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Gibraltar Strait
Mediterranean outflow
Post-glacial sediments
Oxygen isotopes
Carbon isotopes

Détroit de Gibraltar
Veine méditerranéenne
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Oxygène-18
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Mediterranean outflow through the Strait of Gibraltar since 18 000 years BP

Colette VERGNAUD-GRAZZINI [a], Michelle CARALP [b], Jean-Claude FAUGÈRES [b], Éliane GONTHIER [b], Francis GROUSSET [b], Claude PUJOL [b], Jean-François SALIÈGE [a]

[a] Département de Géologie Dynamique et UA-CNRS n° 388, Université Pierre-et-Marie-Curie, 4, place Jussieu, 75252 Paris Cedex 05, France

[b] Institut de Géologie du Bassin d'Aquitaine (IGBA), UA-CNRS n° 197, Université Bordeaux-I, 351, Cours de la Libération, 33405 Talence Cedex, France.

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ABSTRACT

A series of 8 cores recovered east and west of the Gibraltar sill, below or inside the MIW (Mediterranean Intermediate Water) and MOW (Mediterranean Outflowing Water) pathways and within Atlantic waters, between 4° and 8° West, have been investigated for sedimentary structures, mineralogy, trace elements, benthic foraminiferal assemblages, oxygen and carbon-stable isotopes of planktonic and benthic foraminifers and radiocarbon datings of the size fraction $>50\,\mu m$ of the bulk sediment. All data provide evidence of a permanent Mediterranean Outflowing Water since the Last Glacial Maximum (LGM). Study of the covariations of Th/Ta and La/Th ratios, together with similarity in the composition and changes of benthic foraminiferal associations east and west of the sill, suggest a permanent contamination of the Faro drift by a Mediterranean output. Carbon isotopic changes recorded by *G. bulloides* and *Cibicides* sp. display a general pattern close to that reported for Atlantic mid-depth waters : high $\delta^{13}C$ values characterize the LGM, and low $\delta^{13}C$ values characterize the time interval 15 000 years BP-Recent. Detailed analyses of the 15 000 years BP-Recent time interval in the studied cores, however, reveal a clear Mediterranean signature. High $\delta^{13}C$ values are recorded also during phases of deglaciation, around 15 000 years BP, 11 000-10 000 years BP and 3 000 years BP. Such episodes of high ^{13}C content are correlated with the deposition of coarse-grained contourites on the Faro drift and higher smectite + kaolinite/illite + chlorite ratios of the clay sediments. The data suggest a higher intensity of the MOW and well-oxygenated (nutrient-poor) MIW. These episodes bracket intervals of low ^{13}C content, between 18 000-16 000 years BP, 14 000-11 000 years BP and 9 000-5 000 years BP, which are synchronous with the deposition of fine-grained contourites, and a decrease in the S + K/I + C ratios of the clay sediments. In addition, the most recent ^{13}C depletion, near 9 000-8 000 years BP, is coeval with the stagnation of East Mediterranean deep waters, which led to the deposition of sapropel S1. These data suggest that during these invervals, the intensity of the MOW decreased and that the MIW were poorly oxygenated (and nutrient-enriched). But there was no evidence of any current reversal over the Gibralter sill during the last 18 000 years.

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RÉSUMÉ

Circulation de l'eau méditerranéenne à travers le détroit de Gibraltar, depuis 18 000 ans BP

L'étude des structures sédimentaires, des éléments traces, de la minéralogie, des foraminifères planctoniques et benthiques et de leur composition isotopique dans huit carottes prélevées à l'est et à l'ouest du détroit de Gibraltar (en mer d'Alboran, sur la ride du Faro, sur le glacis du Golfe de Cadix et au Cap St-Vincent) au cours de la campagne océanographique Faegas IV, confirme l'hypothèse d'une permanence de la veine d'eau méditerranéenne depuis 18000 ans BP. Les variations conjuguées des rapports Th/Ta et La/Ta ainsi que la grande similitude des associations de foraminifères benthiques de part et d'autre du seuil depuis le dernier maximum glaciaire, impliquent une « contamination » permanente de la ride du Faro par des eaux méditerranéennes. Les variations de composition isotopique du carbone des espèces de foraminifères marqueurs des eaux levantines et intermédiaires présentent des similitudes avec celles enregistrées aux profondeurs intermédiaires de l'Atlantique. Les valeurs de $\delta^{13}C$ sont plus élevées durant le dernier maximum glaciaire et plus basses à partir de 15000 ans BP. Cependant, le détail de l'évolution enregistrée au sein des eaux intermédiaires et de la veine méditerranéenne depuis 15000 ans correspond à un schéma spécifique de la Méditerranée. Des épisodes à valeurs de $\delta^{13}C$ élevées, aux environs de 15000 ans BP, du Younger Dryas et de 3 000 ans BP sont synchrones du dépôt de contourites de texture grossière sur la ride du Faro et d'une augmentation du rapport smectite + kaolinite/illite + chlorite dans les argiles. C'est aussi durant ces épisodes que les assemblages de foraminifères benthiques présentent de plus grandes similarités. Ces observations suggèrent une augmentation de l'intensité de la veine méditerranéenne avec des eaux oxygénées et pauvres en nutriments. En revanche, des épisodes à basses valeurs de $\delta^{13}C$ entre 18000 et 16000 ans BP, 14000 et 11000 ans BP, 9000 et 5000 ans BP sont synchrones du dépôt de contourites à grain fin et de faibles valeurs du rapport S+K/I+C dans les argiles. L'épisode le plus récent serait synchrone de la dernière stagnation du bassin oriental de Méditerranée qui s'est traduite par le dépôt du sapropèle S1. Ces épisodes sont probablement à mettre en relation avec une baisse de l'intensité du flux de la veine méditerranéenne, qui aurait été constituée d'eaux moins bien oxygénées et peut-être plus riches en nutriments. Aucun indice d'une inversion des courants au niveau du détroit de Gibraltar n'a été relevé pour la période de 18000 ans-actuel.

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INTRODUCTION

Because the Mediterranean has a net water deficit due to the evaporation of nearly 1 m annually, the salt and water balance is maintained by a two-layer flow through the Strait of Gibraltar : less dense Atlantic water flows eastward above a westward flowing current of denser and saltier Mediterranean Outflow Water (MOW). The major portion of this outflowing water corresponds to the Mediterranean Intermediate Water (MIW), which is evolved from the Levantine Intermediate Water (LIW; Bryden and Stommel, 1982; 1984; Gascard and Richez, 1985; Kaese and Zenk, 1987; Lacombe and Tchernia, 1972; Lacombe *et al.*, 1981; Lacombe and Richez, 1985; Medoc Group, 1970; Reid, 1978; 1979; Wüst, 1961; Worthington, 1976; among others). As a result, intermediate depths, between about 600 and 2500 m, in the Northeast Atlantic are occupied by a great lens of warm and saline water. This water mass, of higher salinity, flows both westward and northward, finally entering the Norwegian Sea; it may be important in the formation of Norwegian-Greenland Sea bottom water, which, in turn, is an important component of the North Atlantic Deep Water (NADW; Reid, 1979; Fig. 1 and 2).

The outflow of warm, saline and nutrient-depleted water from the Mediterranean thus constitutes an intermediate water source for the modern Atlantic.

It is obvious, however, that the present day pattern of exchanges between the Mediterranean and Atlantic water masses through the Gibraltar Strait might have been slightly to significantly different in the past, in response to climatic fluctuations or tectonic modifications. In particular, inflow from the Atlantic Ocean should depend on the depth of the sills bounding each of the Mediterranean basins. These sills must be deep enough to allow efficient exchange of bottom water between basins, and the sill at Gibraltar must be shallow enough to prohibit the entry of cold dense North Atlantic Deep Water.

In fact, the history of Mediterranean water masses, since the Neogene period at least, is of considerable interest in understanding the evolution of the thermohaline circulation of the entire Atlantic (Vergnaud-Grazzini, 1983; Thunell *et al.*, 1987). For some authors, an outflow of warm and dense water, similar to the present Mediterranean Intermediate Water, existed during the Miocene and ceased at the end of the Tortonian (Keigwin, 1979; Vincent *et al.*, 1980; Bender and Graham, 1981; McKenzie and Oberhaensli, 1985; Benson *et al.*, in press). This outflow was probably reestablished during the Pliocene around 3.0 Ma, and from that time on, might be traced in the North Atlantic (Loubere, 1987; Vergnaud-Grazzini *et al.*, in press). Since then, fluctuations in the MOW intensity may have occurred in relation with the glacial-interglacial cycles of the Northern hemisphere, especially during the late Pleistocene when these cycles became more pronounced (Zahn *et al.*, 1986; 1987); but the impact of such variations on the northeast Atlantic circulation is still a matter of debate. On the basis of sedimentological structures and faunal size distribution, sedimentologists have argued for and against the permanency of the MOW during the last glacial-deglacial time (Diester Haass, 1973; 1974; Huang *et al.*, 1972; Huang and Stanley, 1972; 1974).

In the present study, which is based on a pluridisciplinary approach to cores located west and east of the Gibraltar sill, below the MOW and MIW pathways, we shall endeavour to investigate the relative variations of the MOW since the last glacial maximum. West of the Gibraltar sill, the Mediterranean outflow can at present be traced by a higher ^{13}C content of the dissolved CO_2 (Duplessy, 1972), distinctive Th/Ta and La/Ta ratios of the particulate content (Grousset *et al.*, 1988), benthic foraminiferal assemblages below the flow which are similar to assemblages from the Alboran Sea (Caralp, 1988) and associated sediments deposited as contourites with high smectite/illite ratios (Faugères *et al.*, 1985*a*, *b*, *c*; Gonthier *et al.*, 1984; Stow *et al.*, 1986). Sedimentology, clay mineralogy, trace elements, benthic foraminiferal assemblages, glacial-postglacial patterns of ^{13}C changes of *Globigerina bulloides* and *Uvigerina div.* sp., ^{14}C dates and oxygen isotope stratigraphy of eight cores recovered west and east of the Gibraltar Strait constitute new data in support of a Mediterranean outflow permanency at least since 18 000 years BP.

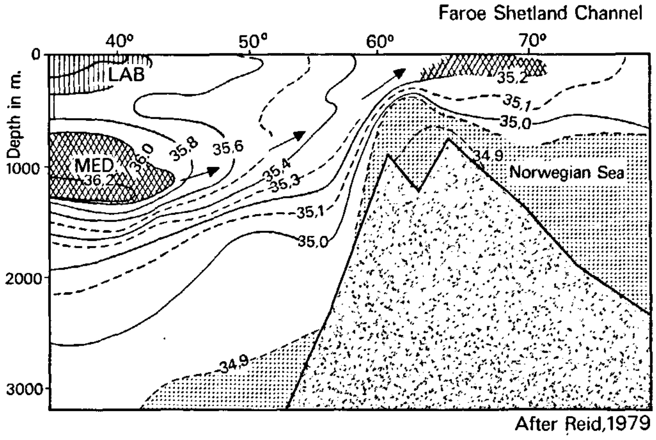


Figure 1

Present-day extent of the Mediterranean outflow at 1 100 *m water depth, in the North East Atlantic* (*after Reid*, 1978-1979).

La veine d'eau méditerranéenne à sa profondeur d'équilibre (1 100 m) en Atlantique Nord (d'après Reid, 1978-1979).

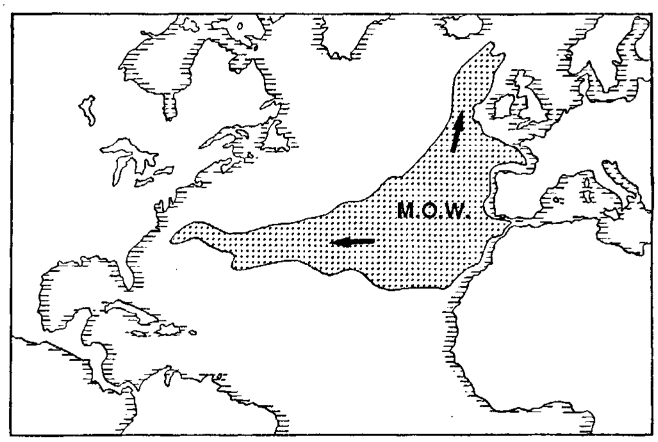


Figure 2

Salinity profile between 36 *and* 76°*N, in the North Atlantic, according to Reid's hypothesis* (*Reid,* 1979).

