BUILDING CONFIDENCE IN SHELL: VARIATIONS IN THE MARINE RADIOCARBON RESERVOIR CORRECTION FOR THE NORTHWEST COAST OVER THE PAST 3,000 YEARS

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In many regions, fluctuations have occurred through time in the local ^{14}C activity of seawater. Evaluating these shifts and their effects on ^{14}C age estimates is difficult, and, as a result, archaeologists working in coastal settings tend to preferentially date charcoal samples over shell. Our research on 18 charcoal–shell pairs from Puget Sound and Gulf of Georgia archaeological sites helps elucidate the spatial and temporal dynamics associated with marine reservoir effects in the Pacific Northwest. This analysis suggests that between 0 and 500 B.P. the regional correction value (ΔR) is 400 years, which agrees with the modern value determined by Stuiver and others. Between 500 and 1200 B.P., however, ΔR dips close to zero, possibly reflecting a decrease in offshore upwelling. From 1200 to 3000 B.P., ΔR returns to 400 years. These data are presented as a Puget Sound/Gulf of Georgia regional correction curve for the late Holocene, which local researchers may use to calibrate dates of marine shell. In addition, we detail our methods for constructing calibration curves and present guidelines for archaeologists working in other coastal settings to develop calibration curves for their regions.

A través del tiempo, en muchas regiones, han ocurrido fluctuaciones en los niveles locales de C^{14} del agua del mar. Evaluar estos cambios y sus impactos en las estimaciones del C^{14} es difícil, y como resultado, arqueólogos que trabajan en áreas costeras tienden a preferir dataciones de carbón vegetal en lugar de dataciones provenientes de conchas marinas. Nuestra investigación de 18 pares de carbón vegetal y conchas provenientes de sitios arqueológicos de Puget Sound y el Golfo de Georgia, ayuda a elucidar las dinámicas espacio-temporales asociadas con los efectos del reservorio marino en el Pacífico Noroeste. Este análisis sugiere que entre 0 y 500 años A.P. el valor corrector regional (ΔR) es de 400 años, lo cual concuerda con el valor moderno determinado por Stuiver y otros; sin embargo entre 500 y 1200 años A.P. el valor de ΔR se acerca a cero, posiblemente reflejando un descenso en el flujo de agua procedente de las profundidades del mar abierto; entre 1200 y 3000 años A.P. el valor ΔR retorna a 400 años. Estos datos son presentados como una curva de corrección regional para el Puget Sound y el Golfo de Georgia durante el Holoceno tardío, la cual puede ser utilizada por investigadores locales para calibrar fechas obtenidas de conchas marinas. Se detallan también nuestros métodos para construir curvas de calibración, y se presentan directrices para que arqueólogos que trabajan en otras zonas costeras desarrollen sus propias curvas de calibración.

For thousands of years, people living in northwestern North America have exploited shellfish. Evidence for this comes from historical observation (Barkan 1987; Fisher 1977; Gunther 1972; Morgan 1979), oral histories (Barnett 1955; Eells 1887; Elmendorf 1992; Nugent 1982; Suttles 1983), and the unmistakable material record of shell deposits (i.e., shell middens) in archaeological sites (e.g., Stein 1992). The harvesting of shellfish for subsistence combined with the ubiquitous nature of shell middens in coastal archaeological contexts makes shell a natural choice for radiocarbon dating. This study investigates the numerical values that are used to correct radiocarbon dates on shells from the Pacific Northwest, in order to provide a firmer basis for their use in archaeological dating. To do so, we compared the apparent ^{14}C ages of paired shell and charcoal samples from archaeological sites in the Puget Sound/Gulf of Georgia region, using collections from the Burke Museum of Natural History and Culture, University of Washington, Seattle.

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To some degree, our concern with the radiometric dating of shell conflicts with established practice. Though both charcoal and shell are present in shell middens, archaeologists prefer to use charcoal to date sites because additional complications arise when dating shells—specifically, the requirement for regional correction factors (Mitchell 1971, 1990; Robinson and Thompson 1981). Shells, however, have distinct advantages over charcoal as chronological markers. They are excreted by short-lived organisms, they are more abundant than charcoal in shell midden sites, and they usually are found as larger fragments that do not require the more expensive techniques of extended counting or accelerator mass spectrometry dating. These larger fragments also do not move downward as easily through porous midden sites. If the uncertainties associated with correcting shell dates could be resolved, shells from museum archives, surface exposures, and excavation levels without charcoal could all be dated with confidence. Any archaeologist who considers chronological issues in the context of coastal sites would naturally benefit from such resolution.

Archaeologists and other users of radiocarbon dating employ calibration curves to align their dates as closely as possible with calendrical timescales (Stuiver et al. 1986). The calibration of dates from samples that formed from atmospheric CO_2, such as charcoal, compensates for differences between past and present (actually, preindustrial) levels of ^{14}C in the atmosphere and for the difference between the actual isotopic half-life and that used in the conventional ^{14}C age calculation (i.e., the age reported by a radiocarbon dating laboratory, corrected for carbon isotopic fractionation in the standard manner described in Stuiver and Polach 1977). Calibration of dates from samples that formed in the oceans, such as shell, must be further corrected for the difference in ^{14}C activity between surface ocean water and the atmosphere (Stuiver and Braziunas 1993; Stuiver et al. 1986; Taylor 1987). Because the ocean does not circulate or mix as quickly or as effectively as the atmosphere, the difference in ^{14}C activity between the surface ocean and atmosphere is dependent on the time and place where the sampled marine organism lived. The difference may also depend on the species of shell, feeding method (e.g., detrital carbon and phytoplankton-derived carbon digestion), and freshwater uptake (Hogg et al. 1998; Ingram and Southon 1996; Tanaka et al. 1986).

The "reservoir effect" in marine samples arises because the oceans are depleted in ^{14}C compared with the atmosphere and the deficiency is transmitted to marine organisms. Consequently, conventional ^{14}C ages of marine samples such as shells will always appear "older" than those of contemporary wood. Archaeologists can overcome this effect by dating pairs of shell and charcoal that were deposited together and then calculating correction factors based on their apparent age differences.

The reservoir correction factor varies in both spatial and temporal dimensions. It is common practice to adjust marine sample dates by subtracting a regionally calculated "reservoir correction" in order to compare shell samples with the ^{14}C ages of contemporary wood. This correction accounts for regional variability in the ^{14}C activity of oceanic carbon (e.g., Northwest Coast region versus California coast region) but neglects possible changes in the reservoir correction through time. Recent research (e.g., Ingram 1998; Ingram and Southon 1996; Kennett et al. 1997; Kovanen and Easterbrook 2002; Southon et al. 1990) indicates that temporal differences in the reservoir effect are just as crucial as spatial variability. Few archaeologists have addressed temporal fluctuations, but a growing body of data indicates that such shifts must be accounted for when discussing radiocarbon ages from marine-derived samples (Ingram 1998; Kennett et al. 1997; Kovanen and Easterbrook 2002).

The research reported here provides specific corrections for sites on the coasts of the Gulf of Georgia (also known as the "Strait of Georgia") and the southern Puget Sound over the past 3,000 years. In addition, guidelines are provided for correcting radiocarbon dates on shell by considering both the location and the time during which the organism lived. Using these guidelines, coastal archaeologists will improve the accuracy of dates from shell, thereby enabling reliable comparisons to dates obtained from charcoal. Determining the temporal character of the reservoir effect has implications not only for accurate dating of human coastal occupations but also for regional climate shifts that may affect archaeologists' interpretations of human behavior. These lines of inquiry are the most recent in a long tradition of reservoir effect scholarship, and it is to this previous research that we now turn.

Previous Reservoir Age Research along the West Coast of North America

Robinson and Thompson (1981) dated mollusks that were collected before 1950 (prior to nuclear weapons testing) in order to define the regional marine reservoir correction for the Northwest Coast of North America. Their research suggested that the conventional radiocarbon age of marine samples from Washington and Oregon should be adjusted by subtracting 801 ± 23 years in order to obtain an age comparable to the ^{14}C age of contemporary wood. In the terminology of radiocarbon dating, this regional marine reservoir correction, R, is the sum of two components: R_g represents the difference in ^{14}C age of the *average* surface ocean relative to the atmosphere, and ΔR is a regional correction that accounts for the difference between the *local* oceanic ^{14}C age and that of the global ocean. The equation is represented as

$$R = R_g + \Delta R.$$

Accordingly, Robinson and Thompson's reservoir correction of 801 ± 23 years for the Northwest Coast may be broken down into components. The 19th-century (preindustrial) value of R_g in the northern hemisphere was 400 years based on the modeled concentration of global atmospheric ^{14}C as compared with the surface ocean concentration of ^{14}C (Stuiver et al. 1998b). The remaining 401-year difference (ΔR) for Washington coastal waters is related to upwelling in the northeastern Pacific, which brings old, ^{14}C-depleted water to the surface and results in older apparent ^{14}C ages. The ΔR value of 401 years for the Pacific Northwest is greater than values farther south along the coast, where ΔR ranges from 220 ± 40 years in southern California to 290 ± 35 years in northern California (Ingram and Southon 1996).

