Isotopic composition, deposition ages and environments of Central Norwegian Caledonian marbles

REIDAR G. TRØNNES & BJØRN SUNDVOLL

Reidar Trønnes, Min.-Geol. Museum, University of Oslo, Sars gate 1, N-0562 Oslo, Norway.
Bjørn Sundvoll, Geological Survey of Norway. Address: Min,-Geol. Museum, Sars gate 1, N-0562 Oslo, Norway.

Tectonostratigraphy of marbles

The C-, O-, and Sr-isotopic chemistry of 48 samples of Central Norwegian Caledonian marbles and metalimestones are used to constrain the extent of post-depositional fluid-carbonate and silicate-carbonate exchange and the sedimentary ages and environments. The marbles occur mainly at three tectonostratigraphical levels: (1) the Helgeland Nappe Complex (HNC) of the Uppermost Allochthon; (2) the Köli-equivalent nappes (KN); and (3) the Seve-equivalent nappes (SN) of the Upper Allochthon. The carbonates in the KN and SN are closely associated with, and are generally deposited on, mafic metavolcanic rocks. The KN-rocks are generally in the greenschist facies and have undergone comparatively little deformation. The carbonates are partly fossiliferous and were deposited on Ordovician ophiolite and island arc fragments falling within two main age groups: 500–470 Ma and 443–437 Ma (Roberts et al. 1984, Pedersen et al. 1992).

The SN-units in the Vestranden gneiss complex are metamorphosed in the amphibolite to granulite facies and have undergone extensive and complex deformation (Solli 1989). Most of the sampled SN-units occur as strongly flattened and isoclinally infolded bands in the basement gneisses. At several locations the marble units are tectonically thickened and thinned by plastic flow. Based on observations further east (in Sweden) the SN originated in the outermost part of the early passive margin of Baltica, and experienced metamorphism up to eclogite facies just prior to 500 Ma (Mørk et al. 1985, Dallmeyer & Gee 1986, Andreasson & Gee 1989).

The HNC includes two lithologically distinct groups: (1) nappes composed of a basement of high-grade gneisses and overlying calcareous metasedimentary rocks, largely pelites and marbles; (2) nappes with mafic and ultramafic rocks of ophiolite affinity overlain by marbles and clastic metasediments (e.g. Thorsnes & Løseth 1991). In terms of age and depositional environment, the ophiolitic sequences of the HNC are equivalent to the Ordovician Köli ophiolites in Trøndelag.

C-, O- and Sr-isotope relations

Trønnes (1994) provides details of the locations of the samples used in this study, as well as the analytical methods and numerical results. The only sample of the high-grade marbles from the Eide area at Nordmøre is classified here as a SN marble. The supracrustals in the Eide may conceivably belong to strongly deformed and metamorphosed KN (P. Robinson, pers.comm. 1993, Trønnes 1994). For the sake of consistency in terms of age and depositional environment, two marble samples associated with Ordovician ophiolite fragments within the HNC are grouped with the Köli units.

The C-, O-, and Sr-isotope relations are shown in Fig. 1. Forty of the 48 analysed samples have more than 95 wt% carbonate and 44 of the samples have more than 90 wt% carbonate (major element data in Trønnes, 1994). The samples are calcite marbles, except for 5 dolomites. In Fig. 1 the samples containing more than 54.8 wt% CaO from marble deposits exceeding 200 m in thickness are separated from the rest of the samples by large symbols. The carbonate fraction in these samples has presumably experienced a minimum of isotopic exchange with silicate (and oxide) minerals within the marble and with the wall rocks during metamorphic (and metasomatic) processes following carbonate deposition.

