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^{14}C AGES OF A VARVED LAST GLACIAL MAXIMUM SECTION OFF PAKISTAN

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ABSTRACT. In a core off Pakistan, we obtained 38 ^{14}C analyses by accelerator mass spectrometry (AMS) from a 4.4-m-thick, expanded, annually-laminated Last Glacial Maximum (LGM) section, bracketed by bioturbated intervals ascribed to the Heinrich-1 (H1) and Heinrich-2 (H2) equivalent events (52 ^{14}C analyses between 24–15 kyr BP). A floating varve age scale, anchored to the oxygen isotope record of the layer-counted GISP2 ice core at the H2/LGM boundary, results in an annually dated record for the LGM from 23,450–17,900 cal BP. The floating varve scale of the LGM provides us with a tentative calibration of local marine AMS ^{14}C age dates to calendar years.

INTRODUCTION

At the Last Glacial Maximum (LGM), an interval at 21,000 ± 2000 calendar years before present (yr BP; Mix et al. 2001), the chronology is mainly based on radiocarbon dates. During Marine Isotope Stage (MIS) 2–3, the conversion of ^{14}C dates into calendar years is complicated because of strong variations which are hardly quantified (during MIS 2) in cosmogenic ^{14}C production and in the relative size and rate of overturning of the various reservoirs of the carbon cycle (Beck et al. 2001). These changes also lead to considerable but unknown variations in the local reservoir age of seawater (Waelbroek et al. 2001; Sarnthein et al. 2001; Staubwasser et al. 2002). During MIS 3 and 2, beyond the range of dendrochronological calibration, ages are mostly tuned to the Greenland Ice Sheet Project 2 (GISP2) record, where annual layers were counted down to 50,000 yr BP (Alley et al. 1997; Meese et al. 1994; Voelker et al. 1998; Stuiver and Grootes 2000). For the LGM (late MIS 2), neither varved and dendrochronological records nor GISP2 signals are available for the precise monitoring of ^{14}C age variations. Published terrestrial records and annually counted, pre-Holocene marine varve records (e.g. Cariaco Basin: Hughen et al. 1998) generally do not extend beyond 15,000 yr BP. However, some data are available from varved lakes—e.g., from Lake Suigetsu in Japan (Kitagawa and van der Plicht 1998, 2000) and from a Bahamian stalagmite (Beck et al. 2001).

The high-resolution laminated records from the oxygen minimum zone (OMZ) off Pakistan (Figure 1) offer an opportunity to fill this calibration gap using a floating varve chronology. Here we examine the laminated LGM sequence in core SO 130-261KL (abbreviated 261KL) (Figure 1) documenting about 5550 calendar yr (if corrected for erosional loss of varves). For comparison, the late Holocene varve record (about 5000 yr BP to Present) in nearby core SO 90-56KA (Figure 1) was studied by von Rad et al. (1999a) and Berger and von Rad (2002). The linear sedimentation rate of core 261KL (about 0.9 m/1000 yr) is almost 3 times higher than that of the thickest LGM sections at the continental slope off the Indus Delta (von Rad et al. 1999b). Hence, this expanded marine laminated LGM section (Figure 2) is unique for the Arabian Sea, and possibly also unique on a global scale.

The objective of this paper is to show the variability of ^{14}C activity in the surface ocean over the LGM by means of varve counts, and to anchor this ^{14}C time series to the GISP2 timescale. Our basic assumption for age control is that the bioturbated intervals in core 261 KL can be correlated with Heinrich events in the North Atlantic and with the corresponding major stadials in the Greenland ice record (Schulz et al. 1998, 2002). Our strategy is to develop a floating varve scale anchored to the

