	‰																		
E10–E6 junction																			
IM–118	Dark grey CM	6.06	1.11	<0.1	0.23	0.06	4620	330000	1330	84.0	2500	0.03	0.014	2.0	19.0	n.d.	n.d.	n.d.	
IM–119	Dark grey CM	15.6	3.39	0.22	0.90	0.11	6470	271000	2150	230	3080	0.07	0.02	1.0	20.6	n.d.	n.d.	n.d.	
IM–120	Dark grey CM	9.88	2.11	0.14	0.60	0.09	2670	312000	790	239	3390	0.07	0.009	1.2	20.6	n.d.	n.d.	n.d.	
IM–121	Dark grey CM	2.82	0.46	<0.1	0.10	0.07	2110	358000	74.9	56.3	4100	0.014	0.006	1.3	21.8	n.d.	n.d.	n.d.	
IM–122	Dark grey CM	3.37	0.68	<0.1	0.16	0.07	2720	348000	477	55.1	3500	0.02	0.008	1.8	21.3	0.25	0.0002	0.70874	
IM–123	Dark grey CM	5.18	1.02	<0.1	0.28	0.06	3480	341000	527	147	5550	0.03	0.010	2.0	17.3	0.83	0.0004	0.70882	
IM–124	Dark grey CM	5.39	1.27	<0.1	0.36	0.05	6280	330000	1620	408	4160	0.10	0.019	3.0	18.4	n.d.	n.d.	n.d.	
IM–125	Dark grey CM	0.93	0.16	<0.1	0.04	0.04	2120	363000	168	30.7	5300	0.006	0.006	2.3	21.0	0.02	0.0000	0.70874	
IM–126	Dark grey CM	1.90	0.38	<0.1	0.07	0.05	2440	357000	143	69.5	4710	0.015	0.007	2.5	20.7	2.12	0.0012	0.70875	
IM–127	Dark grey CM	3.95	0.75	<0.1	0.13	0.06	3560	348000	552	87.6	4710	0.02	0.010	3.2	21.5	1.31	0.0007	0.70879	
IM–128	Dark grey CM	14.6	1.71	<0.1	0.41	0.08	2170	302000	283	178	1840	0.10	0.007	1.5	21.6	n.d.	n.d.	n.d.	
IM–129	Dark grey CM	3.43	0.59	<0.1	0.05	0.07	2800	359000	1040	195	2070	0.09	0.008	2.0	18.6	n.d.	n.d.	n.d.	
MP–104	Dark grey CM	0.65	0.22	0.25	0.06	0.06	5580	377436	n.d.	77	4787	0.016	0.015	1.2	20.5	0.17	4536	0.70861	
Slätvika																			
MP–105	Grey CM	0.82	0.25	0.26	0.07	0.06	6120	372537	n.d.	154	5075	0.030	0.016	3.5	20	0.15	4685	0.70881	
Beisfjord																			
IM–134	Dark grey CM	25.5	2.73	0.33	0.59	0.21	2760	256000	1310	307	1850	0.17	0.011	2.0	17.7	n.d.	n.d.	n.d.	
IM–135	Dark grey CM	21.5	0.98	<0.1	0.27	0.12	2280	286000	449	54.8	1870	0.03	0.008	2.9	18.9	0.78	0.0009	0.70898	
IM–136	Dark grey CM	4.75	0.72	<0.1	0.18	0.08	2130	351000	365	135	3990	0.03	0.006	1.4	20.5	0.29	0.0002	0.70872	
MP–106	Dark grey CM	10.11	1.4	0.32	0.31	0.11	6060	313678	n.d.	462	1552	0.30	0.019	2.2	17.3	n.d.	n.d.	n.d.	
Storvatn, Øvre Håvikdalen																			
IM–137	Dark grey CM	29.9	3.57	0.81	0.43	0.14	3810	235000	1110	470	1230	0.38	0.02	0.3	17.0	n.d.	n.d.	n.d.	
IM–138	Grey CM	6.30	1.02	0.11	0.31	0.15	6430	332000	1140	169	2170	0.08	0.02	2.6	18.9	0.75	0.0009	0.70899	
IM–139	Grey CM	4.01	0.63	<0.1	0.13	0.03	2680	349000	1460	39.9	2770	0.014	0.008	1.3	20.4	0.19	0.0002	0.70893	
IM–140	Grey CM	19.4	2.03	0.38	0.42	0.16	3070	286000	969	240	1820	0.13	0.011	2.6	17.8	n.d.	n.d.	n.d.	

Table 3. (Continued)

Tectonostratigraphic unit, location, sample #, lithology	SiO ₂	Al ₂ O ₃	Na ₂ O	K ₂ O	P ₂ O ₅	Mg	Ca	Fe	Mn	Sr	Mn/Sr	Mg/Ca	δ ¹³ C	δ ¹⁸ O	Rb	Sr	⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr	
	wt. %										μg·g ⁻¹				‰				μg·g ⁻¹
The Evenes nappe complex Elvenes marble Late Cryogenian																			
Karlstad																			
EX58	Grey CM	1.36	0.07	<0.10	0.02	0.12	10560	374454	n.d.	53.9	1911	0.03	0.03	5.3	23.1	0.233	1903	0.0004	0.70790
EX59	Grey CM	2.57	0.57	<0.10	0.21	0.12	10380	366218	n.d.	61.6	1960	0.03	0.03	5.8	21.8	0.152	2040	0.0002	0.70768
Laberget (Salangen)																			
	IM-72	Dark grey CM	6.35	0.77	0.16	0.14	2240	344000	742	38.8	1800	0.02	0.007	6.1	22.5	2.75	2010	0.004	0.70732
	IM-73	Grey CM	12.4	2.12	0.55	0.28	3330	310000	1160	41.0	1360	0.03	0.011	5.2	22.9	0.26	1690	0.0005	0.70751
	IM-74	Pale grey CM	9.95	1.36	0.15	0.30	2460	329000	1090	39.4	1740	0.02	0.007	6.0	23.4	0.49	2060	0.0007	0.70737
	IM-75	Grey CM	12.2	1.53	0.41	0.23	2660	319000	1190	95.2	1280	0.07	0.008	4.2	17.8	n.d.	n.d.	n.d.	n.d.
	IM-76	Grey CM	4.51	0.69	0.19	0.10	1720	354000	822	30.9	2090	0.015	0.005	6.2	20.2	0.46	2300	0.0006	0.70742
	EX46	Grey CM	1.32	0.28	<0.10	0.08	2220	382335	n.d.	53.9	529	0.10	0.006	4.5	19.6	n.d.	n.d.	n.d.	n.d.
	EX47	Grey CM	0.26	0.07	<0.10	0.01	3660	386737	n.d.	69.3	777	0.09	0.009	5.3	22.7	0.046	784	0.0002	0.70737
EX48	Grey CM	2.13	0.72	<0.10	0.17	1500	377223	n.d.	46.2	1159	0.04	0.004	5.7	23.1	0.075	1183	0.0002	0.70720	
Holte																			
	IM-77	Grey CM	12.5	2.60	0.10	0.70	2680	305000	1050	50.7	1290	0.04	0.009	6.7	21.0	0.47	1640	0.0008	0.70741
	IM-78	Grey CM	15.8	2.22	0.50	0.33	1940	292000	1090	71.3	1140	0.06	0.007	6.3	19.3	n.d.	n.d.	n.d.	n.d.
Otteråa																			
	IM-79	Grey CM	3.09	0.92	<0.1	0.20	1290	357000	285	31.3	1160	0.03	0.004	6.0	21.3	n.d.	n.d.	n.d.	n.d.
	IM-80	Grey CM	0.95	0.27	<0.1	0.04	1100	368000	59.0	13.7	1380	0.010	0.003	6.6	23.5	0.09	1480	0.0002	0.70696
	IM-81	Grey CM	1.11	0.34	<0.1	0.06	1330	363000	117	15.9	1220	0.013	0.004	6.6	22.5	n.d.	n.d.	n.d.	n.d.
Lavangen																			
	EX45	Grey CM	21.1	5.22	0.31	1.38	10200	265611	n.d.	123.2	1500	0.08	0.04	7.3	20.7	1.62	1854	0.0026	0.70744
Bjerkvik, Høgebakken																			
	IM-82	Pale grey CM	10.2	1.95	<0.1	0.52	6740	310000	1730	52.6	1060	0.05	0.02	5.7	21.6	n.d.	n.d.	n.d.	n.d.
	IM-83	Pale grey CM	4.79	0.92	<0.1	0.27	4740	344000	1190	33.0	1180	0.03	0.01	5.3	21.4	0.57	1360	0.0012	0.70744
	IM-84	Pale grey CM	10.3	1.63	<0.1	0.47	6620	308000	2060	41.9	1090	0.04	0.02	5.2	21.8	n.d.	n.d.	n.d.	n.d.
	IM-85	Pale grey CM	2.63	0.36	<0.1	0.10	2620	364000	976	21.8	1630	0.013	0.007	5.5	21.6	0.07	1840	0.0001	0.70734

Table 3. (Continued)

