Late Quaternary sea level and environmental changes from relic carbonate deposits of the western margin of India

V Purnachandra Rao*, G Rajagopalan**, K H Vora* and F Almeida*

*National Institute of Oceanography, Dona Paula, Goa 403 004, India.
**Birbal Sahni Institute of Palaeobotany, 53 University Road, Lucknow, India.

Relic carbonate deposits along the western margin of India occur as dolomite crusts, aragonite sands (pelletal / oolitic) and aragonite-cemented limestones, oyster shells, corals, encrusted coralline algal and foraminiferal-dominated nodules. The petrology and mineralogy of the deposits indicate that except for aragonite sands and foraminiferal nodules, the others were formed in shallow marine conditions and serve as sea level indicators. Radiocarbon dates were measured for 62 relic deposits covering the entire margin. The age of these deposits on the continental shelf off Cape Comorin and Mangalore, between 110 and 18 m depth, ranges between 12, 610 ^{14}C yr BP and 6,390 ^{14}C yr BP. On the northwestern margin of India, especially on the carbonate platform (between 64 and 100 m), the age ranges from 17,250 to 6,730 ^{14}C yr BP. The relic deposits of the Gulf of Kachchh at depths between 35 and 25 m are dated at 12,550 – 9,630 ^{14}C yr BP. The age vs. depth plot of the relic deposits further indicates that the Gulf of Kachchh was inundated much early, atleast by 15 ka, after the Last Glacial Maximum, and was subjected to uplift and subsidence during the Holocene. The carbonate platform subsided during the early Holocene. Some of the relic deposits between Cape Comorin and Mangalore plot on or, closely follow the glacio-eustatic sea level curve. Despite abundant siliciclastic flux discharged by the Narmada and Tapti during the early Holocene, the platform off these rivers is largely devoid of this flux and carbonate sedimentation continued until 6,700 ^{14}C yr BP. We suggest that the river-derived sediment flux diverted southwards under the influence of the SW monsoon current and, thereby, increased the turbidity on the shelf and slope southeast of the carbonate platform and facilitated the formation of deeper water foraminiferal nodules off Vengurla-Goa.

1. Introduction

Relic shallow water sediments are exposed on the outer continental shelf of the western margin of India, between the Gulf of Kachchh and Cape Comorin (Nair and Pylee 1968; von Stackelberg 1972). A carbonate platform, also known as Fifty Fathom Flat, extending 4 degrees of latitude, occurs on the outer continental shelf of the northwestern margin of India (figure 1). As a consequence, the width of the relic zone is more in the northwestern part and becomes narrow towards the southwestern margin of India. Several investigators studied the geomorphic features and associated sediments on the outer shelf off western India (Nair 1975; Nair *et al* 1979; Vora and Almeida 1990; Wagle *et al* 1994; Rao *et al* 1994; Rao and Veerayya 1996; Rao *et al* 1996; Vora *et al* 1996; Rao and Wagle 1997). The studies reveal the existence of reefal structures along the shelf break and biohermal structures on the carbonate platform. So far, relic deposits from 20 stations of the carbonate platform and off Vengurla-Goa were dated by radiocarbon methods (Nair 1974; Nair *et al* 1979; Vora and Almeida 1990; Rao *et al* 1994; Rao and Veerayya 1996). Using a few of these dates, Kale and Rajaguru (1985) and Hashimi *et al* (1995) attempted to construct Holocene sea level curves

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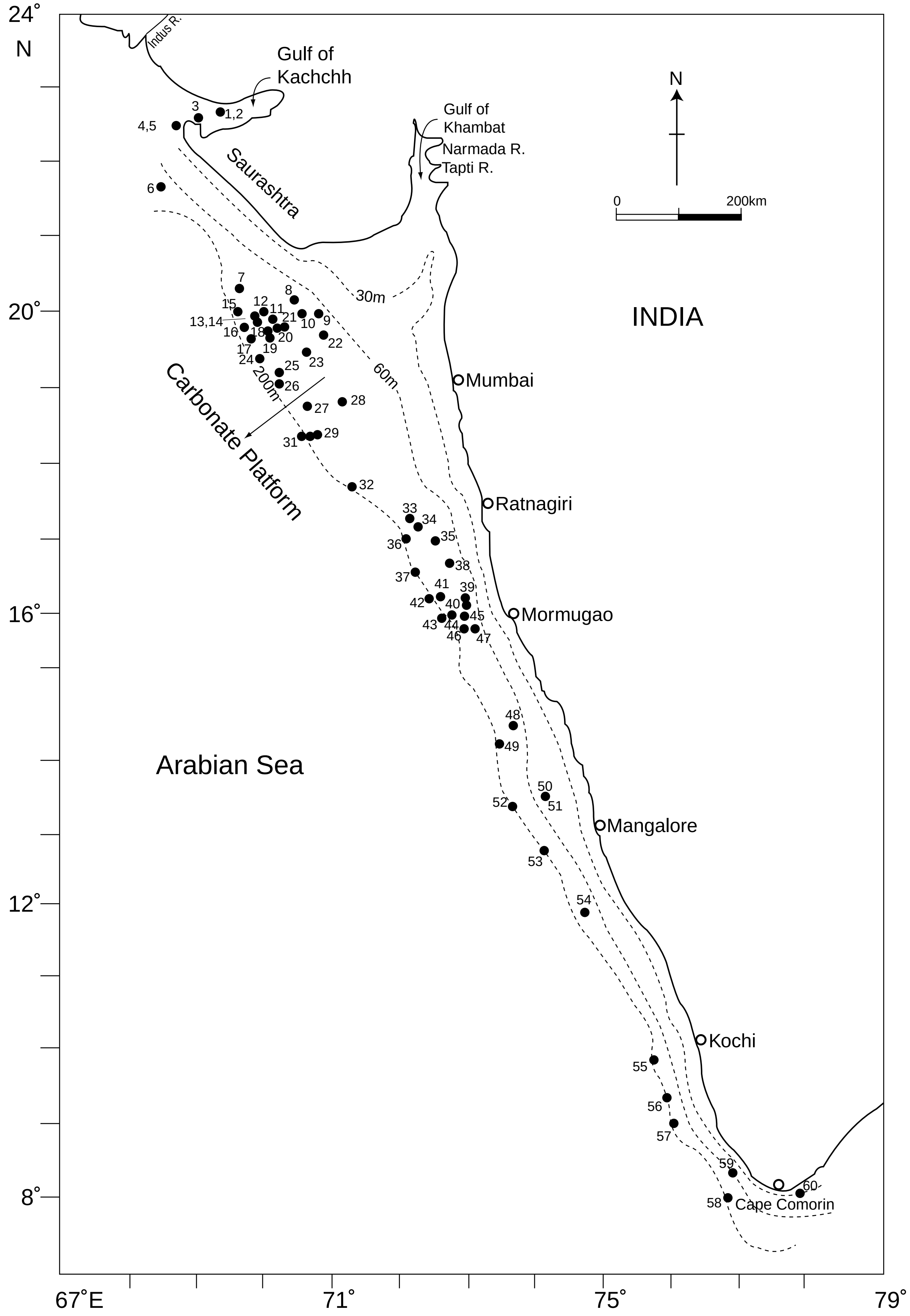