The general approach to determining temporal variation in ΔR is to date shell and wood samples that drew carbon simultaneously from the ocean and atmosphere. The difference between the conventional ^{14}C ages of these samples is partly related to the value of R_g at the time (t) of formation (henceforth, $R_g(t)$). $R_g(t)$ can be removed using the marine calibration curve of Stuiver et al. (1998a). The remaining difference represents $\Delta R(t)$. The updated equation now reads

$$R(t) = R_g(t) + \Delta R(t).$$

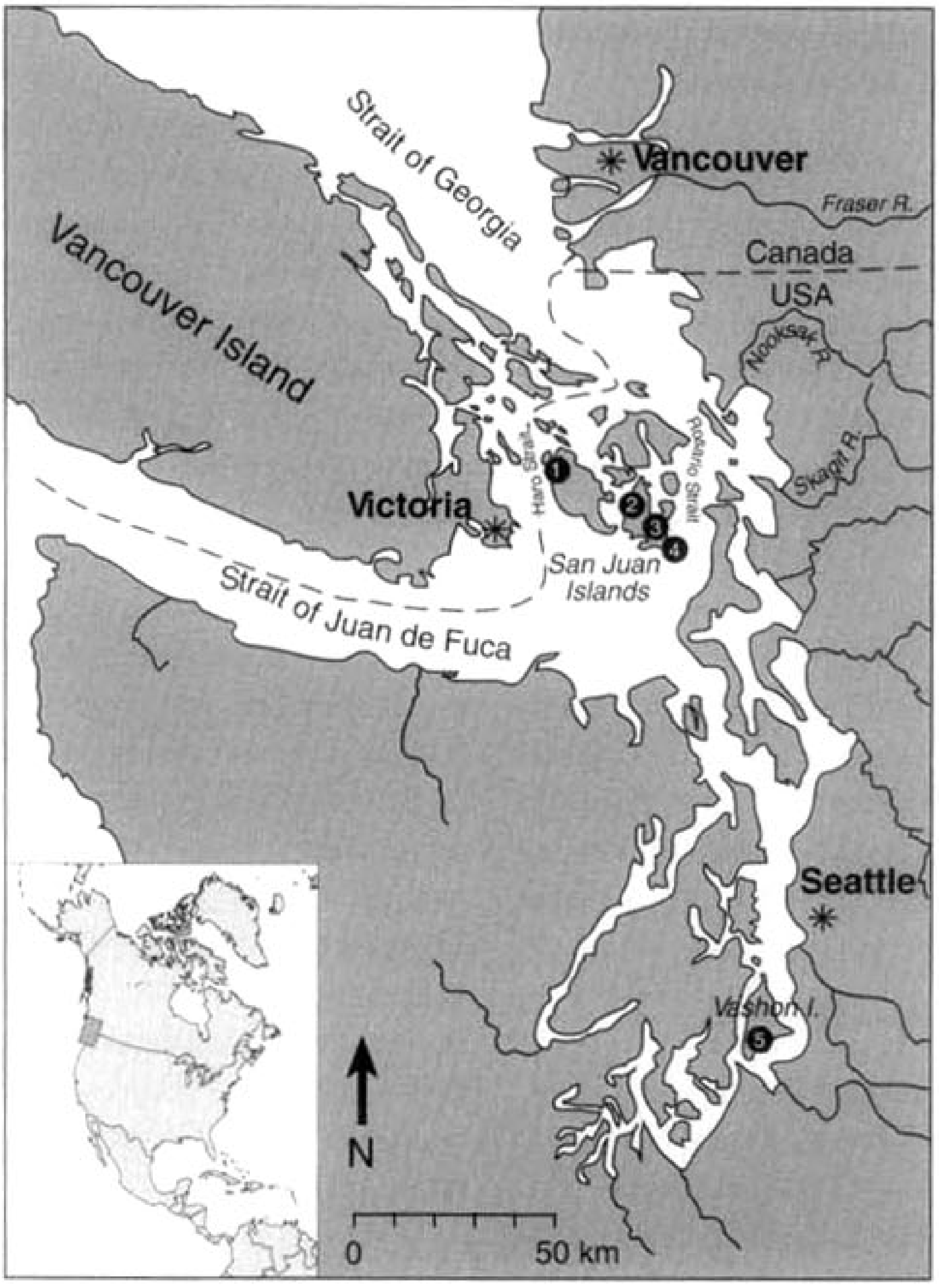
Kennett et al. (1997) investigated the temporal fluctuations in ΔR in the vicinity of Santa Barbara, California, by measuring paired shell and charcoal samples ranging in age from 9200 to 3100 B.P. (Kennett et al. 1997: table 1). These authors found that variations in ΔR correlated with the oxygen and carbon isotopic composition of the shell carbonate, which they attributed to changing intensity of coastal upwelling. Ingram (1998) demonstrated a similar effect in San Francisco Bay, using 15 paired samples from the West Berkeley Shellmound. Periods of high ΔR were found to coincide with aridity, whereas the lowest values of ΔR, in the period 3900–3500 B.P. (Ingram 1998: table 1), correspond to a particularly wet period and suggest a correlation between upwelling and precipitation.

Kovanen and Easterbrook (2002: tables 1–2) report differences in the local reservoir effect for the Fraser Lowland region of the Northwest Coast. There, a total reservoir correction of about 1,100 years more accurately reflects the relationship of shell with contemporaneous wood during the late Pleistocene. The authors attribute their results to operation of a different ocean circulation regime between circa 12,500 and 11,500 B.P.

Methods

Archaeological Materials and Selection Criteria

The samples for this research were removed from collections at the Burke Museum of Natural History and Culture, University of Washington, Seattle. Pairs of charcoal and shell were selected from four shell midden sites in the San Juan Islands and one site on Vashon Island: English Camp Operation D, Fisherman Bay, Mud Bay, Watmough Bay, and Burton Acres Shell Midden (Figure 1). The San Juan Islands are situated in the northwestern corner of Washington State and are bordered by Haro and Rosario straits. Humans have occupied the islands for at least 5,000 years (Stein 2000; Stein et al. 2003), relying on the seasonal abundance of salmon, herring, sea mammals, shellfish, waterfowl, deer, roots, and berries. Vashon Island is located about 100 km south in the protected waters of southern Puget Sound. Archaeological evidence indicates thousands of years of human settlement there, often in the form of shell middens, during which inhabitants harvested a similar suite of



1. 45SJ24, English Camp, San Juan Island
2. 45SJ254, Fisherman Bay Lopez Island
3. 45SJ278, Mud Bay, Lopez Island
4. 45SJ280, Watmough Bay, Lopez Island
5. 45KI347, Burton Acres Shell Midden, Vashon Island

Figure 1. Map of the San Juan Islands and Vashon Island, Washington, and locations of archaeological sites discussed in the text.

Table 1. Excavation Information for Archaeological Sites.

Site name	Site No.	Excavator	Year Excavated	Island	Excavation Interval	References
English Camp, Op D	45SJ24	Julie Stein	1983–1991	San Juan	3-pt provenience	Stein (1992, 2000)
Fisherman Bay	45SJ254	David Munsell	1967–1968	Lopez	3-pt provenience	Field notebooks, Burke Museum, Accn. 1997-115
Mud Bay	45SJ278	David Munsell	1968	Lopez	20 cm	Field notebooks, Burke Museum, Accn. 1996-121
Watmough Bay	45SJ280	David Munsell	1968	Lopez	20 cm	Field notebooks, Burke Museum, Accn. 1996-11
Burton Acres Shell Midden	45KI347	Julie Stein	1996	Vashon	3-pt provenience	Stein and Phillips (2002)

resources (Eells 1887; Elmendorf 1992; Stein and Phillips 2002). See Table 1 and Figure 1 for excavation information and site locations.