Tectonostratigraphic unit, location, sample #, lithology	SiO ₂	Al ₂ O ₃	Na ₂ O	K ₂ O	P ₂ O ₅	Mg	Ca	Fe	Mn	Sr	Mn/Sr	Mg/Ca	δ ¹³ C	δ ¹⁸ O	Rb		Sr	⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr
	wt. %			μg·g ⁻¹								μg·g ⁻¹							
Vassøse																			
IM-86	Grey DCM	3.08	0.09	<0.1	0.03	0.04	40200	306000	72.5	15.6	292	0.05	0.13	1.4	13.4	n.d.	n.d.	n.d.	n.d.
IM-87	Grey CM	8.82	1.94	0.11	0.47	0.02	4480	321000	3680	85.7	1250	0.07	0.014	6.0	18.6	n.d.	n.d.	n.d.	n.d.
IM-88	Grey CM	10.3	2.18	0.14	0.53	0.03	2510	323000	1660	67.2	1530	0.04	0.008	6.4	21.9	2.03	1770	0.0033	0.70712
Elvenes																			
IM-93	Grey CM	5.40	1.29	<0.1	0.36	0.02	2860	337000	752	46.6	1470	0.03	0.008	5.2	22.1	n.d.	n.d.	n.d.	n.d.
IM-94	Grey CM	2.83	0.20	<0.1	0.04	0.02	4730	354000	197	17.1	1860	0.009	0.013	5.3	22.7	0.29	2510	0.0003	0.70698
IM-95	Grey CM	7.25	0.31	<0.1	0.07	0.02	17100	319000	540	58.7	1110	0.05	0.05	4.3	21.6	n.d.	n.d.	n.d.	n.d.
IM-96	Grey CM	0.72	0.20	<0.1	0.04	0.03	1350	364000	54.2	29.3	870	0.03	0.004	5.6	25.7	0.03	780	0.0001	0.70776
IM-97	Grey CM	<0.5	0.15	<0.1	0.03	0.04	1310	373000	26.6	35.2	1030	0.03	0.004	5.7	24.4	0.07	1140	0.0002	0.70764
IM-98	Grey CM	2.43	0.94	<0.1	0.23	0.03	1390	359000	124	94.7	729	0.13	0.004	5.9	22.7	n.d.	n.d.	n.d.	n.d.
IM-99	Grey CM	<0.5	0.09	<0.1	0.01	0.03	4660	372000	439	55.3	947	0.06	0.013	5.6	21.9	n.d.	n.d.	n.d.	n.d.
IM-100	Grey CM	14.2	3.08	0.30	0.72	0.01	5280	288000	7300	82.3	1300	0.06	0.02	6.3	18.9	n.d.	n.d.	n.d.	n.d.
IM-101	Grey CM	4.76	1.21	<0.1	0.28	0.02	2600	337000	1440	57.3	1320	0.04	0.008	5.1	21.0	0.40	1510	0.0008	0.70705
EX43	Grey DCM	5.26	<0.01	<0.10	0.01	0.12	35220	340303	n.d.	23.1	394	0.06	0.10	6.1	20.9	0.308	409	0.0022	0.70800
EX44	Grey CM	4.75	1.42	<0.10	0.36	0.10	1800	363094	n.d.	123.2	720	0.17	0.005	5.7	23.5	n.d.	n.d.	n.d.	n.d.
Henrikkjølen																			
IM-89	Grey CM	11.3	2.63	0.18	0.56	0.02	2840	313000	3470	300	1220	0.25	0.009	5.8	16.0	n.d.	n.d.	n.d.	n.d.
IM-90	Grey CM	7.23	1.31	0.17	0.30	0.11	2630	331000	965	281	2470	0.11	0.008	4.2	19.1	n.d.	n.d.	n.d.	n.d.
IM-91	Grey CM	1.46	0.33	0.11	<0.01	0.06	1790	362000	828	65.7	2660	0.02	0.005	5.8	18.0	0.01	3010	0.0000	0.70862
IM-92	Grey CM	2.07	0.50	<0.1	0.11	0.07	1300	361000	204	267	3030	0.09	0.004	7.1	19.7	0.10	3420	0.0001	0.70863
The Bogen-Salangen nappe complex																			
Late Tonian																			
Espenes																			
IM-37	Pale grey CM	1.10	0.17	<0.1	0.04	0.09	2470	370000	143	34.5	1270	0.03	0.007	4.4	22.4	0.21	1360	0.0005	0.70654
IM-38	White CM	0.69	0.04	<0.1	<0.01	0.10	11700	365000	127	40.8	1190	0.03	0.03	2.7	24.0	n.d.	n.d.	n.d.	n.d.
IM-39	White CM	1.85	0.27	<0.1	0.04	0.13	1890	373000	532	136	1540	0.09	0.005	4.5	18.3	n.d.	n.d.	n.d.	n.d.
IM-40	Pale grey CM	6.47	1.10	<0.1	0.22	0.03	4440	345000	2730	32.6	1640	0.02	0.01	6.1	23.7	0.26	1770	0.0004	0.70737
IM-41	White CM	4.38	0.75	<0.1	0.15	0.11	4000	348000	116	36.5	1860	0.02	0.01	5.1	16.8	0.69	2080	0.001	0.70657
IM-42	White CM	<0.5	0.05	<0.1	0.02	0.04	1520	376000	326	30.7	3060	0.01	0.004	7.5	21.7	0.02	3310		0.70664
IM-43	White CM	<0.5	0.05	<0.1	0.01	0.04	1710	370000	304	24.7	3000	0.008	0.005	7.8	21.1	0.02	3260		0.70659
IM-44	White CM	1.01	0.14	<0.1	0.03	0.10	1890	371000	1370	91.8	2450	0.04	0.005	7.2	20.6	n.d.	n.d.	n.d.	n.d.
IM-45	White CM	1.29	0.21	<0.1	0.04	0.09	2920	371000	3930	151	2030	0.07	0.008	5.9	18.8	n.d.	n.d.	n.d.	n.d.

Table 3. (Continued)

Tectonostratigraphic unit, location, sample #, lithology	SiO ₂	Al ₂ O ₃	wt. %			K ₂ O	P ₂ O ₅	Mg	Ca	μg·g ⁻¹			‰			μg·g ⁻¹			⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr
			Na ₂ O	Al ₂ O ₃	wt. %					Mn/Sr	Mg/Ca	δ ¹³ C	δ ¹⁸ O	Rb	Sr	δ ¹³ C	δ ¹⁸ O	Rb		
Sørreisa	IM-46	White CM	16.8	4.04	1.52	0.17	0.12	1870	283000	1040	84.8	1190	0.07	0.007	4.8	20.7	n.d.	n.d.	n.d.	n.d.
	EX50	Grey CM	6.89	0.89	<0.10	0.13	0.23	4500	354645	n.d.	92.4	2178	0.04	0.01	5.7	25.2	0.143	2311	0.0002	0.70674
	WP 97	Pale grey CM	1.39	0.16	<0.1	0.04	0.09	2500	352000	800	34.3	1250	0.03	0.007	3.9	22.0		1272		0.70656
	WP 122	Pale grey CM	7.60	1.15	<0.1	0.30	0.04	19500	310000	2910	31.8	1460	0.02	0.06	7.4	23.2	n.d.	n.d.	n.d.	n.d.
	WP 124	Pale grey CM	7.56	1.18	0.12	0.36	0.03	22800	303000	3130	41.0	1750	0.02	0.08	7.2	23.6	n.d.	n.d.	n.d.	n.d.
	WP 125	Pale grey CM	2.00	0.27	<0.1	0.06	0.12	1730	360000	1290	41.7	2810	0.01	0.005	7.3	21.7		2813		0.70663
	WP 127	Pale grey CM	33.0	0.43	0.11	0.10	0.03	5730	172000	289	122	238	0.51	0.03	1.6	15.3	n.d.	n.d.	n.d.	n.d.
	WP 146	Pale grey CM	1.66	0.38	<0.1	0.06	0.05	2140	360000	1840	91.2	2550	0.04	0.006	4.6	25.1		2564		0.70664
	WP 202	Grey CM	7.80	1.63	0.20	0.34	0.08	4000	323000	6270	515	1870	0.28	0.01	4.2	24.2		2080		0.70676
	WP 203	Pale grey DCM	<0.5	0.12	<0.1	0.02	0.01	34900	320000	752	25.1	398	0.06	0.11	3.8	21.8	n.d.	n.d.	n.d.	n.d.
Rubbestad	WP 204	Pale grey CM	6.94	0.11	<0.1	0.02	0.02	24900	311000	548	31.2	898	0.03	0.08	6.2	21.9		858		0.70653
	EX51	Pale grey DM	0.45	<0.01	<0.10	<0.003	0.06	132540	222088	n.d.	23.1	116	0.20	0.60	6.2	23.3	n.d.	n.d.	n.d.	n.d.
	EX52	Grey DM	23.9	0.32	<0.10	0.05	0.15	83160	187866	n.d.	92.4	353	0.26	0.44	4.4	21.5	n.d.	n.d.	n.d.	n.d.
Avløsinga	EX53	Grey DCM	17.2	0.23	<0.10	0.04	0.23	38220	286130	n.d.	154	396	0.39	0.13	4.6	16.1	n.d.	n.d.	n.d.	n.d.
	EX55	Grey CM	6.99	1.35	0.50	0.31	0.15	1620	355781	n.d.	207.9	2359	0.09	0.005	4.6	23.8	0.187	2482	0.0002	0.70656
	EX56	Grey CM	14.8	3.50	0.43	0.73	0.10	7800	310128	n.d.	130.9	1626	0.08	0.03	8.1	20.3	n.d.	n.d.	n.d.	n.d.
	EX57	Grey CM	17.7	5.03	0.59	1.08	0.03	17760	272640	n.d.	169.4	1755	0.10	0.07	7.3	23.1	n.d.	n.d.	n.d.	n.d.
Høglund (Salangen)	IM-47	Pale grey CM	3.40	0.25	<0.1	0.05	0.11	1680	359000	110	38.2	1250	0.03	0.005	3.5	26.0	0.22	1400	0.0005	0.70675
	IM-48	Pale grey CM	1.29	0.14	<0.1	0.02	0.11	1860	365000	70.3	41.1	1020	0.04	0.005	3.0	25.9	0.26	1115	0.0007	0.70677
	IM-49	Pale grey CM	1.71	0.11	<0.1	0.02	0.08	2190	363000	71.8	43.4	990	0.04	0.006	2.7	25.8	0.03	1080	0.0001	0.70679
	IM-50	Pale grey CM	5.72	0.40	<0.1	0.11	0.12	1540	352000	345	184	1780	0.10	0.004	3.6	25.1	n.d.	n.d.	n.d.	n.d.
	IM-51	Pale grey CM	5.36	0.39	<0.1	0.13	0.11	1430	350000	224	132	1880	0.07	0.004	3.7	25.2	0.75	2110	0.001	0.70674
	IM-52	Pale grey CM	4.35	0.36	<0.1	0.09	0.09	1590	352000	345	150	1890	0.08	0.005	3.6	25.0	n.d.	n.d.	n.d.	n.d.
	IM-53	Pale grey CM	7.10	0.59	<0.1	0.16	0.10	2080	338000	402	202	1570	0.13	0.006	3.5	24.8	n.d.	n.d.	n.d.	n.d.
	IM-54	Pale grey CM	8.00	0.83	<0.1	0.21	0.10	2100	330000	456	202	1590	0.13	0.006	3.3	24.6	n.d.	n.d.	n.d.	n.d.

