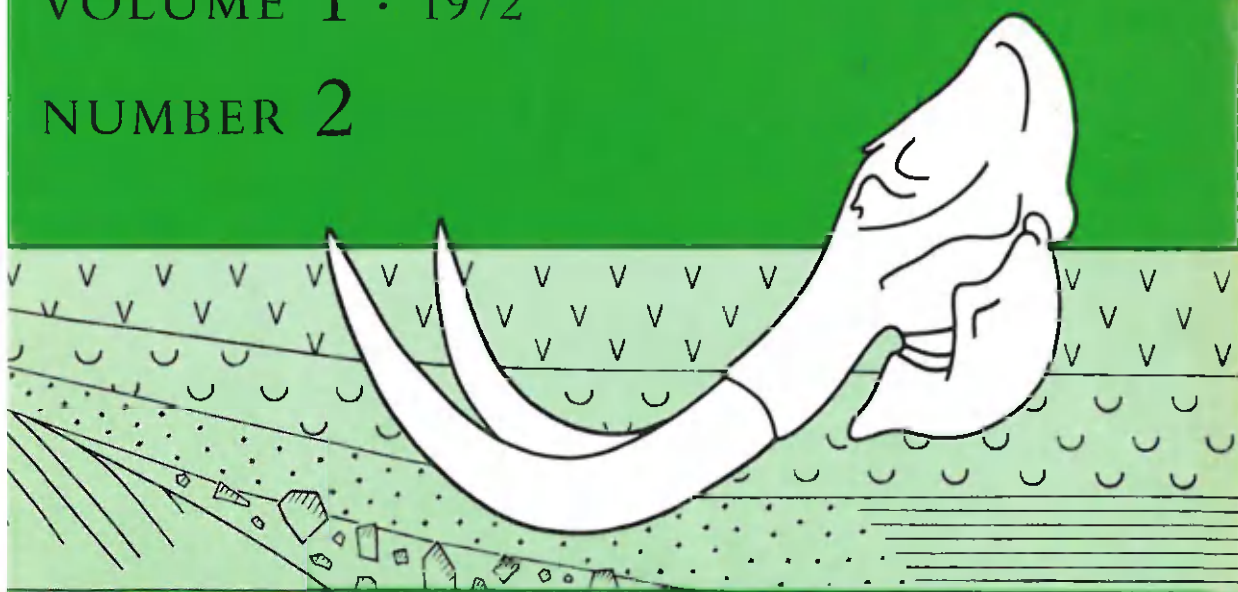# BOREAS

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*Radiocarbon dating of marine shells, including
a discussion of apparent age of Recent shells
from Norway*

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Radiocarbon dating of marine shells, including a discussion of apparent age of Recent shells from Norway

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General problems in determining and interpreting shell C^{14} dates are discussed: calculation methods, factors influencing primary activity (apparent age), and determination of contamination. It is concluded that shell dates are reliable when handled carefully. Measurements on ten shells, collected between 1898 and 1923 on the Norwegian coast, gave apparent ages from 340 ± 75 to 550 ± 80 years, indicating that apparent age is not a significant problem in dating of Norwegian shells.

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C^{14}-dating of marine shells is one of the most important methods for correlating Late Quarternary marine and continental strata. For example, the deglaciation chronology of coastal areas in Scandinavia is to a large extent based on shell datings.

The method is, however, often criticised (Shotton 1967), and several scientists feel the method to be so unreliable that they do not have shells dated. Criticism is often based on a few datings which have yielded obviously erroneous results. A more complete discussion of the method and its sources of error therefore seems necessary.

In the first chapter, calculation methods will be discussed, and the parameters used presented.

Three assumptions are made in the dating of fossils by the C^{14} method:

(1) That the half-life of C^{14} is known.

(2) That the C^{14} activity in organisms at time of death (primary activity) is known.

(3) That exchange of C between the fossils and their environment has not occurred after the organisms' death.

The half-life is discussed by Olsson (1968) and will not be treated in this article. The assumptions on primary activity (2) and on carbon exchange after death (3) are discussed in separate sections.

Measurements of primary activity of recent shells from the Norwegian coast will be presented in the last chapter.

Calculating C^{14} age for marine shells

The calculation and publishing of C^{14} ages for marine shells is carried out somewhat differently at different laboratories (Mangerud 1970). As this has given rise to misunderstandings (Tauber 1970), the various processes of determination will be discussed briefly. Parameters used in the following chapters will also be shown.

Method 1. – The normal procedure for calculating C^{14} age for terrestrial plants, etc., has been published by Callow et al. (1965) and Polach (1969) and can be presented, somewhat simplified, as follows. First the activity of the sample is expressed as per mil of the standard:

$$\delta C^{14} = \frac{A_{sample} - 0.95\ A_{oxal}}{0.95\ A_{oxal}} \cdot 1000 \tag{1}$$

A_{sample} = The measured activity in the sample corrected for natural background.
A_{oxal} = Activity in 1950 of NBS oxalic acid, corrected for background and isotope fractionation (Editorial statement in *Radiocarbon*, 3). 0.95 A_{oxal} is assumed to be equal to the activity of terrestrial plants (wood) of 1950 if the latter were not influenced by industrial or atomic bomb effects.

Variation in the isotopic composition of samples, caused by fractionation (p. 146), is corrected by normalizing to $\delta C^{13} = -25\ ^0/_{00}$ PDB, which is the average value for terrestrial plants (Table 1):

$$\Delta = \delta C^{14} - 2\,(\delta C^{13} + 25)\,(1 + \frac{\delta C^{14}}{1000}) \tag{2}$$

This Δ-value is the usual manner of noting C^{14}-activity, and is used throughout this article.

Using the half-life 5570 years, the C^{14} age (T) is obtained from:

$$T = 8033\ \log_e \frac{1}{1 + \dfrac{\Delta}{1000}} \tag{3}$$

For material derived from terrestrial plants this formula gives the C^{14} age directly. Living plants would thus have nil age if they were not influenced by carbon from fossil fuels and/or atomic bomb testing (p. 155). On the

other hand, present-day hard fresh water, sea water, marine animals, etc., under the same conditions, would have age variations from zero to several thousand years. This is called the apparent age of the sample. More precisely, apparent age of shells is defined as the C^{14} age relative to time of death.

When determining the age of fossil shells according to equation (3), the apparent age must be subtracted to obtain the true C^{14} age $(T_{corr.app})$:

$$T_{corr.app} = T - T_{app} \tag{4}$$

This is usually done by laboratories, but not always. To avoid misunderstandings it is important to state which of the two dates is being used. In my opinion $T_{corr.app}$ should be reported as the age of the sample from dating laboratories. The value of T should, however, be given also, because this is determined only according to standards, and therefore in reality is a measure of the C^{14} activity in the sample.

Method 2. – Another method of shell age determination uses the activity in recent shells (A_{recent}) from the same area as the standard instead of oxalic acid $(0.95\ A_{oxal})$. The activity of the standard and the fossil is then corrected for isotopic fractionation to the same δC^{13} value. This can be $-25\ ^o/_{oo}$ PDB or, more logically, the average for marine shells $0\ ^o/_{oo}$ PDB. In some areas the activity in recent shells is, when corrected to $\delta C^{13}=0$, rather close to the activity in oxalic acid, so that:

$$A_{recent} = 0.95\ A_{oxal} \tag{5}$$

Equation (5) indicates that the isotopic fractionation enrichment of C^{14} in shells (p. 147) relative to terrestrial plants happens to be the same as the decrease of activity which gives apparent age (p. 155). This is used at several laboratories (Radiocarbon Measurements: Comprehensive Index, 1950–1965) including Trondheim. Thus δC^{14} is determined by equation (1) and corrected for fractionation from the normal for marine shells $(\delta C^{13}=0\ ^o/_{oo})$:

$$\Delta_{shell} = \delta C^{14} - 2\ \delta C^{13} \left(1 + \frac{\delta C^{14}}{1000}\right) \tag{6}$$

True age of the shells is obtained directly from the formula

$$T_{shell} = 8033\ \log_e \frac{1}{1 + \dfrac{\Delta_{shell}}{1000}} \tag{7}$$

The correction for apparent age included in this expression is found by setting $T_{corr.\ app} = T_{shell}$. Equations (3), (4), and (7) then give:

$$T_{shell} = T - T_{app} \tag{8}$$

$$T_{app} = T - T_{shell} \tag{9}$$

$$T_{app} = 8033 \left(\log_e \frac{1000}{1000 + \delta C^{14} - 2(\delta C^{13} + 25)\left(1 + \frac{\delta C^{14}}{1000}\right)} \right.$$

$$\left. - \log_e \frac{1000}{1000 + \delta C^{14} - 2\delta C^{13}\left(1 + \frac{\delta C^{14}}{1000}\right)} \right) \tag{10}$$

$$T_{app} = 8033 \log_e \frac{500 - \delta C^{13}}{475 - \delta C^{13}} \tag{11}$$

For $\delta C^{13} = 0$ $^0/_{00}$ this gives $T_{app} = 412$ years
for $\delta C^{13} = -5$ $^0/_{00}$ $T_{app} = 417$ years
and for $\delta C^{13} = +5$ $^0/_{00}$ $T_{app} = 407$ years

This method, therefore, has a 'built-in correction' for the apparent age of ca. 410 years. As will be discussed later, the measuring of 10 recent shells from the Norwegian coast gives an average apparent age of 450 years. Assuming that this value is correct, shell dates from Trondheim are only 40 years too high.

Discussion. – Methods used for C^{14} age determination are of little importance so long as the results are the same. I feel, however, that using equations (1) to (4) has some advantages. That isotopic fractionation and carbon circulation in some areas neutralize each other, as seen in equation (5), is a coincidence. However, this does not apply to marine plants or to marine shells in many areas. Determination according to equation (7) presupposes, therefore, a series of different standards for recent activities (A_{recent}), which can easily make the results non-comparable. Corrections from new research results for recent activities can be many, and C^{14} dates will soon be indistinguishable because these corrections will change the standard. Also in areas where equation (5) is valid, it is valid only because wood was chosen at random and for practical reasons to be the standard. Between atmosphere and terrestrial plants there occurs a depletion of C^{14} by fractionation during photosynthesis, while there is an enrichment between the atmosphere and the ocean (Table 1). It is the addition of the two processes which in some areas makes equation (5) correct, but this is a purely mathematic addition to a process, from terrestrial plants to shells, which is of no importance in nature.

To avoid misunderstandings, I suggest that C^{14} laboratories publish their methods of shell age determination. Further, that the method in equations (1) to (4) be made the standard.

