

## TEMPORAL CHANGES OF THE <sup>14</sup>C RESERVOIR EFFECT IN LAKES

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**ABSTRACT.** Conventional radiocarbon dates for sediment samples from aquatic systems and of coeval terrestrial samples deviate from each other due to the reservoir effect. The reservoir correction is usually assumed to be constant with time for a specific aquatic system. Our studies confirm that seasonal and secular changes are frequent and are governed by the limnological conditions. Lakes have two principal sources of <sup>14</sup>C: atmospheric CO<sub>2</sub> and the total dissolved inorganic carbon (TDIC) of the entering groundwater and runoff. The former has values of ca. 100 pMC; the latter usually has a <sup>14</sup>C value well below 100 pMC. Atmospheric CO<sub>2</sub> enters the lake by exchange *via* its surface. The proportions of these two kinds of input determine the magnitude of the reservoir correction in freshwater lakes. It is mainly a function of the volume/surface ratio of the lake and, consequently a function of the water depth. The surface of lakes with outflow does not change when sedimentation decreases the depth of the water. The depth of Schleinsee Lake in southern Germany has decreased from 30 to 15 m since ca. 9000 BP. As a result, the reservoir correction has decreased from ca. -1550 to -580 yr. In contrast, the depth of Lake Proscansko in Croatia increased with growth of the travertine dam and the reservoir correction changed from ca. -1790 to -2650 yr during the last 8800 yr. The largest fluctuations of lake levels occur in closed lakes in arid regions when the climate changes from humid to arid and *vice versa*. As a result, the reservoir correction of the <sup>14</sup>C dates for the total organic fraction from Lejía Lake in the Atacama Desert of Chile varied between <-1800 yr and -4700 yr over a period of only 1800 yr between 11,500 and 9700 BP. The corresponding reservoir correction for the marl fraction is much higher. In summary, accurate and reliable <sup>14</sup>C dating of lake sediments requires a study of the temporal changes of the reservoir effect by analysis of both the organic and marl fractions. The most reliable <sup>14</sup>C dates are obtained from terrestrial plant remains.

### INTRODUCTION

Deevey *et al.* (1954) discovered that the radiocarbon ages of lake sediments are exaggerated due to the involvement of the total dissolved inorganic carbon compounds (TDIC) dissolved in groundwater entering the lake. They called this phenomenon the “hard-water effect”. TDIC has usually a lower initial <sup>14</sup>C activity than that of atmospheric CO<sub>2</sub>. A comprehensive study on <sup>14</sup>C dates of both the organic matter (OM) and of marl from the same sample from the annually laminated section of the sediments of Schleinsee in southwest Germany provided evidence (Geyh, Merkt and Müller 1971) that during the Holocene the initial <sup>14</sup>C values of these two components underwent seasonal and secular changes. Olsson (1979) found that lower initial <sup>14</sup>C values of samples from aquatic systems can also be associated with groundwater with a low TDIC and recommended that the term “reservoir effect” be used instead. Robinson (1981) investigated the initial <sup>14</sup>C value of shallow ocean water and found daily and seasonal changes along the coast of California as a result of the upwelling of deep ocean water.

In spite of all these findings, the interpretation of <sup>14</sup>C dates of lake and ocean sediments is usually based on reservoir corrections that are constant with time for a specific lake or for a specific coastal region. The modern reservoir effect is also adopted for the past, which is why published chronologies and paleoclimatic conclusions derived from <sup>14</sup>C dates of lake sediments may be misleading or even erroneous.

This paper presents the results on temporal changes of the reservoir effect for three lakes: Lake Schleinsee in southwestern Germany, Lake Proscansko in Plitvice National Park in Croatia, and Laguna Lejía in the Altiplano of the Atacama Desert in Chile.

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### Datable Materials of Freshwater and Saline Lakes

Three components of lake sediments can usually be dated:

1. Macrofossils of terrestrial plants provide the most accurate  $^{14}\text{C}$  dates without the requirement of a reservoir correction, provided the samples were not reworked. The  $^{14}\text{C}$  age/depth sequence, stratigraphic markers (e.g., tephra of known age) or varve counting of the annual laminations allow samples with such problems to be identified. However, terrestrial macrofossils are often absent in lake sediments.
2. Aquatic organic matter is formed mainly in the shallow part of the lake water that is penetrated by light (the epilimnion and the euphotic zone) and consists of phytoplankton, aquatic macrophytes and *Characeae*. It is usually formed during the warm season and deposited during the cold season, when the conditions for survival are no longer present.
3. Authigenic inorganic carbonate (marl, tufa, stromatolites) is precipitated from the TDIC of the shallowest lake water during the warm season between early spring and the end of summer.

Because the source of carbon for these components is different, the corresponding initial  $^{14}\text{C}$  values for sediment samples may deviate considerably from each other and must be interpreted separately.

#### Schleinsee, Southwest Germany

Schleinsee is located in SW Germany (47°35'N, 9°36'E). Both the water depth and sediment thickness are currently *ca.* 15 m. A section with 4015 annual laminations is present within a depth range of 19.6–21.0 m. It has been dated paleontologically as the middle Boreal to the end of the Atlantic. The entire profile was deposited during the Holocene. The lake is fed by a small river and has an outlet. Hence, the lake level has not changed during the Holocene. Pollen analysis shows that marl precipitation has occurred from early spring and late summer. There have been, however, large variations from decade to decade, as reflected in the total  $\text{CaCO}_3$  content. Concentrations between 60% and 72%  $\text{CaCO}_3$  are associated with the pollen season from May to early June, 35% to 54% in July and August, and below 20% in late August and early September (Geyh, Merkt and Müller 1971). The 100  $^{14}\text{C}$  dates were determined for the marl and organic fractions in the laminated section. The corresponding  $\delta^{13}\text{C}$  values and the mineral compositions are given in Table 7 of Geyh, Merkt and Müller (1971).