Table 3. (Continued)

Tectonostratigraphic unit, location, sample #, lithology	SiO ₂	Al ₂ O ₃	Na ₂ O	K ₂ O	P ₂ O ₅	Mg	Ca	Fe	Mn	Sr	Mn/Sr	Mg/Ca	δ ¹³ C	δ ¹⁸ O	Rb	Sr	⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr
	wt. %			μg·g ⁻¹								‰				μg·g ⁻¹		
Flåget road (Salangen)																		
IM-55 Grey CM	1.53	0.24	<0.1	0.05	0.08	2740	365000	151	280	2350	0.12	0.008	2.8	25.3				
IM-56 Grey CM	<0.5	0.08	<0.1	0.01	0.08	1050	367000	37.6	52.2	2320	0.02	0.003	4.7	25.5	0.28	2300	0.0004	0.70647
IM-57 Grey CM	5.37	0.60	<0.1	0.11	0.14	3110	346000	270	103	2210	0.05	0.009	4.8	24.6	n.d.	n.d.	n.d.	n.d.
IM-58 Grey CM	3.69	0.60	<0.1	0.11	0.08	3120	358000	460	88.0	1750	0.05	0.009	4.9	23.8	n.d.	n.d.	n.d.	n.d.
IM-59 Grey CM	8.10	1.18	<0.1	0.37	0.06	20200	308000	1160	68.1	1300	0.05	0.07	6.6	23.6	n.d.	n.d.	n.d.	n.d.
IM-60 Grey CM	1.15	0.13	<0.1	0.04	0.08	1550	365000	203	167	2550	0.07	0.004	6.9	25.4	n.d.	n.d.	n.d.	n.d.
IM-61 Grey CM	4.72	0.74	<0.1	0.18	0.07	2440	341000	515	161	2210	0.07	0.007	4.2	24.6	n.d.	n.d.	n.d.	n.d.
IM-62 Grey CM	3.00	0.50	<0.1	0.10	0.07	1850	363000	616	80.6	1950	0.04	0.005	5.1	25.7	0.15	2130	0.0002	0.70671
IM-63 Grey CM	1.19	0.06	<0.1	0.01	0.08	2170	357000	90.8	140	2540	0.06	0.006	7.2	25.4	0.01	2780	0.0000	0.70651
IM-64 Grey CM	0.76	0.13	<0.1	0.03	0.07	1360	365000	80.4	82.1	2300	0.04	0.004	6.0	26.0	0.1	2480	0.0001	0.70648
EX49 Grey CM	7.89	2.18	<0.10	0.57	0.11	6900	339167	n.d.	123.2	1970	0.06	0.02	5.1	17.9	0.163	2154	0.0002	0.70766
WP 218 Grey CM	4.42	0.21	<0.1	0.05	0.04	23000	321000	1330	35.5	577	0.06	0.07	9.4	20.9	n.d.	n.d.	n.d.	n.d.
WP 222 Grey DM	<0.5	0.03	<0.1	<0.01	0.09	131000	209000	1270	46.1	91.0	0.51	0.63	4.5	25.4	n.d.	n.d.	n.d.	n.d.
WP 224 Grey CM	28.3	1.66	0.63	0.12	0.06	3120	196000	4400	3570	81.6	43.8	0.02	-0.4	18.5	n.d.	n.d.	n.d.	n.d.
WP 285 Grey DCM	11.8	0.34	<0.1	<0.01	<0.01	78200	218000	10200	1480	71.6	20.7	0.36	0.6	19.0	n.d.	n.d.	n.d.	n.d.
WP 242 Grey CM	2.05	0.31	<0.1	0.05	0.07	4000	358000	1050	69.4	892	0.08	0.01	3.5	23.6		1530		0.70680
WP 243 A Grey CM	4.40	0.41	<0.1	0.07	0.12	4540	346000	2000	74.1	2270	0.03	0.01	5.7	20.6		2336		0.70657
WP 243 B White DCM	26.8	0.23	<0.1	0.02	0.04	48000	153000	525	69.8	200	0.35	0.31	2.1	16.9	n.d.	n.d.	n.d.	n.d.
WP 262 Pale grey CM	<0.5	0.03	<0.1	<0.01	0.12	2230	371000	481	218	2380	0.09	0.006	6.4	24.4		2335		0.70649
WP 269-70 Grey CM	2.34	0.35	<0.1	0.08	0.06	4630	351000	2210	108	1380	0.08	0.01	3.0	22.8		1403		0.70667
WP 350 B Grey CM	0.52	0.12	<0.1	0.03	0.05	3050	363000	583	68.3	1300	0.05	0.008	5.4	25.3	n.d.	n.d.	n.d.	n.d.
WP 437 Grey CM	1.79	0.15	<0.1	0.03	0.09	3830	365000	440	45.9	1120	0.04	0.01	2.8	25.4		1084		0.70676
WP 450 Grey CM	8.27	2.01	0.19	0.50	0.05	8210	315000	6020	106	1790	0.06	0.03	4.6	25.1	n.d.	n.d.	n.d.	n.d.
Flågdalen																		
IM-65 Grey CM	4.08	1.02	<0.1	0.28	0.04	5000	345000	2110	81.3	1790	0.05	0.014	4.9	18.4	n.d.	n.d.	n.d.	n.d.
Andørja																		
Drillhole 29																		
VM_1 Pink CM	6.25	1.30	0.18	0.16	0.042	4850	345000	4180	420	467	0.90	0.01	-1.5	16.5	n.d.	n.d.	n.d.	n.d.
VM_2 Pink CM	5.99	1.26	0.23	0.17	0.044	5200	333000	2900	355	219	1.62	0.02	-1.6	16.5	n.d.	n.d.	n.d.	n.d.
VM_3 Pink CM	5.95	1.38	0.31	0.08	0.042	4580	340000	2670	472	306	1.54	0.01	-1.7	17.0	n.d.	n.d.	n.d.	n.d.
VM_4 Pink CM	5.58	1.19	<0.1	0.07	0.042	4560	340000	3350	629	408	1.54	0.01	-1.5	16.4	n.d.	n.d.	n.d.	n.d.

Table 3. (Continued)

Tectonostratigraphic unit, location, sample #, lithology	SiO ₂	Al ₂ O ₃	Na ₂ O wt. %	K ₂ O	P ₂ O ₅	Mg	Ca	Fe $\mu\text{g}\cdot\text{g}^{-1}$	Mn	Sr	$\mu\text{g}\cdot\text{g}^{-1}$			$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$
											Mn/Sr	Mg/Ca	$\delta^{13}\text{C}$ ‰	Rb	Sr
VM_5 Pink CM	2.76	0.63	0.12	0.01	0.029	3940	364000	3070	614	323	1.90	0.01	-1.3	n.d.	n.d.
VM_6 Pink CM	4.69	1.02	0.24	0.10	0.038	3760	351000	3860	462	474	0.97	0.01	-1.6	n.d.	n.d.
VM_7 Grey CM	3.93	0.68	<0.1	0.11	0.078	2410	359000	315	40.7	2770	0.01	0.007	5.3	0.32	2930
VM_8 Grey CM	5.07	1.14	0.11	0.20	0.058	2190	349000	355	42.8	2780	0.015	0.006	5.2	0.69	3130
VM_9 Grey CM	2.97	0.41	<0.1	0.06	0.063	2350	367000	153	41.2	2510	0.016	0.006	5.1	0.39	2700
VM_10 Grey CM	1.35	0.13	<0.1	0.03	0.049	3450	369000	58.1	33.4	1420	0.02	0.009	5.0	0.11	1490
VM_11 Grey CM	0.98	0.07	<0.1	0.01	0.058	1870	376000	27.2	16.5	1110	0.01	0.005	3.4	0.69	1180
VM_12 Grey CM	3.95	0.65	<0.1	0.12	0.078	3090	359000	1320	279	2010	0.14	0.009	3.6	n.d.	n.d.
VM_13 Grey CM	1.55	0.32	<0.1	0.08	0.066	3000	370000	732	397	2500	0.16	0.008	n.d.	n.d.	n.d.
Drillhole 24															
VM_14 Grey CM	2.50	0.33	<0.1	0.07	0.064	2610	360000	83.4	89.7	2210	0.04	0.007	4.8	n.d.	n.d.
VM_15 Grey CM	2.17	0.30	<0.1	0.05	0.013	4100	368000	688	48.5	1280	0.04	0.01	4.7	n.d.	n.d.
VM_16 Grey DCM	4.33	0.80	<0.1	0.16	0.014	59200	273000	1800	89.1	640	0.14	0.22	4.7	n.d.	n.d.
VM_17 Grey CM	12.3	1.77	0.18	0.22	0.034	7800	287000	1180	127	860	0.15	0.03	2.6	n.d.	n.d.
VM_18 Grey CM	18.4	3.83	0.42	0.59	0.167	2200	275000	922	130	1710	0.08	0.008	3.7	n.d.	n.d.
VM_19 Grey CM	3.19	0.28	<0.1	0.04	0.07	3070	362000	103	84.9	1260	0.07	0.008	4.0	n.d.	n.d.
VM_20 Grey CM	4.34	0.55	<0.1	0.12	0.069	3260	362000	1230	218	2090	0.10	0.009	3.6	n.d.	n.d.
VM_21 Grey CM	2.49	0.58	0.13	0.14	0.068	3360	350000	1120	396	2180	0.18	0.01	7.0	n.d.	n.d.
VM_22 Grey CM	3.42	0.66	<0.1	0.14	0.071	3000	348000	137	80.0	1700	0.05	0.009	4.0	n.d.	n.d.
VM_23 Grey CM	5.09	1.15	<0.1	0.20	0.079	2240	327000	368	34.6	2660	0.01	0.007	5.3	0.25	3090
VM_24 Grey CM	2.23	0.33	<0.1	0.03	0.116	6590	342000	93.2	33.5	1590	0.02	0.02	3.9	n.d.	n.d.
VM_25 Grey CM	1.83	0.06	<0.1	0.02	0.206	19100	328000	166	48.8	721	0.07	0.06	3.9	0.42	750
Drillhole 23															
VM_27a Grey CM	8.4	1.64	0.21	0.23	0.114	2580	313000	700	159	1900	0.08	0.008	4.3	n.d.	n.d.
VM_28 Grey CM	5.72	1.40	0.3	0.22	0.073	3710	325000	2000	465	2100	0.22	0.01	5.5	n.d.	n.d.
VM_29 Grey CM	1.54	0.25	<0.1	0.04	0.117	6960	348000	89.2	29.5	1320	0.02	0.02	3.8	0.17	1380
VM_30 Grey CM	1.29	0.17	<0.1	0.03	0.188	7640	347000	471	95.4	994	0.10	0.02	2.7	n.d.	n.d.
VM_31 Grey CM	8.18	1.41	0.27	0.14	0.177	7470	312000	237	40.2	753	0.05	0.02	3.3	n.d.	n.d.
VM_32 Grey CM	7.24	1.44	0.17	0.32	0.013	2490	324000	1010	51.3	1040	0.05	0.008	5.4	n.d.	n.d.
VM_33 Grey CM	7.74	1.40	0.1	0.38	0.016	3030	329000	814	128	1160	0.11	0.009	5.4	n.d.	n.d.
VM_34 Grey CM	2.37	0.29	<0.1	0.05	0.068	2980	357000	155	352	1900	0.19	0.008	4.8	n.d.	n.d.
VM_35 Grey CM	2.36	0.54	<0.1	0.08	0.096	3080	350000	650	372	2370	0.16	0.009	6.1	n.d.	n.d.
VM_36 Grey CM	1.23	0.24	<0.1	0.06	0.068	2650	361000	1400	481	2370	0.20	0.007	5.8	n.d.	n.d.

Abbreviation: n.d. – not detected.

In contrast, a great degree of variability of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios is seen even in a single section (Fig. 15A), and suggests post-depositional alteration. None of the measured samples passed the geochemical criteria (the predetermined set-up limits of Mn/Sr and Mg/Ca ratios and Table 3). Significant positive correlations of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios with SiO_2 and Al_2O_3 abundances and Mn/Sr values (Fig. 15C) indicate that aluminosilicates were one of the major sources of ^{87}Sr in the post-depositional fluids. Consequently, the sample with the lowermost SiO_2 (0.65 wt.%) and Al_2O_3 (0.22 wt.%) abundances and the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.70861 (Table 3; Fig. 15C) is considered to represent a best proxy to seawater composition.