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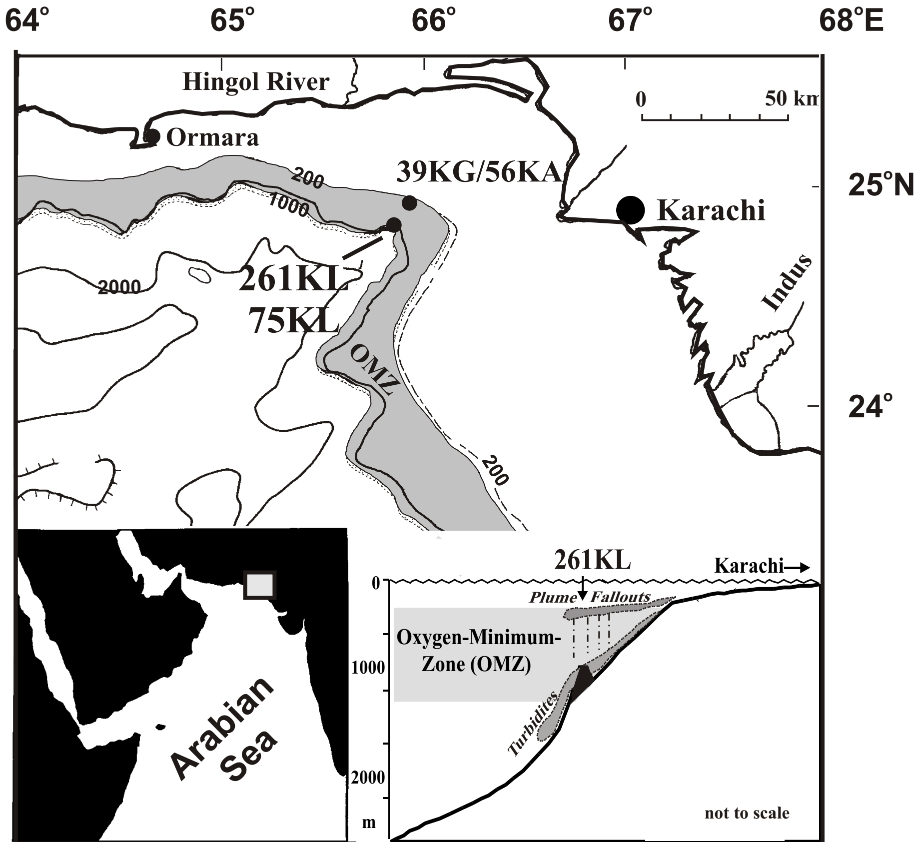

Figure 1 Bathymetry of the continental slope west of Karachi with site SO130-261 KL at the continental margin of Pakistan (OMZ shaded). Inset (lower right): Generalized transect of water mass stratification (OMZ) and turbidite or plume fallout action in the northern Arabian Sea ambient to the core location.

GISP2 ice core scale at the H2/LGM boundary and counting back towards the end of the LGM, making allowances for core disturbance by turbidite erosion (Figure 3; Table 1).

SAMPLES AND METHODS

Samples

To avoid a strong influence by turbidite sedimentation and erosion (Figure 1), core SO 130-261 KL (abbreviated 261KL) was retrieved from the top of an isolated hill between 2 submarine canyons on the upper continental slope west of Karachi (24°46.2′N/65°49.2′E, 873 m water depth; von Rad and Doose 1998). Core 261KL has a total length of 17.86 m and reaches down to Interstadial (IS)-6 (about 34 kyr BP). This core contains a 4.4-m-thick, laminated section of the Last Glacial Maximum (LGM) between the H1 and H2 equivalent stadial events (Figure 2). Core SO 90-75KL (abbreviated 75KL), which contains the same LGM section, was taken from a position very close to core 261 KL. X-radiographs prove that both cores can be precisely correlated using 47 very distinctive coarse-grained marker layers, in part turbidites. No significant sections are missing between the correlated marker beds. Hence, we “spliced” the samples from 75 KL into the record of 261KL (Table 1) and supplemented 48 ^{14}C dates in core 261KL by 4 ^{14}C dates from core 75KL.