The differences between the  $^{14}\text{C}$  ages of the organic and marl coeval fractions range from 0 to +1800 yr (reservoir effect) for samples consisting mostly of 50–80 laminated layers (Fig. 1). There is a trend of an increasing difference with decreasing annual  $\text{CaCO}_3$  sedimentation rate and, therefore, with the season of marl deposition (Fig. 2). The actual trend is more pronounced. The shown tendency is smoothed more in the  $^{14}\text{C}$  dates than in the pollen dates (not shown). The reason is that 50 and more laminated layers were used for the  $^{14}\text{C}$  dating while only 10 were sufficient for the pollen analysis. The mean of the annually fluctuating lime sedimentation rate varies less for 50 yr than for 10 yr. Interpretation of the  $^{14}\text{C}$  dates yielded a long-term, decreasing trend (–1350 to –580 yr; Geyh, Merkt and Müller 1971) of the reservoir correction associated with a trend of increasing  $\delta^{13}\text{C}$  values (–2.5 to +4.0‰) for both fractions for the period since 9000 BP (Fig. 3).

#### Proscansko Lake in Plitvice National Park, Croatia

Lake Proscansko in Plitvice National Park, Croatia (44°53'N, 15°40'E), is *ca.* 30 m deep. It is on the Korana River, dammed by a travertine barrier growing at a rate of *ca.* 1 cm  $\text{a}^{-1}$ . The initial  $^{14}\text{C}$  value was determined by dating calcite-encrusted wood samples collected from the bottom of the lake and from a sediment core (Table 1; Srdoč *et al.* 1985). The  $\delta^{13}\text{C}$  values are constant. Figure 4 shows the initial  $^{14}\text{C}$  values derived from the difference between the  $^{14}\text{C}$  ages of wood and of its carbonate crusts.

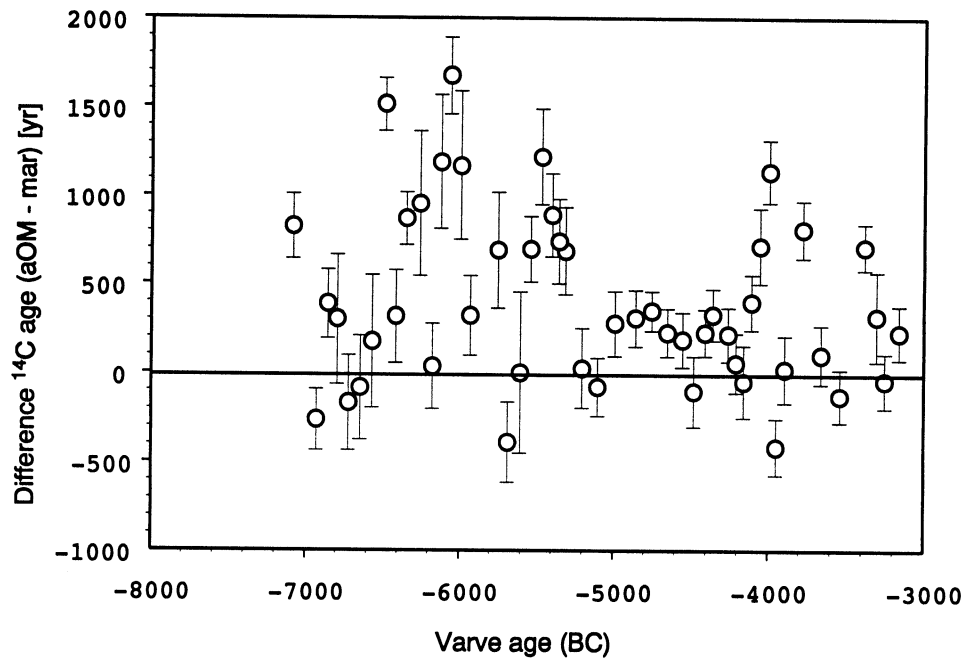


Fig. 1. Difference of the conventional  $^{14}\text{C}$  ages for the aquatic organic matter (aOM) and those for the marl fraction of the annually laminated sediment section of Schleinsee. The  $^{14}\text{C}$  ages for the organic matter are usually larger than those for the marl fraction.