Evenes nappe complex

The Elvenes marble. The most continuous studied calcite marble section located at Elvenes is over 35 m thick. It is situated tectonostratigraphically somewhat below the Bø Quartzite (the regional marker unit). The marble unit constitutes a part of the ENC in the Troms region. Although it may represent a tectonostratigraphic equivalent of marbles known in the Tangen thrust sheet (Fig. 4), it is named informally here as the Elvenes marble. The marbles have been documented in and sampled from several road-cuts in the Karlstad, Lavangen and Elvenes–Høgebakken areas (all locations are listed in Table 3 and marked in Fig. 11). The calcite marbles are pale grey, medium-crystalline, thickly banded rocks with intercalations of calcareous garnet-mica schists and dolomite marbles (Fig. 16A, B).

Thirty-four samples, collected from several localities along a strike-length of over 80 km, represent the entire thickness of the marble unit. The marbles have low but variable contents of SiO_2 and Al_2O_3 (Table 3). In terms of Sr, Mn, Fe concentrations, and Mn/Sr, Mg/Ca, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ ratios, they are comparable to many marble units occurring in the BSNC (Tables 3 & 4). The only difference is their more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ values.

There is a general lack of correlation between $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, and between all these ratios with Sr, Fe, Mn abundances and Mn/Sr and Mg/Ca values (Fig. 16C). However, a great degree of variability of all geochemical parameters, seen even in a single section (Fig. 16B), suggests a certain degree of post-depositional alteration. The lowermost $\delta^{13}\text{C}$ (+1.4‰) and $\delta^{18}\text{O}$ (13.4‰) are accompanied by the highest Mn/Sr ratio (0.13) and the lowermost Sr content (292 $\mu\text{g}\cdot\text{g}^{-1}$), hence also suggesting alteration. The rest of the $\delta^{13}\text{C}$ ratios range between +4.2 and +7.3‰ averaging at +5.7 $\pm$ 0.7‰, $n = 34$ (Table 4). Consequently, $\delta^{13}\text{C}$ at $c. +6\%$ is tentatively suggested as the best proxy for seawater composition. Similar to the C-isotopic composition, there are no clear criteria for deciphering any alteration trends which affected the spread of $^{87}\text{Sr}/^{86}\text{Sr}$ ratio between 0.70696 and 0.70764 (Table 4). A hint from the

two samples with the lowermost Mn/Sr ratios suggests that the least-radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.70696 and 0.70698 (Table 3; Fig. 16C) are good candidates for a seawater proxy.

Henrikkjølen marble. This marble unit, informally termed here the Henrikkjølen marble, has been studied in a single locality. The studied section near Henrikkjølen represents a $c. 10$ m-thick unit documented in a road-cut near Henrikkjølen (Fig. 11). The unit is composed of grey, medium- to coarse-grained, rhythmically interbedded, pure and shaly calcite marbles (0.3–2.0 m thick) and mica schists (0.2–2.0 m thick). All five analysed samples show high Sr contents and all measured $\delta^{13}\text{C}$ values are highly positive (+4.2 – +7.1‰; Table 4). The geochemical screening criteria against post-depositional alteration cannot be set up due to the limited number of analyses. Consequently, an average $\delta^{13}\text{C}$ of $c. +6\%$ (Table 4) is suggested to represent a seawater proxy. One of the two samples analysed for $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70862) shows low SiO_2 (1.46 wt.%) and Al_2O_3 (0.33 wt.%) abundances, a high Sr content (2660 $\mu\text{g}\cdot\text{g}^{-1}$), and low Mn/Sr (0.02) and Mg/Ca (0.005) ratios (Table 3). Hence, this sample passes the geochemical criteria as the least altered. The second sample, having a similar ratio of 0.70863, is marked by the highest Sr content (3030 $\mu\text{g}\cdot\text{g}^{-1}$). Such high Sr contents measured in these two samples should effectively buffer the Sr-isotopic system against post-depositional fluids, and their $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are suggested as an apparent seawater proxy. Hence, the Henrikkjølen and Vassdalen marbles demonstrate similar least altered $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Table 5).

The Bogen–Salangen nappe complex

The Espenes–Sørreisa section (Fig. 7; for location, see Fig. 11). Calcite marbles occurring as numerous beds in a 500 m-thick, composite, lithological section (Fig. 17A) exhibit a considerable variation of Sr (238–3060 $\mu\text{g}\cdot\text{g}^{-1}$, $n = 23$), Mn (25–515 $\mu\text{g}\cdot\text{g}^{-1}$) and Fe (116–6270 $\mu\text{g}\cdot\text{g}^{-1}$) contents and $\delta^{13}\text{C}$ (+1.6 to +7.8‰, $n = 23$), $\delta^{18}\text{O}$ (15.3–25.2‰) and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.70653–0.70676, with one outlier at 0.70737; $n = 12$) (Table 4; Fig. 18). This could be due to a combined effect of tectonic repetition (folding and thrusting) and post-depositional alteration. There is no significant correlation between any isotopic ratio and Mn/Sr (0.008–0.51) or Mg/Ca (0.004–0.060) values (Fig. 18). However, an increase of the Mn/Sr ratio, which is coherent with a depletion in ^{13}C , ^{18}O and increase in $^{87}\text{Sr}/^{86}\text{Sr}$ values, observed in the lower part of the section (74.5–76.5 m; Fig. 17B), suggests involvement of post-depositional alteration. Moreover, the lowest $\delta^{13}\text{C}$ (+1.6‰) and $\delta^{18}\text{O}$ (15.3‰) values are marked by the highest Mn/Sr (0.51; Table 3). Further geochemical screening for postdepositional alteration (Mg/Ca and Mn/Sr < 0.02; Sr > 1000 $\mu\text{g}\cdot\text{g}^{-1}$, SiO_2 < 5 wt.%, Al_2O_3 < 1 wt.%) suggests that only three samples would satisfy these criteria. Consequently, the $\delta^{13}\text{C}$ (+7 to

Figure 16. The Elvenes marble exposed in the road-cut near Elvenes. (A) A pale grey, medium-crystalline, thickly banded calcite marble. (B) A lithological column of the sampled section and geochemical and isotopic characteristics of the marbles. Note a limited degree of δ¹³C variability. (C) Various cross-plots illustrating the lack of correlation between δ¹³C and δ¹⁸O or ⁸⁷Sr/⁸⁶Sr values. Similarly, ⁸⁷Sr/⁸⁶Sr values do not correlate with δ¹³C, Mn/Sr ratios or Sr abundance.

+8‰) and ⁸⁷Sr/⁸⁶Sr (0.70659–0.70664) values in these samples should be considered as the least altered (Table 3). However, five other samples, which do not pass the geochemical screening, show somewhat lower ⁸⁷Sr/⁸⁶Sr ratios ranging between 0.70653 and 0.70657, hence they are likely even less altered. These better preserved ratios

are coupled with the higher δ¹⁸O (up to 25‰) values, hence indicating an apparent stratigraphic variation of Sr isotopic ratios. Consequently, the highest δ¹³C of +8‰ and the ⁸⁷Sr/⁸⁶Sr range between 0.70653 and 0.70664 (Table 5) are considered to represent the best proxy to the original isotopic composition of seawater.

Table 4. Geochemical characteristics, $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ values of calcite marbles studied in the northern Nordland and Troms regions.

<i>Tectonostratigraphic unit/section</i>	<i>Sr, $\mu\text{g}\cdot\text{g}^{-1}$</i>	<i>Mn, $\mu\text{g}\cdot\text{g}^{-1}$</i>	<i>Fe, $\mu\text{g}\cdot\text{g}^{-1}$</i>	<i>Mn/Sr</i>	<i>Mg/Ca</i>	<i>$\delta^{13}\text{C}\text{‰}$</i>	<i>$\delta^{18}\text{O}\text{‰}$</i>	<i>$^{87}\text{Sr}/^{86}\text{Sr}$</i>
The Salangen–Bogen nappe complex								
Espenes–Sørreisa section	238–3060 (1641, n=23)	25–515 (93, n=23)	116–6270 (1497, n=19)	0.008–0.51 (0.09, n=23)	0.004–0.06 (0.05, n=23)	+1.6–+7.8 (+5.3, n=23)	15.3–25.2 (21.4, n=23)	0.70653–0.70676 (0.70668, n=12)
Salangen section	72–2550 (1586, n=32)	36–3570 (266, n=32)	38–10200 (1233, n=31)	0.02–44 (2.1, n=32)	0.003–0.36 (0.03, n=32)	-0.4–+9.4 (+4.3, n=32)	17.9–26.0 (23.6, n=32)	0.70647–0.70766 (0.70672, n=14)
Andørja section	219–2780 (1720, n=29)	16–659 (151, n=29)	27–4180 (633, n=29)	0.01–0.22 (0.08, n=29)	0.005–0.22 (0.02, n=29)	-1.7–+7.0 (+4.5, n=34)	16.0–26.4 (22.2, n=34)	0.70663–0.70680 (0.70669, n=8)
Herjangen section	911–2600 (1708, n=24)	18–170 (67, n=24)	44–5600 (1381, n=24)	0.01–0.16 (0.05, n=24)	0.005–0.12 (0.02, n=24)	+0.3–+6.3 (+4.2, n=24)	17.5–25.8 (22.9, n=24)	0.70640–0.70813 (0.70681, n=15)
Bogen section	431–932 (1216, n=12)	16–196 (180, n=12)	42–931 (368, n=12)	0.01–0.28 (0.008, n=12)	0.007–0.07 (0.03, n=12)	+2.1–+6.5 (+3.8, n=12)	14.6–27.7 (19.3, n=12)	0.70664–0.70714 (0.70688, n=6)
Håfjellet section	1650–2900 (2330, n=15)	6.6–60 (19, n=15)	31–624 (199, n=15)	0.006–0.01 (0.008, n=15)	0.003–0.015 (0.006, n=15)	+3.6–+6.5 (+5.2, n=15)	19.4–26.6 (24.6, n=15)	0.70645–0.70701 (0.70669, n=15)
Evenes nappe complex								
Henrikkjølén section	1220–3030 (2345, n=5)	66–300 (228, n=5)	204–3470 (1367, n=5)	0.02–0.25 (0.12, n=5)	0.004–0.009 (0.007, n=5)	+4.2–+7.1 (+5.7, n=5)	16.0–19.7 (18.2, n=5)	0.70862–0.70863 (n=2)
Elvenes marble	292–2090 (1238, n=34)	14–123 (52, n=34)	26–7300 (1148, n=26)	0.009–0.17 (0.05, n=34)	0.003–0.13 (0.02, n=34)	+1.4–+7.3 (+5.7, n=34)	13.4–25.7 (21.5, n=34)	0.70696–0.70764 (0.70707, n=19)
Narvik Nappe Complex								
Vassdalen marble	759–5550 (2965, n=44)	31–470 161, n=44)	75–3780 (909, n=41)	0.005–0.38 (0.07, n=44)	0.003–0.06 (0.01, n=44)	+0.3–+3.5 (+1.9, n=44)	16.3–22.1 (19.7, n=44)	0.70861–0.70899 (0.70882, n=23)

Table 5. The least altered $\delta^{13}\text{C}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ values in the studied marble formations and their apparent depositional ages as based on the interceptions with $\delta^{13}\text{C}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ reference curves for seawater.

