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NEAR-ZERO $\Delta^{14}C$ VALUES AT 32 KYR CAL BP OBSERVED IN THE HIGH-RESOLUTION ^{14}C RECORD FROM U-Th DATED SEDIMENT OF LAKE LISAN

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ABSTRACT. A high-resolution atmospheric radiocarbon record has been obtained for the interval of 17–36 kyr from U/Th-dated aragonite sediment of Lake Lisan. Reservoir age corrections were applied with reservoir ages of 200, 1250, and 2000 yr, which correlate with the different water levels of the lake. The present ^{14}C record for Lake Lisan shows near resemblance with that of Lake Suigetsu: both converge to the value of $\Delta^{14}C$ ~0‰ at 32 kyr cal BP. Both also show significant differences compared to other reported high-resolution ^{14}C records (e.g. Iceland Sea, Cariaco basin, and Bahamas speleothem). This inconsistency should be addressed by re-assessment of the basic assumptions behind the determination of calendar ages of the various records.

INTRODUCTION

The ratio of ^{14}C to ^{12}C in atmospheric carbon dioxide, which is the basis of radiocarbon dating, is not constant but varies due to changes in the ^{14}C production as well as changes in the carbon cycle. Thus, ^{14}C dating requires a calibration curve for transforming ^{14}C ages to calendar years. Many laboratories contributed to the present calibration curve INTCAL98 (Stuiver et al. 1998), which is a detailed record of ^{14}C age versus calendar age for the interval of 0 to 24 kyr cal BP. The interval between 0 to 11.9 kyr cal BP has been established from ^{14}C ages of tree rings identified from dendrochronology, while the portion from 11.9 to 24 kyr cal BP relies mainly on corals and marine sediments. However, while the tree-ring archive yields a direct relation between the ^{14}C age (recorded as the atmospheric ratio of ^{14}C to ^{12}C) versus identified calendar age, other archives are hampered either by problems with reservoir age determination or by incorrect calendar age identification (e.g. sedimentary hiatuses, problems in precise U-Th dating).

Coral samples have been used to derive calendar ages from 7–41 kyr cal BP by combining U/Th dating and accelerator mass spectrometry (AMS) ^{14}C ages (Bard et al. 1998). The atmospheric $^{14}C/^{12}C$ ratio has been deduced from the corals, assuming a constant marine reservoir age of 400 yr. However, the coral data in combination with floating chronologies yield a detailed calibration curve between 11.9 and 16 kyr cal BP, but for the older ages, the coral data are scarce, and for the interval of 16–24 kyr cal BP, INTCAL98 uses a spline function through the coral data points.

Other detailed ^{14}C records with ages >24 kyr cal BP have been reported, but could not be used for INTCAL98 because of lacking consensus on their validity. Figure 1 shows detailed $\Delta^{14}C$ records for the interval of 15–45 kyr cal BP (all with 1-σ errors) from sediments of the Iceland Sea (Voelker et al. 1998), the Cariaco Basin (Hughen et al. 2004), Lake Suigetsu (Kitagawa and van der Plicht 1998), and a Bahamas stalagmite (Beck et al. 2001). Also shown are the coral data (Bard et al. 1998) and the prior data from Lake Lisan (Schramm et al. 2000) with corrected ^{14}C ages in Haase-Schramm et al. (2004). The various records agree reasonably well for the interval of 15–25 kyr cal BP, but for the higher ages, large discrepancies are present. The Lake Suigetsu record shows lower $\Delta^{14}C$ values than the other records, whereas the stalagmite record shows higher $\Delta^{14}C$ values than the

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others. The ^{14}C records, as determined from foraminifera of the Iceland Sea and the Cariaco Basin laminae, are similar, which may be expected as both age scales, has been derived by matching the stable isotope records with the GISP2 ice core. In spite of the large differences between the records, it is remarkable that all agree with coral data. The data points for Lake Lisan (Haase-Schramm et al. 2004) also agree with the coral data and with the data for the Iceland Sea and the Cariaco Basin.

In this paper, we extend the pioneering work of Schramm et al. (2000) with a high-resolution record of Lake Lisan, the Last Glacial Dead Sea, which existed between 14–70 kyr cal BP (Kaufman 1971; Haase-Schramm et al. 2004). During its highest stand (~170 m below mean sea level), the lake covered a large area of the Jordan-Arava Valley from the Sea of Galilee in the north to Hazeva in the south (Begin et al. 1974). The lake deposits consist of millimeter-thin laminae of aragonite and fine silty detritus, plus gypsum and thicker clastic layers. The annually-laminated authigenic aragonite recorded U and ^{14}C and, thus, provides an excellent opportunity to generate a high-resolution ^{14}C record for ages larger than 15 kyr cal BP, which can be compared with the other published ^{14}C records, illuminating the way to achieve consensus among these apparently conflicting records.

METHODS

Samples were taken from the sedimentary section PZ1, located in the Perazim Valley (southwest of the present Dead Sea), which was used to determine the high-resolution U-Th chronology (Haase-Schramm et al. 2004). The lithology and geochemistry of this section has been thoroughly studied and described (Stein et al. 1997; Haase-Schramm et al. 2004). Aragonite samples were prepared from 1–2 individual laminae scratched from individual sediment blocks that were sampled continuously along the PZ1 section. The average spacing between consecutive samples is 7 cm, corresponding to ~100 yr. Two wood pieces were found within the aragonite, allowing for direct comparison between organic and inorganic carbon.

The ^{14}C analysis was performed at Utrecht University (van der Borg et al. 1997). Acid evolution of CO_2 from the carbonate samples was carried out in an evacuated glass line. Wood samples received an HCl wash to remove carbonate traces before they were combusted to CO_2. The collected CO_2 from the samples was then converted into graphite for ^{14}C analysis.

U-Th ages on the PZ1 sedimentary profile were determined by Haase-Schramm et al. (2004), who provided detailed explanation of the analytical and calculation procedures to achieve ^{230}Th-^{234}U of Lisan aragonite. The calendar age of the aragonite samples was obtained using the age-height regression relation $t = 1.400\ h + 68.54$, with h the height in the PZ1 section in meters and t the calendar age in kyr. The 1-σ error in the calendar age was estimated at 400 yr.