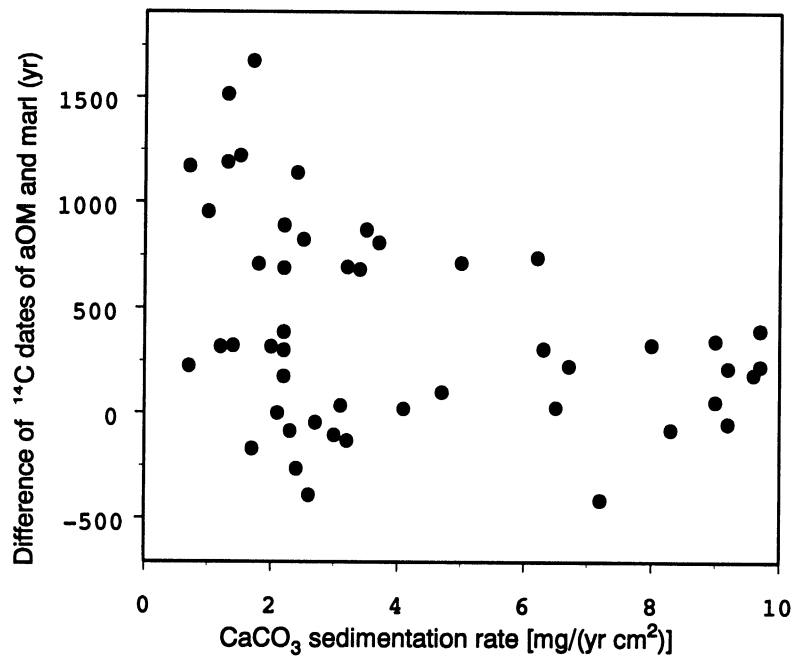


Fig. 2. Increasing difference of conventional  $^{14}\text{C}$  ages for coeval aquatic organic matter and those for the marl fraction with decreasing annual  $\text{CaCO}_3$  sedimentation rate at Schleinsee

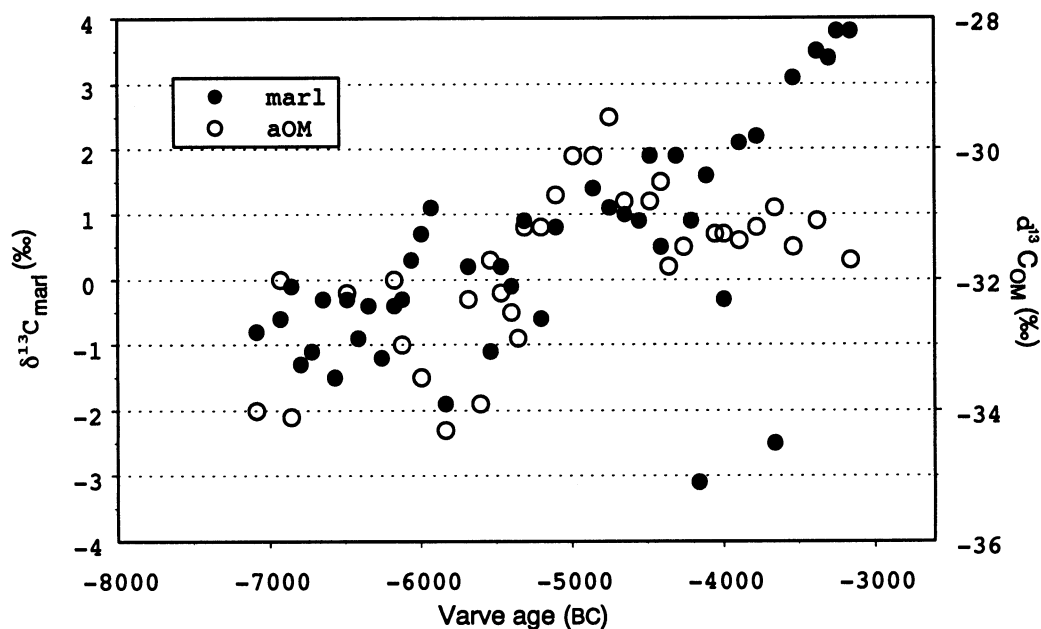


Fig. 3. Increase in the  $\delta^{13}\text{C}$  values for the marl fraction of Schleinsee with decreasing age. The  $\delta^{13}\text{C}$  values of the organic fraction rise less.

TABLE 1.  $^{14}\text{C}$  Results for Samples from Lake Proscansko in Croatia

Lab code	Wood		Marl		Initial $^{14}\text{C}$ value for marl	
	$^{14}\text{C}$ value (pMC)	$^{14}\text{C}$ age (yr BP)	$^{14}\text{C}$ value (pMC)	$^{14}\text{C}$ age (BP)	$^{14}\text{C}$ value (pMC)	$^{14}\text{C}$ age (yr BP)
Hv13436/Hv13439	33.6	8770	26.9	10,560	80.0	1790
Z1307/Z1306 (from 1919)	97.3	195	71.8	2660	73.8	2465
Hv13435/Hv13438	41.7	7025	31.4	9310	69.8	2885

### Laguna Lejía in the Altiplano, Chile

Laguna Lejía is situated at  $23^{\circ}30'\text{S}$ ,  $67^{\circ}42'\text{W}$  at an elevation of 4325 m. The lake has an area of *ca.* 2 km<sup>2</sup>, the catchment area is 198 km<sup>2</sup>. Current precipitation amounts to 150–180 mm a<sup>-1</sup>. The lake water has an electrical conductivity of  $>35,000 \mu\text{S cm}^{-1}$  (high NaHCO<sub>3</sub> concentration) and a pH of *ca.* 8.9. Nothing is known about seasonal changes in the chemical composition of the lake water. There is no vegetation in the area around the lake and flamingos find their food in the shallow, saline water.