Profil de salinité en section verticale, entre les latitutes 36 et 76°N, illustrant l'hypothèse de Reid (1979)

SAMPLING AND METHODOLOGY

A series of cores were collected west and east of the Gibraltar sill, during the French oceanographic cruise Faegas IV (December 1982, Fig. 3 and Tab. 1; Faugères *et al.*, 1984). Detailed sedimentological investigations permitted identification of the main sediment depositional processes in this area and in particular, made it possible to distinguish sequences with hiatuses or reworked sediments from those with hemipelagic or pelagic muds (Faugères *et al.*, 1985*a*, *b*, and *c*).

It was then possible to select 8 cores suitable for the paleoenvironmental reconstructions of the last 18 000 years.

Table 1

Core location and water depth.

Coordonnées et profondeurs des sites de carottage.

Core	Coordinates	Water depth (m)	Area
KS8230	36°27'16N/03°53'18W	795	Alboran Sea
KS8231	36°09'30N/03°16'60W	855	Alboran Sea
KC8241	35°59'65N/04°24'08W	1282	Alboran Sea
KS8232	36°07'01N/02°07'14W	1920	Alboran Sea
KS8228	35°49'89N/08°43'07W	2798	Cadiz Gulf
KC8221	36°53'29N/07°39'00W	586	Faro Drift
KC8226	36°47'50N/07°48'80W	583	Faro Drift
KS8225	37°17'08N/09°19'97W	853	St Vincent Cape
CS70-5	35°44'04N/13°11'00E	1468	Strait of Sicily

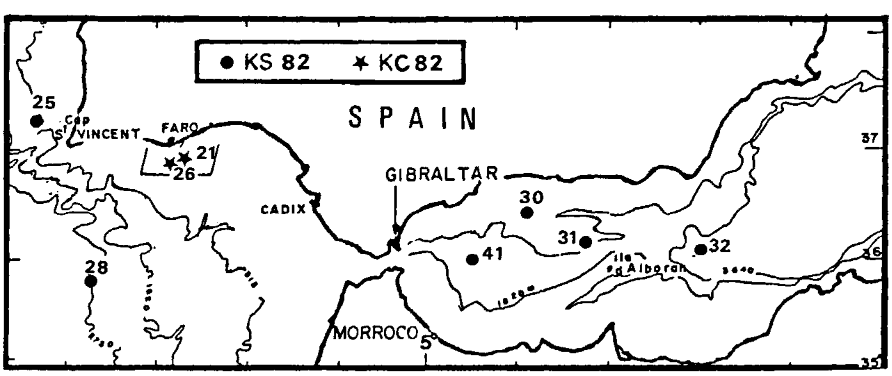


Figure 3

*Location map of the studied cores. Cores KS*8230, *KS*8231, *KS*8232 *and KS*8225 *with* 6 *cm diameter. Cores KC*8221, *KC*8226 *and KC*8241 *with* 10 *cm diameter.*

Carte de localisation des carottes étudiées. Carottes KS8230, KS8231, KS8232 et KS8225 avec un diamètre de 6 cm. Carottes KC8221, KC8226 et KC8241 avec un diamètre de 10 cm.

Table 2

Oxygen and carbon isotope data for cores KS8230, KS8231, KS8232, KC8241 and CS70-5 from the Western Mediterranean and cores KS8225, KC8221, KC8226 from the Atlantic. All data are against the PDB-1 standard. Variations in the diversity index of benthic foraminifers are also reported for cores KS8230 and KC8221.

Compositions isotopiques de l'oxygène et du carbone des foraminifères des carottes KS8230, KS8231, KS8232, KS8225, KC8241, KC8221, KS8226. Toutes les valeurs sont exprimées en parts pour mille par rapport au standard international PDB-1.

Core CS70-5

Depths (cm)	Ages * 1,000 years	$\partial^{18}O^0/_{00}$ *G. bulloides*	$\partial^{13}C^0/_{00}$ *G. bulloides*	$\partial^{18}O^0/_{00}$ *C. pachyderma*	$\partial^{13}C^0/_{00}$ *C. pachyderma*
0	0	0,77	−0,76	3,46	1,30
36	3,14	0,76	−0,36	3,15	1,57
50	4,87	1,57			
55	5,5	0,17	−0,69		
99	7	0,31	−1,11		
150	8,15	0,88	−1,13		
164	8,47	0,51	−1,26		
187	9	1,34	−1,27		
210	10,7	2,34	−0,33		
230	11,1	2,28	−0,79	3,18	1,49
252	11,5	1,62	−1,14		
273	12	1,79	−1,05		
303	12,75	1,99	−0,89		
334	13,5	2,61	−1,00	3,41	1,64
347	13,7	2,50	−0,80	2,57	1,28
389	14,32	2,44	−0,66	2,35	1,15
423	14,85	2,99	−0,67		
437	15	3,55	−0,65	3,53	1,50
455	15,1	3,42	−0,45		
474	15,25	3,22	−0,76	3,12	1,47
488	15,3	3,18	−0,74	3,98	1,58
499	15,4	3,45	−0,62	3,68	1,45
509	15,5	2,21	−1,18	3,64	1,59
522	15,7	3,14	−0,65	3,51	1,36
550	16	3,19	−0,37	3,64	1,62
565	16,5	3,33	−0,74	3,77	1,58
584	17	3,06	−0,05	3,95	1,80
601	17,5	3,07	−0,75	3,95	1,86
615	18			4,51	2

Core KC8241

Depths (cm)	Ages * 1,000 years	$\partial^{18}O^0/_{00}$ *G. bulloides*	$\partial^{13}C^0/_{00}$ *G. bulloides*
0	0	0,04	−0,74
10	1,45	0,01	−0,76
20	1,96	0,53	−0,42
30	2,47	0,19	−0,74
40	2,97	0	−1
50	3,48	0	−1
60	3,99		
70	4,49	0,32	−0,82
80	5,13	0,49	−0,92
90	6,06	0,25	−1,23
100			
110	7	0,43	−1,2
120	8,3	−0,92	−1,53
130	8,6	0,09	−1,38
140	8,8	0,66	−1,33
150	9	0,46	−1,34
160	9,42	0,41	−1,18
170	9,84	0,46	−1,34
180	10,3	1,05	−1,06
190	10,7	1,67	−0,71
200	11,1	1,17	−0,69
210	11,5	0,72	−0,8
220	11,87	1,02	−0,8
230	12,43	1,17	−0,77
240	12,9	0,97	−1,09
250	13,2	1,8	−0,82
260	13,5	2,45	−0,56
270	13,8	2,24	−1,01
280	14,1	1,24	−0,96
290	14,4	1,99	−0,44
300	14,7	2,19	−0,9
310	15	2,54	−0,86
320	16	2,38	−1
330	16,2	2,42	−1,19

Core KS8232

Depths (cm)	*Ages * 1,000 years*	$\partial^{18}O^0/_{00}$ *G. bulloides*	$\partial^{13}C^0/_{00}$ *G. bulloides*
0	0,5	0,37	−0,71
10	1,3	0,33	−0,55
20	2,6	0,63	−0,46
30	3,9	0,35	−0,76
40	5,2	0,15	−1,04
50	6,5	0,59	−0,87
60	7,5	0,21	−1,19
70	8,3	0,31	−1,45
80	9	0,72	−1,21
90	9,56	1,63	−0,90
100	10,1	2,12	−0,40
110	10,7	2,44	−0,50
120	11,1	2,06	−0,50
130	11,5	0,89	−1,18
140	11,8	1,15	−0,77
150	12,1	1,92	−0,72
160	12,34	1,96	−0,69
170	12,62	1,05	−0,96
180	13	1,16	−1,06
190	13,2	1,41	−0,81
200	13,5	2,07	−0,42
210	13,8	2,20	−0,49
230	14,2	2,93	−0,62
240	14,6	3,06	−0,76
250	15	3,32	−0,50
260	15,4	2,88	−0,66
270	15,8	2,92	−0,64
280	16,2	3,16	−0,58
300	16,6	3,17	−0,84
320	17	3,09	−0,71
330	17,3	3,21	−0,64
340	17,6	3,26	−0,36
350	18	3,50	−0,70

Table 2 (*following*)

*Core KS*8230

Depths (cm)	Ages (× 1,000) years	$\partial^{18}O^0/_{00}$ *G. bulloides*	$\partial^{13}C^0/_{00}$ *G. bulloides*	$\partial^{18}O^0/_{00}$ *U. peregrina*	$\partial^{13}C^0/_{00}$ *U. peregrina*	Diversity Index benthic foraminifers
0	0	0,65	−0,58	2,99	−0,55	21
10	1	0,57	−0,5			13
20	1,55	0,68	−0,55	2,07	−0,56	14
30	2,1	0,85	−0,36			14
40	2,33	0,55	−0,49	2,01	−0,51	16
50	2,66	0,98	−0,53	1,69	−0,67	12
60	3	0,97	−0,4	2,05	−0,53	13
70	3,3	1	−0,38	1,92	−0,59	19
80	3,53	0,57	−0,58	1,91	−0,61	14
90	3,76	1,23	−0,45			15
100	4	0,85	−0,77	2,13	−0,51	19
110	5,5	0,73	−0,96	2,04	−0,65	17
120	7	0,46	−1,12	2,09	−0,55	18
130	7,6	0,46	−1,3	1,63	−0,56	17
140	8,3	0,47	−1,13	1,59	−0,75	19
150	8,7	1,3	−0,76	2,19	−0,45	16
160	9	1,46	−0,76	2,1	−0,5	17
170	9,7	1,67	−0,7	2,49	−0,42	18
180	10,7	2,64	−0,25	3,01	−0,26	15
190	11	1,99	−0,53	3,06	−0,34	16
200	12	1,74	−0,89	3,36	−0,09	15
210	13	1,51	−0,89	3,55	−0,11	10
220	13,33	2,99	−0,51	4,02	−0,06	16
230	13,66	2,32	−0,28		−0,06	12
240	14	2,92	−0,53	4,67	−0,22	16
250	14,2	2,57	−0,74			15
260	14,4	3,08	−0,51			17
270	14,6	3,12	−0,55			17
280	14,8	2,73	−0,7			12
290	15	3,21	−0,66			12
300	15,1	2,82	−0,49			14
310	15,3	2,53	−0,81			
320	15,5	2,59	−0,68			
330	15,7					
340	16	2,8	−0,48			

*Core KS*8231

Depths (cm)	Ages * 1,000 years	$\partial^{18}O^0/_{00}$ *G. bulloides*	$\partial^{13}C^0/_{00}$ *G. bulloides*	$\partial^{18}O^0/_{00}$ *U. peregrina*	$\partial^{13}C^0/_{00}$ *U. peregrina*
0	0	0,24	−0,86	1	−0,7
10	1,1	0,39	−0,75		
20	2,2	0,46	−0,5	1,84	−0,61
30	3,3			1,82	−0,7
40	3,66	0,2	−0,95		
50	4	0,72	−0,52	0,89	−0,95
60	5,5	0,62	−1,12	1,34	−1,45
70	7			1,23	−1,25
80	8,3	0,47	−0,86	0,98	−1,22
90	9			1,87	−1,11
100	9,42	0,83	−1,12	2,46	
110	9,84	1,09	−0,83	3,58	−0,65
120	10,24	1,38	−0,9	2,4	−1
130	10,7	2,02	−0,83	3,22	−0,67
140	11,1	1,75	−0,28	2,44	
150	11,5	1,51	−0,28	3,25	−0,53
160	12	1,75	−1,11	4,07	−0,65
170	13	2,6	−0,75		
180	14	2,93	−0,91	3,9	−0,69
190	15	3,17	−0,52	4,21	−0,67
200	15,5	2,91	−0,42	4	−0,47
210	16	2,98	−0,36	3,4	−0,38
220	16,1	2,89	−0,46	3,75	0,05
230	16,3	2,1	−0,63	3,21	−0,03
240	16,4	2,11	−0,37	3,54	−0,17
250	16,6	2,72	−0,32	3,44	−0,17
260	16,7	1,83	−0,52	3,78	0,2
270	16,9	2,3	−0,52	3,47	0,3
280	17	1,86	−0,70	3,76	0,28
				3,63	−0,09
				3,31	−0,16