Factors influencing C^{14} activity in living shells

Isotope fractionation

There are three naturally occurring carbon isotopes: C^{12}, C^{13} and C^{14}. C^{12} yields 98.9 $^0/_0$, while C^{13} yields 1.1 $^0/_0$ and C^{14} only 1.18×10^{-10} $^0/_0$ of the

Table 1. Mean values of δC^{13}, relative to the PDB – standard, for some compounds in nature. References in the text

Atmospheric CO	$- 7 \,^0/_{00}$
Terrestrial plants	$-25 \,^0/_{00}$
Oceanic HCO_3^-	$- 2 \,^0/_{00}$
Marine carbonates (incl. shells)	$0 \,^0/_{00}$
Marine invertebrates	$-15 \,^0/_{00}$
Marine plants	$-13 \,^0/_{00}$

total (Olsson 1968). C^{12} and C^{13} are stable isotopes, while C^{14} disintegrates with a half-life of 5570 years. In several chemical reactions in nature there occurs a fractionation which changes the ratio between the three isotopes. This clearly has great importance for C^{14} datings, because an enrichment of C^{14} will give higher activity and, therefore, too young an age. Both theoretical and experimental results (Craig 1954) indicate a close relationship between fractionation of C^{13} and C^{14}. Carbon 14 enrichment is double the enrichment of C^{13}. This is particularly important for datings as C^{13} is stable, and the content will not change with time, while the C^{14} content will begin to diminish as soon as an organism dies. The C^{13} content in fossils can be measured, and from this fractionation of C^{14} can be corrected (equation (2)).

The C^{13}/C^{12} relationship is studied in connection with different problems. The C^{13} content is then usually given

$$\delta C^{13} = \frac{C^{13}/C^{12}{}_{sample} - C^{13}/C^{12}{}_{standard}}{C^{13}/C^{12}{}_{standard}} \cdot 1000 \,^0/_{00} \tag{12}$$

In geological literature the PDB standard is usually used (Craig 1957a). It is also used in this work and in the references.

δC^{13} values are measured or compiled, for example by Craig (1953, 1957b), Degens (1967), Olsson (1968), Polach (1969) and Mangerud (1970). Average values for some relationships are given in Table 1.

Table 1 indicates fractionation from atmospheric carbon dioxide to the bicarbonate in the ocean and in chemical/biochemical precipitated carbonate. During the transfer of CO_2 (gas) from the air to CO_2 (dissolved) in water, there occurs no (Deuser & Degens 1967) or little (Wendt 1968, Emrich et al. 1970) fractionation, but a larger fractionation occurs with the reaction

$$CO_2 \text{ (dissolved)} + H_2O \rightleftharpoons H^+ + HCO_3^-$$

Variation in marine shell fractionation. – The isotopic composition in shells is for the most part determined by the isotopic composition in the water where molluscs live (Keith et al. 1964). This is clearly seen in the investigations of Mook & Vogel (1967) and Mook (1971), which show that in swiftly moving brackish water estuaries, δC^{13} in shells varies closely with the mechanical mixture of fresh and salt water. There is almost no variation in carbon isotope composition in the open ocean. The variation of δC^{13} in true marine shells is therefore also small. Keith & Weber (1964) have studied

δC^{13} in marine limestones and fossils from all geological periods from the Precambrian to the Quaternary, and find that the isotopic composition of the ocean has been almost constant.

Laboratory investigations (Deuser & Degens 1967; Emrich et al. 1970) show that fractionation varies with temperature. The variations are so small, however, that they are usually overshadowed by other variations under natural conditions.

Keith et al. (1964) find an average variation of 0.73 $^o/_{00}$ (max. 1.71 $^o/_{00}$) in δC^{13} between inner and outer parts of marine shells and an average within community variation from three localities of 2.45 $^o/_{00}$. This is assumed to be due to variation in the food supply.

Lloyd (1964) finds variation in δC^{13} from -3.5 $^o/_{00}$ to 2.4 $^o/_{00}$ in shells from Florida Bay. He shows that δC^{13} diminishes from open ocean to localities with a large supply of organic material from mangrove and marine grass. He supposes that the reason is local production of CO_2 with low δC^{13} in the ocean, through oxidation of this organic detritus. He has not, however, measured δC^{13} in the water and variations due to the intake of the organic material through the food cannot be excluded.

Isotopic fractionation of C^{13}, and thereby C^{14}, in relation to C^{12} is almost constant between atmospheric carbon dioxide, bicarbonate in the ocean, and carbonate in shells. There are, however, some small variations in the fractionation processes between water and shells. By measuring δC^{13} one can in all instances of dating correct for errors in the fractionation process. If δC^{13} is not measured, the discussed variations from the average ($\delta C^{13} = 0$ $^o/_{00}$) are so small that they are often of little importance. A deviation of 1 $^o/_{00}$ will give an error of a little over 16 years, and to obtain an error of 100 years one needs a deviation of 6 $^o/_{00}$, which rarely happens in true marine shells.

Reservoirs and circulation of C^{14}

Bicarbonate in the ocean is enriched in C^{14} by isotopic fractionation during transfer from atmospheric CO_2. At isotopic equilibrium, the ocean should have about 10 $^o/_{00}$ higher C^{14} activity than the atmosphere, and about 46 $^o/_{00}$ higher activity than the C^{14} standard ($0.95A_{oxal}$). It appears, however, that surface waters often have an activity near the standard (equation (5)), while deeper waters can have up to 250 $^o/_{00}$ lower activity. It follows that there is no C^{14} isotopic equilibrium between the ocean and the atmosphere or between different ocean bodies. Instead a 'steady state situation' is thought to exist. This means that the quantity of C^{14} transferred from the atmosphere to the ocean during a certain time period is equal to the sum of C^{14} transferred in the opposite direction and C^{14} undergoing radioactive disintegration in the ocean.

The reason for the lower and varying C^{14} activities in the ocean, which give apparent age, is the exchange of carbon between different reservoirs

Table 2. Carbon content of natural exchange reservoirs, according to Skirrow (1965)

| | Carbon content g/cm^2 | |
	of earth's surface	% of total
Atmosphere	0.125	1.5
Humus	0.19	2.3
Biosphere, land	0.06	0.7
Biosphere, marine	0.002	0.02
Oceanic dissolved carbon, organic	0.533	6.4
Oceanic inorganic carbon, above thermocline	0.20	2.4
Oceanic inorganic carbon, below thermocline	7.25	86.7
Total	8.36	100.02

Table 3. Carbon content of reservoirs with very late exchange with the reservoirs in Table 2. Compiled from data in Skirrow (1965)

	Carbon content g/cm^2 of earth surface
Sediments, organic carbon	633
Carbonates	2340
Crystalline metasediments	1960
Eruptives	600
Sum = Total carbon of rocks and sediments	5533

in nature (Tables 2 and 3, Fig. 1), and the internal carbon circulation in the ocean.

Most writers treat C^{14} exchange from a geophysical viewpoint, using box models and mathematical treatment. This will not be done here, but results from the above methods will be applied to obtain an understanding of C^{14} datings. The parameter most often determined is 'residence time'. This indicates the average time the C^{14} atom remains in a reservoir before it is transferred to another reservoir (Craig 1957b). Residence time is not directly applicable in calculation of C^{14} dates. It is applicable to the understanding of apparent age which is used in calculating C^{14} dates.

A review of C^{14} exchange between different reservoirs based on the natural distribution of C^{14} is given by Craig (1957b). Later determinations of C^{14} exchange in nature are based on measurement of C^{14} produced by nuclear explosions (Münnich & Roether 1967; Bien & Suess 1967; Nydal 1968; Nydal & Lövseth 1970; Walton et al. 1970; Rafter & O'Brien 1970).

The atmosphere. – C^{14} is produced in the upper layers of the atmosphere by cosmic ray bombardment (Fig. 1). This carbon is oxidized immediately to $C^{14}O_2$, and enters atmospheric circulation. The atmosphere is completely mixed within a few years (Nydal 1968; Nydal & Lövseth 1970; Rafter & O'Brien 1970). From a dating viewpoint the mixing can be regarded as immediate. The C^{14} atmospheric variation (Olsson 1970) in the past millenia

COSMIC RAYS

ATMO-SPHERE

STRATOSPHERE	Production of C^{14}
	Oxidiced to $C^{14}O_2$
TROPOSPHERE	Completely intermixed within a couple of years

Exchange at atmosphere-ocean interface

Assimilation, etc.

Respiration, etc.

OCEAN

Several masses of water, with late exchange of carbon

Organisms

Currents

A

B

Transport by rivers etc.

C ←Glacial melt-water

D

BIOSPHERE LAND

HYDROSPHERE (lakes, ice etc.) at CONTINENTS

Sedimentation

Solution

Food

Sedimentation

Weathering

SEDIMENTS AND ROCKS

Fig. 1. Schematic diagram of carbon circulation in nature, with particular emphasis on those processes which have a bearing on the C^{14} content in marine shells. A-B-C-D are shells which absorb carbon from different reservoirs.

has therefore been contemperaneously worldwide, and datings of materials which contain atmospheric carbon are always directly comparable.

C^{14} exchange between the atmosphere and the ocean. – Carbon exchange between the atmosphere and the ocean plays a dominant role in ocean C^{14} activity because this exchange is much quicker than the exchange between the ocean and other reservoirs. For this exchange process the reader is referred to Quinn & Otto (1971). Here I will mention only that the exchange seems to be influenced by an enzyme (Libby 1970) and can therefore vary both in space and time.

There are different estimates of atmospheric C^{14} residence time (Nydal 1968, Rafter & O'Brien 1970, with following discussion), but most estimates give a residence time of 5–15 years in the troposphere before ocean transfer

of the C^{14} atom. The exact value is not important from a dating view point, but two points are significant for an understanding of the problem:

(1) The ocean carbon reservoir is more than 60 times that of the atmosphere (Table 2). If the ocean were completely mixed, the residence time in the ocean, before the C^{14} atom was transferred to the atmosphere, would be ca. 60 times as long as the residence time in the atmosphere. Using a value of 10 years for the atmosphere, the residence time for C^{14} in the ocean would be ca. 600 years. This is the main reason for the low activity in the ocean giving apparent age. This would not be a problem if the ocean mixed quickly, as the atmosphere does, for the apparent age would then be the same for all ocean water and could be determined easily.

(2) The ocean consists of many different water masses with occasional slow internal mixing. For example, from the equator to about 40–50 ° North and South, a relatively well-mixed, stable surface layer above the thermocline is quickly exchanged with the atmosphere. The deeper layer has a very slow exchange, partially exchanging with the mixed layer, and partially exchanging directly with the atmosphere. This increases the average apparent age for the ocean.

Other reservoirs and their exchange with the ocean. – Carbon from the continents is transported to the ocean as particles and in solution (Fig. 1). This includes carbon from the biosphere, as well as radioactively dead carbon from weathered rocks, etc. This carbon is soon distributed in the open ocean. In restricted areas with a large fresh water supply (estuaries, lagoons, etc.) a problem exists similar to the hard water effect in lakes (Broecker & Olson 1961). Shells from such areas (Shell B, Fig. 1) are therefore not suited for C^{14} dating.