Calcareous sediments are not found in the catchment area apart from sodium bicarbonate in the shore zone. The high evaporation rate causes a high content of this salt in the shore sediment, which is why there is a large reservoir of relatively old carbon. A  $^{14}\text{C}$  value of  $60.4 \pm 0.7$  pMC (Hv 19735) was determined for the sodium bicarbonate in the top 50 cm of the shore sediment of another lake. The  $^{14}\text{C}$  value of TDIC of the shallow groundwater entering the lake with a pH of 7.3 is 45.6 pMC (Hv 18064). This low  $^{14}\text{C}$  value and the corresponding high water  $^{14}\text{C}$  age can be partly explained

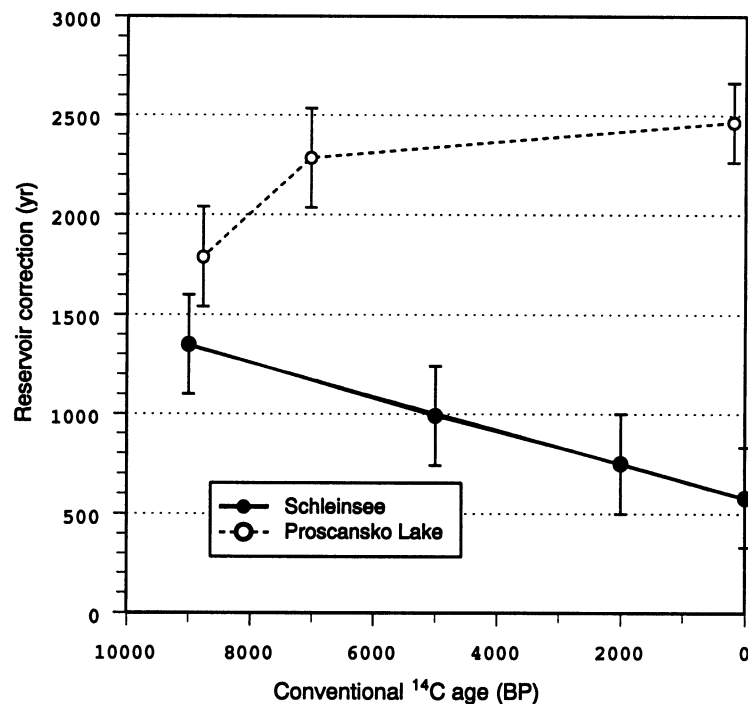


Fig. 4. Long-term changes of the reservoir correction for Schleinsee (Geyh, Merkt and Müller 1971) and Lake Proscansko (Srdoč *et al.* 1986)

by the large catchment area and the resulting long travel distance. Values between 38 and 26 pMC were determined for the bottom lake water, corresponding to conventional  $^{14}\text{C}$  ages of 7735–10,700 BP. In contrast, a subaquatic plant living in this environment with a pH of 8.7 yielded an age of only 1865 BP (79 pMC; Hv 17880). The  $^{14}\text{C}$  dates are compiled in Table 2 and shown in Figure 5.

Lake sediments from the late Pleistocene–early Holocene are exposed in an outcropping section on the southern shore.  $^{14}\text{C}$  dates were determined on samples of total aquatic organic matter, marl, and two terrestrial organic samples—one bird bone and some terrestrial plant fragments. The conventional  $^{14}\text{C}$  ages of the carbonate fraction along the entire exposed section have a small range between 21,000 and 22,300 BP. In contrast, the  $^{14}\text{C}$  ages of the bulk aquatic organic matter scatter widely and are lower.

The  $^{14}\text{C}$  dates of macrorests and the total aquatic organic fraction show an inversion with depth. The deepest sample gave a  $^{14}\text{C}$  age of 13,300 BP, while a sample from the center of the section yielded 15,490 BP (Fig. 5). A bird bone found between these two samples yielded a conventional  $^{14}\text{C}$  age of 10,800 BP. The top sample of aquatic organic matter yielded a  $^{14}\text{C}$  age of 11,700 BP (ETH-6179) and terrestrial plant from the bottom of the profile yielded an age of 11,480 BP (Hv 17799).

## DISCUSSION

### Relationship between $^{14}\text{C}$ Values, $\delta^{13}\text{C}$ Values and Limnological Processes

The isotope compositions of the organic matter and the marl component can be interpreted in terms of the principal controlling processes in lakes in humid regions. In late summer, lakes are often thermally stratified, with warm water in the upper part (epilimnion) and colder water in the lower part

(hypolimnion). When the shallow water cools as winter approaches, a moment will be reached where the cold water from the top circulates to the bottom and bottom water circulates to the top. The lake water becomes well mixed. If water of different bicarbonate concentration is mixed, an excess concentration of  $\text{CO}_2$  builds up, which further increases during the winter as result of the decomposition of dead organic matter. In early spring, the top layer of lake water is warmed and biological activity starts. Inorganic carbonate is precipitated as a result of biological removal of  $\text{CO}_2$  from the lake water and to a lesser extent by degassing due to rising water temperatures in summer. This occurs mainly in the epilimnion, where most biological activity takes place due to the high light flux. The marl thus formed does not reach the lake bottom as long as the bottom water is oversaturated with  $\text{CO}_2$ . For this reason, marl sedimentation is usually restricted to the late warm period of the year.

TABLE 2.  $^{14}\text{C}$  dates and  $\delta^{13}\text{C}$  values from Laguna Lejía and the surrounding area. The depth is given in cm below the top of the sediment outcrop (Grosjean 1994). All sediment samples were taken above the present lake level (currently at 400 cm).