RESULTS AND DISCUSSION

The measured ^{14}C ages of the aragonite samples form a record of the bi-carbonate that was provided to the lake by the incoming runoff and spring water (Stein et al. 1997). The corresponding atmospheric ^{14}C record is obtained by correcting the aragonite ages with the reservoir age of the lake at the time the aragonite was deposited. With the 2 samples of wood remains found within the aragonite layers, we assume to derive reservoir ages the corresponding ages. Table 1 shows the ^{14}C ages measured for the wood and aragonite samples. We determine the calendar age of the aragonite samples from the sample position using the above-mentioned U-Th regression. Assuming a negligible age for the wood when it became locked in the sediment, we obtain reservoir ages of 1250 ± 180 yr at 23.0 kyr cal BP and 200 ± 500 yr at 32.7 kyr cal BP. Previous analyses of aragonite-organic debris pairs from the same horizon suggest a higher reservoir age of 1260 to 2000 yr

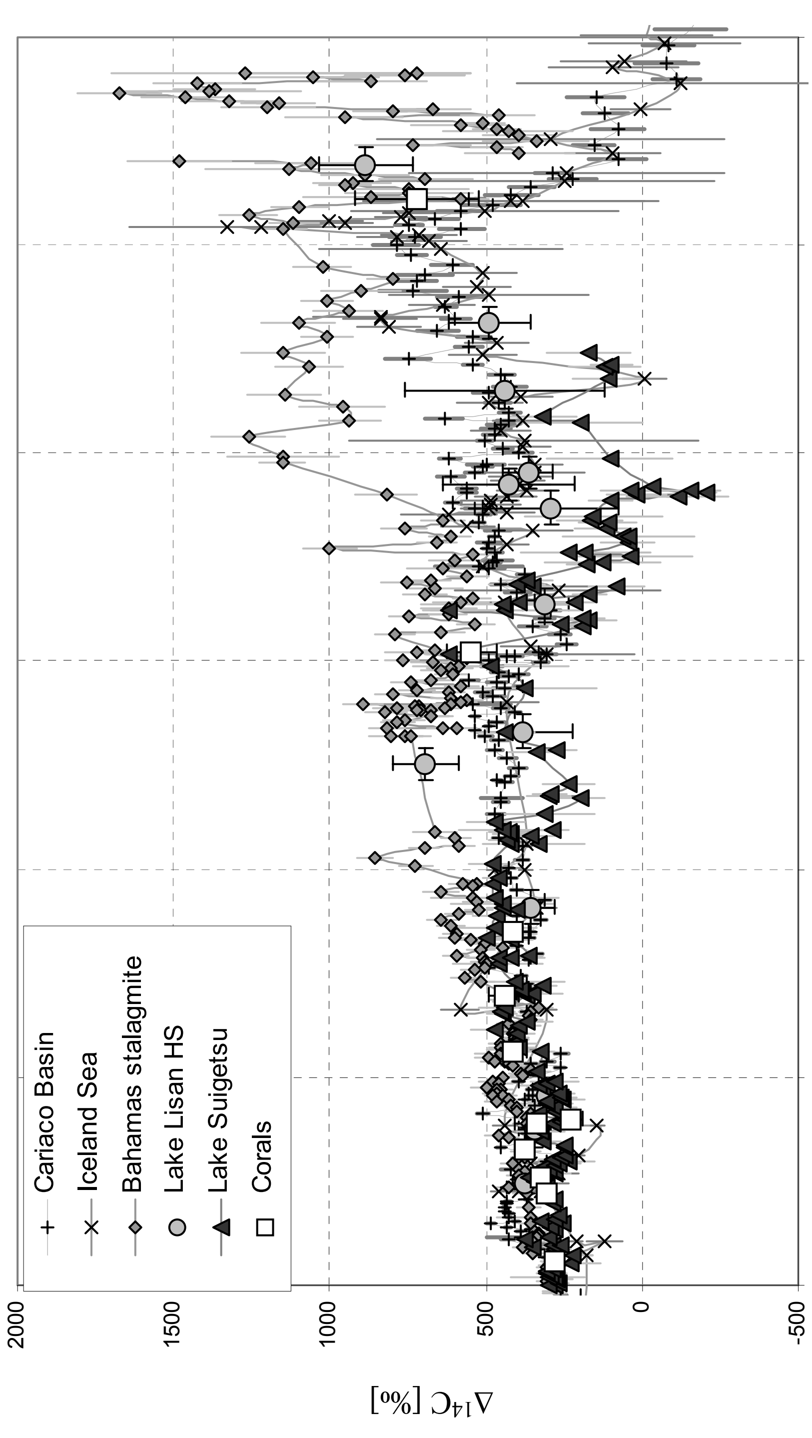

Figure 1 Comparison of high-resolution ^{14}C records versus calendar age from macrofossils of Lake Suigetsu, of sediments of the Iceland Sea and the Cariaco Basin, of a Bahamas stalagmite, of corals, and of aragonite from Lake Lisan.

(average = 1600 ± 250 yr) for the high-stand period of the lake between 19 and 26 kyr cal BP (see data and discussion of the relation between the reservoir ages and the hydrological-limnological conditions in Stein et al., these proceedings).

Table 1 Reservoir age of Lake Lisan from ^{14}C analysis.

Sample name	Height (cm)	U/Th age (cal BP)	Analyzed fraction	$\delta^{13}C$ (‰)	^{14}C age (BP)	Lab code UtC-	Reservoir age (BP)
ID-455w	3247	—	wood	–21.0	20,710 ± 130	12138	—
ID-455a	3247	23,000 ± 400	aragonite	1.6	21,960 ± 130	12172	1250 ± 180
PZ2-2558w	2558	—	wood	–21.9	30,300 ± 400	12278	—
PZ2-2558a	2558	32,700 ± 400	aragonite	1.3	30,500 ± 300	12277	200 ± 500

Using these various reservoir ages, we determine the atmospheric ^{14}C record for Lake Lisan, expressed as $\Delta^{14}C$ values (Table 2). The table includes the height in the section, the calendar age as calculated from the U-series age regression relationship, the estimated reservoir age, and the corresponding $\Delta^{14}C$ values. The uncertainty in the calendar age from U-Th dating for the sample series is smaller than the 400-yr uncertainty deduced from the regression analysis. The average spacing for the samples in the regression analysis was 130 cm, while the average spacing in the high-resolution record is 7 cm. As the regression analysis assumes a constant sedimentation rate, which is likely the largest source of error, the age uncertainty for the sample series is proportional to the spacing, resulting in an average error of 20 yr.

Table 2 Results of the high-resolution ^{14}C analysis for Lake Lisan.