The success of this exercise is based largely on the contextual integrity of the charcoal–shell pairs. In order to ensure spatial and temporal proximity, one sample of charcoal and one sample of shell were removed from the same stratigraphic context, in most cases from the same excavation unit and level. Refer to Tables 2–3 for charcoal and shell sample provenience, respectively. Because of our use of previously excavated collections, not every pair was derived from precisely the same provenience. For example, the charcoal and shell designated B_1 were found in the same 8 l of sediment: Unit 2258, Level 2F, Bucket 005, and 43 cm below surface. Other samples were removed from 1 x 1 m units that were excavated by 20 cm arbitrary levels, such as the M_1 samples from Mud Bay, Unit 15N,2W, and 80–100 cm below surface. And finally, some pairs were removed from the same unit but different levels, such as E_1 charcoal from Unit 105/365, Level 1B, and E_1 shell from Unit 105/365, Level 1H. Such a pairing was only made if the sample positions were within centimeters of each other. In the case of the E_1 samples, level 1B is immediately adjacent to 1H in the same 1 x 2 m unit, and the samples were also in close proximity to one another.

In every case, the shell and charcoal were selected from depositional contexts that, to the best of our knowledge, represent the same time periods. But even with these precautions, there is always a chance that the paired samples did not die or were not deposited simultaneously. Several additional criteria were used when selecting sites, excavation units, and samples in order to minimize potential error:

1. Because estuarine environments introduce younger, freshwater carbon and may bias dates obtained from shell (Little 1993; Ulm 2002), sites selected for this study are located away from major streams or rivers to ensure that the shells grew in water of typical salinity. The contribution of freshwater to these sites is minimal, in part because the land masses of the San Juan Islands and Puget Sound Islands are small; the lack of freshwater was and still is a problem for people inhabiting this landform. The Straight of Georgia and Puget Sound are deep trenches of marine water, unlike the shallow San Francisco Bay estuary, and therefore all of the sites considered in this study are marine in nature.

2. Obvious disturbances recorded on the field notes, such as pits or rodent burrows, were avoided when selecting samples.

3. Charcoal samples from short-lived trees or from twigs, branches, or bark were preferentially selected to avoid the "old wood" problem (see Table 2). Interior wood from long-lived trees can be hundreds of years older than the outermost wood when the tree dies and stops exchanging ^{14}C with the atmosphere, and this can result in a radiocarbon date much older than the actual date of the cutting. This issue is especially important on the Northwest Coast, where trees like Douglas fir (*Pseudotsuga menziesii*), Sitka spruce (*Picea sitchensis*), and western red cedar (*Thuja plicata*) commonly grow for several hundred years.

Kennett and others (2002) note that old wood was probably transported as driftwood to extremely arid Peruvian coastlines, where inhabitants would have found other building material and fuel scarce. Though driftwood is indeed a potential fuel source in the Pacific Northwest, its importance in a heavily forested environment was probably minimal. Furthermore, research indicates that driftwood exhibits low oceanic buoyancy times (ten to 17 months for many conifers) and would not measurably accentuate the old wood problem (Eggertsson 1993).

4. Shell samples were identified to ensure that they belong to taxa that live in saltwater, rather than freshwater, environments (see Table 3) and to verify that the species were locally available and not a by-product of long-distance trade. Taxonomic identification is also useful for the detection, and subsequent avoidance, of any recently introduced species, such as Japanese littleneck (*Tapes japonica*) and soft-shell clams (*Mya arenaria*), which may have been mixed postdepositionally with seemingly older deposits.

Another potentially confounding factor is that any given occupation layer may exist at different depths across the site and, as a result, stratigraphic age reversals may appear when dates from the same site are compared. In the study by Stein et al. (2003) accumulation rates were calculated from several of the same middens used in this research. Results indicate that these middens accumulated rapidly but

Table 2. Radiocarbon Dates for Charcoal Samples.

Figure 2 code	Excavation Unit	Depth (cm)	Lab No.	Material[a]	Identification	δ[13]C (‰)[b]	[14]C Age (yr B.P.)	Calibrated Age ± 2s cal B.P. (cal A.D./B.C.)[c]	Intercept (cal B.P.)[c]
English Camp, Operation D, 45SJ24									
E1	105/365 1B 7	85	BETA 84216	Charcoal/EC	Conifer (not *Pseudotsuga menziesii* or *Thuja plicata*)	-25.0*	1470 ± 90	1540-1260 (A.D. 410-690)	1345
E2	105/365 1T 1	176	BETA 84219	Charcoal/EC	Hardwood	-25.0*	1400 ± 90	1520-1170 (A.D. 430-780)	1301
Fisherman Bay, 45SJ254									
F1	Pit A	20	BETA 119307	Charcoal	Mixed conifer bole	-23.4	530 ± 50	570-500 (A.D. 1380-1450)	540
Mud Bay, 45SJ278									
M1	15N,2W	80-100	BETA 119310	Charcoal	Conifer, mixed branch, bole	-26.6	1190 ± 50	1190-970 (A.D. 760-980)	1074
M2	21N,2W	60-80	BETA 119313	Charcoal	*P. menziesii* branch	-25.0*	1090 ± 70	1180-910 (A.D. 780-1040)	977
M3	21N,2W	120-140	BETA 119314	Charcoal	*P. menziesii* bole and bark	-23.2	1240 ± 60	1290-1050 (A.D. 660-900)	1173
M4	66N,0E	80-100	BETA 119315	Charcoal	*Thuja/Tsuga* branch	-25.0*	690 ± 90	770-520 (A.D. 1180-1430)	660
Watmough Bay, 45SJ280									
W1	12S,0E	60-80	BETA 119316	Charcoal	*Thuja/Tsuga* branch	-23.6	2360 ± 50	2500-2310 (B.C. 550-360)	2354
W2	0N,24W	80-100	BETA 119318	Charcoal	*P. menziesii* branch	-25.0	1560 ± 50	1540-1350 (A.D. 410-600)	1417
W3	0N,24W	100-120	BETA 119319	Charcoal	Conifer branch	-24.0	1580 ± 50	1570-1350 (A.D. 380-600)	1424-1496
W4	1N,9W	120-140	BETA 119321	Charcoal	*P. menziesii* bole	-23.5	2200 ± 50	2340-2100 (B.C. 390-150)	2157-2292
W5	9N,3W	160-180	BETA 119324	Charcoal	Conifer branch	-23.8	2640 ± 40	2810-2720 (B.C. 860-780)	2760
Burton Acres Shell Midden, 45KI347									
B1	2258/2F/005	43	BETA 96005	Charcoal	*Pinus* bark	-25.0*	140 ± 80	300-0 (A.D. 1650-1950)	1-266
B2	2258/2G/244	49	KI 101897	Charcoal/AMS	*P. menziesii* bark	-23.3	1230 ± 40	1260-1060 (A.D. 690-890)	1169
B3	2657/2B/004	16	KI 101898	Charcoal/AMS	*Pinus* bark	-23.6	700 ± 40	690-620 (A.D. 1260-1330)	662
B4	2858/2C/009	34	KI 101899	Charcoal/AMS	*P. menziesii* branch	-22.5	110 ± 50	150-10 (A.D. 1800-1940)	43-245
B5	2958/2D/005	38	KI 101900	Charcoal/AMS	*Thuja/Tsuga* branch	-29.2	180 ± 60	310-50 (A.D. 1640-1900)	1-277
B6	2958/2F/008	65	BETA 96013	Charcoal	*P. menziesii* branch	-25.0*	870 ± 50	800-690 (A.D. 1150-1260)	760

[a]Extended counting (EC) or accelerator mass spectrometry (AMS) performed where noted.
[b]Entries marked by an asterisk (*) are estimated values.
[c]Calibrated wood ages were calculated using CALIB 4.0 (Stuiver, Reimer, Bard, Beck, Burr, Hughen, Kromer, McCormac, van der Plicht, and Spurk 1998) and used to generate a marine model age of shell and an associated reservoir age (ΔR).

Table 3. Radiocarbon Data for Shell Samples.