Depth (cm)	Material	$^{14}\text{C}$ ages (yr BP)	Reservoir correction (yr)	Actual age (BP)	$\delta^{13}\text{C}$ (‰ <sub>NBS</sub> )	Lab code
-2100	Carbonate-coated <i>Characeae</i>	16,715 ± 195	<-6000	11,615	+6.8	Hv 17806
80	Ikaite carbonate	21,060 ± 440	-12,000	9000	+4.1	Hv 19709
110	Bulk organic fraction	11,700 ± 110	-2000	9700	-26.7	ETH-6179
110	Carbonate fraction	21,730 ± 110	-12,000	9700	+6.6	Bern
260	Bulk organic fraction	15,490 ± 160	-5200	10,300	-29.4	ETH-6180
260	Carbonate fraction	22,290 ± 120	<-12,000	10,300	+7.0	Bern
330	Bird bone	10,805 ± 725	0	10,800	-12.5	Hv 20432
390	Bulk organic matter	13,330 ± 110	<-2200	11,100	-27.4	ETH-6180
390	Carbonate fraction	21,140 ± 180	-10,000	11,100	+14.8	ETH-5847
400	Organic terrestrial macrofossils	11,480 ± 70	0		-16.2	Hv 17799
400	Living aquatic plant	1865 ± 95	-1865	0	-7.3	Hv 17880
410	TDIC of lake water	8360 ± 490		0	-2.4	Hv 17802
410	TDIC of lake water	8195 ± 240			+3.0	Hv 18083
410	TDIC of lake water	7735 ± 570			-4.7	
410	TDIC (Laguna lateral)	10,695 ± 545		0	-6.9	Hv 18560
425	$\text{NaHCO}_3$ in soil	4045 ± 215			+3.5	Hv 19735
470	TDIC (water from dug well)	6260 ± 215		0	-2.9	Hv 18064

According to Mook (1970), the TDIC in the water and precipitated carbonates of aquatic systems should be in isotopic equilibrium. Hence, the reservoir effect of the TDIC in the water and that of the precipitated marl is usually similar. This may not be true for the marl that is formed in the topmost lake water. Exchange with atmospheric  $\text{CO}_2$  may increase the  $^{14}\text{C}$  value in the shallow lake water (Broecker and Walton 1959). This effect increases from month to month as more and more carbon in the initial TDIC reservoir is biologically consumed. This explains why the  $^{14}\text{C}$  value increases with decreasing annual  $\text{CaCO}_3$  sedimentation rate (Fig. 2) and the delayed deposition of marl in the year. In the extreme case, the  $^{14}\text{C}$  value of the marl may correspond to that of atmospheric  $\text{CO}_2$  (or even more, due to isotope fractionation; Broecker and Walton 1959). As the aquatic organic matter is formed during the whole year and throughout the euphotic zone of the lake (which is larger than the water layer where carbonate is precipitated), the  $^{14}\text{C}$  value of the organic matter might be less or even not influenced by atmospheric  $\text{CO}_2$  input of the late summer than the marl fraction.



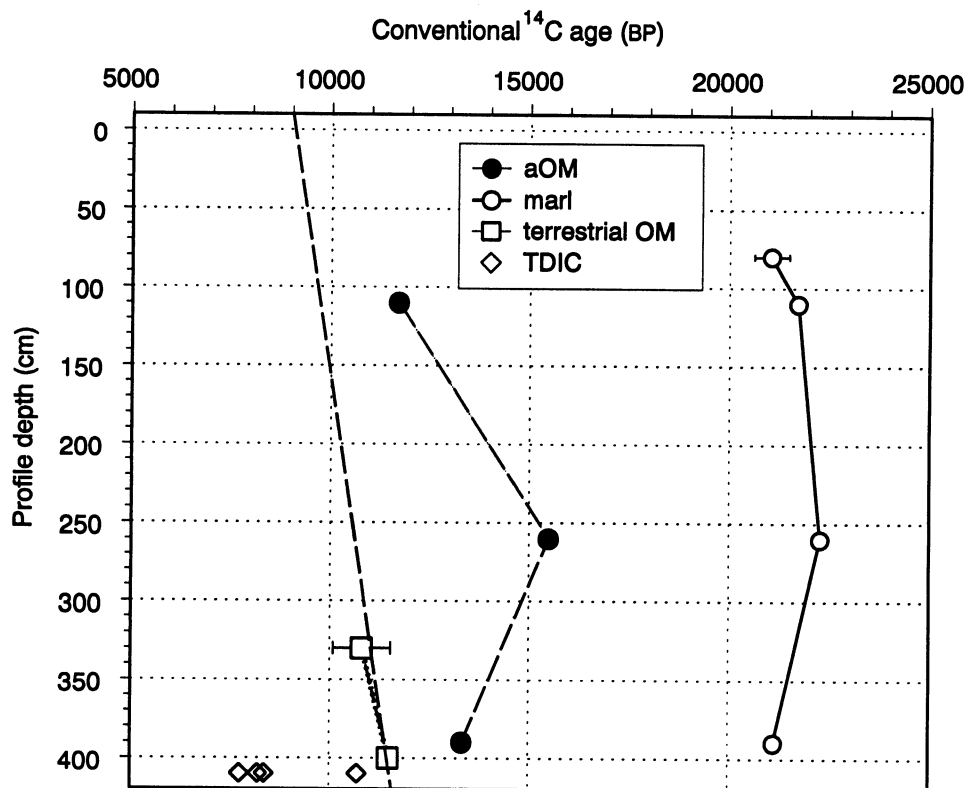


Fig. 5.  $^{14}\text{C}$  ages of total aquatic organic matter, the marl fraction and two terrestrial organic samples (Table 2) from Laguna Lejía in the Atacama Desert of Chile. The dashed line extrapolates the conventional  $^{14}\text{C}$  age for terrestrial organic matter to the top of the sediment profile.