Many of the shell datings performed in Scandinavia are associated with deglaciation. One theoretical problem involved in these datings is the possibility of glacial meltwater containing so much old carbon that it influences the dating (shell C, Fig. 1). Scholander et al. (1962) gives for Storbreen in Norway a content of approximately 0.04 g C per ton of ice, and for Greenland icebergs approx. 0.01 g per ton, while Langway et al. (1965) gives 0.05–0.15 g per ton for North Greenland ice. If the highest figure is used it will correspond to approx. 0.15 mg/l, while sea water contains 28 mg/l (Goldberg 1965). If we make brackish water with a mixture of equal parts of ice and ocean water, approximately 0.5% of the carbon will come from the ice. This is negligible in dating (Olsson 1968). It follows that in sea water with marine shells the influence of old carbon from ice is of no importance.

Carbon is removed from the ocean by sedimentation of dead organisms and other carbonate sediments (Fig. 1). A lesser quantity is added when sediments dissolve on the bottom. This possibly influences C^{14} activity on the ocean floor.

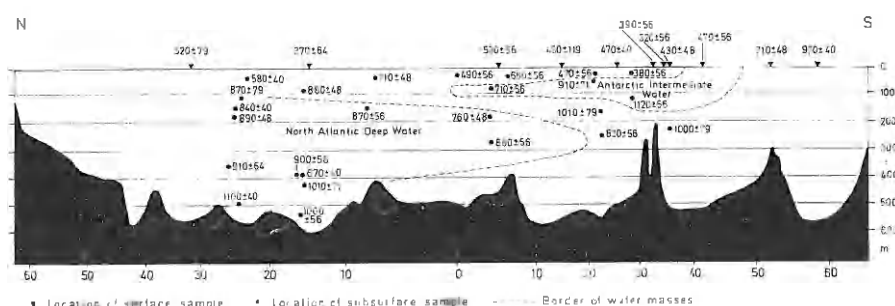The carbon content in rock and sediment (Table 3) is enormous in com-

Fig. 2. Apparent age of samples of sea water from the East Atlantic Ocean. The profile is approximately parallel with the Mid-Atlantic ridge. Profile, designating samples and water mass boundaries according to Broecker et al. (1960). Apparent age of the samples determined by the present author according to equation (3) on the basis of Δ-values for the samples in Broecker & Olsen (1961), corrected for real age.

parison to carbon in other reservoirs (Table 2). A large portion of this carbon has at one time been in the ocean, but the exchange is so slow that it is of little importance for C^{14} activity in the ocean relative to the exchange between the ocean and the atmosphere. Nevertheless, it contributes to the decrease of C^{14} activity in the ocean relative to the atmosphere, as the direct exchange between atmosphere and rock is even slower.

Both the direct exchange between sediment and ocean (Olausson 1969) and the exchange between sediment and ocean via continents, will change during Glacial Periods. These processes therefore contribute slightly to the long-term variations in the ocean, and thereby atmospheric, C^{14} activity.

Internal circulation of C^{14} in the ocean. – There are two specific groups of processes influencing C^{14} distribution in the ocean. Biological production, with associated sedimentation and breakdown of these materials, and circulation of water masses in the ocean.

The main organic production occurs in surface layers. Most organisms are so small and have such low specific weight that at death they do not sink by themselves but follow the same circulation pattern as inorganic carbon in the same water masses. Larger particles of organic material, for example foraminifera, will sink and therefore contribute to a different circulation pattern. According to Olausson (1967) the sedimentation time for carbonate shells is so short that the solution of shells during descent is small and occurs essentially on the bottom. The fact that $CaCO_3$ does not accumulate on the ocean floor under 4000–5000 meters, however, indicates that solution occurs during sedimentation, at least at great depths. According to Lal & Venkatavaradan (1970) these biological and chemical processes are of great importance to carbon circulation in the ocean. This will contribute to an averaging out of the C^{14} activity between the surface and the depths.

The dominant factor in ocean C^{14} activity seems to be ocean circulation. Atmospheric C^{14} is transferred only at the ocean-atmosphere interface. There-

fore, in water masses which do not have contact with the atmosphere, radioactive decay will give a lower C^{14} activity, depending on how long the water has been at depth.

A thorough investigation of the C^{14} activity in the Atlantic is given by Broecker et al. (1960). They compare the activity in the water with water masses and circulation as known from physical oceanography, and find a close correlation (Fig. 2). Between ca. 40°N and 40°S there is a stable surface layer and apparent age in this layer has little variation (320–520 years). In the north, cold water sinks and streams southwards as North Atlantic Deep Water with an apparent age of 800–900 years, while the deepest water has an apparent age of 1000–1100 years. There is also a sinking in the southern region, creating deep water which evidently remains for long periods at depth, since the apparent age reaches 1120 years. In the Pacific Ocean (Bien et al. 1963) the deep water has even higher apparent age, often 2000-2300 years. In areas where old bottom water streams to the surface, the surface will also give high apparent age, as in the southernmost part of Fig. 2, where two samples give 710 and 970 years. Also in other parts of the Antarctic apparent age of 800–1300 years is usually found in surface waters. Rafter & O'Brien (1970) report values down to $\Delta = -269\ ^o/_{oo}$, which corresponds to an apparent age of 2520 years.

As has been seen, mixing of the different ocean water masses is very slow. In contrast to the atmosphere which mixes quickly and has the same C^{14} activities throughout, the ocean consists of many water masses with widely different C^{14} activities (apparent age). This is what creates the greatest problem in C^{14} dating of marine fossils.

When dating fossils whose carbon is derived from deep water, determination of apparent age is especially important. Such datings are rare, however. Most datings are done on fossils which obtained their carbon from surface waters. In ocean areas with a stable and well mixed surface layer there is relatively little variation in apparent age. This is so almost everywhere between ca. 40°N and 40°S (Broecker & Olson 1961) while in higher latitudes there is much more variation, caused by upwelling of deep water in certain areas. A summary of older investigations of C^{14} activity in the ocean is given by Skirrow (1965). For later investigations the reader is referred to Broecker (1966), Münnich & Roether (1967), Bien & Suess (1967) and Rafter & O'Brien (1970).

The ocean circulation change with time. As pointed out by several authors (Skirrow 1965, Olausson & Jonasson 1969, Olsson edit. 1970), it is probable that some changes have been connected with glaciations. This can have given a quite different geography and depth distribution of apparent age than what is found today. This would have altered the atmospheric exchange, and thereby the activity in the atmosphere.

Sources of carbon in shells. – Shell formation is discussed from a zoological viewpoint by Wilbur (1960, 1964), and the chemical composition summarized

by Wolf et al. (1967). There are, however, few investigations with the direct purpose of solving problems connected with C^{14} dating.

There are two external sources of carbon in shells: food and the ocean water. Carbonate can be formed directly from the ocean bicarbonate, or more probably from the $CO_2 - HCO_3 -$ pool inside the shell (Wilbur 1964), where CO_2 is mainly a result of metabolic processes. The relationship between the two sources is not clear. Most bivalve molluscs are deposit or suspension feeders, while the gastropodes show great variation in the food intake (Owen 1966). Organic food is depleted in C^{13} and C^{14} by isotope fractionation (Table 1), and if there is no exchange with the ocean water, this will also influence the isotope composition in the shell (p. 148). Most of the food will, however, have a negligible age, and the isotope composition will then be determined only by the laws of fractionation. Therefore from a dating viewpoint decrease of C^{13} and C^{14} content due to organic food is of less interest, because it can be corrected by measuring δC^{13}.

Significant problems occur if the shells absorb old carbon from the sediments (shell D, Fig. 1). Apart from carbonate there is seldom old organic material near the sedimentation surface, because with good oxygen supply such organic material will break down, or, if sedimentation is rapid, will gradually be buried. Old carbonate will be found on the surface, for example, in areas with loose chalk, where the bottom near the coast is covered with a chalk detritus. Here, burrowing molluscs can have a local environment with lower C^{14} activity than the surrounding ocean. Small particles of $CaCO_3$ can also be taken in with the food, even if these are normally ejected (Owen 1966). C^{13} in the carbonate is close to isotopic equilibrium with the ocean water, and intake of old carbonate will therefore not be seen in δC^{13}. The influence of old carbonate is hardly a problem in the hard rock types on the Norwegian coast, but in calcareous rocks, rock boring species like *Hiatella (Saxicava)* should be avoided. In areas with loose limestone rock types the problem can be investigated by measuring the C^{14} activity in recent shells and the surrounding ocean.

Very few investigations have compared C^{14} activity in recent shells with the activity in the surrounding ocean water. Broecker & Olson (1961) refer to some measurements which give about the same values. However, for the stable isotopes (C^{13}/C^{12}) there are numerous measurements which show that there is almost isotopic equilibrium between the ocean and shells. From a dating viewpoint it is therefore not so important that all the processes for the shells carbon intake are not known. In most instances the C^{14} activity in shells will be close to the activity of the water where the shells live (Shell A, Fig. 1).

Variation in C^{14} activity in time. – It has been mentioned previously that the processes which determine ocean C^{14} activity can vary with time. This also applies to processes which are not discussed, particularly the variation of C^{14} production in the atmosphere. Atmospheric C^{14} variation in time is

investigated by dating objects with a known historic or geologic age. The best results are from dendrochronological datings. The trend in variations to ca. 6000 C^{14} years B.P. (corresponding to ca. 7000 calender years) is now established (Olsson edit. 1970) without a complete understanding of the factors causing the variations.

For marine shells there is at present no method to compare directly C^{14} age and calendar age. This would have to be investigated by comparing C^{14} age of shells and C^{14} age of terrestrial plants of the same age. Again the problem exists that the variations in the ocean because of circulation are not necessarily parallel in all areas.

Industrial effect and atomic bomb effect. – The use of fossil fuel and atomic bomb testing has influenced C^{14} activity in the ocean to the degree that it is very difficult to find the recent natural activity with the desired accuracy.

The rather large increase of C^{14} as a result of bomb testing occurred in 1962. In this connection, however, the increase in the late 1950's are also important.

Use of fossil fuel (coal, oil, natural gas) supplies the atmosphere with great quantities of dead carbon (Olsson 1968). This is known as 'industrial effect' or 'Suess effect', and lowers the C^{14} activity in all reservoirs in exchange with the atmosphere. Broecker et al. (1960) calculated that the activity in the ocean surface has decreased 15 $^{0}/_{00}$ up to 1955 because of this effect, while Broecker & Olson (1961) found that the decrease is less than 10 $^{0}/_{00}$ between 1880 and 1955. It is clear that this effect is of little importance at the beginning of our century, and is negligible before the turn of the century.