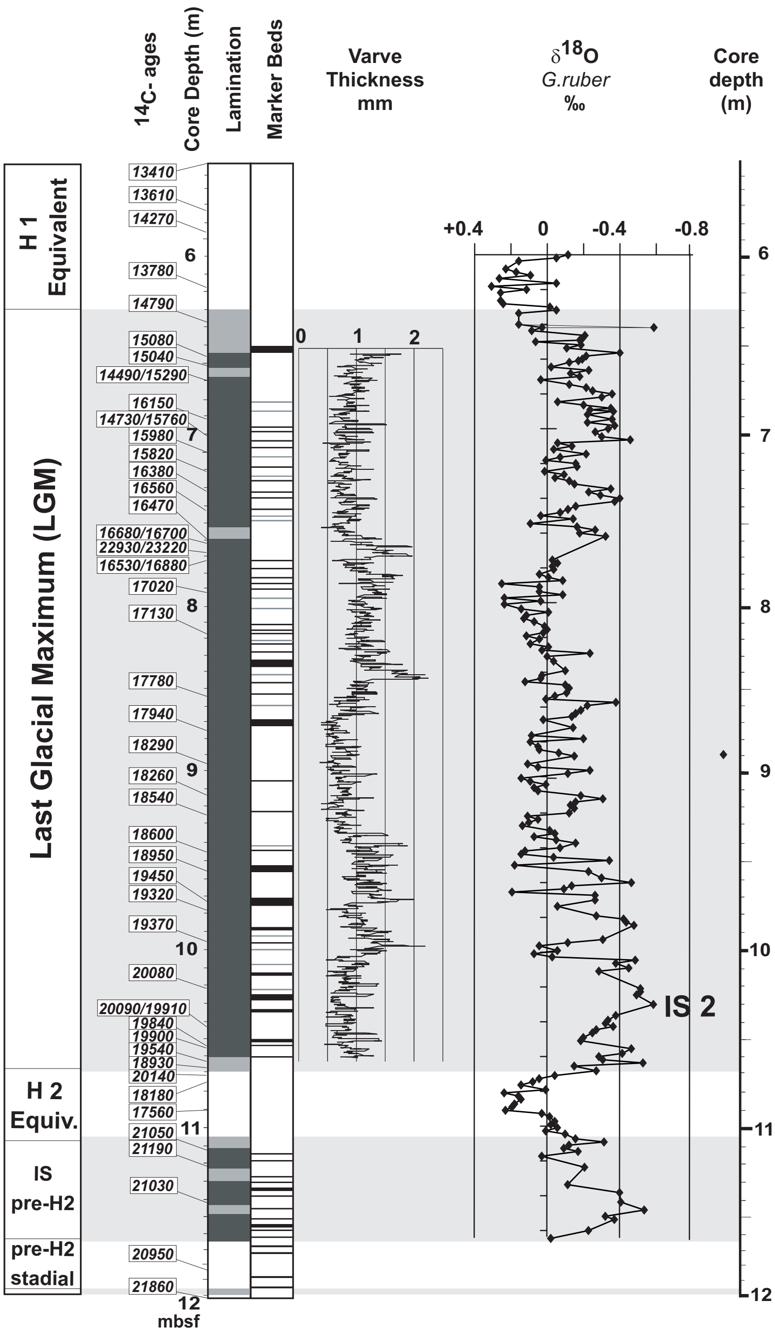

Figure 2 Core SO 130-261 KL (5.40–12.00 m below sea surface: m bsf): Lithology, varve thickness, conventional ^{14}C dates in BP (corrected for a –400 yr reservoir effect) and δ^{18}O record of Globigerinoides ruber versus core depth. Bioturbated (light-colored) and laminated, dark-colored sediment sections (stippled) are marked: distinctly laminated intervals with denser pattern than less distinctly laminated ones. Coarse-grained marker beds include suspension fall-outs and genuine turbidites. Possibly erosive turbidites are indicated by thick lines. The laminated section between 11.65 and 11.08 m bsf is termed "IS pre-H2", whereas the bioturbated section below is called "pre-H2 stadial."