The proportion of atmospheric  $\text{CO}_2$  in the total carbon balance of a lake depends on the ratio of the water volume to the lake surface area (Broecker and Walton 1959). The first parameter is mainly a function of lake depth and decreases with deposition of sediment (Geyh, Merkt and Müller 1971). The water surface area can be considered to be constant for lakes with an outflow. The ratio of water volume to the lake surface area is related to the maximum water depth when the water is dammed by a barrier growing in the river bed. In closed lakes, the water level depends mainly on fluctuations in the precipitation and evaporation rates, which may change considerably when the climate changes from arid to humid climatic conditions or *vice versa*. Other parameters, such as pH, wind action, and stratification of the lake, usually may have a minor influence in freshwater lakes.

#### The Freshwater Lake Schleinsee

The secular change of the initial  $^{14}\text{C}$  value for Schleinsee derived from the  $^{14}\text{C}$  dates for organic matter and marl (Geyh, Merkt and Müller 1971) is shown in Figure 4. The volume of Schleinsee has decreased due to sediment deposition. The reservoir correction for the sediments of Schleinsee decreases by *ca.*  $-86/1000$  yr.

The trend of increasing  $\delta^{13}\text{C}$  value for the marl fraction with decreasing age (Fig. 3) can also be explained by an increasing proportion of atmospheric  $\text{CO}_2$  in the lake water. The  $\delta^{13}\text{C}$  value for TDIC is *ca.*  $-12$  ‰ and that of atmospheric  $\text{CO}_2$  *ca.*  $-7$  ‰. An increasing proportion of the latter car-

bon component must, therefore, shift the  $\delta^{13}\text{C}$  value of TDIC to less negative values. This trend is less visible in the  $\delta^{13}\text{C}$  values for the organic matter. Hence, it may be assumed that the reservoir effect of this fraction is smaller than that of the marl fraction, or is even absent. Similar trends have been observed for Gościąg Lake, Poland (Pazdur *et al.* 1995).

In order to check this hypothesis, the  $^{14}\text{C}$  ages of the marl fraction were compared with the  $^{14}\text{C}$  data for the calibration curve (Stuiver, Long and Kra 1993). Laminated layer-counting provided a floating chronology with a one-year precision. The fixation of our floating to the absolute time scale was done with well-dated palynological markers and a precision of a few centuries (Geyh *et al.* 1971). A constant reservoir correction of  $-1550$  yr applied to the  $^{14}\text{C}$  ages of the marl fraction yields a poor fit (Fig. 6). The maximum reservoir correction shifts the corrected  $^{14}\text{C}$  data below the calibration curve when it is larger than the actual reservoir correction. Only the  $^{14}\text{C}$  ages of those samples which were subject to the maximum reservoir effect fit the calibration curve. A reservoir correction smaller than the maximum value is due to the higher proportion of atmospheric  $\text{CO}_2$  in the carbon budget of the lake at that time. An improvement is obvious if the reservoir correction is assumed to undergo secular changes, beginning with  $-1550$  yr at *ca.* 9000 BP and decreasing to  $-580$  yr today. In 1971, before the calibration curve was available, a range of  $-1350$  to  $-580$  yr was estimated. For the organic matter fraction, the better fit is obtained with a constant reservoir correction of  $-1550$  yr (Fig. 7). That means the carbon influx by atmospheric  $\text{CO}_2$  is small compared to that of the groundwater flux. The reason for this seems to be that the aquatic organic matter is formed much longer during the year and also within a larger water depth where the  $^{14}\text{C}$  value is mainly controlled by that of the TDIC of the groundwater.

In summary, the reservoir effect for the marl fraction has changed considerably during the past, as reflected in both  $^{14}\text{C}$  and  $\delta^{13}\text{C}$  values. This has to be considered when accurate time marks are needed to establish a reliable chronological framework for the past. The  $^{14}\text{C}$  dates of the organic matter fraction seem to have been less affected.