<i>Tectonostratigraphic unit/section</i>	<i>$\delta^{13}\text{C}\text{‰}$</i>	<i>$^{87}\text{Sr}/^{86}\text{Sr}$</i>	<i>Apparent depositional ages, Ma</i>	<i>Geological period</i>
The Salangen–Bogen nappe complex				
Espenes–Sørreisa section	+8	0.70653–0.70664	800–735	Mid–Late Tonian
Salangen section	+7	0.70647	820–810 or 800–735	Mid–Late Tonian
Andørja section	+5	0.70663–0.70665	800–735	Mid–Late Tonian
Herjangen section	+6 [♥]	0.70640 [♥]	820–810 or 800–735	Mid–Late Tonian
Bogen section	+6 [♥]	0.70664 [♥]	800–735	Mid–Late Tonian
Håfjellet section	+6 [*]	0.70645 [*]	820–810 or 800–735	Mid–Late Tonian
Evenes nappe complex				
Henrikkjølén marble	+6	0.70862–0.70863	550 or 425–410	Late Ediacaran or Early Ordovician–Mid Silurian
Elvenes marble	+7	0.70696–0.70698	685–660	Mid Cryogenian
Narvik Nappe Complex				
Vassdalen marble	+2	0.70861	550 or 425–410	Late Ediacaran or Early Ordovician–Mid Silurian

^{*}, [♥] Data from Melezhik et al. (2002a, b) and Melezhik et al. (2003), respectively.

The Salangen section (Fig. 7; for location, see Fig. 11). Several calcite marble beds documented in a c. 1000 m-thick, composite, lithological section exhibit a larger variation of isotopic ratios and elemental concentrations with respect to those observed in the Espenes–Sørreisa section (Fig. 19A vs. Fig. 17): Sr (72–2550 $\mu\text{g}\cdot\text{g}^{-1}$, n = 32), Mn (36–3570 $\mu\text{g}\cdot\text{g}^{-1}$), Fe (38–10200 $\mu\text{g}\cdot\text{g}^{-1}$), contents and $\delta^{13}\text{C}$ (-0.4 to +7.2‰, with one outlier at +9.4‰; n = 32),

$\delta^{18}\text{O}$ (17.9–26.0‰) and $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70647–0.70680, with one outlier at 0.70766; n = 14) ratios (Table 4; Fig. 18). A marble unit observed in direct contact with the IF shows high Sr and Mn abundances, a relatively low $^{87}\text{Sr}/^{86}\text{Sr}$ ratio and relatively high $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values (Fig. 19B).

There is a significant correlation (>99.9%, n = 24) of $\delta^{13}\text{C}$ with Sr (r = +0.53) and Mn (r = -0.55) content, and the

Figure 17. A schist-marble succession with several intervals of IFs observed in the Espenes-Sørreisa area. (A) A composite lithological column of the sampled section and geochemical and isotopic characteristics of the marbles. For the lithological symbols, see Fig. 7. (B) A detailed view of coherent stratigraphic change of isotopic and geochemical parameters near the base of the studied succession containing calcite marble, schist, amphibolites and IF.

Mn/Sr ratio ($r = -0.44$). A strong negative correlation ($>99.9\%$, $n = 12$) exists between the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (if the 0.70766 outlier is excluded; Fig. 18) and Sr content ($r = -0.83$), and $\delta^{13}\text{C}$ ($r = -0.84$). All these suggest a post-depositional alteration of C and Sr isotopic systems. Notably, the least radiogenic, hence the best preserved $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.70647, 0.70648 and 0.70649) have been obtained from three samples (at depths of 500, 184.6 and

153.2 m; Fig. 19) with the lowest SiO_2 (<0.5 – 0.76 wt.%) and Al_2O_3 (0.03 – 0.13 wt.%) contents (Table 3). This indicates that aluminosilicates were one of the major sources of ^{87}Sr in the post-depositional fluids. None of the measured samples passed geochemical criteria (limits in Mn/Sr and Mg/Ca ratios; Table 3). Consequently, excluding two outstanding outliers ($\delta^{13}\text{C}$ at $+9.4\%$ and $^{87}\text{Sr}/^{86}\text{Sr}$ at 0.70766; Table 3; Fig. 18), the lowest

Figure 18. Various cross-plots illustrating geochemical and isotopic features of calcite marbles associated with IFs in southern Troms and Nordland. Geochemical and isotopic data for Rana are from Melezhik et al. (2015); for Håfjellet, Bogen and Herjangen the data are from Melezhik et al. (2003).

$^{87}\text{Sr}/^{86}\text{Sr}$ ratio (0.70647) and the highest $\delta^{13}\text{C}$ (+7‰) are considered to represent a best proxy to seawater composition (Table 5).

The Andørja section (Fig. 7; for location, see Fig. 11). Samples of marbles have been obtained from the

drillcores (Table 3). In the drilled section, the marbles have been observed in three stratigraphic intervals (Fig. 20). Those documented in the uppermost part are pale pink in colour and occur as several thin beds (commonly less than 10 cm). The marbles from the middle and lower intervals are grey and appear as beds with a thickness

Figure 19. A schist-marble succession with several intervals of IFs observed in the Salangen area. (A) A composite lithological column of the sampled section and geochemical and isotopic characteristics of the marbles. For the lithological symbols, see Fig. 7. (B) A detailed view of coherent stratigraphic change of isotopic and geochemical parameters near the base of the studied succession towards the IF. Note that the IF rests upon an uneven palaeotopography of the marble unit, thus illustrating the relative time-order of their deposition.

reaching 5 m (Fig. 20). Similar to other studied sections, the Andørja profile shows considerable variations of all geochemical parameters throughout the stratigraphy (Figs. 20 & 21; Table 4). However, geochemically, the pink and the grey marbles show remarkable differences and form two distinct subsets. The grey marbles have a

higher $\delta^{13}\text{C}$ (from +2.6 to +7.0‰, $n = 34$) with respect to the pink ones (from -1.7 to -1.3‰; $n = 6$). The latter are low in Sr (219–474 vs. 640–2780 $\mu\text{g g}^{-1}$) and higher in Mn (355–629 vs. 16–481 $\mu\text{g g}^{-1}$) and Fe (2670–4180 vs. 27–2000 $\mu\text{g g}^{-1}$) contents (Table 3; Figs. 18 & 21). All these combined with a low $\delta^{18}\text{O}$ (16–17‰) of the pink marbles

Figure 20. A core-drilled marble-schist-amphibolite-gneiss section with IFs at Andørja, geochemical profiles through the upper and lower marble units and photographs of cores representing marble units in all studied drillholes.

are taken as evidence of a severe post-depositional alteration.

The grey calcite marbles exhibit a significant negative correlation of $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70663–0.70680) ratios with Sr abundances (-0.93 , $n = 8$, $>99.9\%$) and $\delta^{13}\text{C}$ values

(-0.83 , $>99\%$). Three samples from the middle marble (hole 29; Fig. 21) and one sample from the lower marble (hole 24) intervals, having the highest Sr concentrations (2510–2780 $\mu\text{g}\cdot\text{g}^{-1}$) and low Mg/Ca (0.006) and Mn/Sr (0.013–0.016), show the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.70663–0.70665). All four samples are characterised by $\delta^{13}\text{C}$

Figure 21. Geochemical and isotopic profiles through all marble units drilled in the succession hosting IFs at Andørja.

of $\sim +5\text{‰}$ (Table 3). Consequently, these $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{13}\text{C}$ ratios are considered to represent the best proxy to seawater composition (Table 5).

The Herjangen section (Fig. 7; for location, see Fig. 11). The section is based on a single road-cut described in detail in Melezhik et al. (2003). The approximately 250 m-thick section consists of a dark grey, thickly banded calcite marble with a c. 10 m-thick unit of calcareous, garnet-mica schists and thin intervals of calcareous mica schists and graphite schists (Figs. 7 & 22A).

Based on data published by Melezhik et al. (2003), the calcite marbles exhibit a moderate variation of isotopic ratios and elemental concentrations (Fig. 22A; Table 4): Sr ($911\text{--}2600\text{ }\mu\text{g g}^{-1}$, $n = 24$), Mn ($18\text{--}170\text{ }\mu\text{g g}^{-1}$), Fe ($44\text{--}5600\text{ }\mu\text{g g}^{-1}$), contents and $\delta^{13}\text{C}$ (from $+0.3$ to $+6.3\text{‰}$), $\delta^{18}\text{O}$ ($17.5\text{--}25.8\text{‰}$) and $^{87}\text{Sr}/^{86}\text{Sr}$ ($0.70640\text{--}0.70693$, with two outstanding outliers at 0.70753 and 0.70816 ; $n =$

15) (Fig. 22). The marbles contain up to 1.2 wt.% total organic carbon, TOC = $0.16\text{--}1.2$ wt.% and are enriched in phosphorus (Melezhik et al., 2003).

There is no significant correlation between any isotopic ratio and Mn/Sr ($0.01\text{--}0.16$) or Mg/Ca ($0.005\text{--}0.12$) (Fig. 18). However, three samples with highly radiogenic Sr-isotopic ratios (0.70693 , 0.70753 and 0.70816) show the highest Mn/Sr ($0.04\text{--}0.05$) and elevated Mg/Ca ratios (Fig. 22B), hence indicating an alteration associated with Mn-rich fluids and dolomitisation. The lowermost $\delta^{13}\text{C}$ values ($+0.3$ and $+1.4\text{‰}$) were measured in samples with the greatest content of total organic carbon (0.61 and 1.2 wt.%; Melezhik et al., 2003), indicating either organic diagenesis or metamorphic reactions or both as the ^{12}C -rich source in the process of post-depositional alteration. Based on these and other criteria Melezhik et al. (2003) suggested the least radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.70640 and the two highest $\delta^{13}\text{C}$ values of $+6\text{‰}$ to

Figure 22. A schist-marble succession with IFs exposed near Herjangen and sampled in the road-cut. (A) A lithological column of the sampled section and geochemical and isotopic characteristics of the marbles (modified from Melezhik et al., 2003). (B) Various cross-plots illustrating that the samples most depleted in ^{13}C show the highest content of C_{org} and the most radiogenic Sr-isotopic ratios show the highest Mn/Sr and elevated Mg/Ca ratios.

represent the best proxy to seawater composition (Table 5).