The marbles associated with the gneiss-metasediment nappe units of the HNC have Sr- and C-isotope compositions distinctly different from those of the SN and the KN calcite marbles (Fig. 1). The O-isotope compositions overlap completely between the three groups, but the $\delta^{18}O$ values are roughly correlated with the CaO contents (corresponding to total carbonate content) of the calcite mables. All of the samples with more than 54.8 wt% CaO from marbles exceeding 200 m in thickness have $\delta^{18}O(SMOW) > 22‰$. Only 4 of the 30 remaining samples have $\delta^{18}O$ values exceeding 22‰. Because no sample has $\delta^{18}O$ exceeding 24‰ and 8 of the 10 large-symbol samples have $\delta^{18}O$ values of 23–24‰, it is likely that this is the origi-
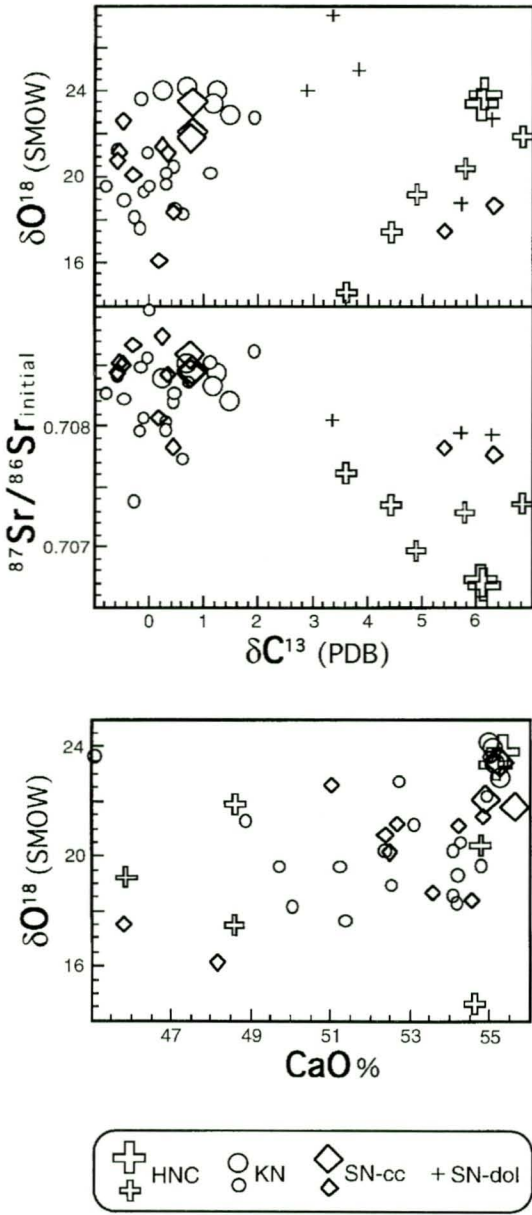
Fig. 1. Sr-O-C-isotopic relations (upper two diagrams) and $\delta^{18}O$–CaO relations of carbonates from the Central Scandinavian Caledonides. Large symbols are for samples with CaO>54.8 wt% from deposits exceeding 200 m in thickness. The $^{87}Sr/^{86}Sr$ initial ratios for the KN, SN, and HNC marbles are calculated at 470, 560, and 600 Ma, respectively. In most of the samples the Rb/Sr ratios are so low that the differences between the initial ratios at 470 Ma and 600 Ma are less than 0.00003. The isotopic analyses were performed on the carbonate fraction of the samples after extraction using 100 % phosphoric acid at 50 °C for the calcite-dominated samples, and at 80 °C for the dolomite-dominated ones. The analytical precision, in the form of 2σ, is 0.0001, 0.2‰, and 0.4‰ for $^{87}Sr/^{86}Sr$, $\delta^{13}C$, and $\delta^{18}O$, respectively.

nal isotope signature of the carbonate fraction in all of the sampled marbles.

Metamorphic and/or metasomatic reactions will affect the O-isotope values more than the C-isotope values because C is much less available than O from the silicate wall rocks and silicate minerals in the marbles. The $\delta^{18}O$ value of an infiltrating fluid will generally not reflect the fluid source, but will rather be buffered towards that of the local wall rock lithology. Metamorphic and magmatic rocks and meteoric and ocean waters have $\delta^{18}O(SMOW)$ values between −50‰ and +15‰, and metamorphic and metasomatic overprint will therefore lower the $\delta^{18}O$ of the marbles. Whereas the local silicate rocks have a large buffering capacity for $\delta^{18}O$, changes in $\delta^{13}C$ will more likely reflect external fluid sources, e.g. CO_2 release during the crystallisation of a mantle-derived magma in the lower crust ($\delta^{13}C(PDB)$ = −5 to −10 ‰). All other sources of C (except carbonates and dolomitisation fluids) are also characterised by negative $\delta^{13}C(PDB)$. Equilibrium fractionation factors for oxygen between calcite and various silicate minerals at metamorphic temperatures are small (1000 ln α calcite/silicate is in the −1.1 to +0.6 range for the fractionation between calcite and quartz, alkali feldspar, plagioclase and muscovite at 450°C, data compiled by Faure 1986). Decarbonation reactions leading to calc-silicate formation will produce coupled ^{18}O and ^{13}C depletions of the remaining carbonate (see Valley 1986, Fig. 3). Several studies have indicated that marbles are commonly relatively impermeable to fluids, even under high-grade metamorphism (Rye et al. 1976, Nablek et al. 1984, Valley 1986).

In Fig. 1 (upper diagram) the samples with > 54.8 wt% CaO from >200 m thick marble units plot in the uppermost right end of elongate 'tails' towards decreasing $\delta^{13}C$ and $\delta^{18}O$ values. These 'tails' with larger $\delta^{18}O$ than $\delta^{13}C$ components, probably result from the interaction of the analysed carbonate fraction with the silicate minerals in the marbles and with possible external fluids. The dolomite marbles in the SN in Vestranden are characterised by considerably heavier C than the average of the SN calcite marbles. The $\delta^{13}C$ in the carbonate fraction may be increased by dolomitisation fluids containing carbon dioxide and/or bicarbonate with heavy carbon equilibrated with (or residual from) methane with extremely light carbon (Murata et al. 1969, Hudson 1977).