Figure 1. Location of the samples along the western margin of India used for petrology, mineralogy and radiocarbon measurements. The numbers correspond to serial number in tables 1 and 2.

for the western margin of India. These two curves are indeed different from one another and also differ with the glacio-eustatic sea level curve of Fairbanks (1989). The data points making the sea level curves in Kale and Rajaguru (1985) and Hashimi *et al* (1995) are largely inferred/estimated ages and, actual measured dates of the samples fall away from the curves. Rao *et al* (1996) have discussed several problems in the data used for preparing these curves and also explained why the curves are unacceptable to represent sea level changes off western India. Moreover, no radiocarbon dates were available for the relic reefs/sediments of the larger part of the western Indian margin (off Goa-Cape Comorin, Saurashtra or the Gulf of Kachchh) when these sea level curves were constructed. In other words, the significance of these relic sediments in relation to late Quaternary sea level and environmental changes has not yet been comprehended. Here, we have determined the age of as many as 42 relic deposits of different types covering the entire margin under the Project "Sea level changes along the western margin of India during the late Quaternary" funded by the Department of Science and Technology, New Delhi. The purpose of the paper is to update the inventory of the radiocarbon ages of relic deposits on this margin, synthesize results on sea level changes in relation to glacio-eustatic sea level and impact of sea level/environmental changes on sediment depositional environment during the late Quaternary.

2. Material and methods

The sediments/sedimentary rocks recovered from the western margin of India during different cruises of *RV Gaveshani* (G), *ORV Sagar Kanya* (SK) and *MV Nand Rachit* (NR) by Peterson Grab. Pipe dredge with chain bag at the bottom and bucket dredge were used for the present study (figure 1). Table 1 shows the locations, depths and description of the sediments and also the samples chosen for different analyses. In the case of dredge samples the location and depth of the samples are estimates of their averages at the start and end of dredging. Samples selected from each station were ultrasonically cleaned. The samples were split into two halves. One half was used for preparing thin sections and studied under petrological microscope. The other half was powdered, subjected to X-ray diffraction studies and then dating by radiocarbon methods were carried out at the Birbal Sahni Institute of Palaeobotony, Lucknow. Minerals present in each sample and ratio of major carbonate minerals are shown in table 1. Dolomite (D), aragonite (A) and high-magnesium calcite (H) are marine minerals; their ratios indicate relative abundance of one mineral with respect to the other. Since low-magnesium calcite (C) can originate from the influence of meteoric water, one should be cautious if its percentage is higher in a given sample. We are aware that the calcite and aragonite have different absorption coefficients for X-rays and peak heights of these minerals in the X-ray diffractogram are not a true reflection of their abundance. We have prepared a calibration curve based on pure mixtures of aragonite (A) and calcite (C). From this curve it is evident that the weight percentage of aragonite is 80%, 70%, 60% and 50% when A/C peak height ratio in the mixture is 1.0, 0.5, 0.3 and 0.18, respectively. Samples analysed here have consistently shown higher A/C ratios (> 2) (see table 1) indicating that the weight percentage of aragonite is $> 90\%$ and therefore the radiocarbon age dating on them is reliable. Oyster shells (see table 1) are originally made up of low-magnesium calcite (C) and the ^{14}C date on them is valid. Measured ^{14}C ages were calibrated using CALIB rev. 4.3 of Stuiver *et al* (1998) and are given in table 2. During calibration a local deviation in ΔR – 100 ± 30 for Goa-Cape Comorin region and 163 ± 30 for Gulf of Kachchh - Goa was used, following Dutta *et al* (2001). Corrected radiocarbon ages are obtained by subtracting surface ocean reservoir age – 400 years and 100 years in local deviation in ΔR. We have discussed the corrected and calibrated radiocarbon ages in the text so that one can compare these ages with the age of the sediments on land. Three sediment samples and a dolomite crust were dated by Accelerator Mass Spectrometer (AMS) at the Woods Hole Oceanographic Institution (WHOI), USA. The conventional radiocarbon ages are younger than that of AMS ages by 500 to 800 years for the samples of the same station (see table 2). This arose because AMS age measurements were made on a few oolite grains carefully picked up from $> 250\,\mu$m fraction, whereas conventional radiocarbon age determinations were done on the sediments in the size range 250–850 μm.

3. Results

3.1 *Relic deposits of the Gulf of Kachchh*

The type of relic deposits recovered along the continental margin varied significantly from north to south (table 1). The samples recovered at different stations from the Gulf of Kachchh are large sheet limestones encrusted by 0.5 to 1.0 cm thick dolomite crusts, 3 cm sized lense-shaped dolomite crusts, corals belonging to the *Faviidae* family (*Leptastrea transversa*) and micritic limestones (table 1; figure 2a). Dolomite crusts

Table 1. *Sample location and description of the samples.*

Sl. no.	Sample no.	Latitude (°N)	Longitude (°E)	Depth (m)	Sampler used	Sediment type; sample chosen for radiocarbon dating	Minerals present in the chosen samples by XRD
1	SK148/23a	22.40	69.26	35	P. D.	3 cm sized lense shaped, grey coloured dolomite crusts; stable isotopes: for calcite $\delta^{18}O = 1.11$‰ VPDB; $\delta^{13}C = 2.27$‰ VPDB; for dolomite $\delta^{18}O = 3.13$‰ VPDB; $\delta^{13}C = -0.75$‰ VPDB	Dol., Hmc., D/H = 1.9
2	SK148/23b	22.40	68.26	35	P. D.	Large sheet limestones	Hmc., Lmc., L/H = 1.3
3	SK148/25	22.36	69.09	25	P. D.	Dolomite crusts; a piece	Dol., Hmc., D/H = 2.5
4	SK148/26a	22.31	68.41	28	P. D.	Abundant Favia Corals; a piece	Ara.
5	SK148/26b	22.31	68.41	28	P. D.	Micritic limestone; broken fragment	Lmc.
6	SK148/27	21.31	68.16	112	P. D.	Grainstone	Ara., Cal., A/C = 8.0
7	J/04	20.23	69.42	85	P. G.	Carbonate sands; 250 − 850 μm fraction	Ara.
8	G72/1466*	19.59	70.53	64	P. G.	Dolomite crusts; Stable isotopes: for calcite $\delta^{18}O = 1.29$‰ VPDB; $\delta^{13}C = 2.46$‰ VPDB; for dolomite $\delta^{18}O = 4.17$‰ VPDB; $\delta^{13}C = -0.96$‰ VPDB	Dol., Hmc., D/H = 2.8
9	G72/1479	19.42	70.18	85	P. D.	*Halimeda*-dominated limestone; Stable isotopes: $\delta^{18}O = 0.72$‰ PDB; $\delta^{13}C = 3.79$‰ PDB	Ara., Cal., A/C = 9.0
10	L/08	19.58	70.47	80	P. G.	Carbonate sands; 250 − 850 μm fraction	
11	G72/1459	19.57	69.43	95	P. D.	*Halimeda*-dominated limestone, a fragment $\delta^{18}O = 0.03$‰ PDB; $\delta^{13}C = 3.86$‰ PDB	Ara., Cal., A/C = 9.6
12	SK148/37	19.57	69.55	75	P. D.	Pelletal limestone	Ara., Cal., A/C = 9.8
13	SK148/36a	19.57	69.55	80	P. D.	Grey coloured pelletal limestone	Ara., Cal., A/C = 8.0
14	SK148/36b	19.57	69.55	80	P. D.	Reddish brown coloured pelletal limestone	Ara., Cal., A/C = 4.6
15	SK111/24	19.57	69.31	148	P. G.	Indurated aragonite mud with borings, a fragment	Ara., Cal., A/C = 10.6
16	SK111/15	19.44	69.46	87	P. G.	Carbonate sands	Ara., Cal., A/C = 2.25
17	14	19.35	69.47	130	P. G.	Oolitic limestone; $\delta^{18}O = 1.66/1.64$‰ PDB; $\delta^{13}C = 4.03/3.75$‰ PDB	Ara.
18	SK111/16	19.44	70.19	84	P. G.	Carbonate nodules overlain by carbonate sands; Grey carbonate nodule (3 cm dia.)	Hmc., Ara., A/H = 0.13
19	SK111/16	19.44	70.19	84	P. G.	Overlying carbonate sands; 250 − 850 μm fraction	Ara., Cal., A/C = 1.4
20	SK111/19	19.43	70.19	81	P. G.	Carbonate sands	Ara., Cal., A/C = 1.74