The Bogen section (Fig. 7; for location, see Fig. 11). The studied section is a 25 m-thick marble unit representing a c. 1500 m-thick succession (Fig. 23A). The unit lies below a garnet-mica schist and above one of the IFs. Based on the published data (Table 3; Melezhik et al., 2003), the marbles do not represent any exception from those described in the previous sections. All studied geochemical parameters show a considerable variation despite the limited length of the stratigraphy (Fig. 23): Sr (431–1800 $\mu\text{g g}^{-1}$, $n = 12$), Mn (16–196 $\mu\text{g g}^{-1}$), Fe (42–931 $\mu\text{g g}^{-1}$) contents; $\delta^{13}\text{C}$ (from +2.1 to +6.5‰, $n = 12$), $\delta^{18}\text{O}$ (14.6–27.7‰) and $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70664–0.70714, $n = 6$)

ratios; and Mg/Ca (0.005–0.07) and Mn/Sr (0.01–0.28) values (Table 4). The marbles contain a measurable amount of TOC (up to 0.3 wt.%, $n = 7$; Melezhik et al., 2003). Similar to the marbles from the Herjangen section, the Bogen marbles are enriched in phosphorus compared with those from other localities (Fig. 18).

No systematic variations of the above-listed elemental concentrations and isotopic ratios have been observed. However, there is a significant correlation of $\delta^{13}\text{C}$ with the Mg/Ca (-0.76 , $n = 12$, $>99\%$) and $\delta^{18}\text{O}$ ratios ($+0.69$, $n = 12$, $>95\%$) and TOC content (-0.75 , $n = 7$, 95% ; Fig. 23B). Consequently, the highest $\delta^{13}\text{C}$ ratio of +6.5‰ (Mg/Ca = 0.005, Mn/Sr = 0.01, $\delta^{18}\text{O}$ = 27.7‰ and TOC = 0.11 wt.%) has been selected to represent a seawater

Figure 23. A marble section with IF exposed near Bogen. (A) A lithological column of the sampled section and geochemical and isotopic characteristics of the marbles (modified from Melezhik et al., 2003). (B) Various cross-plots illustrating alteration trends of C and O isotopic systems (indicated by red arrows) and the lack of correlation of $^{87}\text{Sr}/^{86}\text{Sr}$ values with $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ ratios or Al contents.

proxy. None of the discrimination criteria applies for deciphering the least-altered $^{87}\text{Sr}/^{86}\text{Sr}$ ratio. Melezhik et al. (2003) suggested the least radiogenic ratio of 0.70664 as a seawater proxy (Table 5).

The Håfjell section. The studied section (Fig. 7; for

location, see Fig. 11) is an approximately 200 m-thick unit known as the Fuglevann Marble (Gustavson, 1966). It consists of dark grey, medium-crystalline, thickly banded calcite marble with intercalations of calcareous, garnet-mica and graphite schists, and amphibolite boudins (Fig. 24A).

Figure 24. A marble section with several IF exposed in Håfjället. (A) A lithological column of the sampled section and geochemical and isotopic characteristics of the marbles (modified from Melezhik et al., 2002a, b, 2003). (B) Various cross-plots illustrating a negative correlation of $\delta^{13}\text{C}$ values with SiO_2 abundances (there is an indication of two separate converging trends), and Mg/Ca ratios. In contrast, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios do not show correlation with any geochemical parameters.

Fifteen samples were collected from a single locality (Melezhik et al., 2002a, b) representing almost the entire thickness of the Fuglevann Marble. The marbles are very low in siliciclastic components (Table 3) and are relatively enriched in TOC (up to 0.5 wt.%; Melezhik et al., 2002a, b). They exhibit a high content of Sr, the lowest Mn, Fe concentrations, and Mn/Sr and Mg/Ca ratios in comparison with all other marbles from the previously described sections (Table 4). Moreover, the variations of

all these elemental concentrations and elemental ratios as well as $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values are the smallest of all (Table 4). In contrast, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are highly variable (Fig. 24). These marbles together with those from the Herjangen and Bogen sections are richest in P_2O_5 (Fig. 18).

The $\delta^{13}\text{C}$ values show a negative correlation with SiO_2 ($r = -0.47, n = 15, >90\%$) and Fe ($r = -0.77, n = 15, >99.9\%$) abundances, and Mg/Ca values ($r = -0.56, n = 15, >95\%$;

Fig. 24B), hence suggesting that the dolomitisation and subsequent silica-dolomite reaction have caused the alteration of primary $\delta^{13}\text{C}$ values. Consequently, Melezhik et al. (2002a, b) suggested the $\delta^{13}\text{C}$ of +6.5‰ as the least altered. The observed range in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios does not demonstrate any meaningful dependence upon any geochemical parameters (Figs. 18 & 24B). The stratigraphic plot (Fig. 24A) demonstrates that the $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{13}\text{C}$ ratios are systematically higher above 260 m than below it. Melezhik et al. (2002a, b) inferred that the observed fluctuations may reflect primary stratigraphic variations, and suggested an average value of 0.70669 as a seawater proxy. Here, we take a conservative stand and choose the least radiogenic ratio of 0.70645 as the least altered value (Table 5).

Apparent depositional ages of the carbonate formations based on isotope chemostratigraphy

The apparent depositional ages have been constrained by projection of the 'least altered' $\delta^{13}\text{C}$ and the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios obtained from the studied marble formations (Table 5) onto the seawater reference curves (Fig. 25). The time when the intercepts of both ratios are in agreement has been considered to represent an apparent depositional age of the carbonate protolith. The obtained apparent chemostratigraphic ages are presented in Table 5. Bearing in mind a possibility that some extracted best-preserved $^{87}\text{Sr}/^{86}\text{Sr}$ ratios may still be altered and therefore original depositional values could be somewhat lower, one may rate the obtained apparent depositional ages as minimum ages for most of the Ediacaran, Cryogenian and late Tonian which are marked by a sublinear negative slope of $^{87}\text{Sr}/^{86}\text{Sr}$ through time.

In the BSNC, the $\delta^{13}\text{C}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of all marble formations associated with IFs in the Espenes–Sørreisa, Salangen, Herjangen, Bogen, Andørja and Håfjellet sections are consistent with the deposition of the marble protolith in the late Tonian. Although the obtained age range from 820 to 735 Ma allows no unique resolution, each protolith has clearly been deposited prior to 735 Ma (Table 5; Fig. 25).

The ENC contains two marble units showing distinctly different $\delta^{13}\text{C}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. The least-altered ratios obtained from the Elvenes marble suggest a unique resolution with a rather narrow apparent depositional age of the protolith (685–660 Ma) within the Mid Cryogenian (Table 5; Fig. 25). The second unit sampled in the Henrikkjølen section has $\delta^{13}\text{C}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios suggesting two equally possible ages of the protolith, one within the Late Ediacaran (550 Ma), and the other between the Early Ordovician and Mid Silurian (425–410 Ma) (Table 5; Fig. 25).

In the NNC the Vassdalen marble shows the least-altered $^{87}\text{Sr}/^{86}\text{Sr}$ ratio similar to that obtained from the Henrikkjølen section. Both $\delta^{13}\text{C}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are consistent with either the Late Ediacaran (550 Ma) or the Early Ordovician to Mid Silurian (425–410 Ma) (Table 5; Fig. 25).

The relative time-ordering of marble, diamictite units and IFs

Whether or not the obtained apparent depositional ages of carbonate precursors of the marble units could set a constraint for the time of deposition of intercalated IFs and diamictites largely depends upon their true stratigraphic position. Unfortunately, in the studied areas the schist-marble-IF-diamictite successions have undergone multiphase tectonic reworking which in most cases obliterated evidence of their relative chronostratigraphic order.

In the Rana region, Melezhik et al. (2015) reported two main tectonostratigraphic successions, namely schist-IF-diamictite and marble-IF-diamictite. Unfortunately, an intensive folding and refolding prevented the establishment of the relative time-order of these tripartite units. However, the original, relative, depositional time-ordering between carbonate and IF units has been confidently established in the Salangen area. Fig. 19B demonstrates that the IF rests upon an uneven palaeotopography of the marble unit, hence illustrating the relative time-order of their deposition. Under the condition that the IFs and underlying marble units were originally deposited contemporaneously throughout the studied area, this suggests that the marble-IF-diamictite tripartite unit observed in the Rana region could also represent a true chronostratigraphy. The documented relative time-order thus suggests a transition from carbonate deposition to the accumulation of IFs and then to the formation of glacial diamictites. Consequently, the IFs and diamictites are somewhat younger with respect to the underlying carbonate formations.

Geochemical, isotopic comparison and chemostratigraphic correlation of marbles across southern Troms and northern Nordland

Previous chemostratigraphic studies have been performed in the areas north and south of Ofotfjorden in the county of Nordland. These studies demonstrated that apparent depositional ages of the protolith, representing all major carbonate units of the NNC, ENC and BSNC within the UA and UmA, range from Late Tonian to Early Silurian (Table 6). Moreover, at least six

distinctly different age units can be identified (Fig. 4; Table 6). Importantly, the apparent depositional ages of these different marble units suggest that they have been tectonically emplaced in a non-stratigraphic order (Fig. 4).

The current research in southern Troms has identified at least four distinctly different age units among those marbles which have been sampled so far (Table 6). Previously published and newly obtained $\delta^{13}\text{C}$, $^{87}\text{Sr}/^{86}\text{Sr}$ and Sr data from marbles in Troms and Nordland form several distinct clusters (Fig. 26).

The Narvik Nappe Complex

In the NNC, the marble unit here termed the Vassdalen marble can be confidently traced from southern Troms to northern Nordland (Fig. 11). In the tectonostratigraphic sense it is situated below the Mid Ediacaran Melkedalen Marble (Fig. 11; Melezhik et al., 2014). Unfortunately, the $\delta^{13}\text{C}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ data allow no unique resolution for the apparent depositional age of the protolith, being consistent with either Late Ediacaran or Early Ordovician–Mid Silurian time. These marbles show rather low $^{87}\text{Sr}/^{86}\text{Sr}$ values (Fig. 26A) and together with the Mid Ediacaran marbles (Shuram–Wonoka