Core KC8221

Depths (cm)	Ages * 1,000 years	$\partial^{18}O^0/_{00}$ *G. bulloides*	$\partial^{13}C^0/_{00}$ *G. bulloides*	$\partial^{18}O^0/_{00}$ *U. peregrina*	$\partial^{13}C^0/_{00}$ *U. peregrina*	Depths (cm)	Divers Index benthic foraminifers
0	0,05	0,5	−0,77	1,42	0,64	0	50
6	0,54	0,63	−0,55	2,0	0,79	2	22,8
13	1,17	−0,06	−0,89	1,7	0,75	10	11,5
20	1,8	−0,1	−1,19	1,7	0,58	20	8,2
30	2,7	0,1	−1,14	1,78	0,3	30	5,6
40	3,6			1,75	0,3	39	6,8
50	4,5	0,41	−0,89	1,87	0,09	40	4,5
60	5,4			1,66	−0,04	49	5,8
70	6,3			1,81	0,11	50	2,9
80	7,2	0,35	−1,02	2,15	0,29	59	3,8
90	8,1			1,94	0,24	69	6,5
100	9			1,54	0,06	79	7,7
107	9,98			2,21	0,61	99	6
118	10,51	0,39	−0,39	3,13	0,43	106	12,9
111	9,86	1	−0,51	2,61	0,44	111	6,3
124	10,78	1,19	0,04	2,85	0,55	117	10,4
130	10,96	1,51	−0,54	2,82		122,5	7,7
143	11,25			2,7	0,44	128	8,7
150	11,5			2,46	0,28	134	5
166	12,9			2,62	0,33	142	8,4
174	13,17			2,83	0,21	149	7,7
197	13,95			2,82	0,14	157	6,7
212	14,45			3	0,11	165	9,3
219	14,69			3,62	0,44	173	4,8
224	14,86			3,41	0,35	185	4
229	15			3,83	0,47	200	7,5
238	15,41			3,69	0,17	205	5
245	15,71			3,71	0,21	211	13,8
260	16,33			3,76	−0,1	218	13
280	17,16			3,91	0,23	222,5	12,7
298	17,91			3,92	0,19	227	12,5
						232	14,2
						237	12,5
						244	5,9
						250	11,3
						260	6,3
						270	5
						280	6,2
						290	5,9
						295	8

Core KC8226

Depths (cm)	Ages * 1,000 years	$\partial^{18}O^0/_{00}$ *G. bulloides*	$\partial^{13}C^0/_{00}$ *G. bulloides*	$\partial^{18}O^0/_{00}$ *U. peregrina*	$\partial^{13}C^0/_{00}$ *U. peregrina*
0	1	0,55	−1,43	1,62	0,58
10	4,95			1,57	0,64
18	5,57	−0,15	−1,2	1,71	0,44
20	5,73			1,39	0,42
31	6,59	−0,17	−1,3	1,81	1,17
40	7,29			1,42	0,43
49	8	0,27	−0,82	1,15	0,19
50	8,04				
60	8,48	0,41	−1,17	1,86	0,28
90	9,81			1,73	0,49
100	10,25			2,36	0,82
110	10,7	1,79	−0,03	2,83	0,83
120	10,86	1,07	−0,81	2,63	0,43
130	11,02			2,77	0,43
140	11,18	0,78	−1,03	2,81	0,52
150	11,34			2,67	0,39
160	11,5			2,51	0,31
180	12,57	1,73	−0,43	3,32	0,6
190	13,11	1,36	−0,7	3	0,16
200	13,65	1,96	−0,78	3,35	0,48
220	14,73	2,57	−0,12	3,68	0,45
230	15,23	2,32	−0,63	4	0,65
240	15,69	1,25	−0,91	3,94	0,5
245	15,92			3,36	0,44
250	16,15			2,84	0,27
275	17,30			3,24	0,32
280	17,53			3,43	0,7
290	18			3,91	1,14
300	18,25			3,57	0,49
310	18,51			3,85	0,62
320	18,77			3,81	0,72
330	19,02			3,6	0,65
340	19,27			3,68	0,6
350	19,53			3,73	0,65
360	20			3,75	0,62

Table 2 (*following*)

Core KS8225

Depths (cm)	Ages * 1,000 years	$\partial^{18}O$ °/oo *G. bulloides*	$\partial^{13}C$ °/oo *G. bulloides*	$\partial^{18}O$ °/oo *U. peregrina*	$\partial^{13}C$ °/oo *U. peregrina*
0,2	1,06	0,49	−1,44	1,54	−0,04
3	1,59			1,63	−0,09
7	3,71			1,79	−0,04
11	5,84	0,80	−0,99	1,79	−0,07
16	8,5			1,08	
28	9,27			2,05	0,05
34	9,66	−0,22	−1,58	2,48	−0,04
36	9,79	−0,3	−1,87	1,96	−0,54
39	9,98	1,63	−1,24	2,14	−0,13
41	10,11	0,74	−1,11	2,24	0,13
43	10,24	0,50	−1,25	1,86	0,28
45	10,44	0,06	−1,29	2,17	−0,03
49	10,63	0,76	−1,29	2,36	−0,14
50	10,7	1,84	−0,77	2,59	0
53	11,19	1,24	−0,98		
61	12,51			2,74	−0,54
62,5	12,76	1,85	−0,52	3,23	0,05
64,5	13,09	2,53	−0,61	3,38	−0,26
66,5	13,42			4,23	−0,27
70	14	2,50	−1,24	3,69	−0,44
72	14,33			3,47	−0,63
74	14,66			3,55	−0,32
76	15	2,02	−0,76	4,53	−0,16
80	15,46			3,48	−0,53
82	15,69	2,03	−0,74	3,86	−0,09
83	15,80			3,24	0,17
91	16,73	2,01	−1,13	3,74	−0,07
102	18	2,76	−0,83	3,60	+0,09
106	19,14	1,52	−1,21	3,49	0,04
111	20,57	1,12	−1,45	3,66	0,11
116	22			3,87	−0,06
126	24,49	1,55	−1,03	3,61	−0,04
133	25,85	1,80	−0,99	3,56	−0,05

Four cores are located in the Alboran Sea, two cores are on the Faro drift and one core on the St. Vincent Cape, west of the Gibraltar sill. One core, KS8228, was used for sedimentological purposes only. In addition, core CS 70-5, from the Sicilian Strait, was used only for comparison (Vergnaud-Grazzini *et al.*, 1988).

The chronological framework was provided by ^{14}C datings and oxygen isotope stratigraphy, using the planktonic foraminifera *Globigerina bulloides* for cores KS8230, KS8231, KS8232 and KC8241 in the Alboran Sea and core KS8225 from the St. Vincent Cape and the benthic species *Uvigerina peregrina* or *U. mediterranea* for cores KC8221 and KC8226 from the Faro drift. The ^{13}C records of *U. peregrina* for cores KS8230, KS8231, KS8225 have also been examined.

^{14}C datings were performed on the sediment fraction above 50 μm. The samples were observed under the binocular microscope in order to eliminate detrital particles of carbonate. Redeposition events at the centimetric level, bioturbation or other disturbances may result in the addition of older detrital carbonates (Berger *et al.*, 1985). For this reason, radiocarbon dates are used for general guidance but should be considered as optimized ages. The calculation of radiocarbon dates was based on 95% of the NBS oxalic acid ^{14}C standard. Corrections for isotope fractionation were not applied, since the $\delta^{13}C$ values of the dated carbonates were closed to 0°/oo PDB; in that case, the effect of isotope fractionation on the ^{14}C ages balances the reservoir age of about 400 years of the ocean surface layer.

Samples for oxygen and carbon isotope analyses were taken at 10 cm intervals of the cores. Some 25 to 30 specimens of *G. bulloides*, or 10 to 15 specimens of *Uvigerina*, for each level, were ultrasonically cleaned to remove adhering particles (clays or coccoliths) and roasted under vacuum at 350°C for one hour. CO_2 for isotopic analyses was extracted by reacting the foraminiferal carbonate in 100% phosphoric acid at 50°C in an oven. Evolved gas samples, after a series of on-line distillation steps to obtain pure CO_2, were analyzed in a VG Sira 9-triple collector mass spectrometer. All isotopic data are referred to the PDB reference in the standard δ notation, through the use of intercalibrated standards. The analytical precision of analyses of the carbonate standard run during the period of investigation is 0.06 (1 σ) for $\delta^{18}O$ and 0.04 (1 σ) for $\delta^{13}C$. Standard deviations of separated analyses of the same foraminiferal species are ± 0.14 for $\delta^{18}O$ and ± 0.08 for $\delta^{13}C$.

Clay mineralogy was determined through X-ray diffractometry, using the oriented paste method and measuring X-ray peak heights (Grousset *et al.*, 1988). Mineral definition weighting factors and mathematic procedures follow Biscaye (1965). The study of trace elements was restricted to Ta, La and Th. Analyses were carried out by instrumental neutron activation analysis, using the method defined in Treuil *et al.* (1973). To avoid dilution effects by carbonates, elemental variations are discussed in term of ratios, *e.g.* La/Ta or Th/Ta, which have been plotted against each other (Fig. 6).

Sedimentological investigations essentially concern the lithological and textural variations through the coarse-grained contourites and the interbedded fine-grained contourites of cores KC8221 and KC8226.

Calcareous benthic foraminiferal species of core KC8221 (on the Faro drift, in the upper part of the MOW) and core KS8230 (on the northern slope of the Alboran Sea, under the MIW), have been identified and counted in the granulometric fraction larger than 250 µm, from 10 g of bulk sediment sampled at 10 cm intervals (Lohmann, 1978; Lutze and Coulbourn, 1984). For each sample the total number of specimens and species as well as the diversity index have been calculated (Cita and Zocchi, 1978).

STRATIGRAPHIC FRAMEWORK

Oxygen isotope stratigraphy

The oxygen isotope stratigraphy is based on analyses of the species *G. bulloides*, *Uvigerina peregrina* or *U. mediterranea* (Tab. 2) with correlation between the cores based on the assumption that ice volume is the dominant factor controlling changes in foraminiferal $\delta^{18}O$ values and that the ice volume signal is globally synchronous within the mixing time of the oceans (< 1 000 years for the Atlantic, Broecker and Peng, 1982; < 100 years for the Mediterranean, Lacombe *et al.*, 1981).

In the Alboran Sea, maximum $\delta^{18}O$ values inferred to represent the LGM are shown by *G. bulloides*, in core KS8232, near 350 cm ($\delta^{18}O = +3{,}50^0/_{00}$). By convention, this level has been assigned the age of 18 000 yrs BP. The $\delta^{18}O$ values recorded in the other Alboran Sea cores by *G. bulloides* are generally lower than $+3.50^0/_{00}$. Because the sites of coring are close to each other, there is probably little scale variability in water mass characteristics. Therefore, $\delta^{18}O$ values lower than $+3.50^0/_{00}$ recorded at the base of cores KS8230, KS8231 and KS8241 should correspond to sediments younger than 18 000 yrs BP. West of the Gibraltar sill, in core KS8225, maximal $\delta^{18}O$ values of *G. bulloides* occur near 102 cm ($\delta^{18}O = 2.76^0/_{00}$). In this last core, however, the oxygen isotope stratigraphy is not easily interpretable because of differences between the benthic and planktonic ^{18}O records. Maximal $\delta^{18}O$ values of the benthic foraminifer *Uvigerina peregrina* occur higher in the core ($\delta^{18}O = 4.53^0/_{00}$ at 76 cm). In this core, the 102 cm level has been assigned the age of 18 000 yrs. In cores KC8221 and KC8226, maximum $\delta^{18}O$ values recorded by *Uvigerina* (around $+3.91^0/_{00}$ in both cores) are reached at 298 and 290 cm respectively, suggesting a nearly identical sedimentation pattern for the two cores. These levels are also assigned the glacial maximum age of 18 000 years. Core tops have been assigned an age of 0 years with the exception of core KC8226 which is obviously older.

It is widely recognized that the transition from the last glacial to the present interglacial episode was not unidirectional (Ruddiman and Duplessy, 1986), and this pulsed nature of the deglaciation is apparent on the seven studied cores. In particular, the two main steps, corresponding to Termination IA and Termination IB, can be recognized (Duplessy *et al.*, 1981). Although the 18 000 years event (Last Glacial Maximum = LGM) is not conspicuous on all cores, we have tried to identify the major phases of the deglaciation, following the definition and age assignments of Duplessy *et al.* (1986) and Bard *et al.* (1987*a* and *b*). The dates proposed by these authors are based on accelerator mass spectrometry radiocarbon measurements on hand picked foraminiferal shells from sediments of the Northern Atlantic core CH73-139C. Control points at 15 000, 11 500, 10 700 and 8 000 yrs BP (listed in Table 4 with the corresponding $\delta^{18}O$ values) have been used, together with the most reliable ^{14}C dates, to reconstruct the timescale of the studied records by linear interpolation.