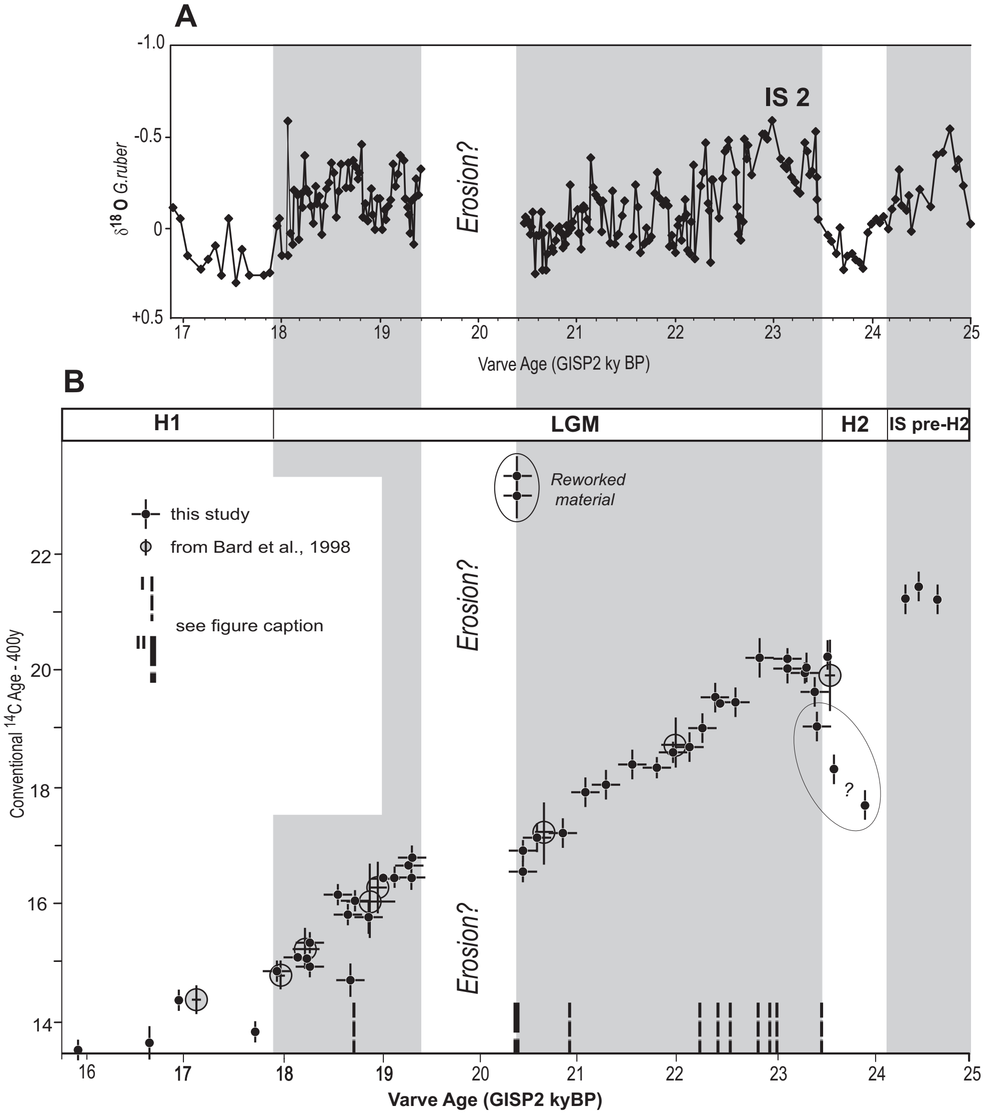

Figure 3 A) Oxygen isotope record of planktonic foraminifer *G. ruber* versus age (cal yr BP) for core 261KL. B) ^{14}C ages in BP from core SO 130-261 KL versus varve-based calendar ages, anchored to the GISP2 age scale 15.8–25 cal kyr BP. Open circles are TIMS ^{230}Th-calibrated coral ^{14}C ages (Bard et al. 1998; Stuiver et al. 1998). Calendar ages in H2 and H1 intervals are rough estimates, based on linear extrapolation of the varve scale assuming linear sedimentation rates. Horizontal and vertical error bars show varve-counting error and standard deviation (2 σ) of ^{14}C ages (see Table 1). The laminated intervals (LGM and IS-pre-H2) are shaded. I = location of moderately thick turbidites (where 20–30 varves may be lost); II = location of major turbidite (7.64–7.70 m bsf) and reworked material, where up to 1000 varves are assumed to have been lost by erosion (see text).

Varve Chronology

Contact prints of X-radiographs of core SO 130-261KL served for fabric studies at the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in Hannover (von Rad et al. 1999a). For varve counts and measuring varve thickness, we used a tree ring measuring facility under a binocular microscope (Aniol 1983) at the Tree Ring Laboratory of the University of Göttingen. The varves of the LGM record of core 261KL were measured twice and by independent investigators (U von Rad and J Erbacher). The differences between these results were used to estimate the counting error between well-defined marker beds. The reproducibility within our varve chronology, which depends on the variable distinctness of the varves and the subjective interpretation, varies considerably from section to section. A conservative summary estimate of the error amounts to ±7% or ±300 varve yr for the whole LGM section.

Counting errors resulting in a systematic under-counting of varve years can be linked to (1) amalgamation of varves due to compaction, (2) local erosion of varves below thick turbidites, and (3) local slumps. The excellent to moderate preservation of lamination shown in our X-radiographs suggests that the first error is unlikely. Erosion below thick turbidites cannot be fully discounted (see below). Local slumps have not been identified in our record, except for a 2–4 cm thick, very indistinctly laminated, sand-rich interval at 7.68–7.70 m below sea floor (bsf), consisting of reworked old material (about 6000 ^{14}C yr older than the overlying and underlying strata, see Table 1). This interval was omitted from our interpretation.

For core 261KL we anchored the "floating varve chronology" at the H2/LGM boundary at 23,450 cal yr BP and tuned it to the annual-layer counted GISP2 timescale (age scale of Meese et al. 1994, employed in Stuiver and Grootes 2000). All age denotations in this paper are in "varve years" BP, which we interpret to be synonymous to "calendar years" BP (before 1950).

AMS ^{14}C Dating

For the ^{14}C calibration of the laminated LGM section in core 261KL, we determined 38 ^{14}C ages by accelerator mass spectrometry (AMS) (Table 1). The spacing of samples in the LGM ranged from 10–25 cm, resulting in an average resolution of a few hundred calendar yr. These dates were supplemented by 14 AMS ^{14}C ages from the underlying bioturbated layers, correlated to H2 and "pre-H2 stadial" and the laminated section in between H2A and H2 (termed "IS pre-H2"), as well as from the overlying H1 interval (Figure 2). The ^{14}C activities were determined with the Leibniz Labor 3 MV HVEE Tandetron AMS system (Nadeau et al. 1997), mostly on monospecific planktonic foraminiferal samples (*Globigerinoides ruber* and/or *G. sacculifer*, depending on the availability of sufficient specimens in each sample; see Table 1). *G. ruber/G. sacculifer* dates from the same sample differ considerably (Table 1, nr 8/9, 11/12, 20/21, 22/23). This suggests that we are dealing with a somewhat noisy record with a scatter probably due to differential species habitats (since *G. sacculifer* produces its last chamber at up to 80 m water depth, it is being influenced by "older water"). A few replicate datings of the same sample (Table 1, nr 18/19, 37/38) give excellent agreement.