Figure 2 code	Excavation Unit	Depth (cm)	Lab No.	Identification	^{14}C Age (B.P.)[a]
English Camp, Operation D, 45SJ24					
E1	105/365 1H	85	BETA 84218	Unidentified	2370 ± 70
E2	105/365 1T 1	176	BETA 84220	Unidentified	2210 ± 70
Fisherman Bay, 45SJ254					
F1	Pit A	20	CAMS 56446	*Veneridae*	2070 ± 50
Mud Bay, 45SJ278					
M1	15N,2W	80-100	CAMS 56447	*Mollusca*	1610 ± 50
M2	21N,2W	60-80	CAMS 56448	*Pelecypoda*	1510 ± 50
M3	21N,2W	120-140	CAMS 56449	*Saxidomus* sp.	3900 ± 40
M4	66N,0E	80-100	CAMS 56450	*Lottidae*	920 ± 50
Watmough Bay, 45SJ280					
W1	12S,0E	60-80	CAMS 56451	*Protothaca staminea*	3150 ± 40
W2	0N,24W	80-100	CAMS 56454	*Pelecypoda*	2330 ± 50
W3	0N,24W	100-120	CAMS 56455	*Balanus* sp.	2170 ± 50
W4	1N,9W	120-140	CAMS 56453	*Stronglyocentrotus* sp.	2240 ± 50
W5	9N,3W	160-180	CAMS 56452	*Gastropoda*	3320 ± 50
Burton Acres Shell Midden, 45KI347					
B1	2258/2F/005	43	BETA 96004	*Protothaca staminea*	790 ± 200
B2	2258/3A/003	53	BETA 96006	*Protothaca staminea*	1110 ± 80
B3	2657/2B/018	23	BETA 96007	*Tresus nuttalia*	1180 ± 80
B4	2858/3A/001	39	BETA 96008	*Tresus nuttalia*	1150 ± 80
B5	2958/2D/005	38	BETA 96010	*Tresus nuttalia*	1040 ± 60
B6	2958/2F/008	62	BETA 96012	*Tresus nuttalia*	1000 ± 60

[a]$\delta^{13}C$ values were estimated at 0 ‰.

not necessarily *uniformly* across a given site, implying that stratigraphic and chronological integrity may only exist within excavated units. This conclusion is valuable to the interpretation of our dated pairs and emphasizes within-unit comparison rather than cross-site comparison.

Radiocarbon Calculations: Determination of $R_g(t)$ *and* $\Delta R(t)$

The data are presented in a way that shows the overall uncertainty in the calibrated age of the sample pairs and the resulting uncertainty in the value of $\Delta R(t)$. Charcoal ages were calibrated using the INTCAL98 calibration curve and the CALIB 4.0 program of Stuiver and others (Stuiver and Reimer 1993; Stuiver et al. 1998a). The charcoal calibrated ages can be converted into marine model ages using the curves shown in the INTCAL98 publication (1998a: figures B16–B19) or in Stuiver and Braziunas (1993: figures 15A–15B). The resulting marine model age is then subtracted from the conventional shell age to obtain $\Delta R(t)$ (see Table 4 for results). The example presented in Table 5 will help illustrate this process.

Of course, all of the values in the Table 5 example have uncertainties associated with them, which lead to a range of possible values for both the quantity $R_g(t) + \Delta R(t)$ and $\Delta R(t)$ derived from it. In Figure 2, $\Delta R(t)$ is displayed as a two-dimensional probability distribution in both reservoir correction, ΔR, and time, t. Each dot corresponds to the outcome of an individual Monte Carlo trial for a given charcoal–shell pair, with the average value for each sample pair represented by a bold dot.[1] The cumulative density of dots at any point in the diagram indicates the probability of our estimate of $\Delta R(t)$. The value of $\Delta R(t)$ is most probable for those periods of time in which the distributions from several samples overlap. For example, at circa 1400 B.P., a cluster of four sets of dots (four charcoal–shell pairs) group together, which increases the probability of any one pair accurately representing $\Delta R(t)$. The errors given in Table 4 are derived from the distributions shown in Figure 2.

Table 4. Marine Model Ages of Shell and Associated ΔR Values.

Figure 2 code	Marine Model Age of Shell (^{14}C yr B.P.)	ΔR (yr)
English Camp, Operation D, 45SJ24		
E1	1825 (+69/-64)	545 (+95/-98)
E2	1772 (+62/-55)	438 (+89/-94)
Fisherman Bay, 45SJ254		
F1	960 (+26/-40)	1110 (+64/-56)
Mud Bay, 45SJ278		
M1	1537 (+82/-14)	73 (+52/-96)
M2	1453 (+76/-49)	57 (+70/-91)
M3	1619 (+89/-84)	2281 (+93/-98)
M4	1113 (+36/-118)	-193 (+128/-62)
Watmough Bay, 45SJ280		
W1	2700 (+18/-18)	450 (+44/-44)
W2	1894 (+82/-51)	436 (+71/-96)
W3	1919 (+69/-36)	251 (+62/-85)
W4	2556 (+80/-57)	-316 (+76/-94)
W5	3007 (+21/-16)	313 (+52/-54)
Burton Acres Shell Midden, 45KI347		
B1	460-608 (+48)	182-330 (+200/-206)
B2	1614 (+48/-77)	-504 (+111/-93)
B3	1119 (+16/-20)	61 (+82/-82)
B4	460-570 (+51)	580-690 (+80/-95)
B5	460-631 (+37)	409-580 (+60/-70)
B6	1235 (+93/-34)	-235 (+69/-111)

Results

Values of $\Delta R(t)$ calculated from the charcoal–shell pairs are listed in Table 4 and shown in Figure 2. In Figure 2, the dashed line at $\Delta R = +401$ years corresponds to the present-day reservoir effect. Eight of the 18 sample pairs (B_1, B_5, E_1, E_2, W_1, W_2, W_3, W_5) give $\Delta R(t)$ values in agreement with the modern value. A ninth sample, B_4, does not technically overlap with the modern value, but its apparent clustering with other samples from the same site (B_1 and B_5) suggests that it is also in close agreement with a modern value of $\Delta R(t)$.

The remaining data differ from the modern value of ΔR and indicate either a change in the ^{14}C activity of coastal surface waters, a difference in the time of death of the associated shell and wood, or contamination of samples. Times when the ^{14}C activity of coastal surface waters increased to a level closer to the average oceanic ^{14}C activity would give $\Delta R(t)$ values less than +401 years. A value of zero would correspond to a time when regional waters had the same ^{14}C activity as the average oceans. Negative values are possible, but, as shown in Figure 2, values of $\Delta R(t)$ cannot be expected to drop below $-R_g(t)$, which represents the difference between the average ^{14}C age of surface ocean water and the calibrated age of contemporary charcoal. This would imply greater ^{14}C activity in the oceans than the atmosphere, where ^{14}C is produced—a situation that is highly improbable. One of our sample pairs (B_2, in Figure 2) from the Burton Acres Shell Midden site exceeds this lower limit and is most likely the result of site disturbance that brought together a young shell and an older piece of wood. The remaining negative values (B_6, M_4, W_4) come from the Burton Acres Shell Midden, Mud Bay, and Watmough Bay sites, respectively. Their placement below the present value of ΔR suggests possible disturbance, especially for W_4; however, the apparent values for M_4 and B_6 are less extreme and lie well within the realm of plausibility.

The opposite effect occurs in two pairs from the Fisherman Bay and Mud Bay sites (F_1 and M_3,

Table 5. Sample Calculation of the Regional Reservoir Correction, ∅R(t)

	$R(t) = R_g(t) + \Delta R(t)$	
t =	Charcoal calibrated ^{14}C age	= 1345 cal B.P.
R(t) =	The difference between the uncalibrated ^{14}C shell age and the calibrated age of contemporary charcoal	= 2370 B.P. – 1345 cal B.P. = 1025 yr
$R_g(t)$ =	The difference between the average ^{14}C age of surface ocean water (marine model age of shell) and the calibrated age of contemporary charcoal	= 1825 B.P. – 1345 cal B.P. = 480 yr
$\Delta R(t)$ =	$R(t) - R_g(t)$	= 1025 yr – 480 yr = 545 yr

Note: Calculation based on radiocarbon data from charcoal-shell pair "E_1". Refer to Tables 2, 3, and 4 for values used in the example.