^{14}C dating (Table 3)

Radiocarbon dates were collected on 33 samples of carbonate sediments, on the fraction coarser than 50 µm. Comparison of coarse fraction ages with bulk ages have been extensively discussed by various authors (Eriksson and Olsson, 1963; Berger *et al.*, 1985; Devaux, 1985). Comparison of the ^{14}C dates of our core sediments with the accelerator dated oxygen isotopic events of the last deglaciation (Bard *et al.*, 1987*b*; Tab. 4) suggests a substantial addition of detrital carbonate in two cores : KS8232 and KS8225 as well as in other cores around ~12 000 years. Therefore, the ^{14}C dates obtained in this study have been used only to

Table 3
^{14}C dates on the sediment fraction > 50 µm. The dates which have been used to generate the interpolated timescales of the various sequences are indicated *
Datation ^{14}C de la fraction de sédiment > 50 µm. Les dates indiquées * ont été utilisées pour établir l'échelle chronologique.

Core	Levels (cm)	^{14}C dates
KS8225		
	22	7985 ± 300
	122*	23725 ± 1000
	200	>25000
KC8221		
	23	9250 ± 150
	190*	15630 ± 1000
	223*	16460 ± 1200
KC8226		
	10*	4950 ± 80
	45	8870 ± 100
	130	10170 ± 800
	200*	13450 ± 1000
	255*	16385 ± 650
KC8241		
	7*	1305 ± 330
	77*	4850 ± 230
	117*	7160 ± 50
	221*	11460 ± 540
KS8230		
	23*	2010 ± 220
	63*	3100 ± 235
	152*	9800 ± 1000
	195	12840 ± 1000
KS8231		
	27*	3255 ± 250
	127*	11000 ± 800
	210	14200 ± 900
	234*	15630 ± 800
	254*	17160 ± 1200
	297*	18270 ± 1000
KS8232		
	108*	9765 ± 500
	248	12925 ± 600
	350	22145 ± 1000

Table 4

Dates and depths (cm) of the ^{18}O events used as control points for the various records. The corresponding $\partial^{18}O$ values are also indicated. The depth location of the 18 000 *years event in core CS70-5 has been slightly modified with respect to that proposed by Vergnaud-Grazzini* et al. (1988) *and is based on the maximal $\partial^{18}O$ values of* Cibicides pachyderma. *No data are available at that depth for* G. bulloides.

Ages et profondeurs dans les carottes (cm) des événements ^{18}O utilisés comme marqueurs chronologiques. Les valeurs correspondantes de ∂^{18}O sont aussi mentionnées. La profondeur de l'événement 18 000 ans dans la carotte CS70-5 a été légèrement modifiée par rapport à celle publiée par Vergnaud-Grazzini *et al.* (1988); la nouvelle évaluation a pris en compte les valeurs maximales de ∂^{18}O de *Cibicides pachyderma.* Il n'y a pas de données pour *G. bulloides* à ce niveau.

	KS 8230		KS 8231		KS 8232		KC 8241		KC 8221	
Ages ($\times 10^3$ yrs)	cm	∂^{18}O *G. bulloides*	cm	∂^{18}O *G. bulloides*	cm	∂^{18}O *G. bulloides*	cm	∂^{18}O *G. bulloides*	cm	(∂^{18}O) *Uvigerina*
8-8.5	*130*	0.46	*80*	0.47	*70*	0.31	*130*	0.09	***90***	**1.94**
10.7	*180*	2.64	*130*	2.04	*110*	2.44	*190*	1.67	***120***	**3.12**
11.5	*210*	1.51	*150*	1.51	*130*	0.89	*210*	0.72	***150***	**2.46**
15	*290*	3.21	*190*	3.17	*250*	3.32	*310*	2.54	***230***	**3.83**
18					*350*	3.50			***298***	**3.92**

	KC 8226		KS 8225		CS 70-5		CS 70-5	
Ages ($\times 10^3$ yrs)	cm	∂^{18}O *Uvigerina*	cm	∂^{18}O *Uvigerina*	cm	∂^{18}O *G. bulloides*	cm	∂^{18}O *Cibicides*
8-8.5	*60*				*164*	0.51		
10.7	*110*	**2.83**			*210*	2.34		–
11.5	*160*	**2.51**			*252*	1.62		–
15	*230*	**4**	*115*	**3.87**	*437*	3.55		3.53
18	*290*	**3.91**	*190*	4.04	*615*	–		4.51

refine the chronologic framework deduced from oxygen isotope stratigraphy. In addition, two faunal events have also been used to correlate the cores inside the Alboran Sea; the "I" event, which is the first rapid increase in *G. inflata* abundances, at or near 6 800-7 000 years, and the "R event", which corresponds to the first occurrence of *G. ruber var. rosea* around 9 000 years (Pujol and Vergnaud Grazzini, 1985; Fig. 4 A and B).

SEDIMENTARY FACIES

From twenty cores collected on the Faro drift (Gulf of Cadiz) for sedimentological investigations, cores KC8221 and KC8226 were selected for paleonvironmental studies.

These two cores show a rather uniform and fine sedimentation; no reworking was detected. In contrast, most of the other cores display sedimentary structures which imply strong and active bottom current effects. Sediment analyses show that 98% of the sediments deposited at present on the Faro drift are contourites (Gonthier *et al.*, 1984). In addition, the sedimentological studies of the cores raised on the Faro drift show that three distinct events correspond to coarser-grained contourites (either sandy silt or silty clay contourites) interbedded with fine grained muddy contourites. These coarser level peaks are also detectable in cores KS8221 and KC8226 (Fig. 5). The stratigraphy proposed for these cores allows us to date the coarser levels; the more recent one corresponds to an age between 3 000 years and the present, the second one to an age between 11 000 and 10 000 years, and the older one to an age between 16 000 and 14 000 years.

Detailed analyses of lithological and textural variations through the coarse grained contourites and the interbedded fine grained contourites suggest that these variations are related to varying intensity of the bottom circulation (Faugères *et al.*, 1986; Stow *et al.*, 1986). The following arguments support this hypothesis :

– The three coarser contourite peaks display clear sedimentary structures with sharp or erosive contacts, while the interbedded muddy contourites show gradational contacts with occasionally well developed laminations.

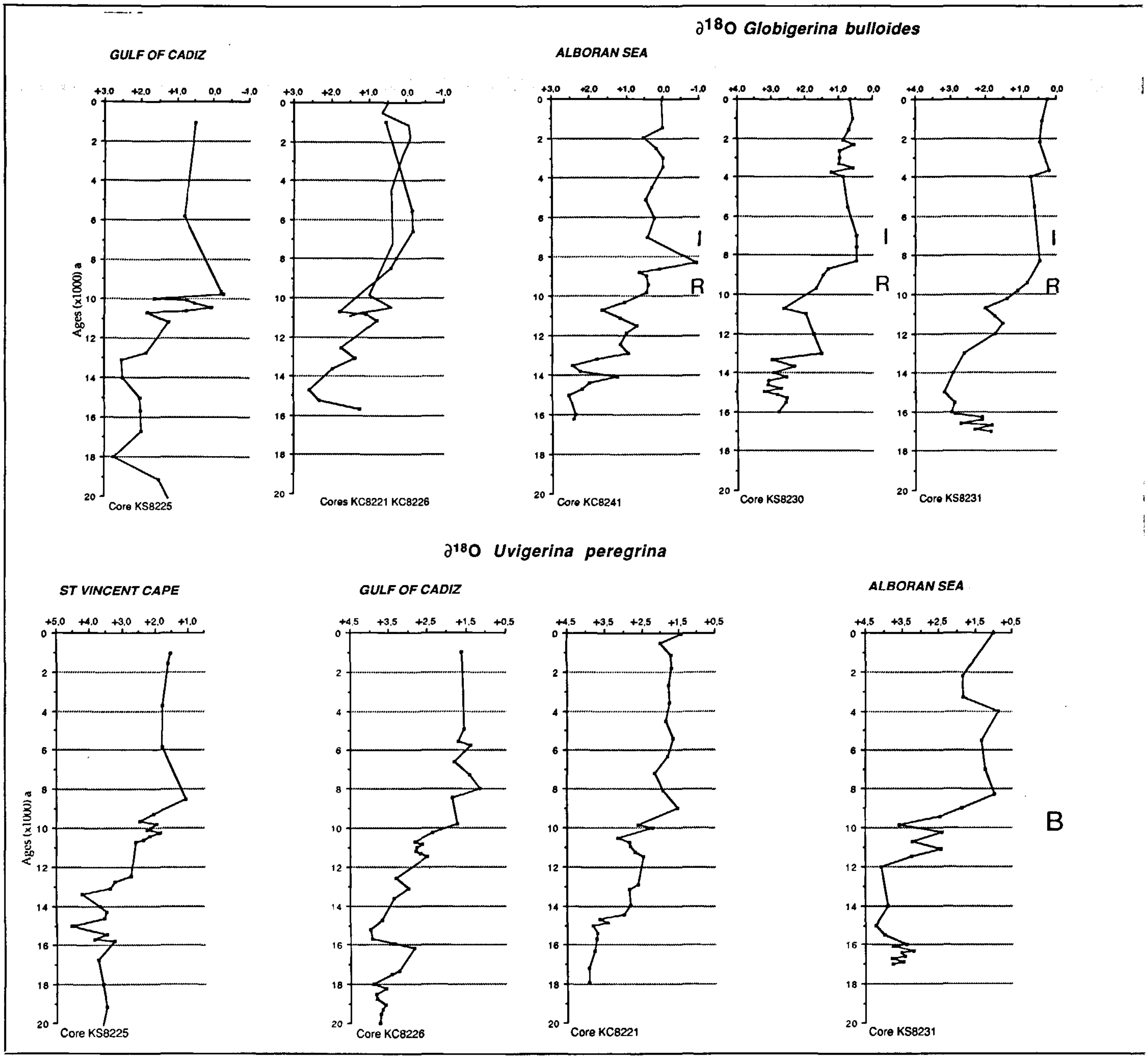
– In a few cores, with very low accumulation rates, these three episodes correspond to significant sedimentary hiatuses. These cores are located in areas of high current intensity where the increase in the velocity has induced erosion.

– The interbedding of coarse-grained with very fine-grained contourites points to currents capable of transporting the coarser elements which, then, either slowed sufficiently to deposit them or were deflected away from the site of deposition.

– On the scale of the drift, all three peaks show a relatively homogenous composition with similar terrigenous and biogenic calcareous components. The sandy fraction is of dominantly biogenic material (50 to 60%), and includes reworked planktonic and benthic foraminifera, miscellaneous shell debris and terrigenous materials including quartz, mica, rare heavy minerals, pyrite and very rare glauconite. Clays minerals account for up to 5-15% of the fraction finer than 63 µm and the percentages of the various species remain rather steady: 45-50% illite, 15-20% chlorite, 15-20% kaolinite and 10-20% montmorillonite. These data suggest a fairly constant sediment source and supply.

– The absence of any typical allochthonous minerals originating either from the Faro canyon or from the adjacent shelf suggests no direct influence of turbidity currents on the drift.

– The mixture of both terrigenous and biogenic components in the coarser fractions and the significant presence of reworked shelly debris and benthic foraminifera point to the influence of bottom currents rather



than a purely pelagic source of biogenic material from increased primary productivity.

– The fact that both the terrigenous and biogenic (planktonic and benthic) contents are higher in the sand fraction of the coarser intervals than in the sand fraction of fine-grained contourites also mitigates against any control by the primary production.

In fact, the sedimentological study of the Faro drift suggests permanent activity of bottom currents and a varying intensity of the Mediterranean outflow, with slower episodes between 18 000 to 16 000 years, 14 000 to 11 000 years, 9 000 to 3 000 years (Fig. 6).

MINERALOGY

Mineralogical and geochemical data on these cores have been extensively reported and discussed previously (Grousset *et al.*, 1988). In the present work, only the major trends will be reported. The clay mineralogy as well as the La/Ta and Th/Ta ratios of the detrital particulate material (which characterize the present day MIW and MOW) have been studied in the surface sediments and along some cores.