Local reservoir ages of 640 yr were estimated for Late Holocene (pre-bomb) sediments in the varved core SO90-56KA (von Rad et al. 1999a); reservoir ages ranging from 780 to >1000 yr were calculated by Staubwasser et al. (2002) for the period 6600–13,000 BP using ^{14}C dates from a nearby core off Karachi. However, we cannot assess the variability of the paleo-^{14}C reservoir effect during the LGM, a period which may have been sensitive to variations in the strength of the thermohaline circulation. We mainly rely on a reasonable fit with the coral data of Bard et al. (1998) between 24 and 20.5 kyr BP (see Figure 3b), and, thus, we apply in this paper the commonly used reservoir age estimate of 400 yr. The corrected ^{14}C ages (–400 yr) were correlated with varve-counted calendar yr tuned to the GISP2 record (Table 1, Figure 3). Since we determined the ^{14}C activity from *G. ruber* and *G. sacculifer* (which are species dwelling in the top 30–80 m of the ocean and mainly during non-upwelling seasons), the influence of differential advection of upwelled "old" deep-water masses may be low.

All varve thickness, ^{14}C ages, and oxygen isotope data of cores SO 90-75 KL and SO 130-261KL were deposited in the PANGAEA data bank (www.pangaea.de/PangaVista?query=vonradu).

Table 1 ^{14}C ages measured in core SO 130-261 KL with calibration to GISP-controlled varve yr (calendar yr) anchored at the H2/LGM boundary at 23,450 yr BP. Note that at a 7.67 m core depth, we supplemented 1000 varves, assumed to be lost by turbidite erosion.

Nr	Lab nr	Core 261KL depth interval (cm)	Average depth (cm)	Plankton Foramaminifer	Corrected ^{14}C activity pMC	Conventional ^{14}C age yr BP (uncorr.)	Standard deviation (± yr)	Reservoir age (400 a) corrected ^{14}C age	Varve age (floating scale) cal yr BP	Comments/ stratigraphic unit[a]
1	KIA 13278	541–546	543.5	*ruber + sacc.*	17.91 ± 0.30	13,810	140	13,410	15,950	Bioturb.(H1)
2	KIA 13279	57–577	574.0	*ruber + sacc.*	17.48 ± 0.23	14,010	110	13,610	16,694	Bioturb.(H1)
3	KIA 13280	583–589	586.0	*ruber + sacc.*	16.10 ± 0.19	14,670	100	14,270	16,982	Bioturb.(?H1)
4	KIA 13281	616–621	618.5	*ruber + sacc.*	17.12 ± 0.23	14,180	110	13,780	17,750	Bioturb.(?H1)
5	KIA 6777	637–639	638.0	*ruber + sacc.*	15.08 ± 0.20	15,190	110	14,790	17,965	Lamin.LGM
6	KIA 6778	656–658	657.0	*ruber + sacc.*	14.54 ± 0.16	15,480	90	15,080	18,164	Lamin.LGM
7	KIA 3807*[b]	897–899*	661.0	*ruber + sacc.*	14.46 ± 0.17	15,440	90	15,040	18,205	Lamin.LGM
8	KIA 10847	668–672	670.0	*sacculifer*	14.18 ± 0.13	15,690	70	15,290	18,307	Lamin.LGM
9	KIA 10846	668–672	670.0	*ruber*	15.67 ± 0.22	14,890	110	14,490	18,307	Lamin.LGM
10	KIA 10167	691–696	693.0	*sacculifer*	12.74 ± 0.15	16,550	90	16,150	18,590	Lamin.LGM
11	KIA 10849	700–702	701.0	*sacculifer*	13.37 ± 0.13	16,160	80	15,760	18,680	Lamin.LGM
12	KIA 10848	700–702	701.0	*ruber*	15.21 ± 0.22	15,130	120	14,730	18,680	Lamin.LGM
13	KIA 10850	708.5–712.5	710.5	*ruber*	13.01 ± 0.13	16,380	80	15,980	18,781	Lamin.LGM
14	KIA 10168	719–723	721.0	*sacc. + ruber*	13.28 ± 0.21	16,220	130	15,820	18,903	Lamin.LGM
15	KIA 12754	731–736	733.5	*sacculifer*	12.38 ± 0.14	16,780	90	16,380	19,182	Lamin.LGM
16	KIA 12755	742–746.5	744.3	*sacculifer*	12.10 ± 0.13	16,960	90	16,560	19,298	Lamin.LGM
17	KIA 3808*	997–999*	759.0	*sacculifer*	12.24 ± 0.15	16,870	100	16,470	19,300	Lamin.LGM
18	KIA 10851	761–765	763.0	*sacculifer*	11.94 ± 0.14	17,080	90	16,680	19,344	Lamin.LGM
19	KIA 10852	761–765	763.0	*sacculifer*	11.90 ± 0.12	17,100	80	16,700	19,344	Lamin.LGM
20	KIA 10169	768–770	769.0	*sacculifer*	5.28 ± 0.12	23,620	180	23,220	20,418	rework. mat./??
21	KIA 10179	768–770	769.0	*ruber*	5.48 ± 0.14	23,330	200	22,930	20,418	rework- mat./??
22	KIA 10853	773–776	774.5	*ruber*	11.63 ± 0.13	17,280	90	16,880	20,459	Lamin.LGM
23	KIA 10854	773–776	774.5	*sacculifer*	12.15 ± 0.13	16,930	90	16,530	20,459	Lamin.LGM
24	KIA 10170	790–794	792.0	*ruber*	11.44 ± 0.17	17,420	120	17,020	20,601	Lamin.LGM
25	KIA 10171	814–818	816.0	*sacculifer*	11.28 ± 0.18	17,530	130	17,130	20,806	Lamin.LGM
26	KIA 10172	852–856	854.0	*sacculifer*	10.41 ± 0.17	18,180	130	17,780	21,107	Lamin.LGM
27	KIA 6779	873–875	874.0	*ruber + sacc.*	10.20 ± 0.13	18,340	100	17,940	21,315	Lamin.LGM