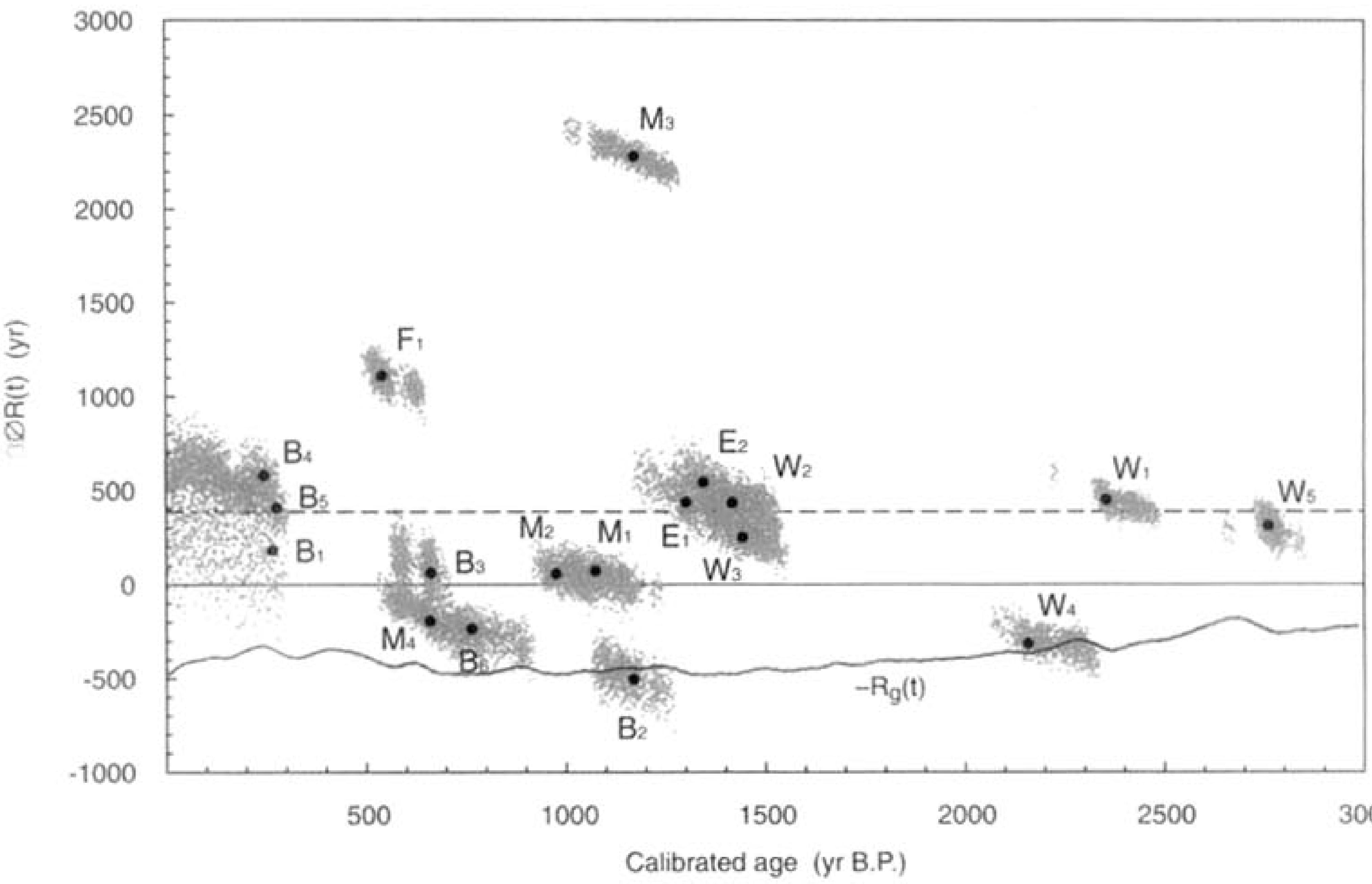


Figure 2. Probability density plot showing estimates of the reservoir correction $\Delta R(t)$ for Puget Sound and Gulf of Georgia, as derived from shell–wood pairs. Grey dots map out the uncertainty regions surrounding each point, based on uncertainties in the calibration of wood ages, the marine model curve, and the radiocarbon dates on shell samples. Samples are recorded by the first letter of the site name (e.g., E = English Camp, F = Fisherman Bay, etc.) followed by an arbitrary number (e.g., E_1, E_2, etc.). The baseline at $\Delta R = 0$ represents the global marine model curve of Stuiver and Braziunas (1993), from which the regional offset in radiocarbon age, $\Delta R(t)$, is determined. The lower curve labeled $-R_g(t)$ indicates the "radiocarbon age" of the atmosphere relative to the global oceans (a "future" value) as a function of time. This is a firm lower limit to the possible value of ΔR; any value falling below this line implies a higher ^{14}C activity in seawater than in the atmosphere, which is impossible. The majority of shell–wood pairs measured in this study give $\Delta R(t)$ values similar to the preindustrial value of 401 years (upper dashed line), but a group of samples dated between 500 and 1200 B.P. suggests a lower $\Delta R(t)$ value during this time.

respectively), in which old shells appear to be associated with younger pieces of wood, giving unreasonably high $\Delta R(t)$ values of circa 1100 B.P. and circa 2300 B.P.

Given the outliers among these data, determining the evolution of $\Delta R(t)$ is a difficult, and somewhat subjective, task. Internal consistency among multiple shell–wood pairs is the most reliable guide. Thus the cluster of points B_1, B_4, and B_5 around ~300 B.P. argues for a value of $\Delta R(t)$ close to the modern value, as does the cluster of four shell–wood pairs between 1300 and 1500 B.P. (E_1, E_2, W_2, W_3). Where there are too few data to assess consistency (e.g., prior to 1500 B.P.) we have adopted the simplest possible assumption, that oceanic conditions and $\Delta R(t)$ were similar to those at the present. Samples W_1 and W_5 at 2350 and 2760 B.P., respectively, are consistent with this assumption, whereas sample W_4 is likely to be an outlier. A further consideration is that changes in oceanic circulation and CO_2 uptake occur slowly, ruling out the possibility of large, rapid fluctuations in $\Delta R(t)$. Thus a rapid oscillation of $\Delta R(t)$ between 300 and 1300 B.P., such as is necessary to include all data points, would violate circulation norms. In this time period, the overlapping points between 660 and 760 B.P. (M_4, B_3, B_6) and the cluster between 970 and 1070 B.P. (M_1, M_2) strongly suggest a value of $\Delta R(t)$ lower than that at present. Sharp swings in $\Delta R(t)$ to accommodate points such as F_1 would require extremely large and rapid changes in the northeast Pacific Ocean carbon cycle about 500 years ago. We are not aware of historical, archeological, or geological evidence supporting such changes. A gradual shift in $\Delta R(t)$ from circa 401 years, to a value close to zero from ~700 to 900 B.P., and then back to circa 401 years again appears to be the most appropriate interpretation of the data.

Excluding the most improbable results and noting that B_6 and M_4 cluster with other samples from Burton Acres and Mud Bay, the data suggest a constant value for $\Delta R(t)$ except in the period between approximately 500 B.P. and 1200 B.P. when $\Delta R(t)$ is consistently lower than its present value of 401 years. The five shell–charcoal pairs from this period (B_3, B_6, M_1, M_2, M_4) give reasonably consistent $\Delta R(t)$ values close to zero, though they come from two separate locations—the San Juan Islands (Mud Bay) and southern Puget Sound (Burton Acres Shell Midden). The agreement among all five data in this time interval indicates a change in water masses mixing in Puget Sound, or upwelling off the Northwest Coast, and is difficult to dismiss as a chance result of disturbance.

Discussion

The observed shifts in ΔR prompted us to consider the physical processes driving those changes and to define a procedure for calibrating dates from this region. Until recently, the procedure for correcting dates from marine samples in the Pacific Northwest has been simply to subtract 801 years, the approximate modern value of the total marine reservoir correction, R (= $R_g + \Delta R$), from conventional ^{14}C dates. This neglects the fact that the global average ^{14}C age of seawater has been changing continuously (Stuiver and Braziunas 1993; Stuiver et al. 1998b), which affects $R_g(t)$, and fails to recognize changes in $\Delta R(t)$ because of shifts in oceanic circulation like the one inferred from this research. Our data give $\Delta R(t)$ values for the last 3,000 years, which, when combined with the calculated values of $R_g(t)$, can be used to create a marine calibration curve for the greater Puget Sound region.

The data indicate that $\Delta R(t)$ was close to its modern value of 401 years during both the last few hundred years (0–500 B.P.) and an earlier period (1200–3000 B.P.). In contrast, during the period circa 500–1200 B.P., $\Delta R(t)$ appears to have dropped close to zero. These three periods were constructed on the basis of the clusters of data in Figure 2 and will be considered separately in the following discussion.

0–500 B.P.