#### **The Freshwater Lake Proscansko**

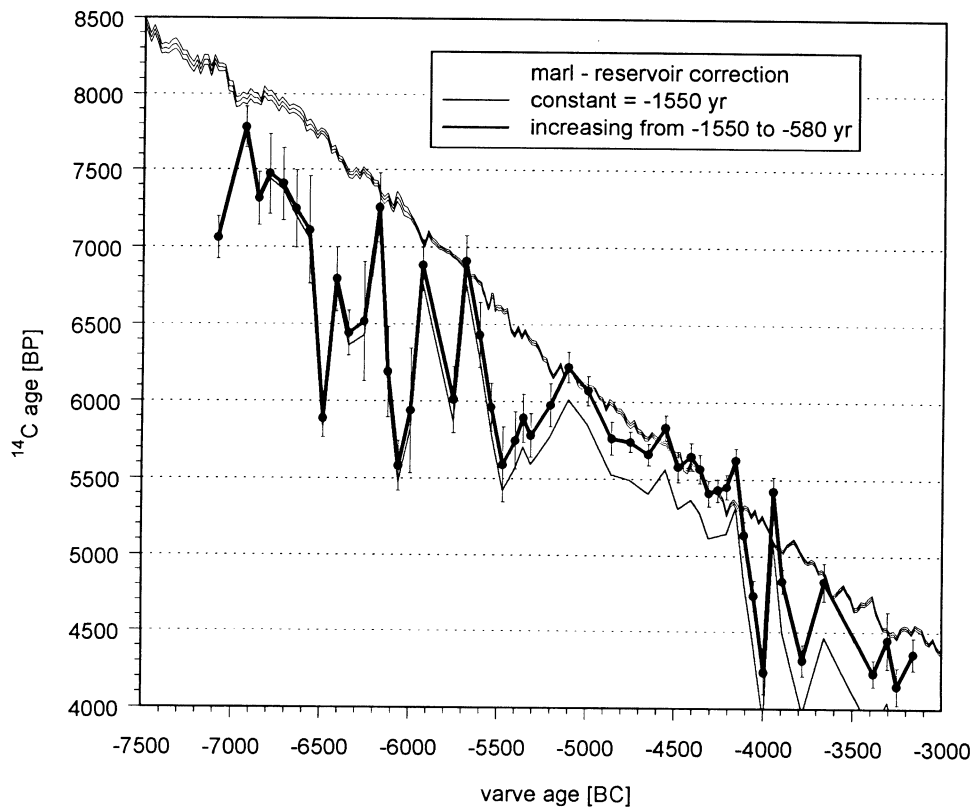
In the case of Lake Proscansko, an opposite trend for the reservoir effect was expected and found (Fig. 4). Water depth and reservoir effect have increased with the growth of the travertine barrier in the valley of the River Korana since 8800 BP. The rate of change of the reservoir correction is smaller than that of the Schleinsee. This may have more than one cause:  $^{14}\text{C}$  dates for wood and calcareous crusts were compared instead of dates from different sediment components. Calcite crusts might also have formed on the bottom of the lake, where the influence of atmospheric  $\text{CO}_2$  is smaller than in shallow lake water where the marl is formed.

#### **The Brackish Water of Laguna Lejía**

Long-term changes in the reservoir effect are also the best explanation for the varying  $^{14}\text{C}$  ages of the organic matter and marl fractions in the sediment profile of Laguna Lejía in the Altiplano of Chile (Grosjean *et al.* 1995). In this case, climatically induced lake-level changes might have been responsible. There is little terrestrial organic matter suitable for dating in this harsh, cold and dry high mountain environment. The fluctuating  $^{14}\text{C}$  dates within the sediment profile are shown in Figure 5. As  $^{14}\text{C}$  in organic matter cannot be lost other than by radioactive decay, the inversion of  $^{14}\text{C}$  age with depth can only be due to a change in the reservoir correction. In contrast, the  $^{14}\text{C}$  ages of the carbonate fraction are more or less constant. Grosjean (1994) initially explained this phenomenon by dissolution and redeposition of carbonate. This can be doubted, as post-sedimentary carbonate exchange should increase and not decrease  $^{14}\text{C}$  activity.



The terrestrial organic macrorests from the basal gravel bed ( $11,480 \pm 70$  BP at 400 cm) and the collagen fraction of an *in-situ* bone ( $10,805 \pm 725$  BP at 330 cm) are not affected by the reservoir effect. A shallow lake of 1 m to maximum 5 m water depth, comparable to the modern lake, developed after 11,500 BP. The total aquatic organic fraction in these sediments yielded  $13,300 \pm 110$  BP (at 390 cm). From these dates, a reservoir correction of  $-2150$  yr ( $= 76.5$  pMC) was calculated (similar to the modern situation) and chronostratigraphic consistency with the date of 11,500 BP from the aquatic organic matter of the basal layer obtained. Subsequently, the lake level increased to its maximum level of  $>25$ -m water depth (Grosjean 1994) during the humid Tauca-Copiasa Phase (Grosjean *et al.* 1995; Servant and Fontes 1978). The AMS  $^{14}\text{C}$  date of the total aquatic organic matter from this sediment section yielded  $15,490 \pm 160$  BP. Thus, a reservoir correction of at least  $-4700$  yr ( $= 55.7$  pMC) is required for chronostratigraphic correlation with the  $^{14}\text{C}$  dates of a bird bone and of the terrestrial macrofossil from the basal layer. As expected, all three dates of the total aquatic organic fraction require a reservoir correction that decreases with increasing water depth.