Figure 25. Temporal trends of $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{13}\text{C}_{\text{carb}}$ in seawater through the Neoproterozoic and Early Palaeozoic. (A) $\delta^{13}\text{C}_{\text{carb}}$ reference curve based on compilations made by Veizer et al. (1999) and Halverson & Shields-Zhou (2011). Blue, shaded boxes and lines (A and B) show the inferred range of glacial events, with the gradational shading in the middle Cryogenian box reflecting the wide range of ages for the mid-Cryogenian glaciation (Halverson & Shields-Zhou, 2011). An apparent range of the Sturtian glacial event shown by horizontal arrow-headed lines is based on Rooney et al. (2014). (B) $^{87}\text{Sr}/^{86}\text{Sr}$ database for reconstructing the proxy to original Silurian–Tonian seawater. Black crosses and circles after Veizer et al. (1999), violet crosses after Denison et al. (1994), orange stars after Derry et al. (1994), red dots after Halverson & Shields-Zhou (2011), rectangles after Kuznetsov et al. (2013). The data, which are considered as the proxy to original Proterozoic seawater, are taken from: 1 – Member I–6, Atar Group (Veizer et al., 1983), 2 – Little Dal Group (Halverson et al., 2007), 3 – Gillen Member, Bitter Springs Formation (Walter et al., 2000), 4 – Inzer Formation, Karatau Group (Kuznetsov et al., 2003, 2006), 5 – Minyar Formation, Karatau Group (Kuznetsov et al., 2003, 2006), 6 – Shaler Group (Asmerom et al., 1991), 7 – Akademikerbreen Group (Derry et al., 1989, 1992; Halverson et al., 2007), 8 – Coates Lake Group (Halverson et al., 2007), 9 – Rasthof Formation, Otavi Group (Yoshioka et al., 2003), 10 – Uk Formation, Karatau Group (Kuznetsov et al., 2003, 2006), 11 – Keele Formation, Windermere Supergroup (Narbonne et al., 1994; Halverson et al., 2007), 12 – Ombaatjie Formation, Otavi Group (Halverson et al., 2007), 13 – Hayhook Formation, Windermere Supergroup (James et al., 2001; Halverson et al., 2007), 14 – Maieberg Formation, Otavi Group (Halverson et al., 2007), 15 – Doushantuo Formation (Yang et al., 1999; Sawaki et al., 2010), 16 – Blueflower Formation, Windermere Supergroup (Kaufman et al., 1993; Narbonne et al., 1994), 17 – Witvlei Group (Kaufman et al., 1993), 18 – Wonoka Formation (Calver, 2000; Walter et al., 2000), 19 – Huqf Group (Burns et al., 1994), 20 – Nama Group (Kaufman et al., 1993), 21 – Tinnaya Formation (Gorokhov et al., 1995), 22 – Ust–Yudoma Formation (Semikhatov et al., 2003), 23 – Pestrosvet Formation (Nicholas, 1996), 24 – Tommotian, Atdabanian, Botomian and Toyonian type sections, Early Cambrian (Derry et al., 1994; Kaufman et al., 1996), 25 – Macha and Tolbacha formations, Early Cambrian (Gorokhov et al., 1995). Note that the Sr-isotope data reported by Kuznetsov et al. (2003, 2006) represent a big discrepancy with respect to other worldwide measurements. The depositional time of the Uk Formation has been based on a Rb–Sr age (664 Ma) and a K–Ar glauconite age (669 Ma) which have not been accepted by other workers who have produced similar compilations. Earlier it has been suggested (Melezhik et al., 2015) that the Uk Formation data should be removed from the compilation until robust radiometric age constraints are available. (C) $\delta^{13}\text{C}_{\text{carb}}$ and combined $^{87}\text{Sr}/^{86}\text{Sr}$ reference curves. Purple, red and black lines designate ranges in $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{13}\text{C}_{\text{carb}}$ values obtained from the least-altered calcite marbles. Vertical red and black arrows indicate apparent depositional ages of the protolith of the marbles associated with IFs in southern Troms and Nordland during Mid–Late Tonian time.

Table 6. Apparent depositional ages for the correlative tectonostratigraphic units in the areas north and south of Ofotfjorden.

Tectonostratigraphic unit	N [♥] $\delta^{13}\text{C}$ ‰	S [♥] $\delta^{13}\text{C}$ ‰	N $^{87}\text{Sr}/^{86}\text{Sr}$ initial	S $^{87}\text{Sr}/^{86}\text{Sr}$ initial	Earlier pro- posed ages (Ma) for the Ofoten region	Corrected ages (Ma) for the Ofoten region, using updated seawater refe- rence curves (Fig. 25)	Geological period
Bogen–Salangen nappe complex							
Liland marble	+6.5*	–	0.70655*	–	650–595*	800–735	Mid–Late Tonian
Hekkelstrand Marble	+3.1*	+5.0*	n.d.	0.70615*	710–700 or 660*	910–850, 830–815 or 800–760	Early–Mid Tonian
Fuglevann Marble	+6.3*	+6.5*	0.70640*	0.70645*	660*	800–735	Mid–Late Tonian
Evenes nappe complex							
Tangen thrust sheet marble	+6.4*	+8.0*	0.70708*	0.70720*	620–610*	680–660	Mid Cryogenian
Evenestangen thrust sheet marble							
White marble	–5.9*	–	0.70870*	–	600–550*	575–570	Mid Ediacaran (SWE)
Variegated marble	–8.3*	–8.5*	0.70824*	n.d.	600–550*	590–580	Mid Ediacaran (SWE)
Dark marble in N./ formation III in S.	+6.0*	+5.0*	0.70821*	0.70826*	440–438*	440–438	Early Silurian (Llandovery)
Ramstad thrust sheet marble in N./ formation II in S.	+0.2*	+2.2*	0.70920*	0.70878*	550–500*	530–510	Mid Cambrian
Steinsland thrust sheet marble in N./ formation I in S.	+6.0*	+5.0*	0.70677*	0.70663*	650–595*	800–735	Mid–Late Tonian
Narvik Nappe Complex							
Melkedalen marble	n.d.	+6.0 [§]	n.d.	0.70772 [§]	610–590 [§]	610–590	Mid Ediacaran

♥N, S – areas north and south of Ofotfjorden.

Data are from Melezhik et al. (2002a)*, (2002b)*, (2003)*, (2008)* and (2014)[§].

‘–’ – formation/data are not available, ‘n.d.’ – not determined, ‘SWE’ – Shuram–Wonoka event.

Figure 26. Previously published and newly obtained $\delta^{13}\text{C}$, $^{87}\text{Sr}/^{86}\text{Sr}$ and Sr abundance data from marbles in southern Troms and Nordland.

excursion) are characterised by the highest abundances of Sr (Fig. 26B).

The Evenes nappe complex

In the ENC the marbles from the Tangen thrust sheet in Ofotfjorden, northern Nordland, appear to have $\delta^{13}\text{C}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ values similar to those obtained for the Elvenes marble in Troms, and hence a similar apparent

depositional age of the protolith (Tables 5 & 6). In both areas, these marbles are situated below the Bø Quartzite (Fig. 11) and, consequently, might also have a similar tectonostratigraphic position. All of this together suggests their chronostratigraphic equivalency.

The marbles studied in the Henrikkjølen section in Troms occur in a similar tectonostratigraphic position to the Early Silurian, Dark marble/formation III (Melezhik et al., 2008) from the Evenestangen thrust sheet in Ofotfjorden, northern Nordland (Figs. 4 & 11). These marbles share similar $\delta^{13}\text{C}$ ratios, but those from Troms show slightly higher $^{87}\text{Sr}/^{86}\text{Sr}$ (Tables 5 & 6; Fig. 26A). Consequently, apparent depositional ages of their protolith are also somewhat different, assuming a similar degree of preservation potential.

The Mid Cambrian marble (Ramstad thrust sheet) known in Ofotfjorden, northern Nordland (Figs. 4, 11 & 26A), has not been identified in southern Troms. The marbles are marked by the highest $^{87}\text{Sr}/^{86}\text{Sr}$ ratio reported from the study area, by near zero $\delta^{13}\text{C}$ and a low Sr content (Fig. 26A, B). The Early Silurian, dark grey marbles as well as the Mid Ediacaran, multicoloured (Fig. 5), strongly ^{13}C -depleted marbles (Shuram–Wonoka Event; Fig. 26A) from the Evenestangen thrust sheet in Ofotfjorden (Fig. 4) have not been found in southern Troms (Fig. 11). However, both have been reported from the Sagelvatn area (Melezhik et al., 2008), just 35 km to the east from the northeastern corner of the study area (Fig. 11).

The Bogen–Salangen nappe complex

In the BSNC, the Hekkelstrand marble known in Ofotfjorden in Nordland (Figs. 4 & 11), with the oldest by far apparent depositional age of the protolith (late Tonian), has not been found in Troms.

All late Tonian marbles associated with the IF plot on a $\delta^{13}\text{C}$ – $^{87}\text{Sr}/^{86}\text{Sr}$ diagram within a field marked by the least radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ values and highly positive $\delta^{13}\text{C}$ values (Fig. 26A). These marbles are also high in Sr content (Fig. 26B). Various cross-plots, summarising the geochemical and isotopic characteristics of these marbles (Fig. 18), reveal two main features which include: (i) overlap of all obtained geochemical and isotopic data; and (ii) large scatter of $^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{13}\text{C}$, $\delta^{18}\text{O}$, Mn/Sr, and MgO/CaO ratios and Sr abundances. The former proves that the marbles have not only similar depositional time, but also similar geochemical characteristics implying similar post-depositional alteration processes. The large scatter indicates that in all studied sections the Sr-, C- and O-isotope systems were subject to a significant degree of post-depositional alteration. However, despite obvious alteration, in every studied section there are samples retaining low $^{87}\text{Sr}/^{86}\text{Sr}$ and high $\delta^{13}\text{C}$ values, and most interestingly, even high $\delta^{18}\text{O}$ values exceeding 25‰. The latter is rather unusual for amphibolite-grade

marbles, and may suggest a substantial degree of selective preservation potential. This illustrates once again that a sizeable database is commonly warranted in finding the few least-altered samples (Melezhik et al., 2001, 2003). The overall $\delta^{13}\text{C}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ data suggest that the IF-associated marbles can be confidently traced across southern Troms from Sørreisa through Ofotfjorden in northern Nordland and farther to the south to the Rana district (Fig. 1).

Apparent depositional environments of the carbonate protolith of the marble formations and amphibolites associated with the IFs

The investigated calcite marbles are relatively pure rocks with a limited amount of siliciclastic components (Table 3). The high Sr contents reaching 2000–3000 $\mu\text{g g}^{-1}$ (Table 4) are indicative of an aragonite precursor (e.g., Veizer, 1983). A sizeable thickness and a large lateral extent, high Sr abundances and purity of the carbonate rocks are all indicative of an open-marine, aragonite-precipitating environment. The overall rock association observed in southern Troms and Nordland suggests that the carbonates were accumulated on a carbonate-siliciclastic shelf.

In Rana, thick carbonate-schist successions accumulated in a sea-shelf environment are associated with massive diamictites, stratified and sorted/graded glacial deposits (Fig. 8). The latter contain oversized clasts and were interpreted as either fluvio-glacial or glaciomarine deposits, and suggest an icehouse environmental condition (Melezhik et al., 2015). The presence of rare amphibolite bodies of possible intrusive origin and unknown age (Bugge, 1948) with no evident synchronous volcanic activity suggests an apparent passive continental margin possibly affected by an incipient rifting (Melezhik et al., 2015).

The Andørja, Salangen and Espenes areas are characterised by the presence of conformable units of intermediate to felsic hornblende-biotite gneisses and biotite gneisses of probable volcanic origin. At Andørja, the gneisses in the ore zone may represent a mixture of intermediate volcanic and volcanoclastic rocks.

In the Håfjellet, Bogen and Salangen (middle level) areas in general, and in the footwall of the uppermost IF in the Sørreisa area, there are a few conformable units of fine- to medium-grained amphibolites of volcanic origin. At Andørja, the IFs and their host rocks bear evidence of periods of active volcanism and deposition of basaltic ash-fall tuffs synchronous with Fe-oxide precipitation. In these ore fields, as well as throughout southern Troms and northern Nordland, in the area between Ofoten

and Sørreisa (Fig. 2), the mafic igneous rocks have quite similar chemistry typical for calc-alkaline and within-plate igneous rocks resembling MORB (Fig. 13).