The youngest values of $\Delta R(t)$ for Puget Sound and surrounding ocean waters agree with the results of Stuiver et al. (1998b) and Robinson and Thompson (1981), in that subtracting the global average seawater age from the actual ^{14}C reservoir age of 801 years gives a value of $\Delta R = 401 \pm 24$ years. Both the data presented here and the earlier work of Robinson and Thompson (1981) indicate that the modern value of $\Delta R \oplus 401$ years for Puget Sound is greater than that for coastal waters to the north and south. Ingram and Southon (1996) obtained a value of $\Delta R = 290 \pm 35$ years along the central Californian coast; Erlandson and Moss (1999) report a 240 ± 50 correction for the Oregon coast; and in the north, Southon et al. (1990) and Josenhans et al. (1997) report values of $\Delta R \oplus 200$ years for coastal British Columbia and the Queen Charlotte Islands.

The higher value of ΔR in Washington waters compared with sites north and south suggests a concentration of upwelling offshore, rather than a localized effect confined to Puget Sound. Waters in the sound are continuously exchanged with the open ocean water and are well mixed vertically while transiting the basin, by tidal pumping over shallow sills (Robinson and Thompson 1981:50; Strickland 1983; cf. also Hogg et al. 1998). Salinity is close to open marine values in most of Puget Sound, and freshwater (from the Fraser, Nooksak, and Skagit rivers) is routed through Haro and Rosario straits east and west of our sites. Moreover, estuarine processes and dilution by freshwater would most likely reduce the value of ΔR, not increase it.

Our data (Figure 2) suggest that ΔR was close to its present value during the past 500 years. The difference between the conventional ^{14}C ages of marine shell samples and their actual calibrated ages throughout this period, therefore, is related to variation of the global average ^{14}C age of seawater as calculated by Stuiver et al. (1998b). Figure 3 illustrates the effect of combining a marine model age of average global surface water, $R_g(t)$ (Figure 3a), with a regional reservoir correction, $\Delta R(t)$ (Figure 3b), for Puget Sound/Gulf of Georgia coastal waters. The curve produced from these components is displayed as Figure 3c and was generated from our data. The marine model age is generated from the INTCAL98 calibration curve (Stuiver et al. 1998a).

Note that the preindustrial period is generally taken as prior to 1850 A.D., or 100 B.P. in Figure 3c; the rise in the ^{14}C age of the surface ocean in

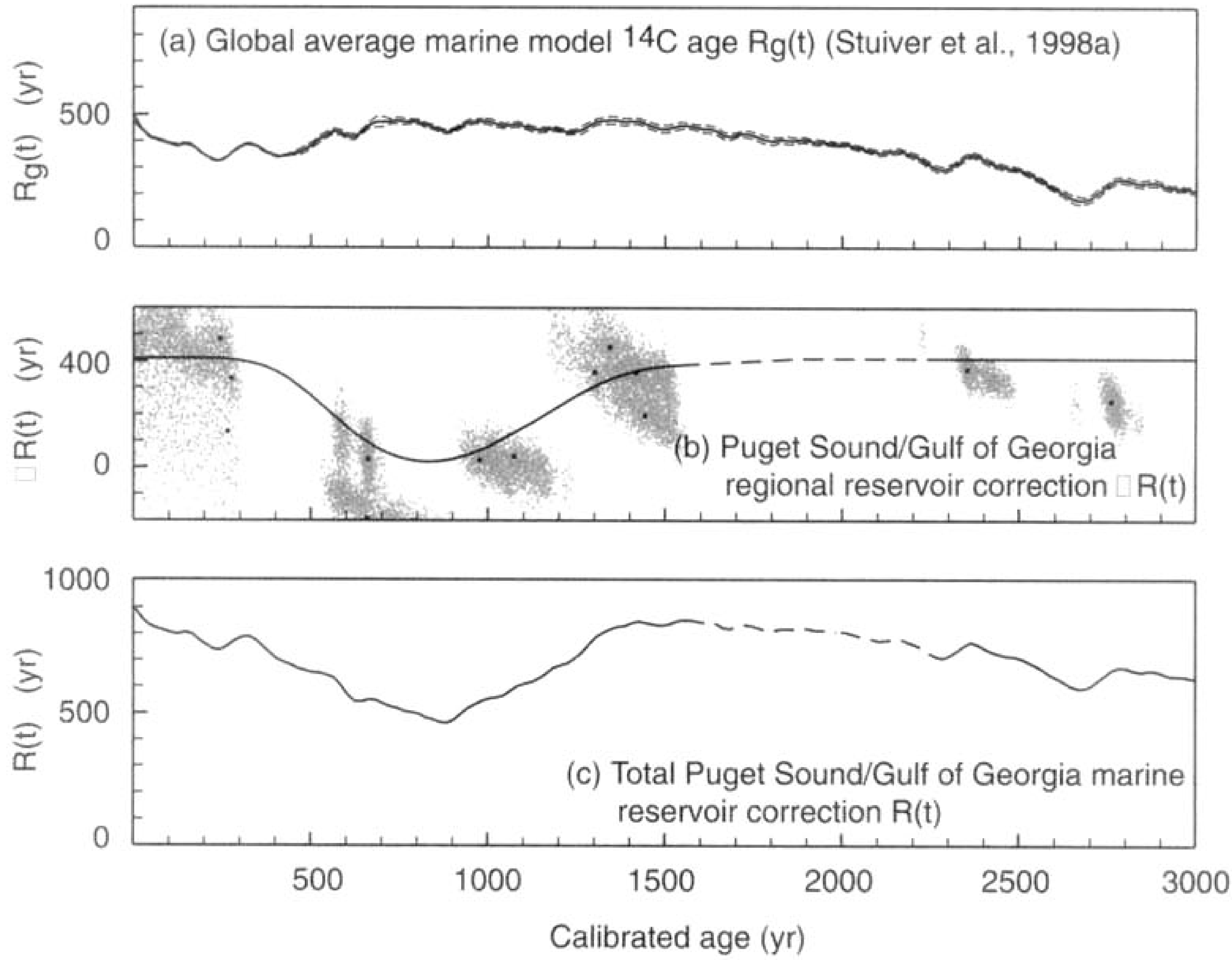


Figure 3. Components of the Pacific Northwest marine calibration curve. (a) The marine model age $R_g(t)$ of average global surface seawater, calculated by Stuiver et al. (1998a). (b) The regional reservoir correction $\Delta R(t)$ for Puget Sound/Gulf of Georgia coastal waters, based on shell–wood pairs measured in this study. $\Delta R(t)$ is assumed constant at 401 years during the intervals 0–500 B.P. and 1200–3000 B.P. but appears to have decreased to a value close to zero between circa 500 and 1200 B.P. Note that the period between 1600 and 2300 B.P. is dashed to reflect the paucity of data points here. The $\Delta R(t)$ curve is a generalized spline fit to the data and is intended to convey their general trend. More data would be required to produce a precise curve with well-constrained uncertainties. (c) The total reservoir correction $R(t)$ obtained by adding the marine model age and $\Delta R(t)$ from Figures 3a–3b. This curve represents the offset between the calibrated age of a sample and its conventional ^{14}C age.

the last 100 years reflects uptake of "old" fossil-fuel-derived ^{14}C by the ocean. During the period from 100 to 500 B.P., the global average ^{14}C age of the surface ocean was generally lower, primarily because of two periods when the average ^{14}C age declined sharply (^{14}C activity in the surface ocean increased). These periods (centered on the early 16th and 18th centuries A.D.) are generally believed to correspond to times when sunspot numbers and solar activity were low, resulting in higher production of ^{14}C by cosmic rays bombarding the upper atmosphere (Stuiver and Quay 1980). The effect was to decrease the apparent ^{14}C age of seawater, resulting in a generally decreasing trend in the total reservoir correction $R(t)$ back to 500 B.P.

500–1200 B.P.

Our results for this period contain a reasonably well-clustered group of samples indicating low values for $\Delta R(t)$ (Figures 2 and 3b). Shell–wood pairs produce clusters at ΔR ⊕60 years (Figure 2; samples B_3, M_1, M_2) and circa –200 years (Figure 2; samples B_6, M_4). The changes in $\Delta R(t)$ were approximated by the curve shown in Figure 3b and then used to construct an illustrative calibration curve from the data (Figure 3c). A spline curve was fitted to the five data mentioned above, which we constrained by the modern value of $\Delta R = 401$ years on either side of the interval where $\Delta R(t)$ decreases. There are too few data to attempt to define the variation of $\Delta R(t)$ more precisely than this spline fit. Therefore, the behavior of $\Delta R(t)$ discussed below should be considered preliminary until further data are obtained.