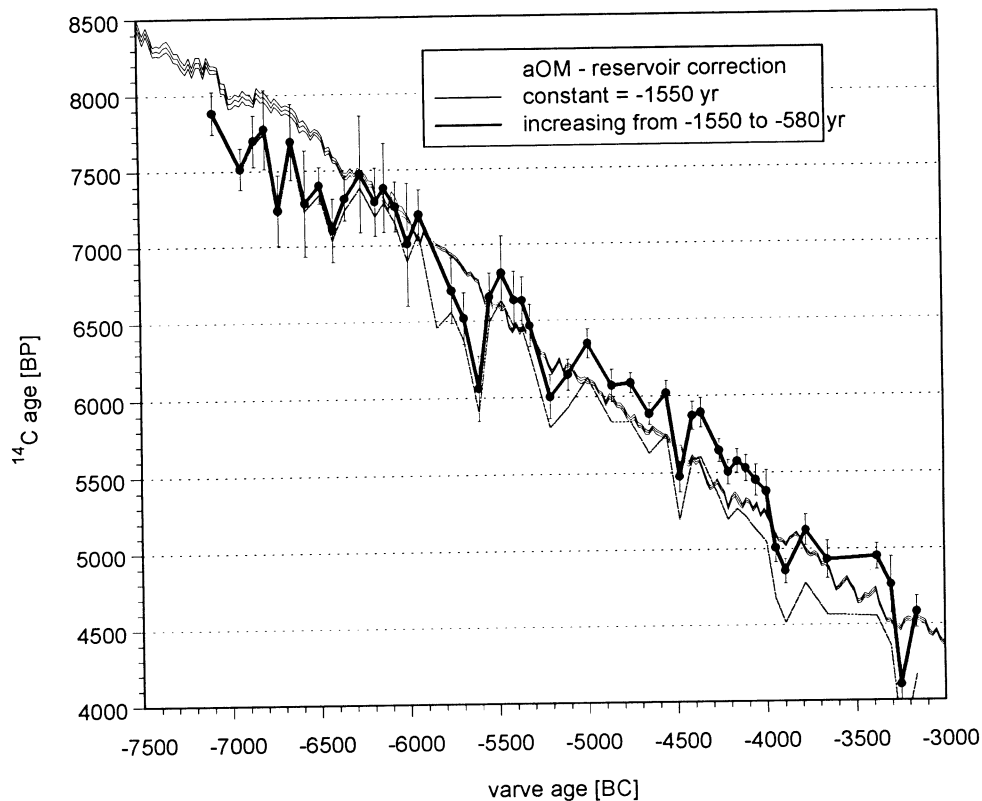


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Fig. 6. Calibration curve and reservoir-corrected  $^{14}\text{C}$  ages of the marl fraction from sediments in Schleinsee (Geyh, Merkt and Müller 1971). The best fit is obtained with an initial  $^{14}\text{C}$  value that undergoes secular change (bold line) starting with  $-1550$  yr for 9000 BP and ending with  $-580$  yr at present. A constant initial  $^{14}\text{C}$  value yields a worse fit.

An independent estimate of the present-day initial  $^{14}\text{C}$  value of organic matter was obtained from the  $^{14}\text{C}$  activity of a modern aquatic plant. In an environment with 24 pMC  $^{14}\text{C}$ , it yielded 80 pMC. Evidently, the plant assimilated mainly atmospheric  $\text{CO}_2$  entering the alkaline lake by exchange through

the water surface. This metabolism may take place in a freshwater environment formed daily by meltwater from an ice layer that forms every night during the winter. Because some TDIC of the underlying lake water, which is depleted in  $^{14}\text{C}$ , is mixed with the fresh water containing atmospheric  $\text{CO}_2$ , the  $^{14}\text{C}$  value of the plant material is  $<100$  pMC. Taking the atmospheric  $^{14}\text{C}$  level of 110 pMC in 1989 into account, the initial  $^{14}\text{C}$  level of the living aquatic plant must be corrected to 72 pMC. This result is in reasonable agreement with the 76.5 pMC estimate for the reservoir effect in the shallow Lake Lejía. As result, the present-day  $^{14}\text{C}$  value for the TDIC of the shallow alkaline lake water is governed by the influence of atmospheric  $\text{CO}_2$ . During the pluvial Tauca-Copiasa Phase, the lake was deep and fresh and the input of atmospheric  $\text{CO}_2$  was low compared to today.



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Fig. 7. Calibration curve and reservoir-corrected  $^{14}\text{C}$  ages of the aquatic organic matter fraction from sediments in Schleinsee (Geyh, Merkt and Müller 1971). The best fit is obtained with a constant initial  $^{14}\text{C}$  value (bold line) of  $-1550$  yr. An initial  $^{14}\text{C}$  value that undergoes secular change yields a worse fit.

The marl precipitates mainly along the interface of the lake water, which is supersaturated with sodium bicarbonate, and the groundwater inflow. The calcium input by the meltwater results in precipitation of  $\text{CaCO}_3$  and explains its low  $^{14}\text{C}$  value of 25 pMC. Consequently, the low  $^{14}\text{C}$  value of the marl reflects the hydrochemical reactions between components of the lake water and the groundwater rather than any loss by radioactive decay. Atmospheric  $\text{CO}_2$  plays a minor role for the  $^{14}\text{C}$  value of marl. In any case, the increase in the reservoir correction of the TDIC during the elevated lake level of the Tauca-Copiasa Phase is still noticeable. For the derived deposition period of the exposed sediment profile between 11,500 and 9700 BP, the reservoir correction of the marl fraction

for the three dated levels changes from -10,000 to -11,900 and finally to -12,250 yr. The corresponding  $\delta^{13}\text{C}$  value increases from +4 to +15‰. The carbonate coating of *Characeae* from the highest shoreline terrace of the paleolake Lejía ca. 26 m above the current lake level is stratigraphically coeval with the sediment between 260 and 110 cm in the section. The  $^{14}\text{C}$  age of 16,715 BP for the coating requires a correction of -5100 yr to put it in the phase with the maximum lake level.

## CONCLUSION

$^{14}\text{C}$  dating of different sediment components from freshwater and saline lakes shows that the initial  $^{14}\text{C}$  values for at least the marl and aquatic organic fractions change considerably during the season in which it is precipitated and during the history of the lake. The reservoir effect for this component mainly seems to be a function of the ratio between the water volume and the lake surface area, which is usually related only to water depth. The latter may change due to deposition of sediment, to growth of a barrier or to climatic changes in the case of endorheic lakes. In this case, the considerable lake-level fluctuations may also affect the initial  $^{14}\text{C}$  value for organic matter. As a consequence, neglecting temporal changes in the reservoir effect may result in an erroneous paleoclimatic interpretation. Due to the observed short-term changes of the reservoir effect it is difficult to derive secular lake-level fluctuations (Pazdur *et al.* 1995) from changes of the initial  $^{14}\text{C}$  values of the lake sediment fractions.

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