Table 1. *(Continued)*

21	SK111/21*	19.44	70.13	98	P. G.	Carbonate sands; well-rounded oolites; Stable isotopes: δ^{18}O = 1.51‰ VPDB; δ^{13}C = 3.97‰ VPDB	Ara.
22	SK111/18	19.44	71.01	68	P. G.	Corals buried by clayey sediments, coral fragments	Ara., Cal., A/C = 8.11
23	M/08	19.30	70.38	82	P. D.	Grains stone	
24	47	19.18	69.50	150	P. D.	Algal-pelletal limestone	
25	SK148/42	19.06	70.16	64	P. D.	Pelletal limestone	Ara., Cal., A/C = 5.9
26	N/10	19.00	70.15	100	P. G.	Carbonate sands; 250 – 850 μm fraction	
27	42	18.40	70.40	98	P. G.	Oolitic limestone	
28	NR2A/112	18.48	71.15	80	P. G.	Carbonate sands; 250 – 850 μm fraction; Stable isotopes: δ^{18}O = 0.82‰ PDB; δ^{13}C = 3.80‰ PDB.	Ara.
29	SK111/05	18.14	70.45	88	P. G.	White carbonate sands; 250 – 850 μm fraction	Ara., Cal., A/C = 10
29A	-do-*	-do-	-do-	-do-	P. G.	Oolites; δ^{18}O = 0.89‰ VPDB; δ^{13}C = 4.32‰ VPDB	Ara., Cal.
30	SK111/08	18.14	70.49	91	P. G.	White carbonate sands; 250 – 850 μm fraction	Ara., Cal., A/C = 6.4
31	SK111/07	18.14	70.47	77	P. G.	-do-	Ara., Cal., A/C = 9.7
31A	-do-*	-do-	-do-	-do-	P. G.	Oolites; δ^{18}O = 1.09‰ VPDB; δ^{13}C = 4.59‰ VPDB	Ara.
32	NR2A/92	17.38	71.20	100	P. G.	Carbonate sands; 250 – 850 μm fraction δ^{18}O = 1.15‰ PDB; δ^{13}C = 4.29‰ PDB	Ara., Cal., A/C = 9.8
33	NR2A/84	17.17	72.12	90	B. D.	Shelly; Oyster shell (18 cm size)	Lmc., Ara., A/C = 0.05
34	NR2A/78	17.13	72.21	85	B. D.	-do- Oyster shell (10 cm size)	Lmc.
35	NR2A/74	17.03	72.40	70	B. D.	-do-	Lmc.
36	E-7	17.00	72.05	180	P. D.	Algal-bryozoan limestone	
37	SK111/01	16.35	72.03	22	P. G.	Corals from Angria Bank	Ara., Hmc., A/H = 0.8
38	G40/725	16.40	72.40	80	P. D.	Foraminiferal-dominated nodules; Grey nodule (10 cm dia.)	Hmc., Cfa.
39	G49/748	16.15	73.00	60	P. D.	Limestone	
40	SK126/45	16.12	73.04	59	P. D.	Coral polyps (5 cm long)	Ara.
41	SK126/49	16.07	72.26	232	G.C.	Grey carbonate nodules occurring 40 cm below the sediment surface in a gravity corer; Grey irregular nodule	Hmc.
42	G49/756	16.15	72.25	90	P. D.	Limestone	
43	G49/765	16.00	72.43	97	P. D.	Limestone	

Table 1. *(Continued)*

Sl. no.	Sample no.	Latitude (°N)	Longitude (°E)	Depth (m)	Sampler used	Sediment type; sample chosen for radiocarbon dating	Minerals present in the chosen samples by XRD
44	NR2A/27	15.59	72.52	95	B. D.	Phosphatized foraminiferal-dominated grey carbonate nodules, Grey nodule (8 cm dia.)	Hmc., Ara., Cfa., A/H = 0.18
45	G29/775	16.50	73.01	90	P. D.	Phosphatised-foraminiferal-dominated grey nodules; Grey nodule	Hmc., Cfa., Ara., A/H = 8.0
46	NR2A/18	15.49	73.06	80	B. D.	-do-	Hmc., Ara., Cfa., A/H = 0.09
47	G49/773	15.50	73.12	68	P.D.	-do-	Hmc., Cfa., Qtz.
48	653	14.38	73.44	58	P. D.	Shells, Pelecypod shells	–
49	SK126/44	14.22	73.29	96	P. D.	Carbonate nodules; Grey irregular nodule (8 cm dia.)	Hmc., Ara., Cfa., A/H = 7.3
50	SK65/2	13.30	74.14	70	P. D.	Corals overlain by foraminiferal encrustations; coral part; Stable isotopes: $\delta^{18}O = -1.11$‰ PDB; $\delta^{13}C = -2.16$‰ PDB	Ara., Cfa., A/C = 9.8
51	SK65/2	13.30	74.14	70	P. D.	Same as above; foraminiferal encrustation part; Stable isotopes: $\delta^{18}O = 1.02$‰ PDB; $\delta^{13}C = -2.66$‰ PDB	Hmc., Cfa., Ara., A/H = 0.11
52	SK126/41	13.21	73.38	105	P. D.	Large surficially weathered reddish brown coral chunks; White part of the Porites coral	Ara.
53	SK126/40	12.47	74.08	110	P. D.	Large surficially weathered reddish brown coral chunks; White part of the Porites coral	Ara.
54	SK126/34	11.48	74.38	100	P. D.	Calcareous Sandstone	Hmc., Qtz.
55	SK126/29	09.41	75.44	98	P. D.	Foraminiferal-dominated grey carbonate nodule; Grey nodule (8 cm dia.)	Hmc., Ara., A/H = 1.03
56	SK126/28	09.14	75.57	88	P. D.	Irregular carbonate encrustations, 15 cm size encrustation	Hmc., Ara., A/H = 0.05
57	SK126/27	08.55	76.01	100	P. D.	Ferruginised coralline algal-dominated carbonate nodules; Nodule (5 cm dia)	Hmc., Ara., Qtz., A/H = 0.19
58	SK126/26	07.56	76.50	90	P. D.	Ferruginised coralline algal-dominated carbonate nodules; Nodule (5 cm dia).	Hmc., Ara., A/H = 0.16
59	G17/150	08.20	77.05	49	P. G.	Carbonate sands; Benthic foraminifera + Mollusks (250 – 850 μm)	Ara., Hmc., A/H = 0.28
60	G17/164	08.12	77.50	18	P. G.	-do-	Ara., Hmc., A/H = 0.18