Sample name	Height (cm)	U/Th age (cal BP)	$\delta^{13}C$ (‰)	^{14}C age (BP)	Lab code UtC-	Reservoir age (BP)	$\Delta^{14}C$ (‰)
PZ1-c14	3654.3	17,380	0.4	16,240 ± 80	11265	1250	267 ± 25
PZ1-c13	3652.0	17,412	2.0	15,650 ± 70	11264	1250	368 ± 24
PZ1-c12	3648.6	17,460	1.2	15,580 ± 90	11263	1250	388 ± 31
PZ1-c11	3642.0	17,552	2.0	15,560 ± 80	11262	1250	407 ± 28
PZ1-c10	3639.2	17,591	3.2	15,720 ± 80	11261	1250	386 ± 28
PZ1-c9	3632.5	17,685	1.1	15,890 ± 80	11260	1250	373 ± 27
PZ1-c8	3626.4	17,770	2.3	16,250 ± 80	11259	1250	326 ± 26
PZ1-c7	3620.2	17,857	1.0	16,380 ± 90	11245	1250	319 ± 30
PZ1-c6	3613.8	17,947	2.6	16,410 ± 100	11244	1250	328 ± 33
PZ1-c5	3610.0	18,000	3.3	16,330 ± 90	11243	1250	350 ± 30
PZ1-c4	3609.5	18,007	3.2	16,260 ± 90	11242	1250	363 ± 31
PZ1-c3	3608.8	18,017	1.7	16,220 ± 100	11241	1250	371 ± 34
PZ1-c2	3608.2	18,025	0.7	15,620 ± 90	11240	1250	479 ± 33
PZ1-c1	3607.5	18,035	1.1	15,910 ± 100	11239	1250	428 ± 36
PZ1-c15	3603.8	18,087	2.1	16,460 ± 80	11266	1250	342 ± 27
PZ1-c16	3598.5	18,161	0.6	16,240 ± 80	11267	1250	392 ± 28
PZ1-c17	3593.5	18,231	3.0	16,380 ± 80	11268	1250	380 ± 27
PZ1-c18	3591.8	18,255	3.3	16,420 ± 90	11246	1250	377 ± 31
PZ1-c19	3584.8	18,353	3.3	16,420 ± 90	11269	1250	393 ± 31
PZ1-c20	3579.7	18,424	1.7	16,520 ± 80	11270	1250	388 ± 28
PZ1-c21	3575.2	18,487	1.6	16,870 ± 80	11271	1250	339 ± 27
PZ1-c22	3567.5	18,595	0.7	16,890 ± 90	11272	1250	353 ± 30
PZ1-c23	3562.6	18,664	–0.5	16,890 ± 100	11273	1250	364 ± 34
PZ1-c24	3557.5	18,735	0.1	16,950 ± 100	11274	1250	366 ± 34
PZ1-c25	3552.2	18,809	1.8	16,990 ± 90	11275	1250	371 ± 31
PZ1-c26	3545.6	18,902	0.2	17,050 ± 100	11276	1250	376 ± 34
PZ1-c27	3539.4	18,988	2.7	17,200 ± 90	11277	1250	365 ± 31
PZ1-c28	3533.0	19,078	3.2	17,630 ± 100	11247	1250	308 ± 33

Table 2 Results of the high-resolution ^{14}C analysis for Lake Lisan. *(Continued)*

Sample name	Height (cm)	U/Th age (cal BP)	$\delta^{13}C$ (‰)	^{14}C age (BP)	Lab code UtC-	Reservoir age (BP)	$\Delta^{14}C$ (‰)
PZ1-c29	3528.8	19,137	0.5	17,500 ± 90	11278	1250	339 ± 30
PZ1-c30	3522.3	19,228	1.1	17,440 ± 100	11279	1250	364 ± 34
PZ1-c31	3516.8	19,305	3.5	17,960 ± 100	11280	1250	290 ± 32
PZ1-c32	3510.9	19,387	0.7	18,070 ± 110	11281	1250	286 ± 35
PZ1-c33	3506.6	19,448	0.2	18,010 ± 100	11282	1250	305 ± 32
PZ1-c34	3501.0	19,526	1.3	18,426 ± 100	11283	1250	251 ± 31
PZ1-c35	3495.1	19,609	2.1	18,280 ± 100	11284	1250	286 ± 32
PZ1-c36	3489.4	19,688	1.0	18,100 ± 100	11285	1250	328 ± 33
PZ1-c37	3483.7	19,768	2.4	18,290 ± 100	11286	1250	310 ± 33
PZ1-c38	3477.9	19,849	1.7	18,510 ± 110	11248	1250	287 ± 35
PZ1-c39	3472.2	19,929	1.7	19,070 ± 100	11287	1250	212 ± 30
PZ1-c40	3467.2	19,999	0.6	18,280 ± 110	11288	1250	349 ± 37
PZ1-c41	3462.2	20,069	1.5	18,690 ± 110	11289	1250	293 ± 35
PZ1-c42	3455.4	20,164	5.7	18,990 ± 130	11290	1250	260 ± 41
PZ1-c43	3443.3	20,334	1.3	19,150 ± 130	11291	1250	260 ± 41
PZ1-c44	3438.3	20,404	0.4	18,740 ± 110	11292	1250	338 ± 37
PZ1-c45	3432.1	20,491	1.2	18,950 ± 120	11293	1250	317 ± 39
PZ1-c46	3426.4	20,570	2.2	19,120 ± 110	11294	1250	302 ± 36
PZ1-c47	3420.0	20,660	3.9	18,910 ± 130	11295	1250	351 ± 44
PZ1-c48	3414.4	20,738	3.3	19,270 ± 120	11249	1250	304 ± 39
PZ1-c49	3406.3	20,852	1.9	19,220 ± 120	11296	2000	460 ± 44
PZ1-c50	3398.7	20,958	0.8	19,220 ± 120	11297	2000	479 ± 44
PZ1-c51	3395.3	21,006	1.4	19,820 ± 170	11298	2000	381 ± 58
PZ1-c52	3392.4	21,046	1.8	19,330 ± 130	11299	2000	475 ± 48
PZ1-c53	3387.6	21,114	2.4	19,620 ± 120	11300	2000	434 ± 43
PZ1-c54	3379.1	21,233	1.9	19,660 ± 130	11301	2000	448 ± 47
PZ1-c55	3373.4	21,312	–0.4	19,520 ± 110	11302	2000	487 ± 41
PZ1-c56	3368.2	21,385	2.9	19,810 ± 110	11303	2000	447 ± 40
PZ1-c57	3363.0	21,458	0.3	19,860 ± 120	11304	2000	451 ± 43
PZ1-c58	3357.4	21,536	0.5	19,720 ± 130	11250	2000	491 ± 48
PZ1-c59	3354.5	21,577	0.9	19,520 ± 120	11305	2000	536 ± 46
PZ1-c60	3350.8	21,629	2.9	19,840 ± 120	11306	2000	485 ± 44
PZ1-c61	3346.0	21,696	4.3	19,910 ± 130	11307	2000	484 ± 48
PZ1-c62	3342.0	21,752	0.5	20,030 ± 130	11308	2000	472 ± 48
PZ1-c63	3336.6	21,828	3.1	20,160 ± 120	11309	2000	462 ± 44
PZ1-c64	3331.4	21,900	3.4	20,140 ± 130	11310	2000	478 ± 48
PZ1-c65	3327.3	21,958	0.8	20,340 ± 120	11311	2000	452 ± 43
PZ1-c66	3321.2	22,043	2.5	20,470 ± 120	11312	2000	444 ± 43
PZ1-c67	3312.6	22,164	2.9	20,820 ± 140	11313	2000	402 ± 49
PZ1-c68	3307.0	22,242	1.3	20,810 ± 140	11251	2000	417 ± 49
PZ1-c69	3300.4	22,334	0.8	20,640 ± 140	11314	2000	464 ± 51
PZ1-c70	3292.2	22,449	–0.3	20,890 ± 140	11315	2000	439 ± 50
PZ1-c71	3286.0	22,536	0.0	21,640 ± 130	11316	2000	325 ± 43
PZ1-c72	3280.7	22,610	0.4	21,070 ± 130	11317	2000	435 ± 46
PZ1-c73	3275.5	22,683	–0.3	21,230 ± 140	11318	2000	419 ± 49
PZ1-c74	3270.2	22,757	0.3	21,470 ± 130	11319	2000	390 ± 45
PZ1-c75	3265.6	22,822	1.8	21,080 ± 120	11320	2000	470 ± 44
PZ1-c76	3260.4	22,894	0.4	21,210 ± 140	11321	2000	459 ± 51
PZ1-c77	3256.8	22,945	2.0	21,230 ± 140	11322	2000	465 ± 51
PZ1-c78	3249.1	23,053	2.8	21,480 ± 170	11252	2000	438 ± 61
PZ1-c79	3244.4	23,118	–0.7	22,110 ± 150	11323	2000	341 ± 50
PZ1-c80	3239.0	23,194	0.2	22,350 ± 140	11324	2000	313 ± 46
PZ1-c81	3232.2	23,289	0.5	21,710 ± 160	11325	2000	438 ± 57
PZ1-c82	3226.0	23,376	0.1	21,950 ± 140	11326	2000	411 ± 49
PZ1-c83	3218.1	23,487	0.1	22,010 ± 140	11327	2000	419 ± 49