In the Andørja, Salangen and Espenes areas, the presence of volcanic rocks in great abundance testifies to an active extrusive volcanism synchronous with accumulation of carbonate, clastic material and Fe-precipitation. Such features are suggestive of a large back-arc basin with a landward shale-carbonate sequence located proximal to volcanic centres and hydrothermal vents.

The palaeotectonic location of the study area

The palaeotectonic and palaeogeographic position of the supracrustal rocks of the ENC and BSNC has been considered in a series of publications (Melezhik et al., 2002a, b, 2003, 2008). The apparent Neoproterozoic depositional ages of carbonate precursors of many marble units combined with the palaeogeographic position of Baltica suggest that a large part of the sedimentary successions forming the ENC and BSNC were initially accumulated along the margin of Laurentia. The presence of intrusive (Råna area) or both intrusive and extrusive rocks (Andørja, Salangen and Espenes areas) in the successions hosting IFs is suggestive of a passive continental margin affected by an incipient rifting (Råna area) or a large back-arc basin with a landward shale-carbonate sequence (Andørja, Salangen and Espenes areas). The sedimentary and sedimentary-volcanic successions were then tectonically transported onto Baltica during the Early Silurian, Scandian collision, at c. 425 Ma.

The complex tectonic imbrication of the polymetamorphosed and polydeformed Neoproterozoic units jointly with Cambrian and Early Silurian carbonate formations also suggests that more than one orogenic episode should be invoked to explain the tectonic juxtaposition of these assemblages. Some of the thrust contacts juxtaposing rocks of Neoproterozoic and Cambrian age and the obduction of the ophiolite complex might have been associated with a Mid to Late Ordovician, Taconian event (Melezhik et al., 2002a, b, 2003; Roberts et al., 2001, 2002, 2007).

Palaeotectonic implications of Mid-Neoproterozoic sediment-hosted IFs in the Caledonides

In all the studied cases, the apparent age of the marble protolith lies within the range 800–735 Ma. In the Salangen, Herjangen and Bogen areas, there is also an alternative age of 820–810 Ma (Table 5; Fig. 25C). Hence, with the given limitations of chemostratigraphic dating,

the apparent depositional age of the precursor to the marbles in all IF ore-fields in the UmA links to Mid-Neoproterozoic, late Tonian time.

Our previous studies demonstrated that most of the UmA marble-schist complexes, including those hosting IFs, were originally accumulated on the Laurentian margin, hence on a continental shelf outside Baltica. During the Early Silurian Scandian collision, at c. 425 Ma, they were tectonically emplaced onto Baltica (Roberts et al., 2001, 2002, 2007; Melezhik et al., 2002a, b, 2003, 2014). The documented, conformable, depositional contacts between the late Tonian calcitic marble and overlying IFs (Fig. 19B) followed in places (the Rana region) by diamictites can reflect either a late Tonian age of both IFs and glacial rocks or an early Cryogenian age within a Tonian (carbonates)–Cryogenian (IFs and diamictites) transitional period. In our previous study (Melezhik et al., 2015), before the Cryogenian–Tonian boundary was moved from 850 Ma to 720 Ma (Shields-Zhou et al., 2016), the Rana and Håfjellet sediment-hosted IFs were compared with successions in other parts of the Caledonide–Appalachian orogen with the conclusion that they were deposited contemporaneously with all other Neoproterozoic (Cryogenian) IFs reported worldwide.

In the Scottish and Irish Caledonides, IFs *per se* of Cryogenian and Tonian age are absent. The iron accumulation is represented by only detrital and diagenetic magnetite cement occurring in magnetite-rich meta-sediments within the “*Disrupted Beds*” (Spencer, 1971).

In northern America, Tonian age diamictites and IFs are unknown. Several Cryogenian age IFs occur on the western margin of the former Laurentian plate (compiled in Cox et al., 2013). These include: (i) the Chestnut Hill IF in western New Jersey; (ii) the Rapitan Group IF in northwestern Canada; (iii) the Tatonduk IF on the Yukon–Alaska border; and (iv) the Tindir Group IF in northeastern Alaska.

The IFs older than Cryogenian have only been reported from Namibia and SE China. In Namibia, in the Congo craton, the glacial Chuos Formation with iron ores overlies the Naauwpoort volcanic rock dated at 746 ± 2 Ma (Hoffman et al., 1996; Condon & Bowring, 2011). This provides a robust maximum age constraint for the Chuos IF and diamictites which hence could be considered as a relevant chronostratigraphic counterpart of the Scandinavian IFs and glacial diamictites. In SE China, the early Neoproterozoic Shilu IF (1000–800 Ma) from Hainan Island, not associated with glacial deposits, may represent another example of Mid-Neoproterozoic, pre-Cryogenian IFs (Sun et al., 2018) similar to the Scandinavian IFs.

All four IFs reported from northern America were accumulated during the breakup of Rodinia after the

initial rifting of the Laurentian margin. All four are interbedded with coarse-grained siliciclastic sedimentary rocks and associated products of synchronous volcanism (Young et al., 1979; Young, 1982; Gates & Volkert, 2004; Cox et al., 2013). Similarly, the Chuos IF and diamictites are associated with an early stage of rifting of the Congo craton (Eyles & Januszczyk, 2007). The above comparison suggests that not all characteristics of the Neoproterozoic Laurentian IFs match those observed in the Scandinavian Caledonides. Importantly, the data compiled by Cox et al. (2013) do not suggest that the Neoproterozoic IFs are or were present on the eastern part of the Laurentian continental margin (e.g., the East Greenland and Scottish–Irish Caledonides and Canadian Appalachians). All known North American IFs are located on the opposite, western margin of Laurentia and therefore cannot have been thrust upon Baltica during the Laurentia–Baltica collision. Hence, the provenance of the Neoproterozoic sediment-hosted IFs in the Scandinavian Caledonides remains equivocal and may even point towards the existence of an unknown microcontinent positioned somewhere between Laurentia and Baltica (e.g., Grenne et al., 1999).

Palaeoenvironmental implications of mid-Neoproterozoic, sediment-hosted, IFs in the Scandinavian Caledonides

More than half a dozen models advanced for explanation of the global reappearance of IFs in the Neoproterozoic (reviewed in Melezhik et al., 2015) are almost all tectonic or climate-driven or both (Knoll et al., 1996; Hoffman & Schrag, 2002; Eyles & Januszczyk, 2004; Kump & Seyfried, 2005; Mikucki et al., 2009; Bekker et al., 2010; Swanson-Hysell et al., 2010; Baldwin et al., 2012). These models, differing in details, share one major feature in common: they link directly or indirectly the global reappearance of IFs in the Neoproterozoic to the onset of global icehouse conditions of Sturtian age (Young et al., 1979; Young, 1982; Gates & Volkert, 2004; Cox et al., 2013). Indeed, the recent review by Cox et al. (2013) has demonstrated that IFs situated in South Australia, Namibia, China (for one exception see Sun et al., 2018), northwestern Canada and the Arabian–Nubian Shield were deposited during the Sturtian glaciations. The global scale icehouse event might have triggered a widespread shift in marine redox conditions causing the iron precipitation.

In the Scandinavian Caledonides, the late Tonian (800–730 Ma) chemostratigraphic ages of the sediment-hosted IFs suggest their deposition during either pre-Sturtian time or perhaps marginally overlapping with the onset of the Sturtian glacial period (717–660 Ma; Fig. 25). However, their deposition coincides with a hypothetical Kaigas glaciation proposed by Macdonald et al. (2010) but subsequently dismissed by Rooney et

al. (2015). One out of seven IFs studied in Troms and Nordland is definitely associated with glacial deposits and was originally accumulated on a glacially influenced siliciclastic-carbonate shelf (Melezhik et al., 2015).

The IFs reported from outside the Scandinavian Caledonides occur in intra-plate basins or in rift-basins developed on continental margins. Many, if not all, are intimately associated with mafic volcanism and have been deposited in volcanically active rift-basins or rift-basins with submarine hydrothermal activities (reviewed in Cox et al., 2013). No Neoproterozoic IF reported from outside the Scandinavian Caledonides is known to have been formed in an open-marine basin (Torsvik, 2003; Li et al., 2013).

All studied Scandinavian IFs and their host shale-carbonate sequences are not in accord with other Neoproterozoic IFs, hence representing egregious outliers. In all studied cases, the sedimentological and geochemical features of carbonate formations match with an open-marine, carbonate-siliclastic shelf environment or a large back-arc basin with a landward shale-carbonate sedimentation. There is no apparent evidence for active synchronous volcanism in Rana, Håfjellet, Bogen and Herjangen. In contrast, the Andørja, Salangen and Espenes–Sørreisa ore fields show evidence of active andesitic and minor basaltic volcanism synchronous with the Fe accumulation (Fig. 7).

Conclusions

1. The C- and Sr-isotope chemostratigraphy reported here provides the first apparent depositional age of the carbonate protolith to amphibolite-grade, calcite marbles which occur associated with iron formations throughout the southern Troms and Nordland regions in the Uppermost Allochthon in the North–Central Norwegian Caledonides.
2. The obtained depositional age range of 800–735 Ma (late Tonian or pre-Sturtian) for the separate areas suggests that the accumulation of Sr-rich marbles was contemporaneous throughout the entire southern Troms and Nordland region over a distance of 350 km. The marbles from these ore fields show rather similar least-altered $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70645–0.70665) ratios and $\delta^{13}\text{C}$ (+6 to +8‰) values.
3. Three other marble units spatially unrelated to iron formations which occur in the Evenes and Narvik nappe complexes show different $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{13}\text{C}$ values matching younger apparent depositional ages of 685–600 Ma (the Elvenes marble), and 550 or 425–410 Ma (the Henrikkjølén and Vassdalen marbles).
4. The chemostratigraphic late Tonian age of the Scandinavian Sr-rich marbles sets up a maximum depositional age for the overlying iron formations and

- diamictites, which, however, does not rule out their formation during a presumed Tonian–Cryogenian transition from carbonate accumulations to the formation of iron ores and deposition of glacial rocks.
5. The schist-marble successions and associated Scandinavian iron formations were originally accumulated on a siliciclastic-carbonate shelf, within either a passive continental margin, showing incipient rifting, or a large back-arc basin, in places glacially influenced.
 6. The Scandinavian, mid-Neoproterozoic iron formations represent an exception from other reported Neoproterozoic counterparts which were all accumulated in clastic sediment-dominated environments, in volcanically active continental rift settings.
 7. The Scandinavian, mid-Neoproterozoic, iron formations and associated schist-marble sequences, similar to other marble-schist sequences of the Uppermost Allochthon, were originally formed outside Baltica, and were subsequently thrust upon the Baltoscandian margin during the Scandian orogeny.
 8. The provenance for the Scandinavian, mid-Neoproterozoic, iron formations remains enigmatic; it can be linked neither to the eastern nor to the western margin of Laurentia, hence hinting towards a passive margin of an unknown, missing microcontinent.

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