Surface sediments display a high smectite content on the Cadiz shelf (Mélières, 1974), at the Guadalquivir mouth, with smectite + kaolinite / illite + chlorite ratios (S+K/I+C) of between 0.75 and 1.27. High values still are encountered on the Faro drift (0.85) and even off the St. Vincent Cape (0.61). On the deep Atlantic part of the sill, these ratios are lower than 0.6. A symmetrical pattern (west-to-east gradient) has been observed for the Alboran Sea (Auffret *et al.*, 1983; Cossement *et al.*, 1985). An excess of smectite has previously been observed in the present-day particulate suspended matter (SPM) of the Mediterranean water

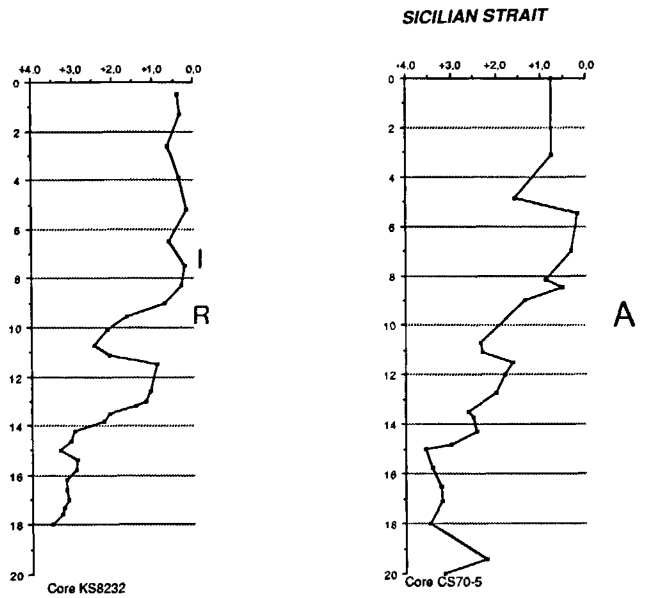


Figure 4

A: Oxygen isotope stratigraphy based on analyses of G. bulloides *for cores located in the Sicilian Strait (CS 70-5), in the Alboran Sea (cores KS8230, KS8231, KS8232 and KC8241) and within the Mediterranean Outflowing Water, west of the Gibraltar Strait (cores KC8221, KC8226 and KS8225. The "R" event (≈first postglacial reoccurrence of* G. ruber *var.* rosea *near 9 500 years BP) and the "I" event (=first postglacial reoccurrence of* G. inflata *near 7 000 years BP are indicated. B: Oxygen isotope variations of* Uvigerina peregrina *in some of the cores (cores KS8231, KC8221, KC8226 and KC8225).*

A : Stratigraphie isotopique à partir des variations de $\delta^{18}O$ de *G. bulloides* dans les carottes du détroit siculo-tunisien (CS 70-5), de mer d'Alboran (KS8230, KS8231 KS8232 et KC8241) et de la région Ouest de Gibraltar (dans la veine méditerranéenne) (KC8221, KC8226 et KS8225). Les événements faunistiques R (premier influx post-glaciaire en mer d'Alboran de *Globigerinoides ruber* var. *rosea*, à environ 9 500 ans BP) et I (premier influx post-glaciaire en mer d'Alboran de *Globoratalia inflata*, à environ 7 000 ans BP) sont indiqués. B : Courbes de variation des valeurs de $\delta^{18}O$ d'*Uvigerina peregrina* dans les carottes KS8231, KC8221, KC8226 et KS8225.

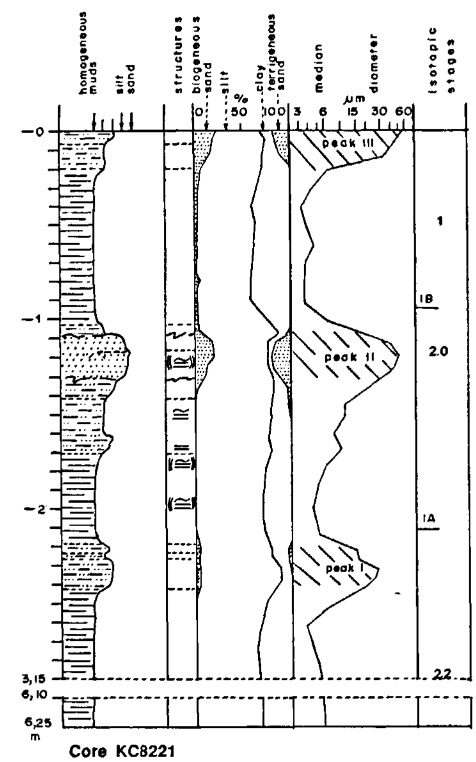


Figure 5

Structure, lithology and median grain size in core KC8221

Structure, lithologie et variations de taille du grain médian dans la carotte KC8221.

mass (Pierce and Stanley, 1975), as well as in the surface sediments located along the MIW trajectory (Grousset *et al.*, 1988). Smectite-rich SPM contaminated by the Guadalquivir on the Atlantic side of the strait, may be considered as negligible; in Cadiz bay, they are deflected eastward by surface currents (Mélières, 1974) and may constitute only a minor part of the input to the Faro drift. The clay mineral particles carried into the Atlantic by the MOW seem to be

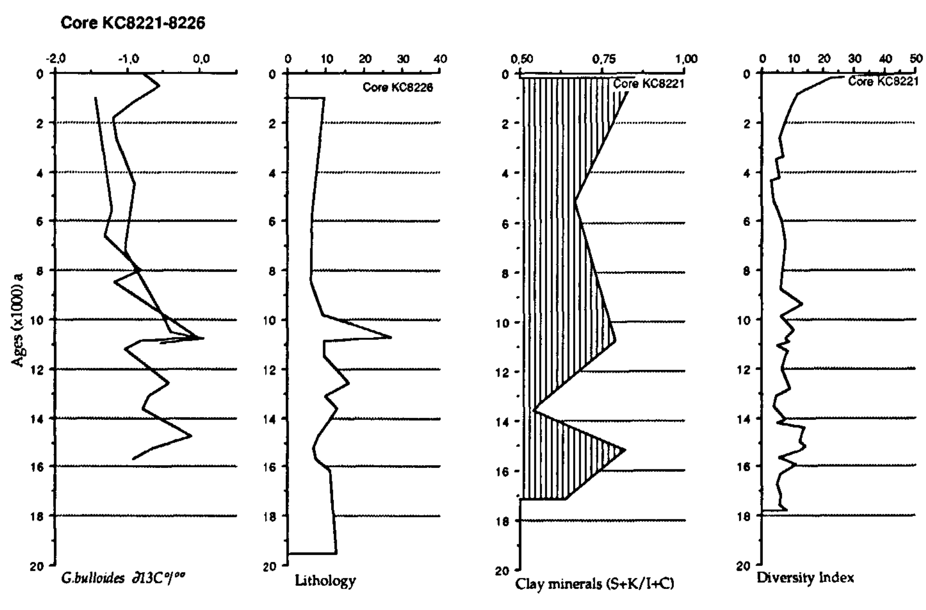


Figure 6

A: The $\delta^{13}C$ record of G. bulloides *in cores KC8226 and KC8221. B: Changes in median grain size (in μm) in core KC8226. Episodes of higher grain size are located around 10-11 000 years, 15 000 years and 18 000 years. C: Changes in the clay mineral ratio (S+K/I+C) (smectite+kaolinite/illite+chlorite) in core KC8221. D: Diversity index of benthic foraminifera in core KC8221.*

A : Variations des valeurs de $\delta^{13}C$ de *G. bulloides* dans les carottes KC8221 et KC8226. B : Variations de taille du grain médian dans la carotte KC8226. Les valeurs les plus élevées se trouvent à 10000-11 000 ans, 15 000 ans et 18 000 ans. C : Variations du rapport des espèces argileuses S+K/I+C (smectite+kaolinite/illite+chlorite) dans la carotte KC8221. D : Variations de l'index de diversité des foraminifères benthiques dans la carotte KC8221 progressively deposited along the slope within an approximately 800-1 200 m depth range. Mineralogical evidence of this deposition may be found as far north as Lisbon (smectite >20%).

These sediment transport processes may be detected for the entire post-glacial time on the Faro drift (core KC8221). They were more intense during three main events (S+K/I+C ratios >0.75) which coincide with the three coarser contourite episodes defined by Faugères *et al.* (1985*c*) at ~16 000/14 000 years, ~11 000/10 000 years and in the late Holocene (Fig. 6). There is no evidence of such mineralogical events either in core KS8228 in the deep Atlantic, west of the sill (S+K/I+C ~0.47-0.67) or in core KS8231 in the Alboran Sea, east of the sill (S+K/I+C ~0.3-0.59). Unfortunately, we have only six data points in core KC8221, too few for meaningful interpretation; however, geochemical tracers corroborate this hypothesis.

The ratios La/Ta and Th/Ta have been plotted against each other (Fig. 7). Two distinct mixing lines emerge, one from the samples of Guadalquivir, Faro drift and Alboran Sea, and the other for the samples of the open Atlantic. This means that Mediterranean and Atlantic deposits are geochemically discriminated. End-members were previously proposed for these mixing lines : the African aeolian source, the Atlantic source (deep-sea clay background) and the Guadalquivir River source (Grousset *et al.*, 1988). These data show that all the Faro drift samples (core KC8221), including those corresponding to the deposition of coarse grained contourites and the interbedded ones, are located along the "Alboran" mixing line. This relationship suggests that since the last glacial maximum there has been a constant contamination of the Faro drift by a Mediterranean output. In contrast, no Alboran sample (core KS8231) can be found along the "Atlantic" mixing line (core KS8228; Fig. 7). This implies that there may not have been any detectable particle bottom transport from the Atlantic into the Alboran Sea for the past 18 000 years. Unfortunately, these tracers do no allow us to draw conclusions about surface current intensities in the Alboran Sea.

If a current reversal took place, it should have resulted in much lower values of the S+K/I+C ratios, and Mediterranean (Alboran Sea) samples should plot along the La/Ta *vs* Th/Ta Atlantic mixing line in Figure 7. Both of these characteristics, which can be used to define current reversals, are not observed in the cores presented here, suggesting, in agreement with Cossement *et al.* (1985), that no current reversal has taken place during the last 18 000 years.

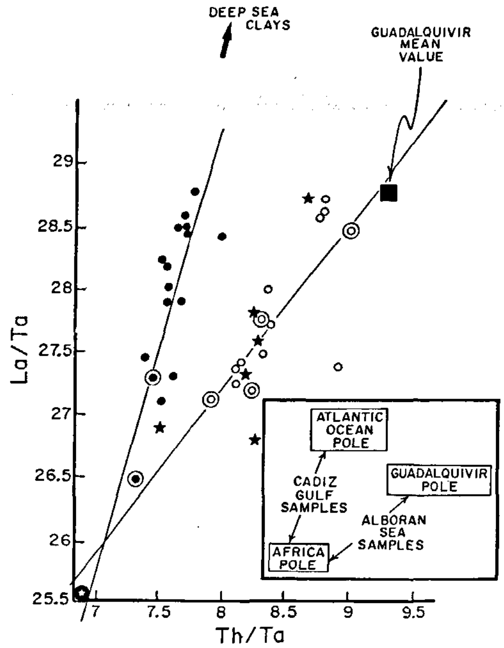


Figure 7

Mixing lines obtained with La/Ta versus Th/Ta in three cores: KS8231-Alboran Sea (o), KS8228-open Atlantic (•) and KC8221-Faro drift (*). Present-day (surface) samples are circled and concern only the Gulf of Cadiz (~5° to 9°W) and the Alboran sea. The circled white star is the Loukkos river (Morocco) sample.

Droite de mélange (La/Ta versus Th/Ta) dans trois carottes : KS8231, en mer d'Alboran (o), KS8228, dans l'Atlantique ouvert (•) et KC8221 sur la ride du Faro (*). Les échantillons actuels (de surface) sont encerclés et concernent uniquement le Golfe de Cadix et la mer d'Alboran. L'étoile vide encerclée concerne la rivière de Loukkos (Maroc).

BENTHIC FORAMINIFERA

Benthic foraminiferal data of two cores located in the epibathyal depths of both sides of the Gibraltar sill, core KS8230, in the Alboran Sea (MIW) and core KC8221 on the Faro drift (MOW) are presented here. The benthic foraminiferal assemblages of the two cores are rich and well diversified (high diversity index). In core KS8230, the diversity index remains rather steadily between 15 and 20 for the last 18 000 years. Only very small fluctuations are displayed within this range of values (Fig. 8); percentages of the various species also remain rather constant (Tab. 5). These observations suggest that since the Last Glacial maximum, the bottom water environment did not change much on the northern slope of the Alboran basin. This points to a permanent flow of the MIW since that time.

The mean species assemblages of core KC8221 is similar to that of core KS8230. The diversity index as well as the percentages of the various species, however, display stronger variations in the Gulf of Cadiz than in the Alboran Sea for the same time span. In the Gulf of Cadiz, the diversity index, which is generally less than 5, increases on three occasions: near 16 000-14 000 years, 11 000-10 000 years and in the Late Holocene where it is greater than 10. In fact, during these intervals, epibathyal benthic assemblages become similar (and highly diversified) in the two cores, suggesting similar physico-chemical parameters of intermediate water masses on both sides of the Gibraltar sill.