Table 2 Results of the high-resolution ^{14}C analysis for Lake Lisan. *(Continued)*

Sample name	Height (cm)	U/Th age (cal BP)	δ^{13}C (‰)	^{14}C age (BP)			Lab code UtC-	Reservoir age (BP)	Δ^{14}C (‰)		
PZ1-c84	3204.7	23,674	1.6	21,850	±	140	11328	2000	481	±	52
PZ1-c85	3196.4	23,790	0.2	22,230	±	140	11329	2000	432	±	50
PZ1-c86	3188.4	23,902	1.3	22,310	±	140	11330	2000	438	±	50
PZ1-c87	3181.6	23,998	1.6	22,310	±	160	11331	2000	454	±	58
PZ1-c88	3174.2	24,101	1.1	22,450	±	170	11253	2000	447	±	61
PZ1-c89	3167.8	24,191	1.4	22,680	±	150	11332	2000	422	±	53
PZ1-c90	3157.9	24,329	1.3	22,680	±	150	11333	2000	446	±	54
PZ1-c91	3149.0	24,454	1.8	22,680	±	160	11334	2000	468	±	58
PZ1-c92	3141.2	24,563	1.5	22,640	±	150	11335	2000	495	±	56
PZ1-c93	3133.1	24,677	1.8	23,070	±	140	11336	2000	436	±	50
PZ1-c94	3125.7	24,780	–0.5	23,390	±	180	11254	2000	398	±	63
PZ1-c97	3102.4	25,106	1.5	23,420	±	100	11622	2000	448	±	36
PZ1-c98	3095.4	25,204	1.4	23,370	±	120	11623	1250	343	±	40
PZ1-c99	3084.3	25,360	1.0	23,200	±	100	11624	1250	398	±	35
PZ1-c100	3074.4	25,498	–0.2	23,480	±	110	11625	1250	373	±	38
PZ1-c101	3063.5	25,651	2.0	23,700	±	120	11626	1250	361	±	41
PZ1-c102	3053.5	25,791	1.3	23,640	±	120	11627	1250	394	±	42
PZ1-c103	3046.3	25,892	0.8	23,600	±	120	11628	1250	419	±	42
PZ1-c104	3038.7	25,998	1.5	23,940	±	110	11629	1250	377	±	38
PZ1-c105	3029.7	26,124	0.9	24,380	±	140	11630	1250	324	±	46
PZ1-c106	3020.2	26,257	2.1	24,070	±	110	11631	1250	398	±	38
PZ1-c107	3010.9	26,387	0.1	24,280	±	120	11632	1250	384	±	41
PZ1-c108	2999.7	26,544	1.3	24,630	±	120	11633	1250	350	±	40
PZ1-c109	2991.0	26,666	2.6	24,630	±	120	11634	1250	370	±	41
PZ1-c110	2982.4	26,786	2.4	25,040	±	110	11635	1250	321	±	36
PZ1-c111	2972.9	26,919	2.2	25,000	±	110	11636	1250	349	±	37
PZ1-c112	2965.3	27,026	0.2	25,110	±	110	11637	1250	348	±	37
PZ1-c113	2959.0	27,114	0.7	25,390	±	110	11638	1250	316	±	36
PZ1-c114	2953.3	27,194	1.7	25,220	±	130	11639	1250	357	±	44
PZ1-c115	2947.5	27,275	2.0	25,240	±	130	11640	1250	367	±	44
PZ1-c116	2940.3	27,376	1.4	25,470	±	120	11641	1250	345	±	40
PZ1-c117	2933.0	27,478	3.0	25,480	±	120	11642	1250	360	±	41
PZ1-c118	2927.2	27,559	–0.5	26,160	±	130	11643	1250	262	±	41
PZ1-c119	2923.1	27,617	0.3	26,210	±	130	11644	1250	263	±	41
PZ1-c122	2907.5	27,835	1.8	25,740	±	120	11647	1250	375	±	41
PZ1-c120	2906.4	27,850	1.5	26,080	±	130	11645	1250	320	±	43
PZ1-c121	2899.7	27,944	0.9	25,840	±	140	11646	1250	376	±	48
PZ1-c123	2893.8	28,027	1.6	26,290	±	130	11648	1250	314	±	43
PZ1-c124	2884.8	28,153	0.7	26,250	±	130	11649	1250	341	±	43
PZ1-c125	2876.6	28,268	1.9	26,380	±	150	11650	1250	338	±	50
PZ1-c126	2868.4	28,382	1.3	26,590	±	130	11651	1250	321	±	43
PZ1-c127	2863.0	28,458	1.7	26,930	±	120	11652	1250	278	±	38
PZ1-c128	2855.4	28,564	1.5	26,860	±	140	11653	1250	306	±	46
PZ1-c129	2852.4	28,606	1.2	27,210	±	140	11654	1250	257	±	44
PZ1-c130	2841.9	28,753	1.9	26,860	±	120	11655	1250	336	±	40
PZ1-c131	2835.2	28,847	1.4	26,880	±	120	11656	1250	348	±	40
PZ1-c132	2832.2	28,889	2.0	27,120	±	120	11657	1250	315	±	39
PZ1-c133	2828.6	28,940	1.5	27,230	±	120	11658	1250	305	±	39
PZ1-c134	2826.7	28,966	2.0	27,160	±	140	11659	1250	321	±	46
PZ1-c135	2820.5	29,053	1.3	27,580	±	150	11660	1250	267	±	47
PZ1-c136	2818.8	29,077	1.0	27,650	±	150	11661	1250	260	±	47
PZ1-c137	2813.4	29,152	0.5	27,700	±	130	11662	1250	263	±	41
PZ1-c138	2804.8	29,273	0.4	27,780	±	130	11663	1250	269	±	41
PZ1-c139	2796.1	29,395	1.6	27,550	±	150	11664	1250	325	±	49
PZ1-c140	2789.4	29,488	3.3	27,600	±	150	11665	1250	332	±	50