Table 1 ^{14}C ages measured in core SO 130-261 KL with calibration to GISP-controlled varve yr (calendar yr) anchored at the H2/LGM boundary at 23,450 yr BP. Note that at 7.67 m core depth, we supplemented 1000 varves, assumed to be lost by turbidite erosion. *(Continued)*

Nr	Lab nr	Core 261KL depth interval (cm)	Average depth (cm)	Plankton Foraminifer	Corrected ^{14}C activity pMC	Conventional ^{14}C age yr BP (uncorr.)	Standard deviation (±yr)	Reservoir age (400 a) corrected ^{14}C age	Varve age (floating scale) cal yr BP	Comments/ stratigraphic unit[a]
28	KIA 10173	894–896	895.0	*sacculifer*	9.77 ± 0.16	18,690	130	18,290	21,580	Lamin.LGM
29	KIA 3809*[b]	1138–1140*	912.0	*sacculifer*	9.80 ± 0.15	18,660	130	18,260	21,820	Lamin.LGM
30	KIA 12756	926–929	927.5	*sacculifer*	9.46 ± 0.13	18,940	110	18,540	22,000	Lamin.LGM
31	KIA 12757	944–947	945.5	*sacculifer*	9.39 ± 0.13	19,000	110	18,600	22,158	Lamin.LGM
32	KIA 10174	956–958	957.0	*sacculifer*	9.00 ± 0.16	19,350	140	18,950	22,283	Lamin.LGM
33	KIA 10175	973–975	974.0	*sacculifer*	8.45 ± 0.15	19,850	150	19,450	22,422	Lamin.LGM
34	KIA 10176	978–980	979.0	*sacculifer*	8.58 ± 0.16	19,720	150	19,320	22,485	Lamin.LGM
35	KIA 10177	993–996	994.5	*sacculifer*	8.54 ± 0.18	19,770	170	19,370	22,620	Lamin.LGM
36	KIA 10178	1020–1022	1021.0	*sacculifer*	7.81 ± 0.17	20,480	180	20,080	22,887	Lamin.LGM
37	KIA 11255a	1041–1046	1043.5	*ruber*	7.98 ± 0.16	20,310	160	19,910	23,165	Lamin.LGM
38	KIA 11255b	1041–1046	1043.5	*ruber*	7.80 ± 0.11	20,490	110	20,090	23,165	Lamin.LGM
39	KIA 11254	1054–1059	1056.5	*sacc. + ruber*	8.05 ± 0.12	20,240	120/110	19,840	23,321	Lamin.LGM
40	KIA 3810*	1248–1250*	1057.0	*sacculifer*	7.99 ± 0.14	20,300	150	19,900	23,328	Lamin.LGM
41	KIA 6780	1063–1065	1064.0	*ruber + sacc.*	8.36 ± 0.12	19,940	120/110	19,540	23,430	Lamin.LGM
42	KIA 11253	1067–1070	1068.5	*ruber + sacc.*	9.02 ± 0.17	19,330	150	18,930	23,450	LGM/H-2 / ??
43	KIA 6781	1071–1073	1072.0	*ruber + sacc.*	7.75 ± 0.12	20,540	130	20,140	23,540	Bioturb. (H2)
44	KIA 13282	1074–1078	1076.0	*ruber + sacc.*	9.90 ± 9.16	18,580	130	18,180	23,620	Bioturb. (H2) / ??
45	KIA 13283	1088–1092	1090.0	*ruber + sacc.*	10.70 ± 0.17	17,960	130	17,560	23,925	Bioturb. (H2) / ??
46	KIA 6782	1112–1114	1113.0	*ruber + sacc.*	6.92 ± 0.11	21,450	130	21,050	24,348	Lam.(IS pre-H2)
47	KIA 11252	1121–1124	1122.5	*ruber + sacc.*	6.80 ± 0.11	21,590	130	21,190	24,458	Lam.(IS pre-H2)
48	KIA 11251	1141–1144	1142.5	*ruber + sacc.*	6.94 ± 0.12	21,430	140	21,030	24,653	Lam.(IS pre-H2)
49	KIA 11250	1181–1186	1183.5	*ruber + sacc.*	7.01 ± 0.15	21,350	180/170	20,950	—	pre-H2 stadial
50	KIA 6783	1201–1203	1202.0	*ruber + sacc.*	6.26 ± 0.11	22,260	150	21,860	—	pre-H2 stadial
51	KIA 6784	1433–1435	1434.0	*ruber + sacc.*	4.02 ± 0,12	25,810	240	25,410	—	pre-H2 stadial
52	KIA 6785	1456–1458	1457.0	*ruber + sacc.*	4.08 ± 0.12	25,700	240/230	25,300	—	Bioturb.(H2A)