In the deep water the influence of fossil fuel and bomb testing is relatively small. Recent natural activity can therefore still be measured directly in the deep water. In surface layers the influence is so great and so uneven that measuring for this purpose is not possible. Some measurements of the water's activity were performed before 1960, and these can give some major features. For shells the situation is somewhat different in that there are museum materials collected a long time ago, without any influence from bomb testing, and with little or no influence from industrial effect. It is shells of this type which are used in the present investigation.

Conclusions

Isotopic fractionation is so well known that it does not create any problem in C^{14} dating of shells.

Sea water has an apparent age due to:

(a) The combination of late exchange through the atmosphere-ocean interface, with the oceanic carbon reservoir being 60 times that of the atmosphere. This is the most important factor causing apparent age of seawater.

(b) Carbon circulation in the ocean being determined mainly by the circulation of the water, this being very slow in deep ocean areas. Various water masses have, therefore,

varying apparent age (from 200–300 years to 2500 years) depending on how long the water has been at depth.

(c) Supply of old carbon from the continents and the ocean floor. The significance of this for the ocean is not known, but is probably not great. In restricted areas with a large supply of fresh water this can have large local significance, and shells from such areas are not suitable for C^{14} dating.

Carbon in shells is almost in isotopic equilibrium with the surrounding water, and shells have, therefore, approximately the same apparent age as the sea water. The only problem in addition to the ocean's apparent age would be areas containing old lime detritus (for example chalk) on the bottom.

Carbon exchange after death

Carbon contamination from other sources is always a problem in C^{14} dating. There is no doubt that this is a considerably greater source of error for $CaCO_3$ than for many other materials, because $CaCO_3$ is chemically more active than, for example, wood.

In limestone areas contamination can cause high ages, due to dissolved dead carbon in ground water. In most cases, however, carbon in the groundwater originates from modern carbon in the atmosphere, humus etc., and contamination gives young ages of fossils. In very old fossils, small amounts of modern carbon will affect the dating seriously, and shell datings giving ages above 20,000 years should be treated with scepticism. Regarding effects of contamination, reference is made to Polach & Golson (1966) and Olsson (1968).

There are two main types of contamination. The first is 'mechanical' contamination by particles or by solutions which enter the interstices and can become absorbed. Olsson et al. (1968) show that this is a considerable source of error in foraminifers and other small shell particles. This should not be a major problem if hard, tight molluscs are used.

The other type of contamination is carbon isotope exchange between $CaCO_3$ and the environment. According to Craig (1954) recrystallization (used in the wide sense of the word) by solution and reprecipitation is the only mechanism for such isotopic exchange fast enough at the temperatures found in nature to have any importance for C^{14} dating. The problem can be stated as follows: If it can be proven that recrystallization has not occurred, then isotopic exchange has not occurred. There exists a possibility for exchange if there has been recrystallization, and it would be very possible that an incorrect dating would result. Thus it is necessary to discuss methods used in determining whether recrystallization has occurred or not.

Dating of outer and inner parts of shells. – Recrystallization will probably not occur simultaneously in all parts of the shell. Exchange of carbon during recrystallization probably occurs more extensively in the outer than in the inner part. B. G. Andersen (1968) has obtained for shells dated at ca.

11,000 years 820 ± 280 and 1560 ± 200 years higher age on the inner than the outer fraction (standard deviation (s) for differences calculated by me according to the formula $s = \sqrt{s_1{}^2 + s_2{}^2}$, where s_1 and s_2 are standard deviations for the measurements).

Most laboratories dispose of the outer part of the shells and date only the inner part. This increases the shell date accuracy. Even better, Olsson & Blake (1961) removed the outer part and then separated the remainder into an outer and an inner part. If the deviation between these two parts is small there is an indication, but no proof, that there is little or no contamination.

Measuring of C^{13}/C^{12}. – Shell carbonate is almost in isotopic equilibrium with atmospheric CO_2. Carbon in groundwater will also often have an isotopic composition close to equilibrium, and an exchange of carbon can therefore not be discovered by measuring δC^{13}. If the groundwater has a strong isotopic deviation, e.g. resulting from dissolved humus, this will show up in the δC^{13} of the shell. In that case a lower δC^{13} value (Bathurst 1971), in the direction of the value for fresh water shells (which can be as low as $\delta C^{13} = -15$ $^0/_{00}$ PDB), is obtained. At δC^{13} values under -3 $^0/_{00}$ PDB for marine shells the possibility for contamination must be scrutinized. It is, however, not possible to separate this effect from the influence of fresh or brackish water at the time of primary shell formation. As discussed previously, this is also a considerable source of error. Marine shells with low δC^{13} value must therefore be looked at with scepticism regarding C^{14} dating.

The advantage of using δC^{13} in order to detect contamination is that it is often measured for fractionation corrections, and no further measurements are needed.

Measuring of O^{18}/O^{16}. – Every mechanism which permits change in the isotopic composition of carbon in the carbonate must also permit changes in the isotopic composition of oxygen (Craig 1954). Measuring of O^{18}/O^{16} should, according to Craig, be a better criterion for carbon exchange with the environment than C^{13}/C^{12}. In marine shells the O^{18} content varies greatly with the sea temperature which, therefore, must be known. Also in this instance, the influence of fresh or brackish water on the primary shell formation gives the same effect as recrystallization. O^{18}/O^{16} values will give results but not a clear answer.

Examining mineralogical composition. – Calcium carbonate in shells occurs as high magnesium calcite, low magnesium calcite, and aragonite (Taft 1967, Bathurst 1971). The factors influencing the relationship between the minerals at the time of shell formation are summarized by Wilbur (1964). High magnesium calcite and aragonite are metastable and will in time recrystal-

lize to the stable low magnesium calcite. The processes for these recrystal-
lizations and the factors which influence them are discussed by Bathurst
(1971).

The calcite-aragonite recrystallization process can be used in several ways.
The safest one is finding species which primarily consist of only one mineral,
either aragonite or high magnesium calcite. If fossil shells are found which
consist only of the same metastable mineral, then recrystallization has not
occurred. There are, however, few species which have only aragonite or
high magnesium calcite shells in cold ocean areas.

Similar methods can be used on shells where the relationship between the
minerals is known. The best method would be to use shells in which the
composition varies little with the environment.

Another method utilizes shells primarily composed of low magnesium
calcite which are less subject to recrystallization. In this instance miner-
ological composition cannot be used for determining if recrystallization
occurred.

The mineral content is quickly examined and requires small samples.
This is perhaps the method which is best suited for routine examinations.
However, one must first determine the primary mineralogical composition
of species which are best suited for dating in the different areas.

Visual determination. – Surface/volume ratio is much greater in porous shells
than in hard, tight shells. This allows for greater possibility of carbon ex-
change with the surrounding water during recrystallization.

Many shells have primarily fine surface textures. During dissolution and
reprecipitation these will disappear (Taft 1967) and surfaces will become
smooth. In addition, holes will be present if there has not always been equi-
librium between the shells and the environment. Rönnevik (1971) shows
from one locality that shells with good surface textures and preserved
periostracum are recrystallized less than shells without periostracum and
with weak surface textures.

For C^{14} dating hard, non-porous, thick shells with a fresh surface and
preserved textures should be used. These visual criteria are referred to by
several authors, but must be emphasized here. These criteria are easily
determinable in the field, and they give considerable assurance.

Levels of structures. – There are many fine structures in shells (Wilbur 1964,
Bathurst 1971). Together with the large surface textures discussed above,
the fine structures will also be damaged during recrystallization by dissolu-
tion and reprecipitation. This can be discovered during microscope studies
of the shell structures. This is time consuming and will perhaps not be
possible for routine datings.

These fine structures can be preserved during solid state recrystallization
(Taft 1967), but this type of recrystallization has no importance in the time

period and temperatures (Bathurst 1971) which are relevant for C^{14} datings. Neither does solid state recrystallization offer a possibility for isotope exchanges.

Conclusions. – Inherent problems exist in marine shell dating because of carbon isotope exchange after deposition. Several methods for determining the occurrence of isotopic exchange exist. On the basis of the foregoing discussion the following is suggested:

(1) A thorough selection of shells according to visual criteria.
(2) Removal of outer part of the shell before dating.
(3) Separate dating of the outer and inner part of the remaining shell.
(4) C^{13}/C^{12} ratio determination.

These four points can be met at most laboratories. For further research, measuring mineralogical composition seems to be the method best suited for routine analysis. In this case, basic research in recent materials is necessary.

Dating of recent shells on the Norwegian coast

Samples and methods. – The shells are from the collections at the Zoological Museum at Bergen University. The molluscs were collected alive, and they were possibly kept in alcohol shortly after being collected. Later they were kept in dry storage. The datings were carried out at Trondheim Radiological Dating Laboratory, while the C^{13}/C^{12} was measured at Karolinska Institutet, Stockholm.

Prior to dating the shells were scrubbed with a steel brush, washed in luke-warm water, then rinsed in distilled water. 10–20% of the outer part of the shells was then removed by solution in HCl.

The measured activities were corrected for the radioactive decay between the collection year and 1950. All C^{14} activities and ages which are given refer, therefore, to the year of death and not to 1950.

The shells were collected between 1898 and 1923 (Table 4), and some of them can be slightly influenced by the industrial effect. The shells were larger than 15 g, and had an age of up to 20–30 years. This will reduce the importance of industrial effect, but implies also that the carbonate is somewhat older than indicated by the year of collection. The industrial effect and living age of shells operate in opposite directions, and the error in apparent age would hardly exceed 20 years, and is probably much lower. Therefore, no corrections are used for these errors.

Information about the shells and the measuring results are given in Table 4. The differences in ages are so small (from 340 ± 75 to 550 ± 80) that it is difficult to determine whether the differences are due to measurement precision or due to real differences in shell activities.

Table 4. Dated shells. Latitude and longitude can be ca. 2′ in error. The parameters are calculated from equatic given in the text. Ages given are relative to year of death. To obtain real C^{14} dates, the difference between 1950 a year of collection should be added. No corrections for industrial effect are used.