Table 2 Results of the high-resolution ^{14}C analysis for Lake Lisan. *(Continued)*

Sample name	Height (cm)	U/Th age (cal BP)	$\delta^{13}C$ (‰)	^{14}C age (BP)			Lab code UtC-	Reservoir age (BP)	$\Delta^{14}C$ (‰)		
PZ1-c141	2782.4	29,586	1.4	28,040	±	160	11666	1250	276	±	51
PZ1-c142	2775.0	29,690	1.7	27,430	±	120	11692	1250	394	±	42
PZ1-c143	2767.4	29,796	1.4	28,410	±	140	11693	1250	250	±	44
PZ1-c144	2759.3	29,910	1.1	28,720	±	150	11694	1250	219	±	46
PZ1-c145	2752.1	30,011	1.5	28,440	±	140	11695	1250	278	±	45
PZ1-c146	2743.8	30,127	1.4	28,750	±	150	11696	1250	247	±	47
PZ1-c147	2736.8	30,225	2.0	28,750	±	150	11697	1250	262	±	47
PZ1-c148	2730.1	30,319	1.8	28,990	±	150	11698	1250	239	±	46
PZ1-c149	2724.1	30,403	3.6	29,130	±	150	11699	1250	230	±	46
PZ1-c150	2714.6	30,536	2.3	29,260	±	190	11700	1250	230	±	58
PZ1-c151	2705.8	30,659	0.5	29,260	±	160	11701	1250	248	±	50
PZ1-c152	2699.0	30,754	2.1	29,230	±	150	11702	1250	267	±	47
PZ1-c153	2690.1	30,879	1.5	29,410	±	190	11703	1250	258	±	60
PZ1-c154	2687.0	30,922	1.5	29,130	±	150	11704	1250	310	±	49
PZ1-c155	2680.1	31,019	1.7	29,130	±	150	11705	1250	325	±	49
PZ1-c156	2672.2	31,129	2.0	29,630	±	160	11706	1250	262	±	50
PZ1-c157	2667.0	31,202	1.8	29,470	±	160	11707	1250	299	±	52
PZ1-c158	2661.7	31,276	1.2	30,030	±	170	11708	1250	222	±	52
PZ1-c159	2638.7	31,598	0.5	29,800	±	300	12380	1250	308	±	98
PZ1-c160	2637.7	31,612	–0.1	29,900	±	300	12381	1250	294	±	97
PZ1-c161	2629.7	31,724	–3.9	28,800	±	300	12382	1250	504	±	112
PZ1-c162	2621.9	31,833	–0.1	29,700	±	300	12383	1250	362	±	102
PZ1-c163	2616.1	31,915	1.0	30,200	±	300	12384	1250	293	±	97
PZ1-c164	2613.8	31,947	0.5	29,600	±	300	12385	1250	398	±	104
PZ1-c165	2608.0	32,028	2.0	30,700	±	280	12386	1250	231	±	86
PZ1-c166	2600.5	32,133	1.9	30,600	±	280	12387	200	108	±	77
PZ1-c167	2594.6	32,216	–1.4	31,100	±	350	12388	200	52	±	92
PZ1-c168	2588.2	32,305	–1.1	30,600	±	290	12389	200	131	±	82
PZ1-c169	2586.7	32,326	2.8	30,700	±	300	12390	200	120	±	84
PZ1-c170	2586.2	32,333	1.0	31,300	±	300	12391	200	40	±	78
PZ1-c171	2582.8	32,381	–0.5	31,600	±	300	12392	200	8	±	75
PZ1-c172	2570.4	32,554	–3.3	31,500	±	350	12393	200	42	±	91
PZ1-c173	2567.6	32,594	–1.1	32,000	±	350	12394	200	–16	±	86
PZ1-c174	2547.7	32,872	–0.8	31,200	±	350	12395	200	124	±	98
PZ1-c175	2544.3	32,920	–0.5	31,600	±	300	12396	200	76	±	80
PZ1-c176	2537.6	33,014	–0.7	31,700	±	300	12397	200	75	±	80
PZ1-c177	2530.1	33,119	0.9	31,100	±	300	12398	200	173	±	88
PZ1-c178	2524.8	33,193	1.6	31,500	±	300	12399	200	126	±	84
PZ1-c179	2519.0	33,274	2.4	31,500	±	300	12400	200	137	±	85
PZ1-c180	2514.1	33,343	0.4	31,700	±	300	12401	200	118	±	84
PZ1-c181	2508.1	33,427	0.6	31,900	±	350	12402	200	102	±	96
PZ1-c182	2502.1	33,511	1.7	32,100	±	350	12403	200	86	±	95
PZ1-c183	2497.0	33,582	1.8	31,900	±	350	12404	200	123	±	98
PZ1-c184	2491.0	33,666	1.4	32,400	±	350	12405	200	66	±	93
PZ1-c185	2484.8	33,753	1.0	32,000	±	350	12406	200	132	±	99
PZ1-c186	2477.1	33,861	0.7	32,100	±	400	12407	200	133	±	113
PZ1-c187	2470.9	33,947	1.0	32,200	±	400	12408	200	131	±	113
PZ1-c188	2463.6	34,050	0.7	32,400	±	400	12409	200	117	±	111
PZ1-c189	2455.3	34,166	0.6	32,300	±	400	12410	200	147	±	114
PZ1-c190	2454.3	34,180	–2.2	32,100	±	350	12411	200	177	±	103
PZ1-c191	2447.9	34,269	1.0	32,300	±	400	12412	200	161	±	116
PZ1-c192	2439.2	34,391	–1.7	32,400	±	400	12413	200	164	±	116
PZ1-c193	2415.2	34,727	–1.0	32,500	±	400	12414	200	197	±	119
PZ1-c194	2330.2	35,917	0.8	32,500	±	400	12415	200	382	±	138
PZ1-c195	2327.6	35,954	1.8	33,900	±	400	12416	200	166	±	116