As pointed out by Caralp (1988), some benthic foraminiferal species which live in the epibathyal zone (Parker, 1958) appear to be linked to the MIW in the Alboran Sea and to the MOW in the Atlantic. Among these species are *Uvigerina peregrina, Planulina ariminensis* and *Amphicoryne scalaris.* All these species are abundant in the two studied cores. In core KS8230, variations of these species since the LGM are in phase and parallel, with low percentages between 18 000 and

14000 years, and higher percentages between 14000 years and the present. In core KC8221, variations of these species are more irregular. For instance, *P. ariminensis* occurs in the uppermost sediments and during the late Holocene part of the two cores. The percentages of this species remain rather uniforme troughout core KS8230, east of the sill. West of the sill, in core KC8221, this species occurs at three points only (with percentages from 5 to 10%), between 18000 and 14000 years, between 11000 and 10000 years and in the Late Holocene (Fig. 8).

Another species, *Cibicides pseudoungerianus*, is ubiquitous and essentially related to the nutrient supply to bottom sediments. Although its abundance increases near 16000-14000 years and in the early Holocene in the two cores, its generally high abundance can be related to a constant input of nutrients in the epibathyal zone on both sides of the sill.

Hyalinea balthica which may be regarded as a useful indicator of cold shelf water masses (Ross, 1984; Cossement *et al.*, 1985; Caralp, 1988) occurs on both sides of the Gibraltar sill and displays higher percentages during cold stratigraphic periods. While it is abundant between 18000 and 10000 years in core KS8230 (with percentages as high as 30%), it occurs only during the coldest episodes of this interval in core KC8221, *i.e.* between 18000 and 15000 years, and between 11000 and 10000 years.

Other species which are presently living in young, well-oxygenated water bodies like the modern North Atlantic Deep Water (NADW) (Lohmann, 1978; Schnitker, 1980) such as *Cibicides wuellerstorfi*, *Cibicides kullenbergi* and *C. robertsonianus*, may be found in the deeper sediments of the Gulf of Cadiz (*e.g.* core KS8228) as well as in shallower sediments below the NADW.

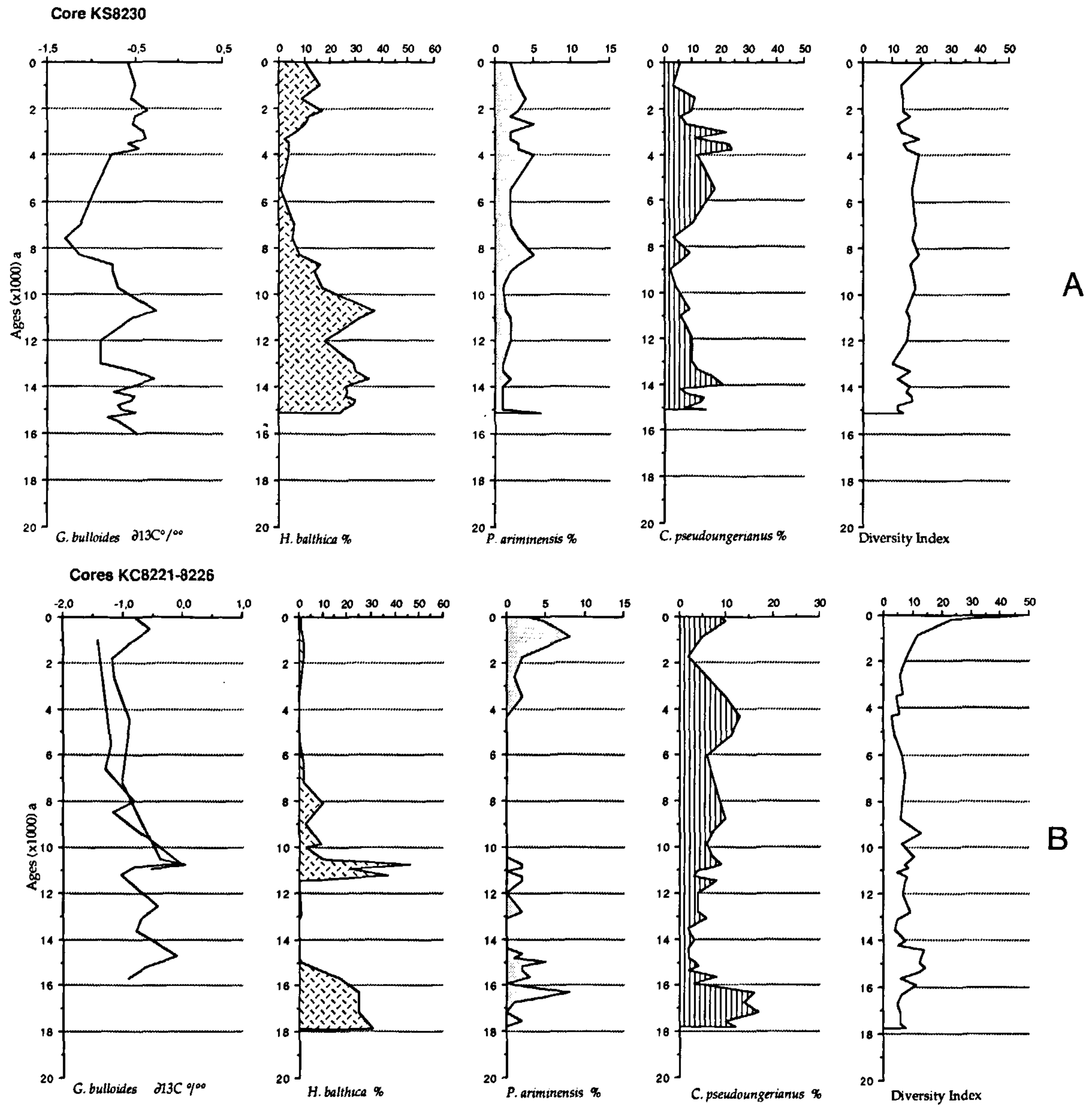


Figure 8

Benthic foraminiferal changes. A: in core KS8230, in the Alboran Sea. B: in core KC8221, on the Faro drift. From the left to the right: 1) The ^{13}C *record of* G. bulloides*; 2) Variations in the relative percentages of* Hyalinea balthica*; 3) Variations in the relative percentages of* Planulina ariminensis*; 4) Variations in the relative percentages of* Cibicides pseudoungerianus *; 5) Variations of the diversity index*

Variations enregistrées par les foraminifères benthiques. A : en mer d'Alboran, dans la carotte KS8230. B : sur la ride du Faro, dans la carotte KC8221. De gauche à droite : 1) Variations des valeurs de $\delta^{13}C$ de *G. bulloides*; 2) Variations des pourcentages relatifs de *Hyalinea balthica*; 3) Variations des pourcentages relatifs de *Planulina ariminensis*; 4) Variations des pourcentages relatifs de *Cibicides pseudoungerianus*; 5) Variations de l'index de diversité.

Table 5
Percentages of the various species of benthic foraminifers in cores KS8230 and KC8221.
Pourcentages relatifs des différentes espèces de foraminifères benthiques dans les carottes KS8230 et KC8221.

CORES	CORE DEPTH (cm)	A. tubulosa	A. scalaris	B. dilatata	B. quadrilatera	B. subaenariensis	B. aculeata	B. costata	B. gibba	B. marginata	C. auriculus	Cassidulina sp.	Chilostomella sp.	C. lobatulus	C. pseudoungerianus	C. involvens	G. affinis	G. pseudospinescens	G. altiformis	G. neosoldanii	G. orbicularis	H. rhodiensis	H. elegans	H. balthica	L. peregrina	Lenticulina sp	M. barleeanum	N. commune	Lagena sp.	P. crassa	P. polymorpha	P. ariminensis	Pseudonodosaria sp.	P. quinqueloba	P. guerreri	P. murrhina	Rectuvigerina sp.	S. schlumbergeri	S. bradyana	S. bulloides	S. canaliculata	Trifarina sp.	Triloculina sp.	U. mediterranea	U. peregrina	V. bradyana	Assorted Miliolidae	Other
KC 8221	0	1	16					2		1	1		1	3	9		3		3		3	1	2	1		4	3		1			3	1	1	1	1	1	1	1			2	1	32	1		1	1
	2		15							2		1		4	10		2		5		2	1	2	1	1	3	2		2			5						3	2	1		2		30	1		3	
	10		15					4		1	1	1		3	5		1		1	2	3	1	1	2		2			2		1	8		1	1			2	1	1		2		35	1		2	
	20		12					5					2	2	2		1		2		2			2		1	1					2			1			4					51			6	4
	30		6					7						1	6		1		3		2			1		1	1		3			1			1			2	1	1		1		50	6		3	2
	40		5			1		4		1				4	10		2		9		1		1			4	1		1			2				1		3		1	1			20	22		4	2
	50		12					3		2						13		4				3			2	1	1	2					2		1	1			5							42	3		2	
	59		18					6						2	11		6		10		10			2		1	4											4		2					13	5		3	3
	69		13							1				1	6		6		5		3			10		1	1		1						1	1		2		1	1			40	5		1	
	79		17													7		5		3		8			3			4											7		2					29	9		4	2
	99		10											2		10		1		4					3			1											5		2					36	19		6	2
	106		10						2	2						7		1				1		6	10		1	3											4		4					21	25		3	
	111		4					1		2		2	1	2	6				6		6		11	9	2		12											1		9					11	10		4	1
	117									3				1	7		1				3	1	3	46	1		9								1			1		7					11	5		1	
	122							1		11				2	9		1				2		1	20	1	2	14					2		2					4		6					11	5		1	5
	128		3						3	5		1		2	7		2						1		37	1		12					2			1			1		5					7	9		1	
	134		16			1		1		5	1				4		3				2	1	3		1		17		1							1	1		1		4					13	14		9	1
	142		11		1					15			1	1	3		1				1		2	1	1		11		1			2		1					1		1	1			9	25		8	2
	149		19		3			1		6			1	3	8		6				3						11		1			2						2		3					11	13	3	3	1
	157		15							13			1	1	4	1	2							1			2	10											2		3	1			18	23		3	
	165		13							6			1	1	4		3				1		2		1	1	9					2						2		3					16	27		7	1
	173		20		1					7				1	6	1	1						1		1		9											4		1					21	18	1	6	1
	185		29			2				6						2								2				5											2							14	23	3	8	4
	200		17							2						3		2						2	1			6											5		4					13	27	2	12	4
	205		18							10															10			11											6							13	24	2	6	
	211		5			1				9						2		1				1			17			4													1					26	28		3	2
	218		4					1		10		1		1	2		1				1			25			5					2		1		1		1		1					13	24		5	1
	222		4					1		11				1	2		1				1			26	1		3		2			1				1		1		2					19	19		4	
	227							2		7	1				3		1				1		1	31	1		15					5		1					1		1					21	15		3	
	232		1		1					5	1	1			4		2				2			31			12			1		2						2		1					19	12		2	1
	237				1						2	1		1	2		2				3			27			8			1		2		1						3					18	23		3	2
	244				4			2			5	1		1	8		3				2			19			10					3						2		9					13	14		1	2
	250				6			5			10				3		2				5			23			8											2		8					11	14		2	1
	260				1			8			6	1		5	16		7				4		1	8			14					8								4					10	4			3
	270				2	1		2			7				14	1	1				4		1	17			15		2			1			3			2		6					14	3		4	
	280				4	1		5				6			17		6				5			14		1	13		1							3			2		5					8	5	1	2	1
	290				3	1		7				3		2	10	1	3				6		1	11		1	17		3			2			2			3		3					14	4		1	3
	295				6			4				6		1	12		6				4			13			15									2			2		3					19	2		3	2
KS 8230	0	1	9				1					1	2			2		2		2			10	1	2	3	1	2			2						1	2	1					20	30		3	2
	2		5												6		7	2	1		2			10		3	3		3			3						2	2							31	19			1
	10	2	3											3		3		3		6			16		3	5					3						5							23	18		3	4
	20		3				1							11		8	2	2		9			9		1	2					4													44	3			1
	30		5				1							10		4		3		1			17		1	2					3				1	1	3							31	17			
	40		8									1		6		2		3		2			12		3	5	1				2				1		2							35	16		1	
	50		7											8			1	4		4			10		2	5					5						3							38	11			2
	60		4											22		1	1			2			7		3	2					2		1				4							37	11			3
	70		6					1						2	11		2		2		3			2	1	4	5	1				2		1				3			2			35	16		1	
	80		6											23		2		5		6			4		6	1					3						3			2			25	13		1	
	90	1	1											1	24		4		3		2			4		2	1	1				3						2							32	15			1
	100		6					1					1		12		3		2		8			4		3	1	1				5		1			1	1		1					28	20		1	
	110		2					3							18		6		5		3			1		2	6		3				2		1				4		2					25	15			2
	120		3			1		7							1	10		2	1	12		9	1		6	1	3	2	1				2													21	16			1
	130		2			1		3							1	3		1		24		6			5		4	2	1				3						2							31	10		1	
	140		3	1		1		3								9		3	2	14		9			8		3	6	1				5						1	1	2					21	6		1	
	150		3	1		2									2	5		1		3		4			16		9	6	1				3						3		3					32	5			
	160		4			5	2							1	2		1	1	6		4			14			7					2						1		2					34	13		1	
	170		3			4								1		4		5		4		3			17		1	6	1				1					1	2	1		1			30	15			
	180		1			8	1							1	9		1		1		1			37			6	1				1						1							20	11			
	190		2			14								1	6		1	1	3		1			32			6					2			1			1		1					24	4			
	200		1			3	1								4	10			2	2		1	1		18			4					2						6							32	12			1
	210					11		4								10		1							29			8					1						3							27	5			1
	220					7								2	12		2	1	3		1	1		30			11		2			1													17	7		1	2
	230					7		2						2	17		2	2							35			10					2													14	6			1
	240			3		1	1	1						4	21			1			1			26			9		1			1													17	10		1	2
	250					3	1								2	6		2				1			27			5					1		1						1					2	47		1	
	260					1	1						1	1	8		2				1			26	1		8					1			1		1			1					3	43		1	
	270					2	1						1	2	14		2	1						30			4	1		1		1			2		1			1	1			1	34			
	280					1								1	13		2	1						29			10	1				1													1	37			3
	290					1		1						4	8		4				1			25			16					1								2						31			3
	300					6								8	15		5								24			6	4				6								1	3			3	15			4