[a] ?? = apparent ^{14}C outliers (see text).

[b] * = 4 dates in core SO 90-75KL with equivalent core 261KL depths (for stacking method, see Methods section; the actual 75 KL core depths are for KIA 3807: 8.97–8.99 m, for KIA 3808: 9.97–9.99 m, for KIA3809: 11.38–11.40 m, and for KIA 3810: 12.48–12.50 m).

Stable Oxygen Isotopes

Two-hundred-forty samples were picked from selected depths and prepared for stable isotope and geochemical analysis. This led to a resolution of about 20–30 yr. Stable carbon and oxygen isotopes were analyzed from 10–15 specimens of the planktonic foraminifer *Globigerinoides ruber* (315–400 µm size fraction) by Dr Joachimski (University of Erlangen), using mass spectrometric standard methods. All values are reported in per mil (‰) relative to the PeeDee Belemnite (V-PDB) standard (Figure 3a). The stable isotope curve is also matched by the lightness and color values (measured with a GEOTEK color scanner), which in the Northern Arabian Sea cores have been successfully used as a stratigraphic tool to estimate organic carbon contents of the sediments (Schulz et al. 1998).

RESULTS AND DISCUSSION

Laminated Hemipelagic Sediments

On the basis of laminated and non-laminated sediment sections in many cores investigated off Pakistan (including core 261 KL), the paleoclimate and paleocirculation along the upper slope of the northeastern Arabian Sea fluctuated between the following 2 extremes:

1. Oxygen-deficient bottom water conditions (well-developed oxygen minimum zone, OMZ) were documented during the laminated (late) Holocene period, the Preboreal, the Bölling/Alleröd warm spell, the LGM, and the Dansgaard-Oeschger Interstadials (IS 1–24).
2. Fully-oxygenated bottom water conditions occurred during the Younger Dryas and the Heinrich-equivalent stadials H1 to H7 (Schulz et al. 1998, 2002; von Rad et al. 1999b). The stadials H2 and H1 intervals are clearly reflected by $\delta^{18}O$ maxima of *G. ruber*, whereas the interstadials IS2 and IS pre-H2 are characterized by $\delta^{18}O$ minima. The middle part of the LGM (approximately 20,500–22,500 yr BP) shows more positive $\delta^{18}O$ values (Figure 3a). Sub-Milankovich climate changes were correlated peak-by-peak with the Dansgaard-Oeschger cycles and Heinrich events in the GISP2 $\delta^{18}O$ record (Dansgaard et al. 1993; Schulz et al. 1998, 2002).

The sediment laminae form couplets of light and dark laminae, in total approximately 0.4–0.8 mm thick (Figure 2). By comparison to a Holocene section in the nearby core SO 90-56KA (von Rad et al. 1999a), we regard the couplets as the result of seasonal variations in terrigenous and organic sediment supply, that is, as annual varves. In the central LGM section (9.5–8.7 m bsf), varve thickness has reached a minimum (suggesting reduced terrigenous river input due to more arid conditions in the Makran hinterland).

Plume Fallouts and Turbidites

The laminated sediments in core 261KL are interbedded with 47 silt- and/or sand-sized marker beds, which are a few mm up to a maximum of 30 mm thick. Whereas the thickest 10 beds are clearly graded (with mollusc/pteropod debris and large mud pebbles near the base and a sharp erosional contact to the underlying laminae), the majority of marker beds are ungraded (marked differently in Figure 2). Accordingly, we regard most of the latter beds as fallouts from turbid sediment plumes caught in the pycnocline on top of site 261 KL. In contrast, the thick, graded beds are interpreted as genuine turbidites which, in part, when thicker than 0.5 cm, may have been erosional, in total, possibly cutting out a few cm of laminated sediment, possibly up to 260 varves between 6.3 and 10.7 m core depth. Ten further thick turbidites, below which we assume an erosion perhaps reaching up to 30 varves, are also marked in Figures 2 and 3. Furthermore, we assume that up to 1000 varves were lost below the thick turbidite associated with a slump approximately 7.68–7.70 m bsf (see below).