Lab. No.	Species	Locality	Lat. N	Long. E	Sample depth m	Date of collec- tion	Corrected for radioactive decay between time of collection and 19					
							δC^{13} per mil	δC^{14} per mil	Δ per mil	Appar- ent age $(T=T_{app})$ years	Δ_{shell} per mil	T_{sl} yea
T–951	*Buccinum undatum*	Leikanger, Sognefjord	61°11′	6°48′	20–40	1912	$+0.8$	$+3$	-49 ± 9	400 ± 75	$+2$	–
T–952	*Linia excavata*	Vangsnes, Sognefjord	61°10′	6°39′	300	1920	$+2.1$	-3	-57 ± 9	470 ± 75	-8	
				Between								
T–953	*Chlamys septcmradiatus*	Fjærlands- fjorden, Sogn	61°13′ and 61°22′	6°34′ 6°85′	180–200	2/5/ 1909	$+2.7$	-5	-60 ± 10	500 ± 80	-10	
T–954A	*Cyprina islandica* Outer fraction (50%)	Ideosen, Herdla, Hordaland	60°34′	5°00′	ca. 10	Sept. 1923	$+1.9$	$+5$	-49 ± 9	400 ± 75	$+1$	–
T–954B	Inner fraction (50%) of T–954A	,,	,,	,,	,,	,,	$+2.2$	0	-54 ± 9	450 ± 75	-4	
T–954	Mean of A and B	,,	,,	,,	,,	,,	$+2.1$			430 ± 60		
T–955	*Cyprina islandica*	Sollesnes, Jondal, Hardanger	60°18′	6°17′	20–50	17/7/ 1908	$+2.6$	-5	-60 ± 9	490 ± 75	-10	
T–956	*Tapes pullastra*	Mosterhavn, Hordaland	59°42′	5°24′	15	1918	-0.2	$+5$	-45 ± 11	370 ± 90	$+5$	–
T–957	*Modiolus modiolus*	North Sea, approx.half way between Bergen and Shetland	60°38′	2°35′	110–115	28/6/ 1906	$+1.9$	-1	-54 ± 9	450 ± 75	-4	
T–958	*Mytilus edulis*	Komagfjord, Finmark	70°16′	23°24′	0–10	10/8/ 1922	0.0	-14	-63 ± 9	520 ± 75	-14	
T–959	*Chlamys septemradiatus*	Brevikfjord, Telemark	59°03′	9°42′	100–120	29/11/ 1898	$+0.8$	-15	-66 ± 10	550 ± 80	-16	
T–960	*Modiolus modiolus*	Grønholm- sund, Risør, Aust-Agder	58°44′	9°18′	10	July 1905	$+1.4$	$+12$	-42 ± 9	340 ± 75	$+9$	–
Mean of samples							$+1.5$	-2	-54	450 ± 40	-5	

Water circulation and apparent age in the fjords. – The first problem concerning the Norwegian fjords is whether the water is really sea water or whether it is so brackish that the hard water problem discussed earlier exists. According-ing to Sælen (1967), the salinity in the West Norwegian fjords below 20 metres depth exceeds $30^0/_{00}$ the year round. On the surface the salinity varies from almost fresh water to 34 $^0/_{00}$, depending on the time of year. However, the brackish water layers always seem to be just a few metres deep (Sælen 1967, Gade 1970). As seen from these simple criteria, it is clear that Nor-wegian fjord water, at least below some metres depth, is almot pure sea water. In considering C^{14} fossil dating it is important to keep in mind that
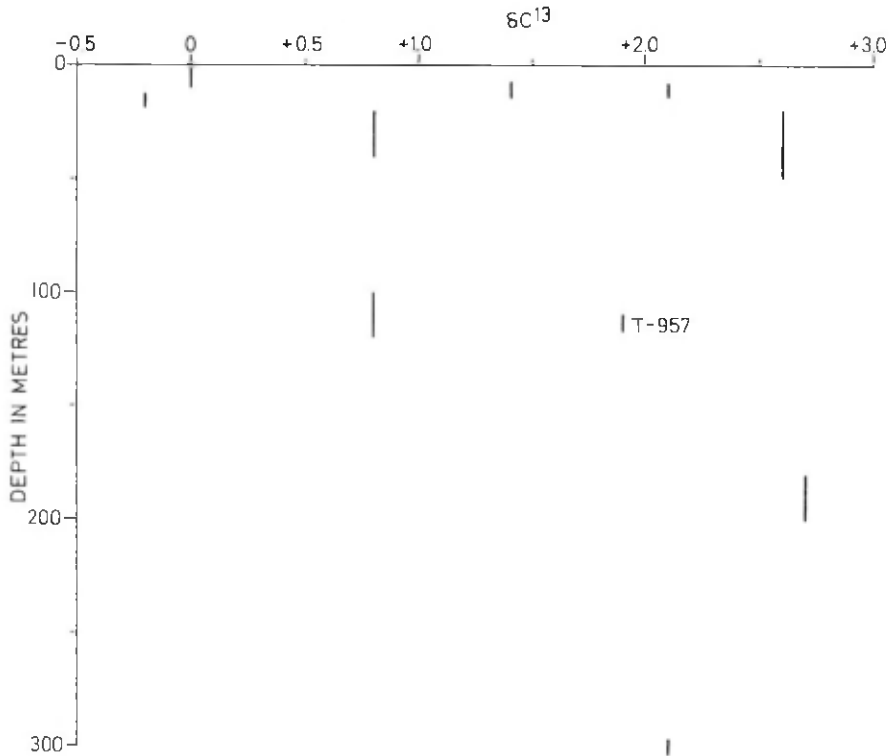
Fig. 3. Relation between δC¹³ and depth for the measured samples from the Norwegian coast (Table 4). T-957 is the North Sea sample.
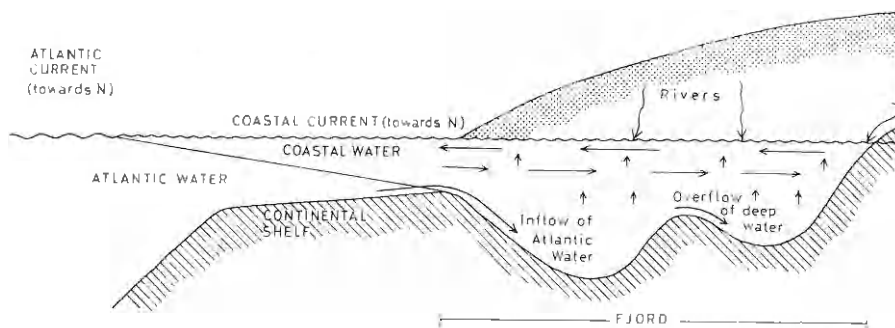

Fig. 4. Schematic cross section showing different water masses and circulation patterns lengthwise through a fjord in West Norway.

dated molluscs almost always have lived at some metres depth where clay sedimentation exists.

δC¹³ for the measured shells varied between -0.2 $^0/_{00}$ and $+2.7$ $^0/_{00}$ (Table 4). According to the results from Keith et al. (1964) and Mook (1971) this indicates clearly that the shells lived in pure sea water, with little or no freshwater influence. Fig. 3, however, suggests that the small variations in
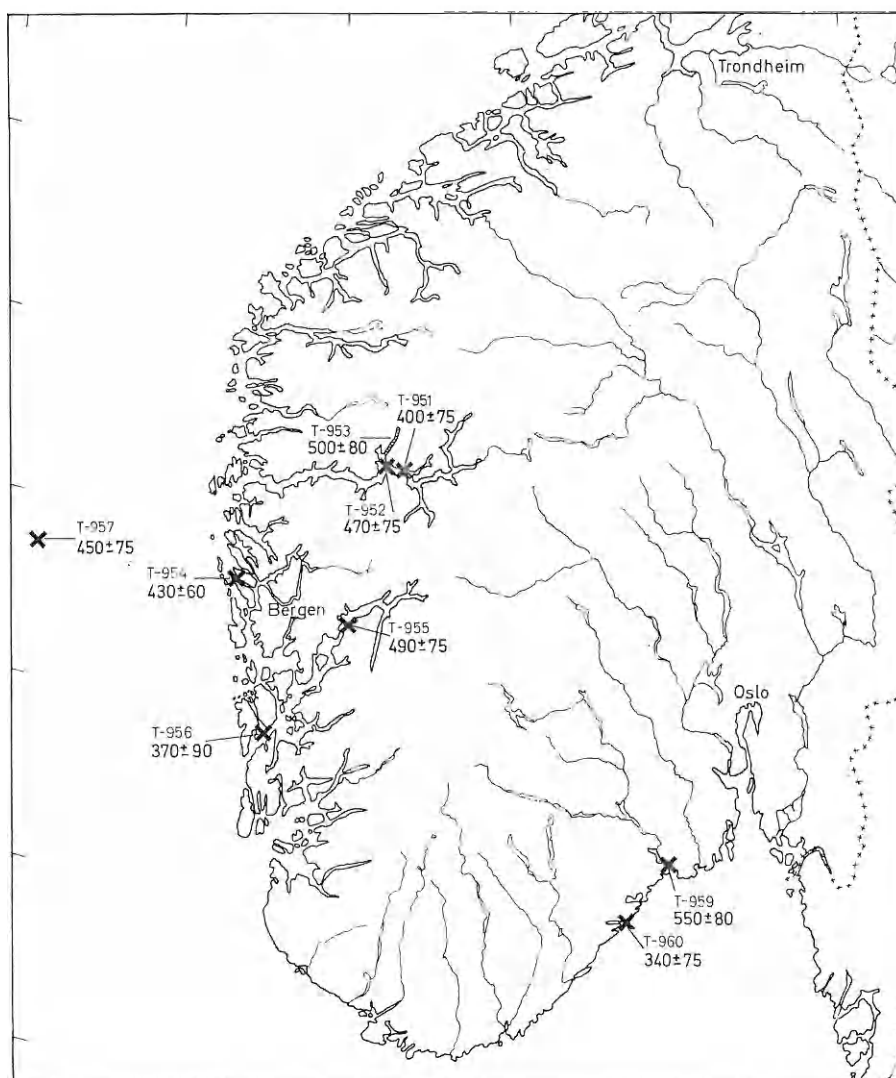
Fig. 5. Localities and apparent ages for samples (Table 4), except T–958 which is from North Norway (Fig. 9).

the δC^{13} values can be due partly to mixing with fresh water in the surface layers.

Circulation in the fjords consists of two main types (Sælen 1967): Circulation in the higher layers and circulation in the deep basins (Fig. 4).

Surface layer circulation is determined to a great extent by the supply of fresh water, but for the problem at hand can be considered continuous and very rapid. Exchange occurs mainly with coastal waters outside fjord mouths (Fig. 4), but also with the deep water in the fjord (Gade 1970).

Renewal of the fjords' deep water usually occurs under the conditions shown in Fig. 4, where coastal water rises so that a wedge of the Atlantic

Fig. 6. Relation between apparent age and depth for all samples (Table 4). T–957 is the sample from the North Sea.
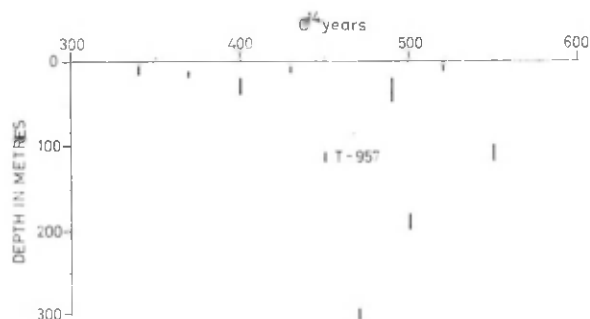
Water (salinity approx. 35 $^0/_{00}$) reaches beyond the sill of the fjord and flows into the basin. The surface fjord water will then be raised. Renewal of deep water is relatively frequent in many fjords. Both in Nordfjord (Sælen 1967) and Oslofjord (Gade 1970) there has been a certain amount of influx of bottom water to the outer basins almost every year, while there are several years between penetration to the basins further in. Some Norwegian fjords have almost stagnant bottom water (Ström 1936), and it is also known that sea water can be trapped at the bottom of lakes for several thousand years (Ström 1961). These water masses probably have high apparent ages. However, molluscs and other organisms needing oxygen cannot live in this water. It is also assumed that the volume of stagnant water in most cases is so small that it is negligible when mixed with overlying water masses.