These species however, have never been observed at the same bathymetric levels, on either the Faro drift or the northern slope of the Alboran Sea, between 18 000 years and the present time (Caralp, 1988).

Therefore, the similarity of benthic epifaunal foraminiferal assemblages (diversity index and species distribution) on both sides of the Gibraltar sill, increased at three times since the LGM: between 18 000 and 14 000 years, between 11 000 and 10 000 years and in the Late Holocene. These observations suggest that during these episodes, the east-west flow of Mediterranean waters was similar to that of the present.

CARBON ISOTOPE VARIATIONS

The distribution of ^{13}C in the oceans is determined by equilibration with the atmosphere and CO_2 output through photosynthesis and evaporation in surface waters, by mixing between water masses of different isotopic compositions, by replenishment by the general circulation patterns and CO_2 pumping through carbonate precipitation in bottom waters, and by *in situ* addition of CO_2 from the decomposition of organic and inorganic material in intermediate waters. Photosynthesis in surface waters preferentially extracts ^{12}C from seawater, causing the enrichment in ^{13}C of the surface water ΣCO_2. The present geographic distribution of the $\delta^{13}C$ values of the ΣCO_2 in the ocean is thus closely related to the nutrient and oxygen content of the various water masses and is strongly dependent on circulation patterns (Broecker, 1982; Broecker and Peng, 1982; Kroopnick, 1985).

In the present-day Mediterranean, which is a three layered system, distinct ^{13}C contents characterize the different water masses during the season of high stratification. Intermediate waters (MIW) display rather steady physico-chemical parameters and form a very homogeneous lens with high $\delta^{18}O$ values ($1.8^0/_{00} \leqslant \delta^{18}O \leqslant 1.6^0/_{00}$) decreasing from east to west, and $\delta^{13}C$ values of the ΣCO_2 around $+1^0/_{00}$ in their source region, in the eastern basin. The $\delta^{13}C$ values also decrease from east to west by about $0.2^0/_{00}$. The value of 0.9 $\delta^{13}C^0/_{00}$ is rather constant in the western basin (Pierre *et al.*, 1986). These data suggest that this intermediate water mass collects a relatively low amount of organic carbon after it has formed. This hypothesis is consistent with the oligotrophic character of the Mediterranean (Murdoch and Onuf, 1974), in which only minor amounts of organically derived ^{13}C-depleted carbon dioxide are released to greater water depths. This effect is further enhanced by the short residence time of waters of about 100 years (Lacombe *et al.*, 1981). On the other hand, in a region of deep and intermediate water formation such as the Mediterranean Sea, an important seasonal mixing of the different water layers should result in $\delta^{13}C$ time distributions closely coupled in surface, intermediate and deep waters. This fact is today reflected in the surface-to-deep $\Delta\delta^{13}C$ gradient, which is around $0.5^0/_{00}$ during the season of higher water masses stratification (late spring to late summer) and around $0^0/_{00}$ in winter and in the areas of deep and intermediate water formation (Pierre *et al.*, 1986; unplished data). Therefore one should expect the major changes in the $\delta^{13}C$ values of the total dissolved CO_2 to occur almost simultaneously in the different water masses and to be reflected in the $\delta^{13}C$ values of foraminiferal shells.

In the Alboran Sea, high $\delta^{13}C$ values are recorded in the deeper layers of the Glacial Mediterranean Intermediate Waters from 18 000 to 15 000 years BP by the benthic foraminifer *Cibicides pachyderma* (Oppo and Fairbanks, 1987). A similar pattern has also been reported for the Sicilian Strait and the Ligurian Sea (Vergnaud-Grazzini *et al.*, 1988; unpublished data; Fig. 9 A). Previous studies have documented the utility and reliability of this genus for $\delta^{13}C$ measurements (Belanger *et al.*, 1981; Graham *et al.*, 1981; Curry and Lohmann, 1982; Duplessy *et al.*, 1984). Although its $\delta^{13}C$ value is lower than the expected isotopic equilibrium value, the measured $\delta^{13}C$ values are close to those of the ΣCO_2.

The comparison of the Mediterranean ^{13}C records with those reported for intermediate depths in the Atlantic (Sarnthein *et al.*, 1988) reveals some similarities (Fig. 9 A). As for Atlantic intermediate depths ^{13}C records (for instance in core 16004-1, 29°58.7′N/10°32.8′W, 1 512 m water depth or core 16006-1, 29°14.8′N/11°29.8′E, 796 m water depth), $\delta^{13}C$ values of the ΣCO_2 (from 18 000 years BP up to 15 000 years BP) are higher than – or close to – modern ones. Then, the $\delta^{13}C$ values decrease with this negative episode lasting until about 5 000-4 000 years BP. The ^{13}C changes registered between 18 000 years BP and the present by *G. bulloides* is slightly different and more complex. Although this species does not precipitate its shell in isotopic equilibrium with ambient ΣCO_2 (unpublished data) we postulate that it is a good recorder of the relative variations of the isotopic parameters in the MIW upper layers. Studies on the yearly distribution of living forms of this species show that peaks of maximal abundances are not directly linked to the water temperature (Loubere, 1981; Pujol, 1980). In the Western Mediterranean, maximal abundances are recorded in spring, when a new stratification of the waters sets in after the nearly homogeneous thermohaline structure of the winter (Lacombe and Tchernia, 1972; Vergnaud-Grazzini, 1973). In addition, in most areas of the western Mediterranean basin, *G. bulloides* has been found in the upper part of the mixing layers of inflowing Atlantic waters and westward flowing Mediterranean waters (MIW). At that depth, the overlapping halocline and thermocline allow a strong nutriclide to form. Recycled nutrients accumulate against this density barrier forming a nutriclide (Minas *et al.*, 1984; Jacques *et al.*, 1986). This nutriclide is responsible for a new production of phytoplankton at the base of the photic zone, upon which *G. bulloides* may develop (Hemleben and Spindler, 1983).

Today, the $\delta^{13}C$ values of this species remain rather constant (around $-0.74^0/_{00}$) latitudinally across the Western Mediterranean (from the Sicilian Strait in the east to the Faro drift in the west). This feature has occurred several times since the LGM. Table 6 presents the $\delta^{13}C$ values of *G. bulloides* corresponding to the major well dated ^{18}O events. These data suggest that near 15 000 and 8 500 years BP, Mediterranean Intermediate Water was characterized by rather steady parameters, within the western basin at least. Between 11 500 and 10 700 years BP a greater variability existed, but no clear gradient can be deduced from our data. In fact the various carbon isotope records of *G. bulloides* for the last glacial-deglacial cycle are rather similar on a 22° longitudinal transect (from the Strait of Sicily in the east to Cape St. Vincent in the west; Fig. 9 B).

$\delta^{13}C$ values higher than – or equal to – present day values are recorded by *C. bulloides* during the LGM,

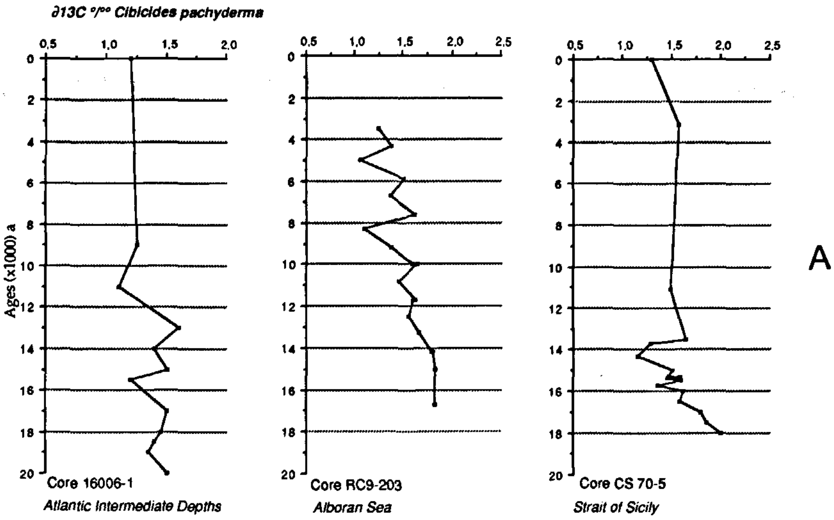
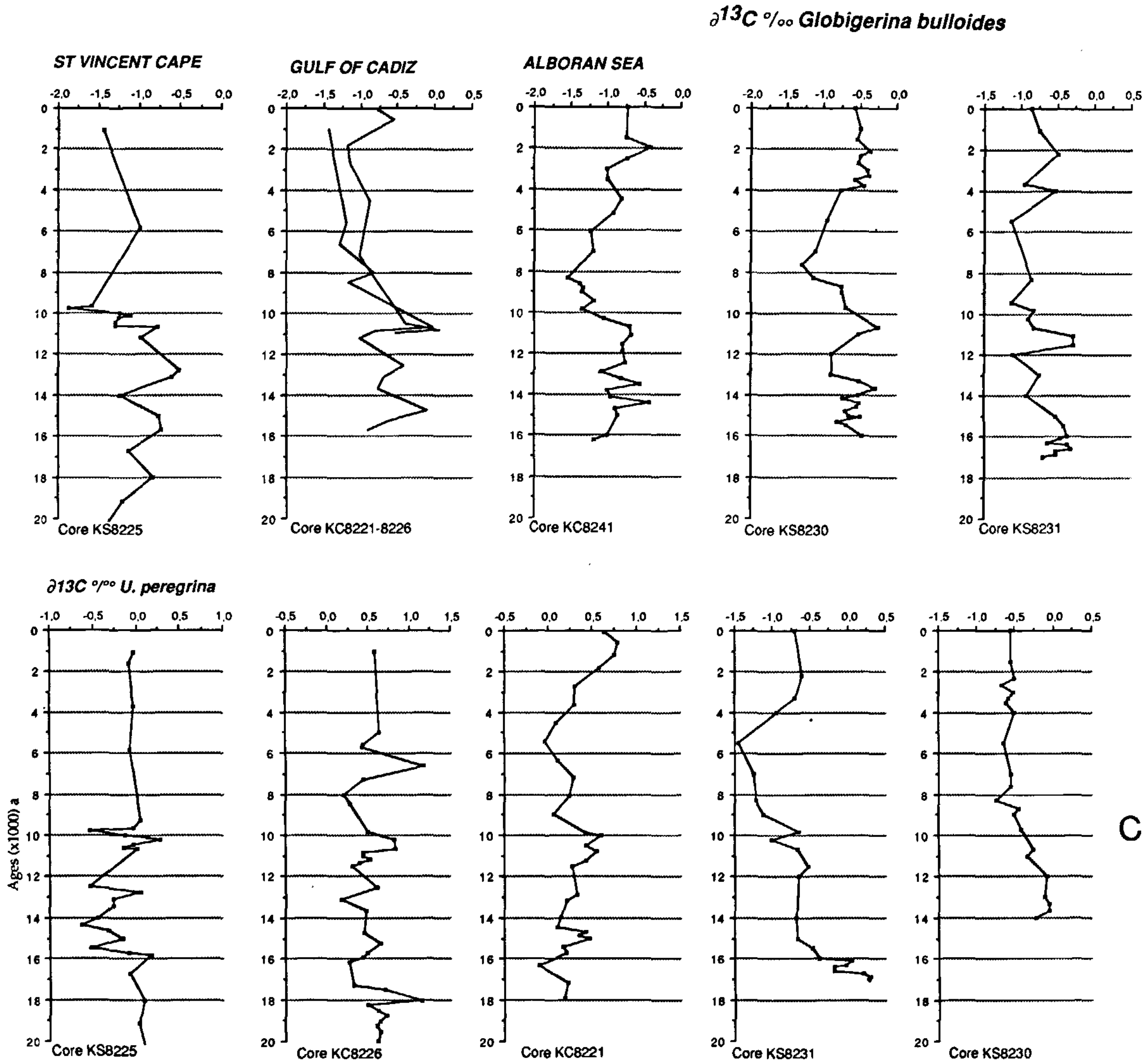