Changes in reservoir age comparable to these have been observed at other sites on the Pacific coast and attributed to changes in oceanic upwelling or climate. Kennett et al. (1997) identified two periods in the Holocene, one at 3500 B.P. and the other at 9000 B.P., when the ^{14}C activity of waters in the Santa Barbara Channel increased, shifting the local ΔR value from circa 225 years to circa –50 years. These authors attributed the changes to either reduced average wind strength accompanied by decreased coastal upwelling or alterations in the currents bringing water into the channel. Likewise, Baumgartner and Southon (1996) reported declining values of $\Delta R(t)$ over the past 1,500 years in the Santa Barbara Basin, which they, too, attribute to a progressive decrease in upwelling. In a study of paired shell–charcoal samples from the West Berkeley Shellmound in San Francisco Bay, Ingram (1998) also found strong evidence of temporal variations in $\Delta R(t)$. Ingram's study revealed a period between 3800 and 2900 B.P. from which eight shell–charcoal pairs give consistent values of 30 ± 90 years, compared with the modern ΔR value of 365 ± 35 years. The shift in $\Delta R(t)$ is attributed to wet climatic conditions and enhanced freshwater input from the nearby San Joaquin River.

The reduced $\Delta R(t)$ values in our study are more likely attributed to changes in oceanic circulation than to freshwater runoff. The sample pairs in question come from two sites, in the San Juan Islands and southern Puget Sound, which have very different degrees of exposure to freshwater runoff and therefore would not be expected to exhibit similar values of $\Delta R(t)$. More likely, the shift toward lower $\Delta R(t)$ in the period 500–1200 B.P. reflects a period of decreased upwelling offshore.

There is always a chance that the observed patterns are the result of contaminated samples. In this case, organic matter adhering to a shell sample might result in humic or fulvic acid contamination, thereby reducing $\delta^{13}C$ values and leading to younger apparent radiocarbon ages. This effect can be avoided by submitting shells to a phosphoric acid digestion procedure that preferentially liberates CO_2 from the carbonate, rather than from organic compounds. Our shells were submitted to this procedure, and we therefore regard humic and fulvic acid contamination as extremely unlikely. Regrettably, we did not request measurement of stable isotope ratios for the shell samples. If a shellfish had acquired metabolic terrestrial carbon during its life (perhaps through feeding on phytoplankton or detrital organic matter; see Tanaka et al. 1986), it might exhibit depleted $\delta^{13}C$ values and a concomitant reduction in ^{14}C age. Although our patterned data suggest a real temporal deviation in $\Delta R(t)$, these values are nonetheless dependent on the absence of terrestrial carbon in the shell samples. We highly recommend that this step be performed in future reservoir effect studies.

The change in $\Delta R(t)$ during this period has important implications for the correction and interpretation of marine ^{14}C dates. Reduced values of $\Delta R(t)$ imply a corresponding reduction in the total reservoir age to be used when correcting marine dates. As discussed above, the total correction, $R(t)$, is the sum of the global average ^{14}C age of seawater throughout the period, $R_g(t)$, and the regional effect, $\Delta R(t)$, shown in Figures 3a and 3b, respectively. Their sum ($R(t)$; shown in Figure 3c) decreases from circa 750 years at the beginning of the period to a minimum value of less than 500 years. In other words, the conventional ^{14}C age of a shell formed in this period may be offset from its calibrated age by as little as 500 years, compared with the modern-day offset of 801 years. Subtraction of the modern value of 801 years from the conventional ^{14}C age of such a shell would lead to a serious underestimation of its age.

1200–3000 B.P.

Although there is one anomalous result from a pair of samples dated at circa 2200 B.P. (W_4), the remaining six pairs (E_1, E_2, W_1, W_2, W_3, W_5) from this time interval overlap or lie close to the present value of $\Delta R = 401$ years. We therefore take this as the appropriate value of $\Delta R(t)$ throughout the period. The implication is that oceanic conditions were similar to those of the present, in keeping with Holocene terrestrial climate and vegetation records that indicate the establishment of modern conditions west of the Cascade Range by this time (e.g., Sea and Whitlock 1995).

Assuming a constant value for $\Delta R(t)$ during this period, variations in the total reservoir correction $R(t)$ are again related solely to changes in the ^{14}C age of seawater. As shown in Figure 3c, $R(t)$ declined gradually (going back in time from 1200

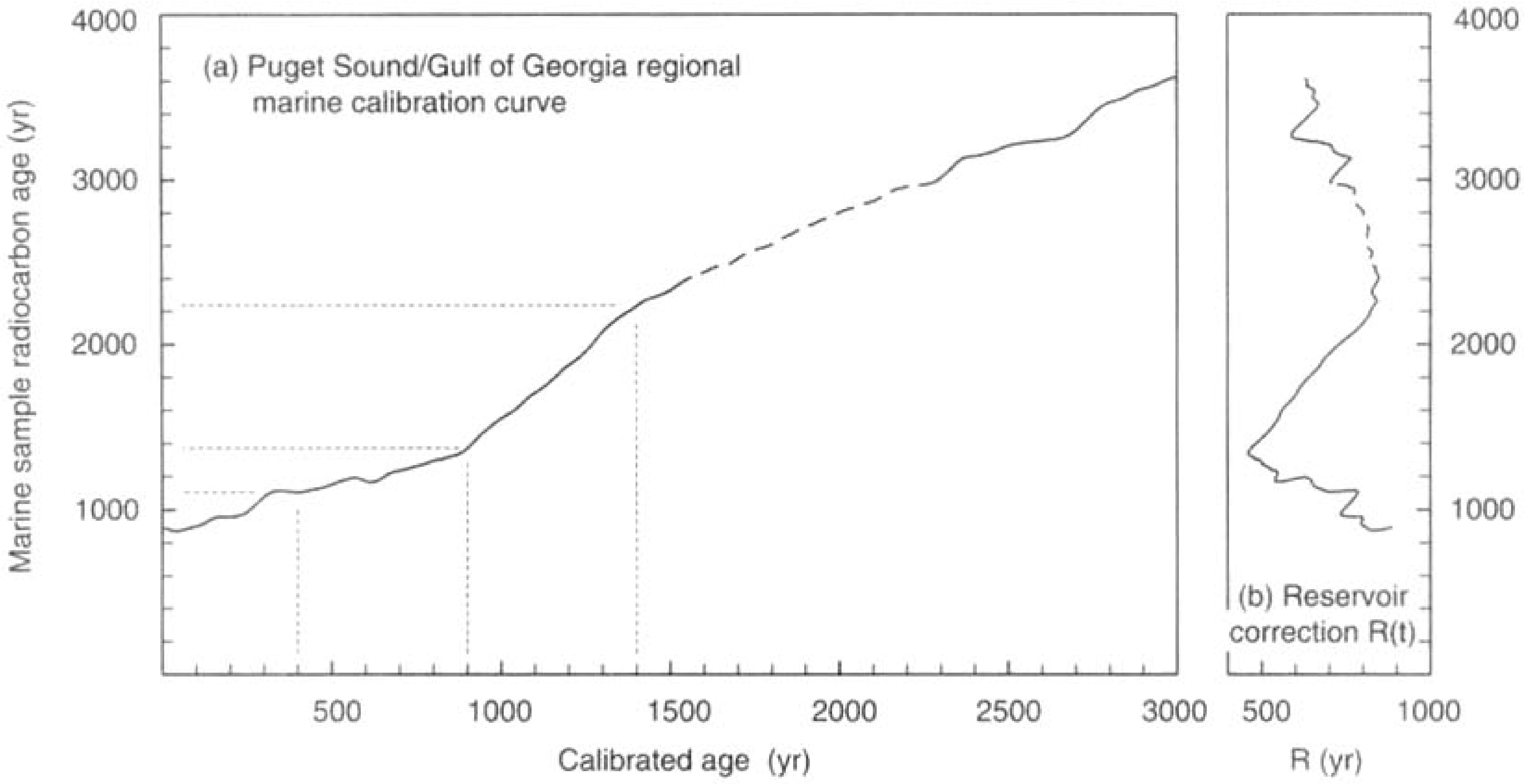


Figure 4. (a) Calibration curve for Puget Sound/Gulf of Georgia, relating the conventional ^{14}C age of a marine sample (vertical axis) to its calibrated age (horizontal axis). Note that the curve is dashed in portions where we have few data points. (b) A plot of the total reservoir correction *R*(*t*) versus conventional ^{14}C age. The curve is equivalent to that of Figure 3c but presented in a way that allows *R*(*t*) to be applied to measured ^{14}C ages, in order to find their corresponding (unknown) calibrated ages. Starting with the conventional ^{14}C age of the sample, the plot gives a value of *R*(*t*). Subtracting this from the conventional ^{14}C age gives the calibrated age. Note that, as with terrestrial samples, calibration of marine ^{14}C dates may give multiple ages in a few time intervals where the curve is double or triple valued. For example, a shell giving a conventional ^{14}C age of 1,110 years has three possible *R* values—785, 735, and 693 years—which would indicate any of three calibrated ages: 325 B.P., 375 B.P., or 417 B.P.