Most of the shells were collected in fjords or at fjord mouths (Fig. 5), but from different places. All samples are therefore included in the same diagram (Fig. 6) which shows apparent age in relation to depth. I will, however, emphasize that none of the samples are from the deepest fjord basins, which are up to 1300 metres deep (Sognefjorden). Only 3 samples are taken from below 100 metres in the fjords (Fig. 6). However, these all gave an apparent age of over 470 years, and can indicate a higher age in the deep water. One would in that case expect greater variations on the surface, depending on the mixing between rising deep water and regular surface water. It is not possible to draw certain conclusions on the basis of so few observations, but Fig. 6 indicates that the deep water in the fjords remain for such long periods that it influences apparent age by a few decades.

The Norwegian coast. – A current along the Norwegian coast starts at the mouth of The Baltic Sea and follows the coast north to the Barents Sea (Fig. 8). This is pure Baltic water at Öresund, but it is soon mixed with North Sea water and obtains a salinity of 25–30 $^0/_{00}$ or more. Farther along the coast it is mixed mainly with waters from the Atlantic Ocean which lie partly outside and partly under the coastal water (Figs. 4 and 9). Eggvin (1940) gives an average velocity for this coastal current of approx. 9 nautical
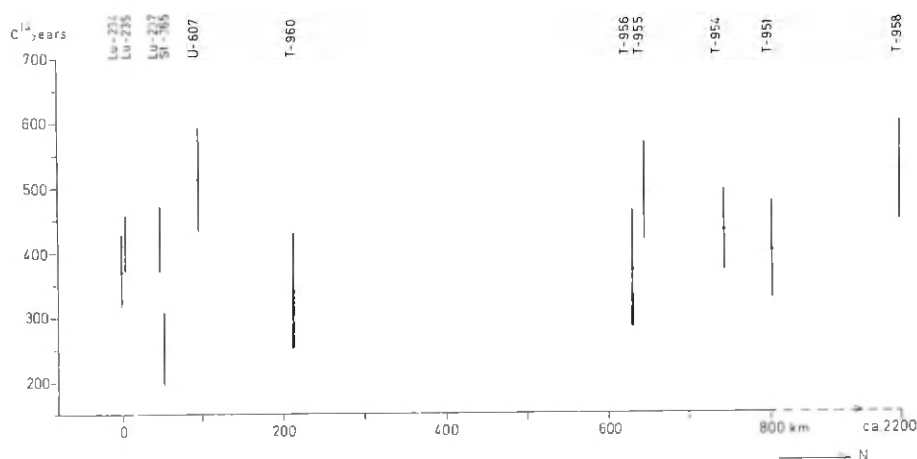
Fig. 7. Apparent ages (with standard deviations) of different samples, shown in a profile along the coastal current from Göteborg (0 km) to North Norway (2200 km). For locations of the samples, see Fig. 9. The exact location of sample U–607 is not known, but the error is small in any case. Only samples from depths less than 50 meters are included in order to avoid samples from other water masses.

miles per 24 hours. This means that a water mass can be transported along the entire Norwegian coast in about 6 months.

Fig. 7 shows a profile parallel with the coastal current. In order to be certain that the samples are from coastal waters, only samples from less than 50 meters depth are used. The samples from the fjords are plotted at the mouth of the fjords because the fjords' surface water has such a rapid exchange with the coastal water.

There is no significant (Fig. 7) variation in apparent age in the coastal current from Göteborg to western Norway. The reasons for this are the great velocity of the current and the small variation in apparent age of the water masses which are mixed in the current. This also means that from Göteborg upwards the influence of Baltic water is negligible. In the southerly part of the Baltic Sea the water has an apparent age of only 30–170 years (Engstrand 1965).

The North Sea and the Norwegian Sea. – The North Sea Water consists essentially of water from the Atlantic which enters north and south of Shetland as well as through the English Channel (Fairbridge et al. 1966). Other water masses brought in are water from the Baltic Sea and fresh water from land, but all these are small in relation to Atlantic Water. Except in the Norwegian Channel the entire North Sea is less than 200 meters deep, and strong currents with numerous large and small eddies effect a thorough mixing of the water masses (Breen 1965).

The Norwegian Sea is a large ocean area with depths to 4000 meters.

Fig. 8. Schematic map of surface currents in the Norwegian Sea and surrounding area, according to Sverdrup (1952). Deep, dense water outflows schematically according to Worthington (1970).

→ Surface current
⇒ Deep water outflows
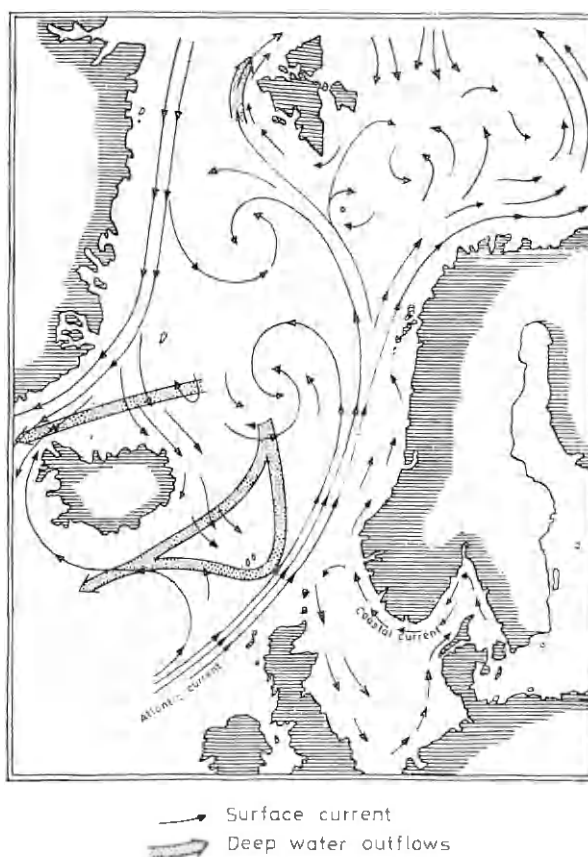
The hydrographic conditions are therefore more complicated and can only be treated schematically. The reader is referred further to Mosby (1960, 1962) and Worthington (1970). What is important for the present problem is that all instreaming to the Norwegian Sea from other ocean areas occurs as surface currents (Figs. 8 and 9). There is also a surface current to the west, out of the Norwegian Sea to the Atlantic. On the other hand, in the easterly and middle parts of the Norwegian Sea the Atlantic Water is cooled and sinks, later to stream out of the Norwegian Sea as deep water (Fig. 8) (Worthington 1970).

Fig. 9 shows published datings of ocean water and marine organisms from the Norwegian Sea and the surrounding area. As seen in Table 5, the datings from the Norwegian Sea itself and Spitsbergen are carried out on samples collected after 1952. These datings are therefore influenced both by industrial effect and atomic bomb effect. It is impossible to determine exactly how significant these influences are, but they are probably less than 200–300 years. By the middle of the 1950's influence of atomic bomb testing seemed to be so great that it surpassed influence from fossil fuel, so that the samples

Table 5. References for samples in Fig. 9. For some samples (Y–606, U–133, U–121, U–122, U–1058) shells are used for which the exact year of death is not known. For the other shells the year of death is assumed to be identical with the year of collection.

Lab. No.	Material dated	Altitude/depth metres	Year of collection	Reference			
St–322	Seawater	0	1957	Östlund & Engstrand 1963			
St–331	,,	0	1957	,,	,,	,,	,,
St–332	,,	0	1957	,,	,,	,,	,,
St–334	,,	0	1957	,,	,,	,,	,,
St–335	,,	−337	1957	,,	,,	,,	,,
St–336	,,	0	1957	,,	,,	,,	,,
St–458	,,	0	1959	,,	,,	,,	,,
St–459	,,	−1000	1959	,,	,,	,,	,,
St–460	,,	0	1959	,,	,,	,,	,,
St–365	Seaweed (*Fucus serratus*)	−0.5——−5	1905	,,	,,	,,	,,
L–599B	Molluscs (*Cardium edule*)		1960	Broecker & Olson 1961			
L–576i	Molluscs (*Nucella lapillus*)		1840	,,	,,	,,	,,
L–576h	Molluscs (*Nucella lapillus*)		1900	,,	,,	,,	,,
Y–606	Molluscs (*Several species*)	−2——−15	1959–1960	Stuiver & Deevey 1962			
U–133	Molluscs (*Astarte borealis*)	+0—+0.5	1952	Olsson 1960			
U–121	Molluscs (*Astarte borealis*)	+1	1958	,,	,,		
U–122	Molluscs (*Buccinum glaciale*)	+1.5	1958	,,	,,		
U–2058	Molluscs (*Macoma calcarea*)	0—+2	1966	Olsson et al. 1969			
U–607	Molluscs (*Patella vulgata*)		ca. 1935	,,	,,	,,	
Lu–234	Molluscs (*Balanus sp.*)		1920–1940	Håkansson 1969			
Lu–235	Molluscs (*Buccinum undatum*)		1920–1940	,,	,,		
Lu–237	Molluscs	Shallow water	1889–1904	,,	1970		

collected after this time probably gave too low an apparent age. The results of variable influence from industrial and atomic bomb effects on the datings from the Norwegian Sea can be as great as the measured variations in apparent age. It is therefore pointless to discuss these variations further. However, datings from Spitsbergen, Greenland, and Iceland seem to give a somewhat higher apparent age than datings from Scandinavia.