Two calcite marble samples (Fig. 1) from the northernmost part of Vestranden have elevated $\delta^{13}C$ values at the same level as the HNC marbles (see Trønnes 1994). Several of the marbles

within assumed SN in the northernmost part of the Vestranden area are associated with mica schists and calc-silicate gneisses (calcareous metasediments?) rather than with mafic metavolcanites. These marbles may have a depositional age and environment similar to the HNC marbles. Work in progress (Trønnes et al. in prep.) seeks to clarify whether the carbonate deposits in the Indre Folla and Kongsmoen areas are of HNC affinity.

The $^{87}Sr/^{86}Sr$ ratios of the carbonate fraction may be changed by interaction with the silicate minerals in the marbles and external fluids. Diagenetic and metamorphic processes may cause increasing $^{87}Sr/^{86}Sr$ ratios in marbles interlayered or mixed with alkali feldspars and micas. This tendency is expected for the HNC carbonates associated with continental clastic material. In the SN and KN carbonates which are interlayered and mixed with mafic volcanic or volcanoclastic material, isotope exchange with the silicate fraction and the wall rocks will lower the $^{87}Sr/^{86}Sr$ ratios of the carbonate fraction. This tendency is observed in Fig. 1. In particular, a sample from the Hølonda carbonate–andesite breccia has the lowest $^{87}Sr/^{86}Sr$-ratio (0.7074) of all the KN samples in Fig. 1.

Depositional ages and environments

The global time variations in Sr- and C-isotope ratios in seawater and marine carbonates have been summarised by Faure (1986) and Veizer & Hoefs (1976), respectively. New data for the Proterozoic–Phanerozoic transition is presented in Derry et al. (1992) and Kaufmann et al. (1993).
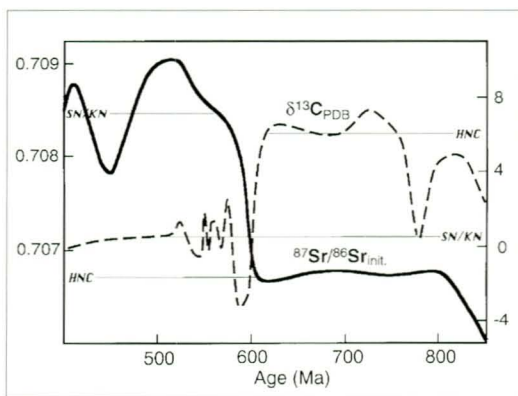

Fig. 2. Global time variations in Sr- and C-isotope ratios in seawater and marine carbonates from 850 to 400 Ma. The smooth curves represent best estimate values summarised from Veizer & Hoefs (1976), Faure (1986), Derry et al. (1992) and Kaufmann et al. (1993). The isotopic composition of the carbonates from the HNC, SN and KN least affected (or unaffected) by post-depositional processes are shown by horizontal, thin lines.

Fig. 2 is a simplified diagram based on these compilations.

A comparison of the Sr- and C-isotope ratios in the least altered carbonates within the different tectonic and stratigraphic groups of Fig. 1 with the global evolution curves of Fig. 2 results in estimated depositional ages of 600–750 Ma for the non-ophiolitic marbles of the HNC. The least altered SN- and KN-marbles are isotopically overlapping and intersect the seawater evolution curve for Sr at 470 and 560 Ma. The independent age constraints on these nappe units (Roberts et al. 1984, Dallmeyer & Gee 1986, Mørk et al. 1988, Pedersen et al. 1992) establish the depositional ages as Ordovician and Vendian or Early Cambrian for the KN- and SN-marbles, respectively.

The overlapping isotopic compositions of the Seve and Köli marbles renders such data useless for correlation and discrimination between Upper Allochthon marbles in the central Norwegian Caledonides. However, the Sr-C-isotope composition is potentially a useful complement to geological field relations for the discrimination between late Proterozoic and Ordovician marbles within the Uppermost Allochthon in Nordland and Troms.

The environments of the Late Proterozoic HNC carbonates differ markedly from those of the Ordovician (KN) and the Vendian or Early Cambrian (SN) marbles. Whereas the Proterozoic carbonates are interlayered with thick epiclastic sedimentary units, the younger carbonates were almost invariably deposited directly on top of mafic lavas or pyroclastics. The SN carbonates were probably deposited along the early passive margin of Baltica (Andreasson & Gee 1989). Palaeomagnetic reconstructions of the movement of Baltica during Vendian and Cambrian times (Torsvik et al. 1992) indicate that the SN carbonates were deposited at latitudes of about 30°S. Based on faunal evolution, the deposition of the KN ophiolite-related carbonates may have occurred on the Laurentian side of the Iapetus Ocean before, during and after obduction of the ophiolites (Pedersen et al. 1992), although other data favour a relationship to Baltica (Sturt & Roberts 1991, Bjørlykke et al. 1993). In the Early to Mid Ordovician the Iapetus-facing parts of Baltica and Laurentia were located at latitudes of about 40°S and 10°S, respectively (Torsvik et al. 1992).

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