*AMS ages were determined on these samples: **P. G.** – Peterson Grab; **P. D.** – Pipe dredge; **B. D.** – Bucket dredge; **Hmc** – High-magnesium calcite; **Lmc** – Low magnesium calcite; **Dol.** – Dolomite; **Ara.** – Aragonite; **Qtz** – Quartz; **D** – Dolomite; **H** – High-magnesium calcite; **A** – Aragonite; **C** – Low-magnesium calcite.

Table 2. *Details of samples and their radiocarbon ages along the western margin of India.*

Sl. no.	Sample no.	Lab code at BSIP	Depth (m)	Description of the radiocarbon dated sample	Measured radiocarbon age (yr BP)	Corrected radiocarbon age	Calibrated age (ka)	Reference
1	SK148/23	BS1794	35	Dolomite crusts	13, 050±400	12,550	14.33	This paper
2	SK148/23a	BS1776	35	Sheet limestone	23, 480±230	22,980	–	-do-
3	SK148/25	BS1778	25	Dolomite crust	11, 160±100	10,660	12.47	-do-
4	SK148/26a	BS1779	28	Coral	10, 130±140	9,630	10.81	-do-
5	SK148/26b	BS1784	28	Micritic limestone	> 40, 000		–	-do-
6	SK148/27	BS1799	112	Grainstone	21, 350	20,850	–	-do-
7	J/04	–	85	Aragonite sands	10, 400±300	9,900	10.95	Ref. 1
8	G72/1466*	WHOI28795	64	Dolomite crust	17, 750±85	17,250	20.34	This paper
9	G72/1479	–	85	*Halimeda* Limestone	9, 285±180	8,785	9.81	Ref. 2
10	L/08	–	80	Aragonite sands	9, 960±160	9,460	10.46	Ref. 1
11	G72/1459	–	95	*Halimeda* Limestone	8, 470±125	7,970	8.85	Ref. 2
12	SK148/37	BS1889	75	Grainstone	9, 990±150	9,490	10.47	This paper
13	SK148/36a	BS1803	80	Grainstone	9, 680±120	9,180	10.28	-do-
14	SK148/36b	BS1892	80	Grainstone	10, 460±130	9,960	10.99	-do-
15	SK 111/24	BS1398	148	Indurated aragonite muds	11, 630±163	11,130	12.99	-do-
16	SK 111/15	BS1404	87	Aragonite sands	7, 590±160	7,090	7.90	-do-
17	14	–	130	Oolitic limestone	11, 850±210	11,350	13.15	Ref. 3
	14D	–	130	-do-	11, 980±185	11,480	13.28	Ref. 3
18	SK 111/16	BS1400	84	Carbonate nodule	12, 500±190	12,000	13.83	This paper
19	SK 111/16	BS1402	84	Aragonite sands	7, 230±140	6,730	7.56	-do-
20	SK 111/19	BS1406	81	Aragonite sands	7, 840±160	7,340	8.14	-do-

Table 2. *(Continued)*

Sl. no.	Sample no.	Lab code at BSIP	Depth (m)	Description of the radiocarbon dated sample	Measured radiocarbon age (yr BP)	Corrected radiocarbon age	Calibrated age (ka)	Reference
21	SK111/21*	WHOI	98	Aragonite sands	12, 250±50	11,850	13.49	-do-
22	SK111/18	BS1598	68	Coral	3, 050±180	2,550	2.70	-do-
23	M/08	–	82	Grains stone	8, 960±200	8,460	9.21	-do-
24	47	–	150	Algal-pelletal Limestone	11, 150±130	10,650	12.48	Ref. 1
	47D		150	-do-	11, 040±400	10,540	12.33	Ref. 1
25	Sk148/42	BS1804	64	Grainstone	11, 000±140	10,500	12.54	This paper
26	N/10	–	100	Aragonite sands	11, 330±350	10,830	12.74	Ref. 1
27	42	–	98	Oolitic limestone	9, 200±140	8,700	9.70	Ref. 1
28	NR2A/112	Fr112	80	Aragonite sands	8, 340±185	7,840	8.64	Ref. 2
29	SK 111/5	BS1445	88	Aragonite sands	9, 490±140	8,990	9.91	This paper
29A	SK111/5*	WHOI	88	Oolites	10, 250±45	9,750	10.98	-do-
30	SK 111/8	BS1449	91	Aragnoite sands	12, 940±130	12,440	14.28	-do-
31	SK 111/7	BS1447	77	-do-	10, 680±140	10,180	11.63	-do-
31A	-do-*	WHOI	-do-	-do-	11, 100±45	10,600	12.51	-do-
32	NR2A/92	FR0092	100	Aragonite sands	10, 080±250	9,580	10.72	Ref. 2
33	NR2A/84	BS1457	90	Oyster shell	9, 700±110	9,200	10.28	This paper
34	NR2A/78	BS1456	85	-do-	12, 420±130	11,920	13.81	-do-
35	NR2A/74	BS1454	70	-do-	11, 230±160	10,730	12.74	-do-
36	E-7	–	180	Algal-bryozoan Lime stone	10, 420±250	9,920	11.00	Ref. 4
37	SK 111/1	BS1394	22	Coral	240±110	–	–	This paper
38	G29/725	–	80	Carbonate nodule	8, 400±150	7,900	8.84	Ref. 5