Figure 9

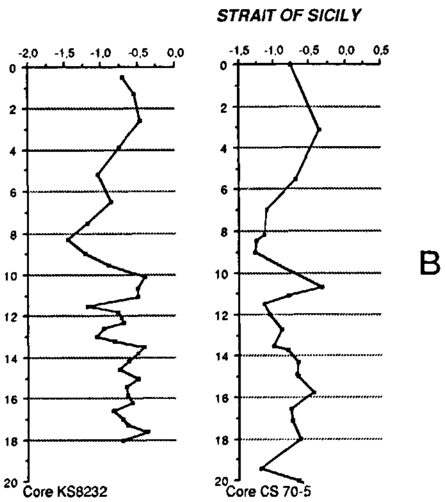
A: The ^{13}C *records of* Cibicides pachyderma*—in Atlantic intermediate depths: core* 16006-1 (*after Sarnthein* et al., 1988)*; in the Alboran Sea: core RC9-203* (*after Oppo and Fairbanks,* 1987)*; in the Sicilian Strait: core CS 70-5* (*after Vergnaud-Grazzini* et al., 1988). *B: The* $\delta^{13}C$ *record of* G. bulloides *for the last* 18 000 *years in the Sicilian Strait* (*core CS70-5*)*, in the Alboran Sea* (*cores KS8230, KS8231, KS8232, KC8241*) *and west of Gibraltar on the Faro drift* (*cores KC8221 and KC8226*) *and at Cape St. Vincent* (*core KS8225*)*. C: The* $\delta^{13}C$ *records of* Uvigerina peregrina *in cores KS8225, KC8226, KC8221 and KS8231.*



near 15 000 years, near 11 000-10 000 years and in the Late Holocene near 3 000-2 000 years. An average difference between the $\delta^{13}C$ values recorded during the LGM and the late Holocene (18 000 years/3 000-0 years) as well as between the "Younger Dryas" and the late Holocene (10 000-11 000 years/3 000-0 years) may be calculated for all the cores located along the MIW pathway. For *G. bulloides*, these differences are small, near $0^0/_{00}$ for the LGM/Late Holocene change and $+0.2^0/_{00}$ for the Younger Dryas/late Holocene change. Glacial $\delta^{13}C$ values of *Cibicides* are about $0{,}4^0/_{00}$ higher than late Holocene ones.

For the last deglaciation, change of the mean carbon isotopic composition of the total dissolved CO_2 in the global ocean accounts for $+0{,}32^0/_{00}$, glacial $\delta^{13}C$ values being lower than Holocene ones (Duplessy *et al.*, 1988). However, recent findings based on oxygen and carbon isotope analyses of foraminiferal shells

A : Variations des valeurs de $\delta^{13}C$ de *Cibicides pachyderma* dans une carotte atlantique à la profondeur des eaux intermédiaires : carotte 16006-1 (d'après Sarnthein *et al.*, 1988) en mer d'Alboran : carotte RC9-203 (d'après Oppo et Fairbanks, 1987), dans le détroit Siculo-Tunisien : carotte CS70-5 (d'après Vergnaud-Grazzini *et al.*, 1988). Variations des valeurs de $\delta^{13}C$ de *G. bulloides* depuis 18 000 ans, dans le détroit siculo-tunisien (carotte CS70-5), en mer d'Alboran (carottes KS8230, KS8231, KS8232, KC8241), sur la ride du Faro (carottes KC8221 et KC8226) et au Cap St-Vincent (carotte KS8225). C : Variations des valeurs de $\delta^{13}C$ d'*Uvigerina peregrina* dans les carottes KS8225, KC8226, KC8221 et KS8231).



from Atlantic, Indian and Meditarranean cores provide evidence for higher glacial $\delta^{13}C$ values of intermediate depth ΣCO_2 (Boyle and Keigwin, 1987; Duplessy *et al.*, 1988; Kallel *et al.*, 1988; Oppo and Fairbanks, 1987; Sarnthein *et al.*, 1988; Zahn *et al.*, 1987; among others). This is interpreted as the consequence of enhanced nutrient depletion of mid depth waters during the last glacial time. Boyle (1988) presents paleochemical evidence that nutrients and metabolic CO_2 were shifted from intermediate waters into deeper waters during glacial time. The withdrawal of nutrients from intermediate ocean waters also prevents oxygen depletion in these waters.

In the *G. bulloides* ^{13}C records, the episodes of high $\delta^{13}C$ values bracket episodes of ^{13}C depletion between 14000 and 12000 years BP, 9000 and 5000 years BP. These episodes of ^{13}C decrease may have corresponded to an important oxygen decrease in the upper layers of Intermediate and Outflowing Mediterranean Water. The most recent one, between *ca* 9000-5000 years BP, also coincides with the onset of the deep water stagnation in the Eastern Mediterranean basin, which apparently culminated around 8000 years BP and resulted in the deposition of sapropel S1 (Vergnaud-Grazzini *et al.*, 1986; Anastasakis and Stanley, 1986). Higher sea surface temperatures and fresh water contamination for the surficial species, as well as oxygen decrease induced by a major stratification of the water masses for the intermediate depths species, may have been responsible for a ^{13}C depletion generalized to the entire water column. The reduced oxygenation of the water column is also supported by the disappearance of oxygen sensitive species such as *C. pachyderma*, in the Sicilian Strait. By contrast, the infaunal genus *Uvigerina div. sp.* is always well represented. The $\delta^{13}C$ values of this genus are strongly dependent on the delivery of organic CO_2 to the sediment (Zahn *et al.*, 1986). The timing of the episode of ^{13}C decrease recorded by this species: 9000 to 5000 years BP is in good agreement with that recorded by *G. bulloides* (Fig. 9C). These data also point to a nutrient enrichment and oxygen decrease at intermediate depths at this time.

Moreover, the high $\delta^{13}C$ values recorded by all benthic and planktonic species around 15000 years, 10000-11000 years as far west as Cape Saint-Vincent, as well as the ^{13}C depletion recorded around 12000-14000 and 9000-5000 years, constitute a specific Mediterranean signature. Small differences between the various records (Fig. 9) may result either from sedimentary disturbances (at the centimetric level) or from the uncertainty brought about through the calculation of interpolated ages, assuming that the sedimentation rate was constant between two control points. The similarity of the ^{13}C signals on both sides of the Gibralter sill and their specificity with respect to those of the Atlantic Intermediate Water for the past 15000 years at least (and perhaps 17000 years) supports the hypothesis of a permanency of the Mediterranean Outflowing Water since that time.

The episodes of high $\delta^{13}C$ values recorded since 15000 years BP also correlate with the deposition of coarse grained contourites on the Faro drift (Fig. 7). This

Table 6
The $\partial^{13}C$ values of G. bulloides *at the various well-dated ^{18}O events.*
Valeurs de $\partial^{13}C$ de *G. bulloides* des niveaux correspondant à des événements ^{18}O bien datés.

Dates of ^{18}O events (*10^3 *a*)	8226 $\partial^{13}C$	8221 $\partial^{13}C$	8241 $\partial^{13}C$	8232 $\partial^{13}C$	8231 $\partial^{13}C$	8230 $\partial^{13}C$	CS70-5 $\partial^{13}C$	Average $\partial^{13}C$
0		−0.77	−0.74	−0.7	−0.86	−0.58	−0.76	−0.74
8-8.5	−1.17		−1.38	−1.45	−0.99	−1.30	−1.26	−1.25
10,7	−0.03	−0.39	−0.71	−0.50	−0.83	−0.25	−0.33	−0.47
11,5			−0.80	−1.18	−0.28	−0.89	−1.14	−1.02
15	−0.63		−0.86	−0.50	−0.52	−0.66	−0.65	−0.65
18				−0.70			−0.74	−0.72

suggests that the MOW velocity may have increased during such episodes. This increased velocity may have simply resulted, however, from the glacially lowered sea level and the diminished section of the Gibraltar Strait, at least for the cooler episodes (Poutiers, 1987). A temperature effect (together with a low nutrient level) cannot, however, be excluded. The lower sea surface temperatures recorded during these episodes may have resulted, through partial equilibration of surface waters at temperatures around 13°C, in $\delta^{13}C$ values close to the measured $1{,}8^0/_{00}$ (Mook *et al.*, 1974). The rapid mixing of Mediterranean waters resulted in deep CO_2 $\delta^{13}C$ values close to surficial ones.

Although the $\delta^{13}C$ records of intermediate depth ΣCO_2 are, on the whole, rather similar for the Atlantic and the Mediterranean (with higher values being recorded during the Last Glacial Maximum, up to 17000-15000 years BP, a distinct Mediterranean signature can be detected in the ^{13}C records of the past 15000 to 17000 years, on both sides of the Gibraltar sill. The mapping of this signature in eastern Atlantic sediments presents us the opportunity to investigate the variations of past MOW fluxes. In present conditions, howewer, it is difficult to assign to variations in Mediterranean outflow a role in generating the variations of the nutrients content and oxygenation of North Atlantic Intermediate Waters during glacial and deglacial periods. In fact, examination of the fluxes of water masses participating to the formation of North Atlantic Deep Water today, indicates that Mediterranean waters, with a flux of about 0.6×10^6 m^3/s, contribute only a few per cent to the NADW (Worthington, 1976). The Mediterranean outflow would thus have to increase substantially to become a dominant and determinant source of intermediate water nutrients for the Atlantic.

CONCLUSION

The sedimentological signature of the Mediterranean Outflow Water is observed in the deposition of contourites on the Faro drift, with high smectite content and specific La/Ta and Th/Ta ratios. Noticeable variations in these parameters occurred at three different times since 18000 years: around 17000 years, between 14000 and 12000 years and between 9000 and $\sim$5000 years, suggesting that the intensity of the Mediterranean outflow decreased during these episodes. A comparison of the lithological sequences with the $\delta^{13}C$ records shows that the negative $\delta^{13}C$ excursions recorded by *G. bulloides* west of Gibraltar, in the Alboran Sea and in the Sicilian Strait, correspond to periods when muddy contourites were deposited. The low $\delta^{13}C$ values suggest that the MIW and the MOW were less oxygenated and nutrient-enriched. This is corroborated by an almost synchronous decrease in the $\delta^{13}C$ values of the infaunal genus *Uvigerina*. The decrease of oxygenation may have resulted from a major stratification of the waters masses and a concomittant decrease in the east-west flux of Intermediate and Deep Mediterranean waters. Such large-scale features could have been caused by a major entry of less saline Atlantic waters at the beginning of the deglaciation (Ruddiman and McIntyre, 1981) and by the stagnation of Eastern Mediterranean waters between 9000 and 7000 years BP.

In contrast, the high ^{13}C contents recorded during glacial and cooler episodes (at 18000 years BP, around 15000 years BP, between 11000 years and 10000 years BP, and—to a lesser degree—, in the late Holocene), suggest a better oxygenation and a low nutrient content of Mediterranean Intermediate Waters. They also correspond to the deposition of coarse grained contourites, suggestive of a higher intensity of the MOW. However, these data do not permit speculation on the values of the past MOW fluxes. The main conclusions are in good agreement with recent observations reported by Zahn and Sarnthein (1986) and Zahn *et al.* (1987), based on stable isotope data of Atlantic cores raised off the northwestern coasts of the Morocco. These authors also suggested a permanent, but changing Mediterranean outflow during the last deglaciation. In view of the data presented above, the hypothesis of a current reversal above the Gibraltar sill at any time between 15000 years (or 17000 years) BP and the present day, appears somewhat unrealistic.

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