B.P.), reaching a value of 220 years by 3000 B.P. The total reservoir correction at this time was therefore 630 years. As discussed above, correcting ^{14}C dates on marine samples from this period by subtracting 801 years, instead of the correct, time-dependent value of $R(t)$, would underestimate their true ages.

Construction of a Calibration Curve for Marine Samples from the Pacific Northwest

The results discussed in the previous section provide a basis for calibrating conventional ^{14}C ages of marine samples from the Pacific Northwest. The simplest way of doing this is to construct a curve relating conventional ages to their corresponding calibrated ages, in the same way as the familiar tree ring calibration curve (Stuiver et al. 1998a). To use the curve in Figure 4a, the conventional date of a marine sample is located on the vertical axis and a horizontal line traced across to intersect the curve. The x-axis value at the point of intersection is the calibrated age. An alternative, though entirely equivalent, procedure can be used based on the reservoir correction curve in Figure 4b. In this case, tracing across from a conventional ^{14}C age on the y-axis gives a value for the reservoir correction, $R(t)$, on the x-axis. Subtracting this value from the conventional age gives a result that should be directly comparable to a calibrated wood age. It must be stressed that the curves in Figure 4 are based on our estimates of $\Delta R(t)$ for Puget Sound and Gulf of Georgia waters and therefore apply only to marine samples from this region. Equivalent calibration curves for other geographic areas may be produced in the future using similar methods to those used in this study.

Relationship between ^{14}C Ages of Archaeological Shell Samples and Their Calibrated Ages

The calibration curve in Figure 4a shows how the actual ages of marine samples translate into radiocarbon ages. One interesting aspect of the curve is that differences in its slope cause clustering or dispersal of ^{14}C ages. The effect is most pronounced in the period surrounding circa 900 B.P., when $\Delta R(t)$ dropped to its lowest value. The drop in $\Delta R(t)$ causes a flattening of the calibration curve from circa 400 to 900 B.P. and a pronounced steepening prior to this time. Thus the ^{14}C ages of a sequence of marine samples deposited over 500 years from 900 to 1400 B.P. would be effectively spread out over a circa 860-year range from 1370 to 2230 B.P. (see dotted lines in Figure 4). Those ages of samples deposited over the next 500 years would be compressed into a much narrower range of circa 270 years, from 1370 to 1100 B.P.

The clustering of ages into the time when $\Delta R(t)$ was rising and the calibration curve is relatively flat has the potential to distort our perception of the intensity of cultural activity. Using the example developed above, deposits accumulating from a uniform level of activity between 400 and 1400 B.P. would produce dates clustered into the small window of time from 1100 to 1370 B.P. more than three times as frequently as dates in the range 1370–2230 B.P., giving the false impression of heightened activity and an increased deposition rate. Changing concentrations of atmospheric and marine carbon highlight the potential danger of relying on uncalibrated ^{14}C dates and underscore the need for the careful calibration of ^{14}C ages and appropriate application of reservoir corrections.

Conclusion

The marine reservoir effect, consisting of both geographic and temporal components, is known to affect the calibration of shell dates and other materials that derive their carbon from the oceans. As shell is one of the most abundant materials found in Northwest Coast archaeological sites and in many coastal sites around the world, it is only proper that archaeologists devote more time toward understanding the dynamics of oceanic reservoir effects and their impact on datable materials. We are not advocating that shell necessarily be preferred over charcoal when selecting radiocarbon samples. Indeed, charcoal may be targeted for dating precisely in order to avoid additional correction issues. Often, however, shell represents the only source of datable material for a given feature or strata or offers greater stratigraphic integrity than charcoal. It is for these reasons that continued refinement of marine reservoir effects is so imperative.

Although the recognized difficulties in dating shells have come a long way in achieving geographic specificity, the need for temporal corrections in local reservoir ages is recognized as an essential step in correcting shell dates. The results reported here indicate that temporal fluctuations in the reservoir age do exist for certain Pacific Northwest waters during the late Holocene. A failure to recognize and incorporate these effects into the correction of marine-derived radiocarbon dates may lead to the false clustering of dates around a central age or the false spreading of dates that are actually clustered. Conversely, Northwest Coast archaeologists who employ the correction curve produced in this report will lend greater confidence to shell dates and to the subsequent construction of regional chronologies of human occupation.

Some archaeological interpretations may change with the development of a correction curve that takes into account both the geographic and temporal aspects of the marine reservoir. For example, interpretations in the Pacific Northwest that could benefit from more precise dating include clarifying uncertainties in cultural phase boundaries; correlating events in the Gulf of Georgia culture area with those in Puget Sound, coastal British Columbia, and coastal Oregon; understanding the colonization and abandonment of island versus mainland landscapes; and documenting the degree to which human adaptations were contemporaneous with natural disasters (earthquakes, volcanic eruptions, mudslides, tsunamis, etc.).

Although few studies of this nature have been performed, our data corroborate those of researchers investigating archaeological shell in other parts of the Pacific Ocean. We anticipate that reservoir correction research in other parts of the world will also discover temporal variations in the reservoir age, in addition to well-known geographic variations (Stuiver and Braziunas 1993). More studies of this nature are required to build comprehensive regional marine calibration curves that span the Holocene. Archaeologists are demanding greater accuracy from their methods and therefore must pay greater attention to calibration issues.

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Notes

1. Uncertainties in the calculations we have performed cannot be easily represented by conventional "error" statistics, because the end results are strongly non-Gaussian. We need to combine uncertainty in three things to obtain confidence limits on ΔR:

i. uncertainty in the shell ^{14}C age, which we believe is dominated by accelerator mass spectrometry counting-statistical errors and is therefore probably close to Gaussian

ii. uncertainty in the marine model age, for which we take the Gaussian error limits given by Stuiver and Braziunas (1993)

iii. uncertainty in the calibrated age of the charcoal is represented by a probability density curve and may be multipeaked if the ^{14}C age has multiple intersections with the INTCAL calibration curve; for these uncertainties, we used the probability density curves provided by CALIB 4.0

The two major difficulties with combining these uncertainties to obtain confidence limits are that one of them (iii) is non-Gaussian and error in the final quantity $\Delta R(t)$ is strongly correlated with error in the calibrated age. In order to obtain confidence limits we used a Monte Carlo procedure, that is, we simulated the errors based on i, ii, and iii above and computed the calibrated age and $\Delta R(t)$ many times *for each sample*, mimicking the results of doing each of our experiments 800 times. Each of the Monte Carlo trials produces a {calibrated age, $\Delta R(t)$} pair, which plots as a single, small grey dot in Figure 2. Repeating this 800 times for each sample gives a plot in which the density of dots represents the likelihood of the result lying at any given point in {calibrated age, $\Delta R(t)$} space. The confidence limits on the individual $\Delta R(t)$ values in Table 4 are derived from the same probability density calculation. In essence, this is from the density of dots projected onto the x- or y-axis directions in Figure 2. It is evident from the asymmetric cluster of dots in Figure 2 that the upper and lower confidence limits on the calibrated ages and $\Delta R(t)$ values are unequal in most cases.

The graphical representation is a useful way to show the overall uncertainty of our calculations because (1) it shows the joint probability distribution in calibrated age and $\Delta R(t)$ about each result; (2) hence it shows the correlation between these parameters and how the degree of correlation varies from sample to sample (e.g., compare points M_3 and W_5); (3) it shows how asymmetric the confidence intervals in calibrated age and $\Delta R(t)$ can be (e.g., points B_1, B_4, and B_5 or point W_1); and (4) it shows the full probability distribution for each point, not a distribution truncated at 68 or 95 percent confidence.

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