Table 2. *(Continued)*

39	G49/748	–	60	Limestone	7,850±130	7,350	8.18	Ref. 5
40	SK126/45	BS1386	59	Coral polyps	2,890±90	2,390	2.50	This paper
41	SK126/49	BS1388	232	Algal nodule	19,260±280	18,760	22.15	-do-
42	G49/756	–	90	Limestone	9,440±150	8,940	10.00	Ref. 5
43	G49/765	–	97	-do-	8,380±140	7,880	8.82	Ref. 5
44	NR2A/27	BS1452	95	Phosphatized carbonate nodule	8,840±120	8,340	9.21	This paper
45	G49/775		90	-do-	7,500±200	7,000	7.85	Ref. 6
46	NR2A/18	BS1451	80	-do-	8,510±140	8,010	8.91	This paper
47	G49/773	–	68	-do-	8,300±135	7,800	8.69	Ref. 6
48	653	–	58	Shells	9,140±130	8,640	9.70	Ref. 4
49	SK126/44	BS1385	96	Carbonate nodule	11,480±230	10,980	12.92	This paper
50	SK65/2	–	70	Coral part	8,280±140	7,780	8.64	Ref. 7
51	SK65/2	–		Foraminiferal part	8,090±210	7,590	8.41	Ref. 7
52	SK126/41	BS1384	105	*Porites* coral	13,110±150	12,610	14.77	This paper
53	SK126/40	BS1381	110	*Porites* coral	12,020±140	11,520	13.42	This paper
54	SK126/34	BS1379	100	Calcareous sandstone	15,070±300	14,570	17.33	This paper
55	SK126/29	BS1378	98	Carbonate nodule	8,970±160	8,470	9.44	-do-
56	SK126/28	BS1376	88	Irregular algal encrustation	9,840±150	9,340	10.33	-do-
57	SK126/27	BS1375	100	Carbonate nodule	10,050±290	9,550	10.81	-do-
58	SK126/26	BS1373	90	-do-	12,150±310	11,650	13.48	-do-
59	G17/150	BS1460	49	Benthic foraminifers+ mollusks	8,100±150	7,600	8.42	-do-
60	G17/164	BS1462	18	-do-	6,890±90	6,390	7.31	-do-

*AMS age; **Ref. 1** – Nair *et al* 1979; **Ref. 2** – Rao *et al* 1994; **Ref. 3** – Rao and Veerayya 1996; **Ref. 4** – Nair and Hashimi 1980; **Ref. 5** – Vora and Almeida 1990; **Ref. 6** – Borole *et al* 1987; **Ref. 7** – Rao and Lamboy 1996; **D** – Duplicate analysis.

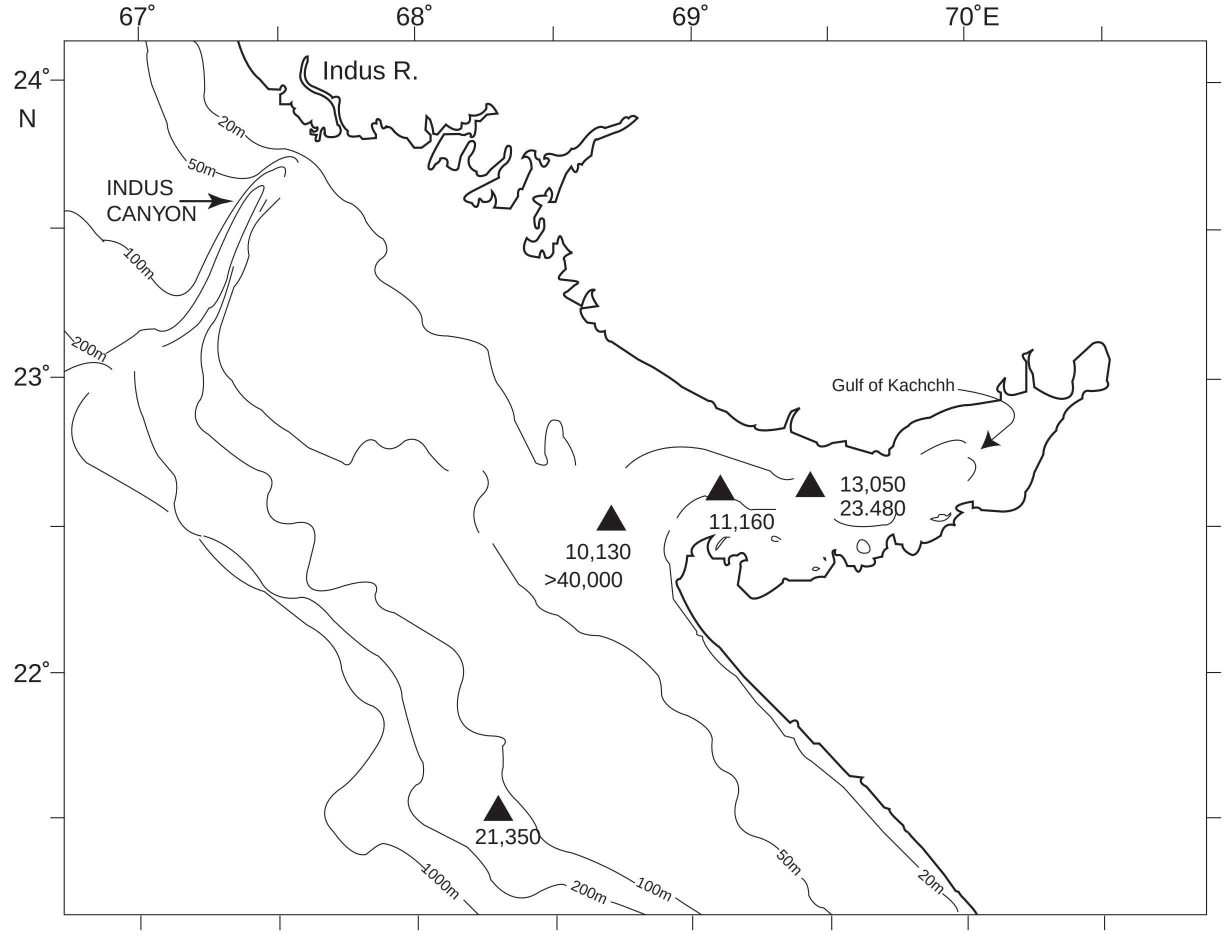

Figure 2**(a)**. Measured radiocarbon ages of the samples off the Gulf of Kachchh.

consist of quartz, dolomite and high-magnesium calcite, whereas the associated sheet limestones consist of calcite and quartz. Thin sections indicate that the dolomite crusts consist of abundant thin dolomite micro-laminations or laminations with trapped sediment detritus (figure 3a–b). SEM studies indicate that these laminations are caused by encrustation of microbial filaments, which were dolomitized directly (figure 3c). Rod-shaped and elongated dolomite microparticles resembling fossilized bacteria are also abundant (figure 3d). Oxygen (δ^{18}O = 3.13‰) isotopes of the dolomite (table 1) indicate its formation in hyposaline conditions. The carbonate minerals (dolomite and high-magnesium calcite) forming the dolomite crust are marine. The ages of the dolomite crusts at 35 m and 25 m are 12,550 ^{14}C yr BP (14.3 ka) and 10,660 ^{14}C yr BP (12.5 ka), respectively. The corals at 25 m are dated at 10.8 ka. The ages of the sheet limestones (22,980 ^{14}C yr BP) and micritic limestones ($> 40,000^{14}$C yr BP) respectively are at the extreme end and beyond the ages datable by ^{14}C method (table 2; figure 2a).