All datings from the Norwegian Sea (Fig. 9) are between 250 and 600 years. This fits well with the water circulation described above, where the surface water in the Norwegian Sea has remained on the surface and has been exchanging carbon with the atmosphere for some time. Nowhere is there a proven upwelling of old deepwater. This is in direct opposition to conditions at corresponding latitudes in the Southern Hemisphere (see, for
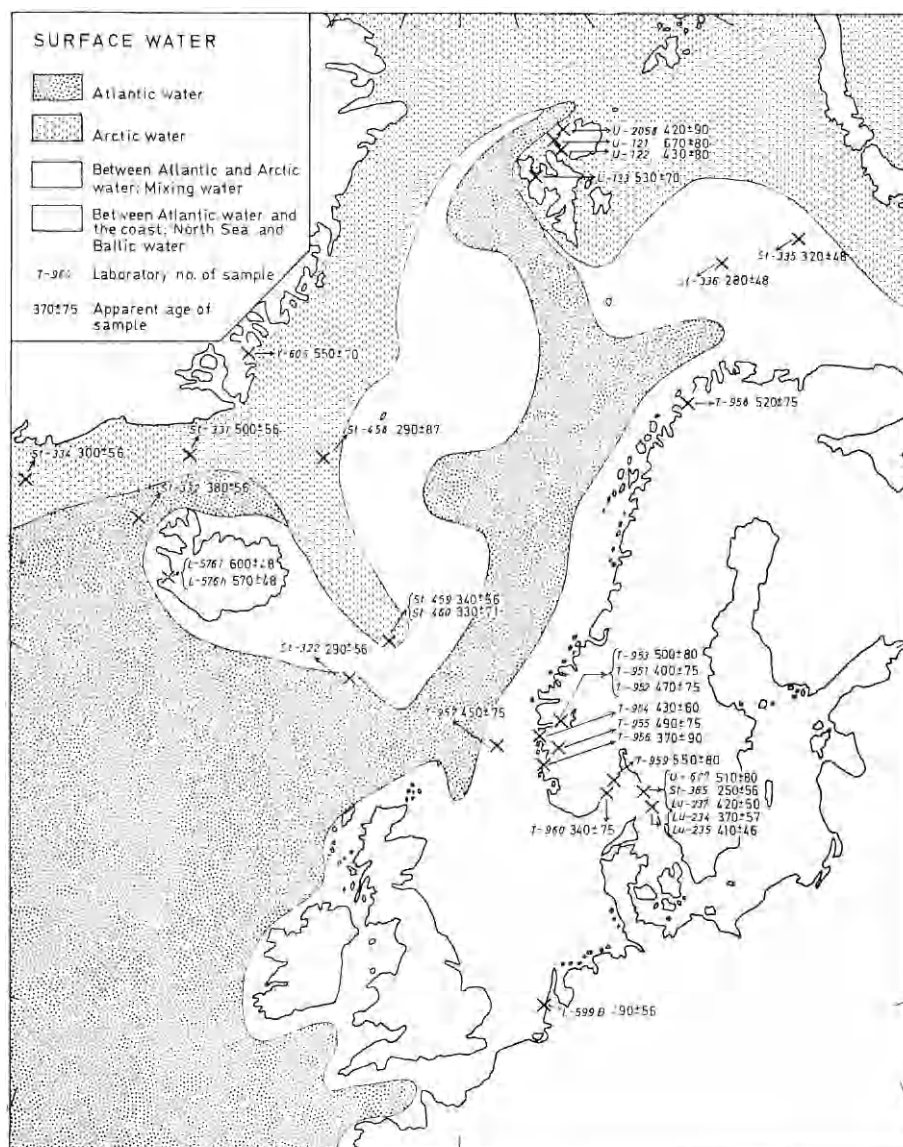
Fig. 9. Compilation of published measurements, indicating apparent age of sea-water or marine organisms from the Norwegian Sea and surrounding areas. Surface water according to Mosby (1960). References for dated samples in Tables 4 and 5. Many samples were collected after 1952 (Table 5), and accordingly, are influenced by both industrial and atomic bomb effects. These errors are uncorrected, and are assumed to be a maximum of $\pm 200–300$ years. Therefore the comparability of the datings is restricted. For several samples apparent ages are calculated by me from Δ–values given in references (Table 5). These are corrected for year of collection (deviation from 1950), and age rounded off, while the standard deviations are not rounded off.

example, Fig. 2 and Rafter & O'Brien 1970) where apparent age varies greatly on the surface, and ages up to 2500 years have been found.

Conclusions. – There are small variations in apparent age of sea water and marine organisms in the Norwegian Sea and surrounding areas. Along the coast of Norway, this is a result of surface water from the Atlantic playing a dominant role in the water balance. Secondly, circulation in this area is so rapid that little or no difference in apparent age results, except perhaps that some differences occur as a result of the deepwater in the fjords remaining there for a few decades.

Concerning C^{14} dating, then, the sea around Norway can for the present be seen as a water mass with apparent age of 450 ± 40 years, determined as the mean of the measurements in Table 4. This value should be considerably more reliable than previous estimates, which are based either on few measurements or include samples influenced by industrial and atomic bomb effects (Mörner 1969). Using shell dates in correlations one should, nevertheless, figure on a greater uncertainty, as it is still possible that some real differences in apparent ages exist, and the averaging of the whole area is therefore not strictly correct.

The strong influence of the Atlantic Water is very important when discussing variations in apparent age back in time. As long as the Atlantic Current has entered the Norwegian Sea, one can assume that changes in apparent age have been parallel in the entire area. I shall not here discuss the conditions during maximum glaciation but merely stress that for the last 14,000 years there is no reason to believe that there have been any changes in the Atlantic Current.

The deposit at Blomvåg (Mangerud 1970) is perhaps the only one in Norway in which a direct comparison of marine shell and terrestrial plant datings is possible. However, as pointed out by Andersen (1968), there is a fairly good agreement in the Norwegian correlations between dating of shell and other material. Considering the climate variations of short duration in Late Weichselian in northwest Europe (Mörner 1969; Mangerud 1970; Tauber 1970; Berglund 1971) the agreement between datings of marine shells and terrestrial plants is so good that systematic deviation can hardly be more than 200–300 years. There is, however, good reason to investigate this further.

Conclusions

(1) The calculation of C^{14} dates and publishing of results is done differently at various laboratories. The user must be alert to whether or not there has been a correction for apparent age, as this could mean a difference of several hundred years. Calculation procedures should be standardized internationally.

(2) Shells living at present, and other marine organisms, would have a C^{14} age at death, called apparent age, which can vary from 200–300 years to more than 2500 years and is due to carbon circulation in nature. This apparent age must be corrected for in C^{14} datings.

(3) Measuring of apparent age on 10 recent shells from the Norwegian coast gave between 340 ± 75 and 550 ± 80, the average being 450 ± 40 years. Apparent age is therefore not seen as a significant problem in dating of Norwegian shells. Datings from Trondheim Radiological Dating Laboratory are corrected for an apparent age of 410 years. If the above calculation of 450 years is assumed to be correct, the corrected shell datings give only a 40 ± 40 years high ages.

(4) Contamination after deposition is a major source of error in shell dating. This error can be reduced considerably by a careful selection of shells according to visual criteria. There is also a theoretical basis for more precise methods, but these methods require first an investigation of recent material for the species in question in each area.

In old shells contaminations of only small quantities of younger carbon will cause great errors. One should be very sceptical of shell datings which give more than 20,000 years.

(5) There is no doubt that there are more inherent problems in shell dating than in the dating of terrestrial plant materials. The problems can be solved, however, and if handled carefully, the results can be just as reliable. However, an uncertainty of 200 years or so should be considered because of carbon circulation in nature.

REFERENCES

Andersen, B. G. 1968: Glacial geology of western Troms, North Norway. *Norges Geol. Unders. 256.* 160 pp. Oslo.

Bathurst, R. G. C. 1971: Carbonate sediments and their diagenesis. *Developments in Sedimentology 12.* 620 pp. Amsterdam.

Berglund, B. E. 1971: Late-glacial stratigraphy and chronology in South Sweden in the light of biostratigraphic studies on Mt. Kullen, Scania. *Geol. Fören. Stockholm Förh. 93,* 11–45.

Bien, G. S., Rakestraw, N. W. & Suess, H. E. 1963: Radiocarbon dating of deep water of the Pacific and Indian Oceans. *Bull. Inst. Océanogr. Monaco 61 : 1278,* 1–16.

Bien, G. & Suess, H. 1967: Transfer and exchange of C^{14} between the atmosphere and the surface water of the Pacific Ocean. *Radioactive Dating and Methods of Low-level Counting,* 105–115. Internat. Atomic Energy Agency. Vienna.

Breen, O. 1965: *Havlære*. 112 p. Fabritius & Sønners forlag, Oslo.

Broecker, W. S. 1966: Radioisotopes and the rate of mixing across the main thermiclones of Ocean. *Jour. Geophys. Res. 71.* 5827–5836.

Broecker, W. S., Gerard, R., Ewing, M. & Heezen, B. C. 1960: Natural radiocarbon in the Atlantic Ocean. *Jour. Geophys. Res. 65*, 2903–2931.

Broecker, W. S. & Olson, E. A. 1961: Lamont Radiocarbon Measurements VIII. *Radiocarbon 3*, 176–204. New Haven, Connecticut.

Callow, W. J., Baker, M. J. & Hassall, G. I. 1965: National Physical Laboratory Radiocarbon Measurements III. *Radiocarbon 7*, 156–161. New Haven, Connecticut.

Craig, H. 1953: The geochemistry of the stable carbon isotopes. *Geochim. et Cosmochim. Acta 3*, 55–92. Pergamon Press Ltd. London.

Craig, H. 1954: Carbon 13 in plants and their relationships between carbon 13 and carbon 14 in nature. *Jour. Geol. 62*, 115–149.

Craig, H. 1957a: Isotopic standards for carbon and oxygen and correction factors for mass-spectrometric analysis of carbon dioxide. *Geochim. et Cosmochim. Acta 12*, 133–149. London.

Craig, H. 1957b: The natural distribution of radiocarbon and the exchange time of carbon dioxide between atmosphere and sea. *Tellus 9*, 1–17. Stockholm.

Degens, E. T. 1967: Stable isotope distribution in carbonates. *In* Chilingar G. V., Bissell, H. J. & Fairbridge, R. W. [eds.] Carbonate rocks. *Developments in Sedimentology 9B*, 193–208. Amsterdam.

Deuser, W. G. & Degens, E. T. 1967: Carbon isotope fractionation in the system CO_2 (gas) – CO_2(aqueous) – HCO_3^-(aqueous). *Nature 215*, 1033–1035.

Duursma, E. K. 1965: The dissolved organic constituents of sea water. *In* Riley, J. P. & Skirrow, G. [eds.]: *Chem. Oceanography 1*, 433–475. Academic Press, London, New York.

Eggvin, J. 1940: The movements of a cold water front. *Rept. Norwegian Fishery Marine Inv. 6*, 1–151. Bergen.

Emrich, K., Ehhalt, D. H. & Vogel, J. C. 1970: Carbon isotope fractionation during the precipitation of calcium carbonate. *Earth and Planetary Science Letters 8*, 363–371. Amsterdam.

Engstrand, L. G. 1965: Stockholm Natural Radiocarbon Measurements VI. *Radiocarbon 7*, 257–290. New Haven, Connecticut.

Fairbridge, R. W., Ichye, T. & Berry, J. 1966: North Sea. *In* Fairbridge, R. W. [ed.]: *The Encyclopedia of Oceanography*, 543–552. New York.

Gade, H. G. 1970: Hydrographic investigations in the Oslofjord, a study of water circulation and exchange processes. *Report 24* (mimeo.) 285 pp. Geophys. Inst. Div. A. Phys. Oceanography. Univ. Bergen.