Stratigraphic Correlation with GISP2 and Age Control

In core 261KL, the bioturbated pre-H2 stadial (or "H2A" interval) below 11.73 m bsf is overlain by a laminated interstadial (11.73–11.05 m bsf), named "IS pre-H2" in this paper (Figure 2). Although the lamination in this section is indistinct, we counted approximately 700 varves. This section has 3 ^{14}C ages (Figure 3) around 21,500 ^{14}C yr BP (24,900–24,200 cal yr BP, using reservoir ages between 400 and 1000 yr), which match the GISP2 age of this interstadial (H Schulz, personal communication 2003). The subsequent bioturbated section was assigned to H2, which has a midpoint age of 23,800 cal yr BP in GISP2. The H2 equivalent in core 261KL shows 2 peaks of heavy δ^{18}O values which fit to the "cool" peaks of 24,060 and 23,760 cal yr BP in GISP2. We assigned the top of this bioturbated H2 equivalent at 10.71 m bsf to the H2/LGM boundary with a GISP2 age of 23,450 yr BP (Meese et al. 1994; Stuiver and Grootes 2000) and employed this age as base of our new floating varved LGM timescale. On the basis of annual-layer counting, the uncertainty of the GISP2 timescale amounts to less than ±2%, down to an age of 39,852 yr BP (Meese et al. 1994).

Within the lowermost part of the laminated LGM section of core 261KL, we note 2 marked peaks of light ("warm") δ^{18}O values (Figures 2 and 3), which match the respective peaks in GISP2 of the IS2 interstadial at about 23,300 and 23,000 cal yr BP, respectively (H Schulz, personal communication 2003). The laminated LGM sediments were counted up to a core depth of 6.515 m bsf (varve age: 18,100 yr BP). Indistinct lamination, with a thickness of about 1 mm, continues up to a core depth of 6.30 m bsf (estimated varve age: 17,900 ± 300 yr BP), varves which were disturbed by subsequent bioturbation. In the overlying sediments, which are fully bioturbated, the δ^{18}O record shows a distinct change towards heavier values. We assigned this section overlying the laminated LGM to H1. In total, the laminated LGM record (10.71–6.30 m bsf) contains 4300 ± 300 varves. Further, 1250 varves may be lost by turbidite erosion, as outlined above. Accordingly, the section between H2 and H1 may originally have consisted of 5550 varves, which would result in a varve age of 17,900 yr BP for the base of H1. This age matches the approximate age of the LGM/H1 boundary at GISP2 (about 18,000 yr BP; Grootes and Stuiver 1997) and at various North Atlantic sediment cores (Sarnthein et al. 2001).

Distribution of ^{14}C Ages

The 38 ^{14}C age dates in the LGM section (Table 1) show a generally consistent pattern, where the ages increase with increasing core depth (Figure 2). Two ^{14}C dates at 7.69 m bsf (Table 1: nr 20, 21), which are some 6000 yr too old, form obvious exceptions, a result of downslope sediment reworking (Figure 3). X-radiography indicates that these sediments consist of indistinctly-laminated, foraminifera-enriched sand, apparently stemming from the nearby upper slope or outer shelf. Furthermore, 3 apparent ^{14}C outliers occur in the interval of H2 (Table 1, nr 42, 44, 45) dates that appear 1–3 kyr lower than expected, for unknown reasons.

Unfortunately, the strongly anoxic sediment section results in an early diagenetic alteration of magnetic mineral phases and does not produce any reliable geomagnetic record (N Nowaczyk, personal communication on the basis of about 280 geomagnetic measurements in core 261KL, November 2000). Hence, this evidence lacks for confirming or disproving any potential geomagnetic event in control of the cosmic ^{14}C production, as achieved by the North Atlantic paleointensity stack since 75,000 yr BP (Laj et al. 2000).

CONCLUSIONS

We measured 38 AMS ^{14}C ages from a 4.4-m-thick, expanded, annually-laminated marine sediment section of the LGM in core 261KL from the oxygen minimum zone off Pakistan. The section is bracketed by bioturbated sediment segments assumed equivalent to the H1 and H2 events. On the basis of varve counting and supplementing various varve segments lost by turbidite erosion, a floating age scale was constructed and anchored to the annual-layer counted age scale of the GISP2 ice core at the H2/LGM boundary. The new annually resolved varve record covers the LGM from 23,450 to approximately 17,900 BP at the base of H1, with a data gap possibly extending from 20,400–19,400 yr BP.

A close-up of the age-depth correlation (Figure 3b) reveals a number of ^{14}C jumps and plateaus. In a future publication, we will attempt to compare the variability of the ^{14}C concentration found in core 261KL from the northeastern Arabian Sea to ^{14}C dates calibrated by coral ages (Bard et al. 1998) and by varve counts from the Lake Suigetsu record (Kitigawa and van der Plicht 1998, 2000). Further calibration efforts are required to expand the INTCAL 98 ^{14}C timescale of Stuiver et al. (1998) further back across the last glacial stage.

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