3.2 *The carbonate platform*

The relic sediments on the carbonate platform are largely aragonite sands, which are tan in colour landward and shiny white offshore. Thin section studies on these grains indicate that some of these sands are Crustacean faecal pellet-dominated (Rao *et al* 1994), while others are oolite-dominated. Age of the aragonite sands ranges from 12,440 to 6,730 ^{14}C yr BP (14.3 to 7.6 ka). The sands at trough portions of sand ridges (see Wagle *et al* 1994) exhibit older ages than that of the crest (tables 1–2; figure 2b). *Halimeda*-dominated and pelletal/oolitic limestones and, indurated aragonite muds with several borings and serpulid encrustations, similar to hardground deposits, were found closer to the seaward edge of the platform (table 1). Acicular aragonites are the dominant cements in them. The ages of the limestones mostly lie between 9,920 and 11,480 ^{14}C yr BP (11 ka to 13.3 ka) (figure 2b). Relatively young corals (2.7 ka) buried under siliciclastic sediments were recovered in one Peterson Grab station (SK-111/18), while at another

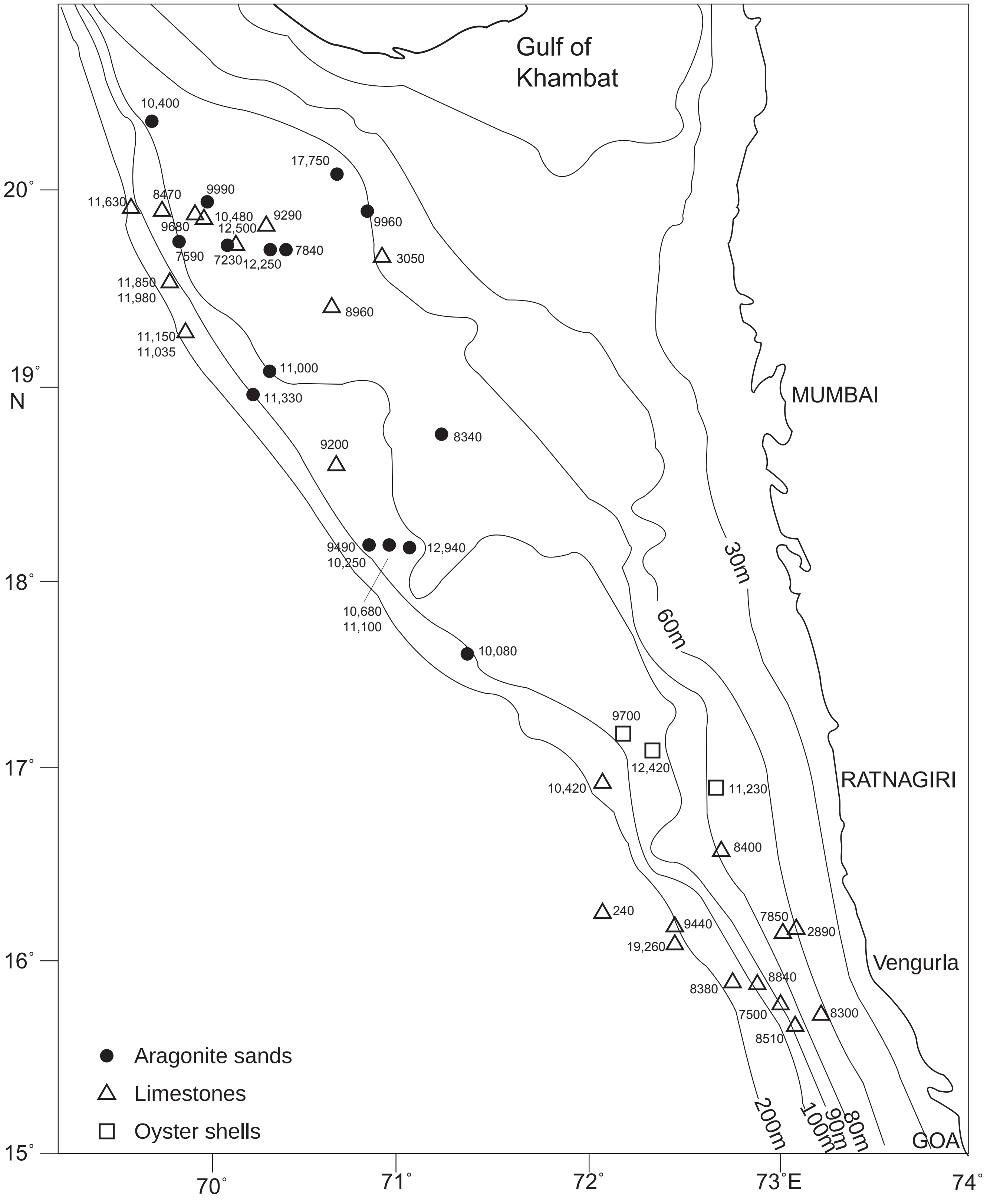

Figure 2(**b**). Measured radiocarbon ages of the samples on the carbonate platform and Ratnagiri-Goa.