Figure 2 shows the present $\Delta^{14}C$ record for Lake Lisan corrected for variable reservoir ages (VR). The dashed line indicates the effect in $\Delta^{14}C$ due to deviation from the 1250 yr reservoir age. The present Lake Lisan $\Delta^{14}C$ record agrees with the Lake Suigetsu record until 33 kyr cal BP (the best fit with Lake Suigetsu data is obtained for Lisan reservoir ages of 2000 yr between 20.9 and 25.2 kyr cal BP, and 200 yr between 32.1 and 36.0 kyr cal BP). Structures at 18, 22, 31, and 32 kyr cal BP are recognized in both records. Clearly, the structures at 18 and 22 kyr cal BP are not represented well by the INTCAL98 curve. The close correspondence of the ^{14}C record of lakes Lisan and Suigetsu lends support to the varve counting of the latter in this interval. This means that the $\Delta^{14}C$ ~0‰ observed in the Lake Lisan record at 32 kyr cal BP is confirmed by the ^{14}C record of Lake Suigetsu, where no reservoir age effect plays a role in the ^{14}C data obtained from macrofossils. The new Lake Lisan record agrees with both the coral data, except for the coral data point at 30 kyr cal BP, and the Lake Lisan HS data (Haase-Schramm et al. 2004), except for the data point at 27 kyr cal BP. At 34 kyr cal BP, the Lake Suigetsu record shows a number of different $\Delta^{14}C$ values (Figure 1) which may be indicative of a depositional hiatus. A 2-kyr hiatus would shift the data points to higher ages and higher corresponding $\Delta^{14}C$ values (Figure 2) in agreement with Lake Lisan data.

While the ^{14}C record of Lake Lisan resembles the Lake Suigetsu record, both are different from the $\Delta^{14}C$ values Bard (1998) modeled, based on the paleomagnetic compilation by Guyodo and Valent (1996) and the ^{10}Be production compilation by Frank et al. (1997). The present Lake Lisan record shows a maximum $\Delta^{14}C$ of ~450‰ at 25 kyr cal BP and a minimum $\Delta^{14}C$ of ~0‰ at 32 kyr cal BP, while the model of Bard indicates steadily increasing $\Delta^{14}C$ values toward a maximum $\Delta^{14}C$ of ~350‰ at 30 kyr cal BP. Obviously, other parameters play a role in the ^{14}C record. The $\Delta^{14}C$ ~0‰ at 32 kyr cal BP deduced from lakes Lisan and Suigetsu suggests that the production of ^{14}C was similar at that time to the present day or the same combination of production with the global reservoir carbon exchange prevailed. This matter, which we regard as a fundamental observation, requires further study and modeling.

The similarity of the $\Delta^{14}C$ records of lakes Lisan and Suigetsu lends support to the validity of both calendar chronologies up to 34 cal ka BP, but for ages >25 kyr cal BP, their $\Delta^{14}C$ values are clearly lower than the ^{14}C records of the Iceland Sea, the Cariaco Basin, and the Bahamas stalagmite. In the case of the stalagmite record, the reservoir age of 1450 yr, as derived for the interval of 11–16 kyr cal BP, was assumed for the whole age scale, which may not be justified. However, even zero reservoir age would not be sufficient to reduce the ^{14}C vales sufficiently for matching the other ^{14}C records. Only overestimation of the calendar age record can explain the difference with the Lake Lisan record. Reduction of the calendar age scale of the Iceland Sea and the Cariaco Basin—which were both determined from correlation with the GISP2 core—by 3% and the stalagmite by 5–10%, is sufficient to obtain a reasonable consensus with the present Lake Lisan record (Figure 3). Such a shift could indicate a wrong age assessment for the records of the Iceland Sea and the Cariaco Basin, which both depend on comparison with GISP2 data. In the case of the speleothems, the age assessment depends completely on the assumptions regarding the reservoir age and those related to the presence of initial Th and $^{234}U/^{238}U$ as well as the closed-system condition. The study of the behavior of the U-Th and ^{14}C system in the Lisan aragonite certainly indicated that unlike pristine corals, the initial Th factor can cause shifts in the U-Th calendar ages (Haase-Schramm et al. 2004).

CONCLUSION

We established a high-resolution ^{14}C record for Lake Lisan for the interval of 17–36 kyr cal BP by analyses of authigenic aragonite and application of variable reservoir ages determined by aragonite-organic debris pairs from the same stratigraphic horizons. The calendar ages of the aragonites were determined by U/Th (Haase-Schramm et al. 2004).