Goldberg, E. D. 1965: Minor elements in sea water. *In* Riley, J. P. & Skirrow, G. [eds.]: *Chem. Oceanography 1*, 163–196. Academic Press, London, New York.

Håkansson, S. 1969: University of Lund Radiocarbon Dates II. *Radiocarbon 11*,430–450. New Haven, Connecticut.

Håkansson, S. 1970: University of Lund Radiocarbon Dates III. *Radiocarbon 12*, 534–552. New Haven, Connecticut.

Keith, M. L., Andersson, G. M. & Eichler, R. 1964: Carbon and oxygen isotopic composition of mollusk shells from marine and fresh-water environments. *Geochim. et Cosmochim. Acta 28*, 1757–1786. Pergamon Press, Oxford.

Keith, M. L. & Weber, J. N. 1964: Carbon and oxygen isotopic composition of selected limestones and fossils. *Geochim. et Cosmochim. Acta 28*, 1787-1816. Pergamon Press, Oxford.

Lal, D. & Venkatavarandan, V. S. 1970: Analysis of the causes of C^{14} variations in the atmosphere. *In* Olsson, Ingrid U. [ed.]: *Radiocarbon Variations and Absolute Chronology*, 549–570. Almqvist & Wiksell, Stockholm.

Langway, C. C., Jr., Oeschger, H., Alder, B. & Renaud, A. 1965: Sampling polar ice for radiocarbon dating. *Nature 206*, 500–501.

Libby, W. F. 1970: Ruminations on radiocarbon dating. *In* Olsson, Ingrid U.[ed.]*Radiocarbon Variations and Absolute Chronology* 629–640. Almqvist & Wiksell, Stockholm.

Lloyd, R. M. 1964: Variations in the oxygen and carbon isotope ratios of Florida Bay mollusks and their environmental significance. *Jour. Geology 72*, 84–111. Chicago.

Mangerud, J. 1970: Late Weichselian vegetation and ice-front oscillations in the Bergen District, western Norway. *Norsk Geogr. Tidsskr. 24*, 121–148. Oslo.

Mörner, N. A. 1969: The Late Quaternary history of the Kattegatt Sea and the Swedish west coast. *Sveriges Geol. Undersökning C : 640.* 487 pp. Stockholm.

Mook, W. G. 1971: Paleotemperatures and chlorinities from stable carbon and oxygen isotopes in shell carbonate. *Paleogeogr., Palaeoclim., Palaeocol. 9,* 245–263. Amsterdam.

Mook, W. G. & Vogel, J. C. 1967: Isotopic equilibrium between shells and their environment. *Science 159.* 874–875.

Mosby, H. 1960: Surrounding seas. *In* Sömme, A. [ed.]: *A Geography of Norden,* 18–26. J. W. Cappelens Forlag, Oslo.

Mosby, H. 1962: Water, salt and heat balance of the North Polar sea and of the Norwegian Sea. *Geofys. Publ. 24,* 289–313. Oslo.

Münnich, K. O. & Roether, W. 1967: Transfer of bomb C^{14} and tritium from the atmosphere to the ocean. Internal mixing of the ocean on the basis of tritium and C^{14} profiles. *Radioactive Dating and Methods of low-level Counting,* 93–104. Internat. Atomic Energy Agency. Vienna.

Nydal, R. 1968: Further investigations on the transfer of radiocarbon in nature. *Jour. Geophys. Res. 73,* 3617–3635.

Nydal, R. & Lövseth, K. 1970: Prospective decrease in atmospheric radiocarbon. *Jour. Geophys. Res. 75,* 2271–2278.

Olausson, E. 1967: Climatological, geoeconomical and paleooceanographical aspects on carbonate deposition. *Progr. Oceanogr. 4,* 245–265. Pergamon Press, Oxford & N.Y.

Olausson, E. 1969: On the Würm–Flandrian boundary in deep-sea cores. *Geologie en Mijnbouw 48,* 349–361.

Olausson, E. & Jonasson, U. C. 1969: The Arctic Ocean during the Würm and Early Flandrian. *Geol. Fören. Stockholm Förh. 91,* 185–200.

Olsson, Ingrid 1960: Uppsala Natural Radiocarbon Measurements II. *Am. Jour. Sci. Radiocarbon Supp. 2,* 112–128.

Olsson, Ingrid U. 1968: Modern aspects of radiocarbon datings. *Earth-Sci. Rev. 4,* 203–218. Amsterdam.

Olsson, Ingrid U. [ed.] 1970: *Radiocarbon Variations and Absolute Chronology.* 653 pp. Almqvist & Wiksell, Stockholm.

Olsson, Ingrid & Blake, W. 1961: Problems of radiocarbon dating of raised beaches, based on experience in Spitsbergen. *Norsk Geogr. Tidsskr. 18,* 47–64. Oslo.

Olsson, Ingrid U., El-Gammal, S. & Göksu, Y. 1969: Uppsala Natural Radiocarbon Measurements IX. *Radiocarbon 11,* 515–544.

Olsson, Ingrid U., Göksu, Y. & Stenberg, A. 1968: Further investigations of storing and treatment of Foraminifera and mollusks for C^{14} dating. *Geol. Fören. Stockholm Förh. 90,* 417–426.

Östlund, H. G. & Engstrand, L. G. 1963: Stockholm Natural Radiocarbon Measurements V. *Radiocarbon 5,* 203–227.

Owen, G. 1966: Feeding. *In* Wilbur, K. M. & Yonge, C. M. [eds.] *Physiology of Mollusca 2,* 1–51. New York, London.

Polach, H. A. 1969: Optimisation of liquid scintillation radiocarbon age determinations and reporting of ages. *Atomic Energy in Australia 12 (3)* 21–28. Australia.

Polach, H. A. & Golson, J. 1966: *Collection of Specimens for Radio-Carbon Dating and Interpretation of Results.* 42 pp. Australian Institute of Aboriginal Studies. Canberra.

Quinn, J. A. & Otto, N. C. 1971: Carbon dioxide exchange at the air-sea interface: flux augmentation by chemical reaction. *Jour. Geophys. Res. 76,* 1539–1549.

Radiocarbon Measurements: Comprehensive Index, 1950–1965. 1967: New Haven, Connecticut.

Rafter, T. A. & O'Brien, B. J. 1970: Exchange rates between the atmosphere and the ocean as shown by recent C^{14} measurements in the South Pacific. *In* Olsson, Ingrid U. [ed.] *Radiocarbon Variations and Absolute Chronology,* 355–378. Almqvist & Wiksell, Stockholm.

Rönnevik, H. C. 1971: Kvartærgeologi på ytre del av Haugesundshalvøya. 66 pp. [*Unpublished thesis; Univ. Bergen.*]

Scholander, P. F., deVries, H., Dansgaard, W., Coachman, L. K., Nutt, D. C. & Hemmingsen, E. 1962: Radio-carbon age and oxygen–18 content of Greenland icebergs. *Medd. Grönland 165,* 1–26.

Shotton, F. W. 1967: The problems and contributions of methods of absolute dating within the Pleistocene Period. *Geol. Soc. London Quart. Jour. 122,* 357–383.

Skirrow, G. 1965: The dissolved gases – carbon dioxide. *In* Riley, J. P. & Skirrow, G. [eds.] *Chem. Oceanography 1*, 227–317. Academic Press, London, New York.

Strøm, K. M. 1936: Land-locked waters. *Norske Vidensk.Akad., Mat. –Naturvit. Kl. 1936.* 85 pp. Oslo.

Strøm, K. 1961: A second lake with old sea-water at its bottom. *Nature 189*, 913.

Stuiver, M. & Deevey, E. S. 1962: Yale Natural Radiocarbon Measurements. VII. *Radiocarbon 4*, 250–262. New Haven, Connecticut.

Sverdrup, H. U. 1952: *Havlære*. 110 pp. Fabritius & Sønners Forlag, Oslo.

Sælen, O. H. 1967: Some features of the hydrography of Norwegian fjords. *In* Lauff, G. H [ed.]: *Estuaries*, 63–70. Am. Assoc. Adv. Sci. Publ. 83, Washington, D.C.

Taft, W. H. 1967: Modern carbonate sediments. *In* Chilingar, G. V., Bissell, H. J. & Fairbridge, R. W. [eds.]: Carbonate rocks. *Developments in Sedimentology 9A*, 29–50. Amsterdam.

Tauber, H. 1970: The Scandinavian varve chronology and C^{14} dating. *In* Olsson, Ingrid U. [ed.]: *Radiocarbon Variations and Absolute Chronology*, 173–196. Almqvist & Wiksell, Stockholm.

Walton, A., Ergin, M. & Harkness, D. D. 1970: Carbon-14 concentrations in the atmosphere and carbon dioxide exchange rates. *Jour. Geophys. Res. 75*, 3089–3098.

Wendt, I. 1968: Fractionation of carbon isotopes and its temperature dependence in the system CO_2–gas–CO_2 in solution and HCO_3–CO_2 in solution. *Earth and Planetary Science Letters 4*, 64–68. Amsterdam.

Wilbur, K. M. 1960: Shell structure and mineralization in molluscs. *In* Sognnaes, R. F. [ed.]: Calcification in Biological Systems. 15–30. *Am. Ass. Advancement Science. Pub. 64.*

Wilbur, K. M. 1964: Shell formation and regeneration. *In* Wilbur, K. M. & Yonge, C. M. [eds.]: *Physiology of Mollusca 1*, 243–282. Academic Press. New York.

Wolf, K. H., Chilingar G. V. & Beales, F. W. 1967: Elemental composition of carbonate skeletons, minerals, and sediments. *In* Chilingar, G. V., Bissell, H. J. & Fairbridge, R. W. [eds.]: Carbonate rocks. *Developments in Sedimentology 9B*, 23–150. Amsterdam.

Worthington, L. V. 1970: The Norwegian Sea as a Mediterranean basin. *Deep-Sea Research 17*, 77–84. Oxford, London, New York, Paris.

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REFERENCES

Anderson, Elaine: Quaternary evolution of the genus *Martes* (Carnivora, Mustelidae). *Acta Zool. Fenn. 130.* 132 pp. Helsinki/Helsingfors.

Hecker, R.F. (Геккер, Р. Ф.) 1957: *Введение в палеоэкологию.* [*Introduction to Palaeoecology.*] 83 pp. Госгеолтехиздат, Москва.

Pettijohn, F.J. & Potter, P.E. 1964: *Atlas and Glossary of Primary Sedimentary Structures.* 370 pp. Springer-Verlag, Berlin, Göttingen, Heidelberg, New York.

Seilacher, A. 1963: Lebensspuren und Salinitätsfazies. *In* Unterscheidungsmöglichkeiten mariner und nichtmariner Sedimente. *Fortschr. Geol. Rheinl. Westf. 10,* 81–94. Krefeld.