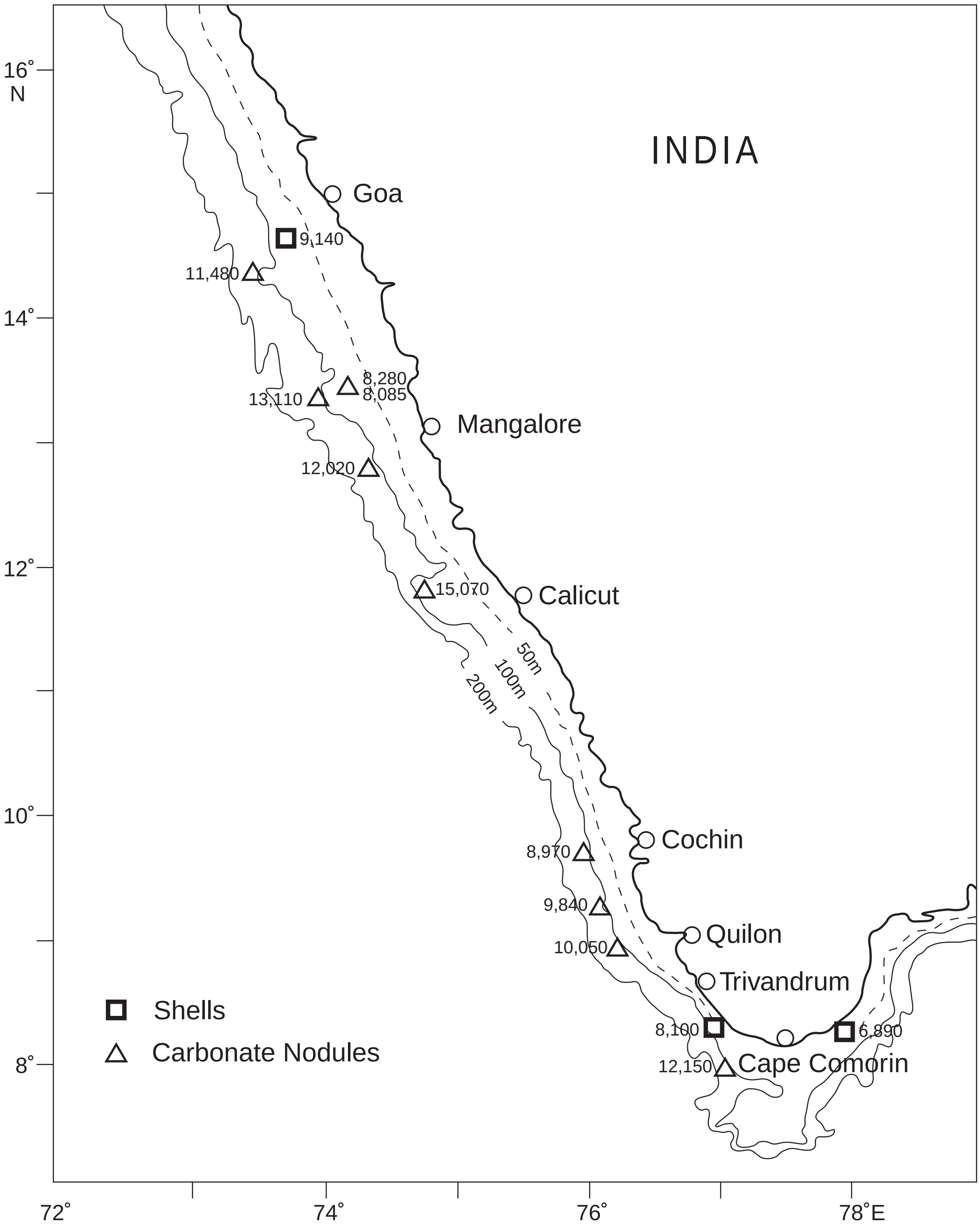

Figure 2(c). Measured radiocarbon ages of the samples off Goa-Cape Comorin.

station (SK-111/16) coralline-algal nodules (dated 12,000 ^{14}C yr BP) occur beneath the aragonite sands dated at 6,730 ^{14}C yr BP (7.6 ka). A shell zone comprising of oyster shells of different sizes occurs off Ratnagiri (table 1; figure 2b; figure 4a). The largest shells have the oldest age (11,920 ^{14}C yr BP) (table 2). Dolomite crusts also occur at 64 m water depth on the northeastern edge of the platform. Dolomite, high-magnesium calcite and quartz are dominant minerals and, feldspar, marcasite and pyrrhotite are minor. SEM studies indicate that the crust contains irregularly laminated dolomitized cyanobacterial filaments (figure 5a) or laminated microbial mats with entrapped particles (figure 5b–c) and dolomite microparticles (5 μm) resembling fossil bacteria or their aggregates

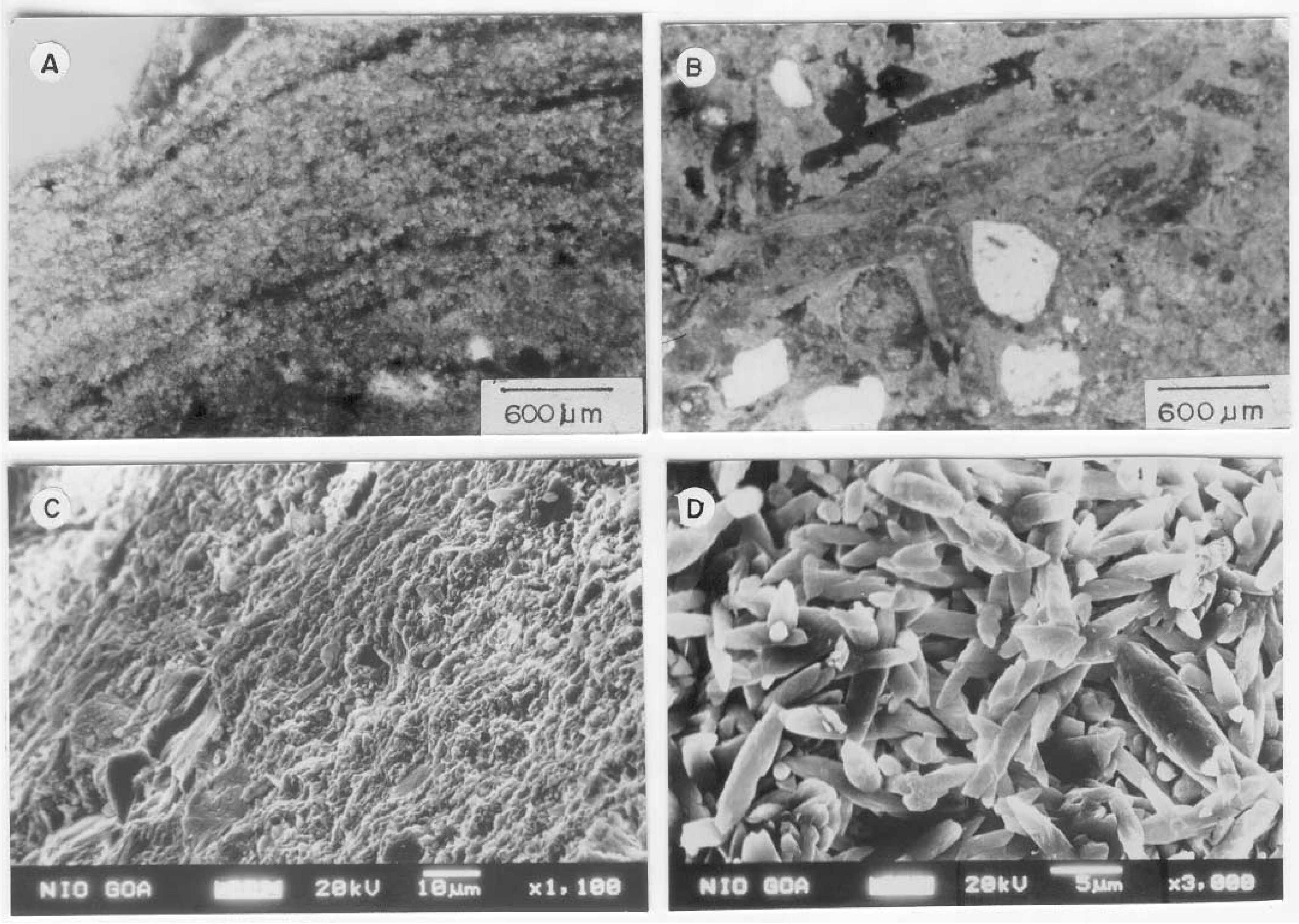

Figure 3. Thin section photomicrographs **(A–B)** and SEM photographs **(C–D)** of the dolomite crust from the Gulf of Kachchh. **(A–B)** Thin microlaminations with trapped sediment detritus; **(C)** Dolomitized microbial laminations and **(D)** long rod-like dolomite microparticles resembling fossil bacteria.