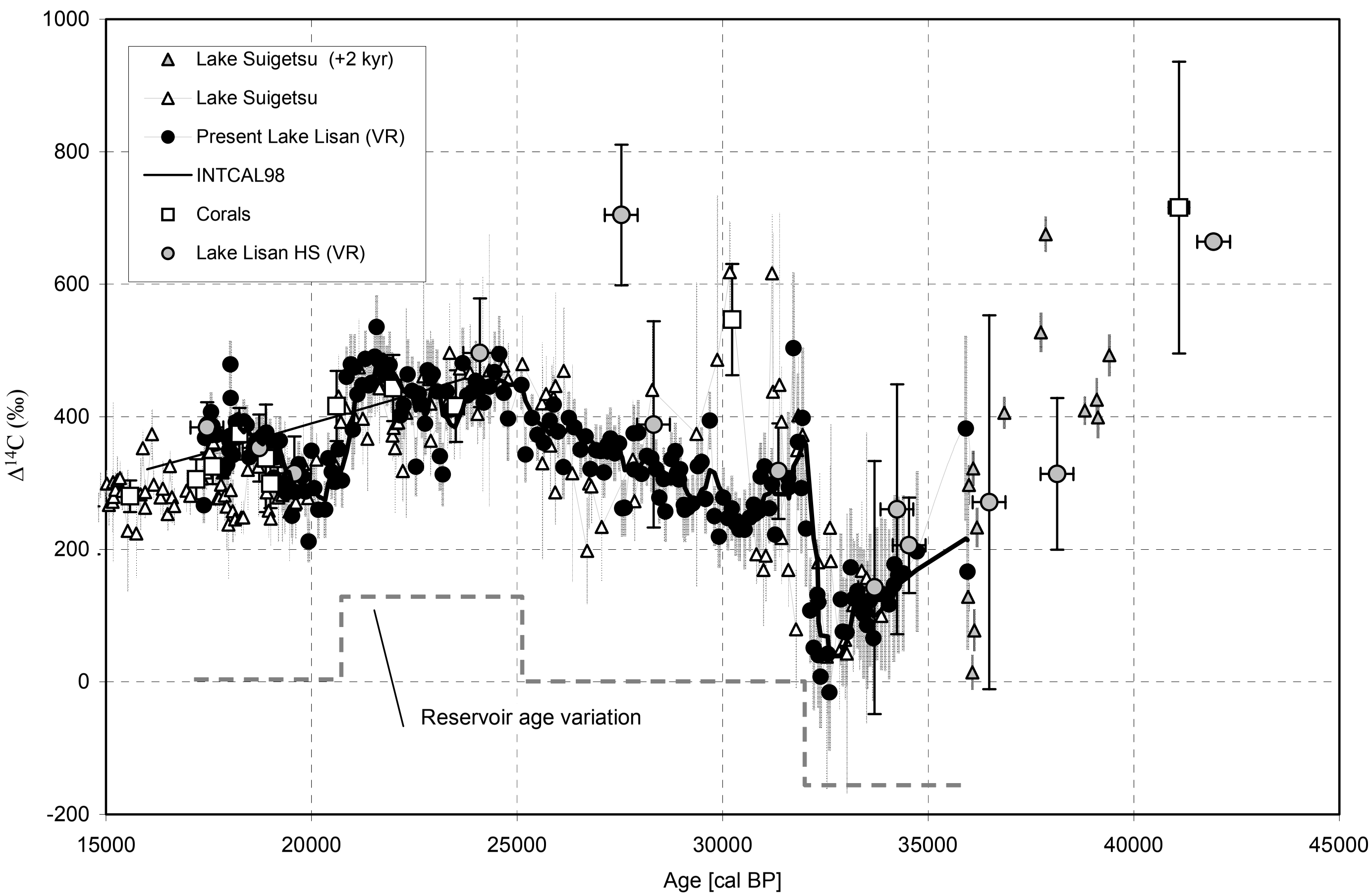

Figure 2 Comparison of the present ^{14}C record of Lake Lisan with that of Lake Suigetsu, and with the data points for Lake Lisan HS (i.e. Haase-Schramm et al. 2004), and with coral data. The present data for Lake Lisan were corrected for a variable reservoir age (VR) with values of 200, 1250, and 2000 yr. The dashed line indicates the difference (expressed as $\Delta^{14}C$ values) with respect to the 1250 yr reservoir age.

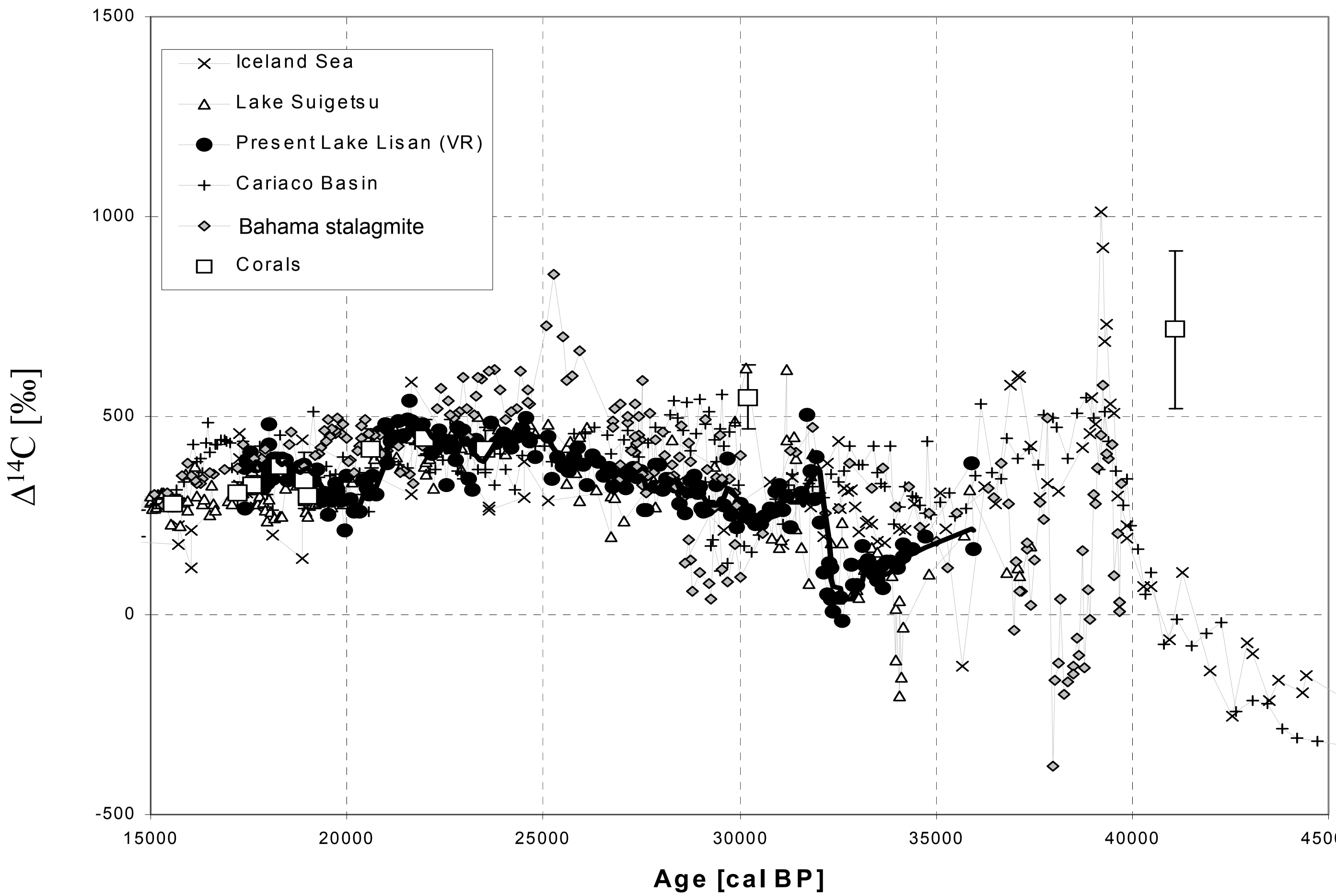

Figure 3 Comparison of ^{14}C records of the lakes Lisan and Suigetsu with the modified ^{14}C records of the Iceland Sea, the Cariaco Basin, and the Bahamas stalagmite. In the modified records, the calendar age scale was modified for ages >25 kyr cal BP by 3% for the records of the Iceland Sea and the Cariaco Basin, and 5–10% for the Bahamas stalagmite.

The present ^{14}C record of Lake Lisan resembles that from Lake Suigetsu. This observation supports both the validity of the varve counting used for the calendar age scale for Lake Suigetsu up to 33 kyr cal BP, and the use of variable reservoir ages in the Lake Lisan record.

Both the Lisan and Suigetsu records converge to $\Delta^{14}C$ ~0 at 32 kyr cal BP, suggesting an atmospheric production rate similar to present-day conditions or the same combination of production with the global reservoir carbon exchange.

The Lake Lisan and Suigetsu records do not show agreement with the modeled ^{14}C record, taking into account the effect of the geomagnetic field on the ^{14}C production. They also do not agree with the ^{14}C records of the Iceland Sea, Cariaco Basin, and the Bahamas stalagmite. However, a reasonable consensus with these other records is obtained by reducing the calendar age scale by 3% for the records of the Iceland Sea and the Cariaco Basin, and 5–10% for the Bahamas stalagmite.

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REFERENCES

Bard E, Arnold M, Hamelin B, Tisnerat-Laborde N, Cabioch G. 1998. Radiocarbon calibration by means of mass spectrometric $^{230}Th/^{234}U$ and ^{14}C ages of corals: an updated database including samples from Barbados, Mururoa and Tahiti. *Radiocarbon* 40(3):1085–92.

Bard E. 1998. Geochemical and geophysical implications of the radiocarbon calibration. *Geochimica et Cosmochimica Acta* 62(12):2025–38.

Bartov Y, Goldstein SL, Stein M, Enzel Y. 2003. Catastrophic arid episodes in the Eastern Mediterranean linked with the North Atlantic Heinrich event. *Geology* 31:439–44.

Beck JW, Richards DA, Edwards RL, Silverman BW, Smart PL, Donahue DJ, Herrera-Osterheld S, Burr GS, Calsoyas L, Jull AJT, Biddulph D. 2001. Extremely large variations of atmospheric ^{14}C concentration during the last glacial period. *Science* 292:2453–7.

Begin ZB, Ehrlich A, Nathan Y. 1974. Lake Lisan—The precursor of the Dead Sea. *Geological Society Survey Israel Bulletin* 63:1–30.

Frank M, Schwarz B, Baumann S, Kubik PW, Suter M, Mangini A. 1997. A 200-kyr record of cosmogenic radionuclide production rate and geomagnetic field intensity from ^{10}Be in globally stacked deep-sea sediments. *Earth and Planetary Science Letters* 149:121–9.

Guyodo Y, Valet J-P. 1996. Relative variations in geomagnetic intensity from sedimentary records: the past 200,000 years. *Earth and Planetary Science Letters* 143:23–36.

Haase-Schramm A, Goldstein SL, Stein M. 2004. U-Th dating of Lake Lisan aragonite (late Pleistocene Dead Sea) and implications for glacial East Mediterranean climate change. *Geochimica et Cosmochimica Acta* 68(5):985–1005.

Hughen K, Lehman S, Southon J, Overpeck J, Marchal O, Herring C, Turnbull J. 2004. ^{14}C activity and global carbon cycle changes over the past 50,000 years. *Science* 303:202–7.

Kaufman A. 1971. U-series dating of Dead Sea Basin carbonates. *Geochimica et Cosmochimica Acta* 35:1269–81.

Kitagawa H, van der Plicht J. 2000. A 40,000-yr varve chronology from Lake Suigetsu, Japan: extension of the ^{14}C calibration curve. *Radiocarbon* 42(3):369–80.

Schramm A, Stein M, Goldstein SL. 2000. Calibration of the ^{14}C timescale to >40 ka by ^{234}U-^{230}Th dating of Lake Lisan sediments (Last Glacial Dead Sea). *Earth and Planetary Science Letters* 175:27–40.

Stein M, Starinsky A, Katz A, Goldstein SL, Machlus M, Schramm A. 1997. Strontium isotopic, chemical and sedimentological evidence for the evolution of Lake Lisan and the Dead Sea. *Geochimica et Cosmochimica Acta* 61(18):3975–92.

Stein M, Migowski C, Bookman R, Lazar B. 2004. Temporal changes in radiocarbon reservoir age in the Dead Sea-Lake Lisan system. *Radiocarbon*, these proceedings.

Stuiver M, Reimer PJ, Bard E, Warren Beck J, Burr GS, Hughen KA, Kromer B, McCormac G, van der Plicht J, Spurk M. 1998. INTCAL98 radiocarbon age calibration, 24,000–0 cal BP. *Radiocarbon* 40(3):1041–83.

van der Borg K, Alderliesten C, de Jong AFM, van den Brink A, de Haas AP, Kersemaekers HJH, Raaymakers JEM. 1997. Precision and mass fractionation in ^{14}C analysis with AMS. *Nuclear Instruments and Methods in Physics Research B* 123:97–101.

Voelker AHL, Grootes PM, Nadeau M-J, Sarntheim M. 2000. Radiocarbon levels in the Iceland Sea from 25–53 kyr and their link to the earth's magnetic field intensity. *Radiocarbon* 42(3):437–52.