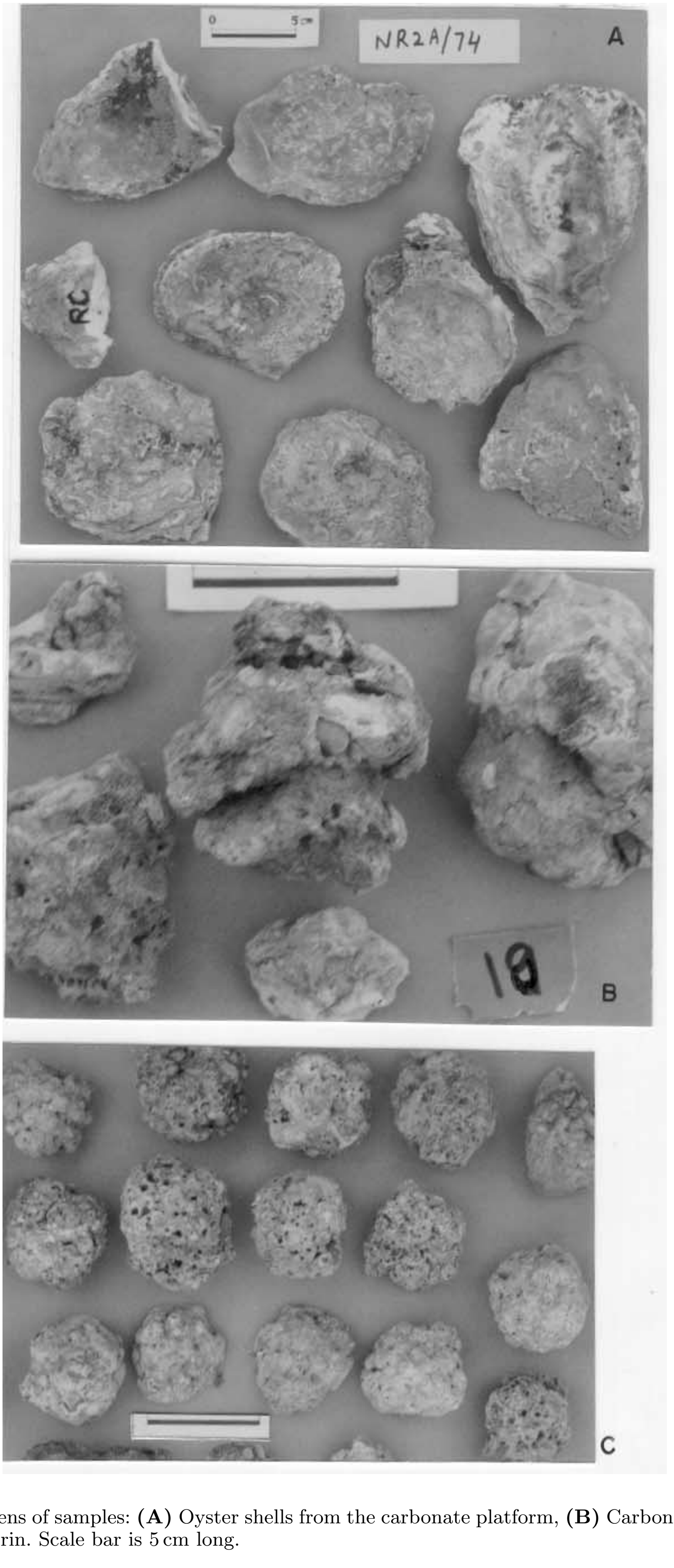

Figure 4. Hand specimens of samples: **(A)** Oyster shells from the carbonate platform, **(B)** Carbonate nodules off Vengurla and **(C)** off Cape Comorin. Scale bar is 5 cm long.

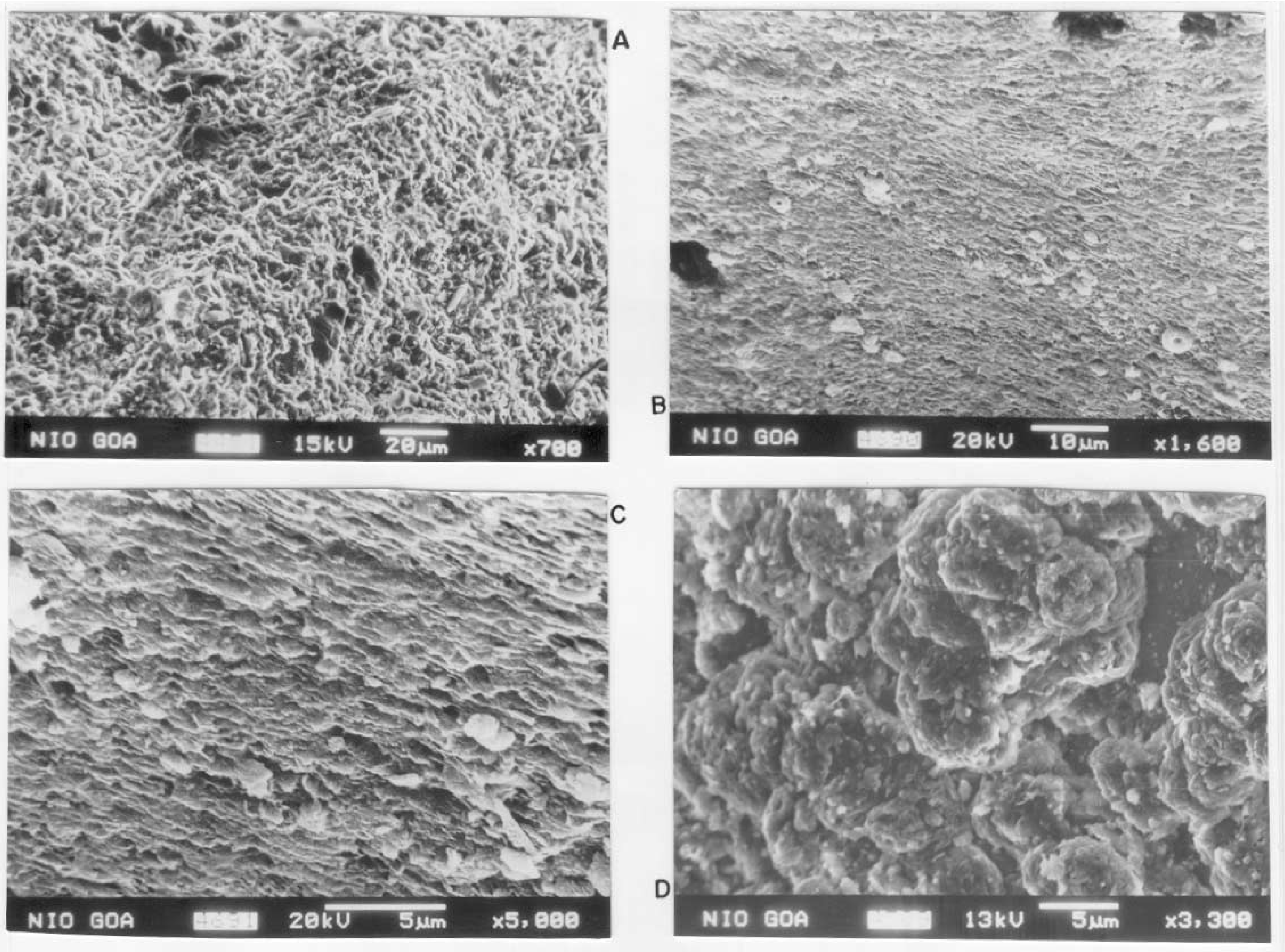

Figure 5. SEM photomicrographs of dolomite crusts from the carbonate platform. **(A)** Wrinkled dolomitized microlaminations of cyanobacteria, **(B)** cyanobacterial mats with trapped sediment detritus, **(C)** enlargement of 'B', and **(D)** ovoid to rounded dolomite microparticles and their aggregations, resembling bacterial aggregates.

(figure 5d). Oxygen isotopes ($\delta^{18}O = 4.17‰$) of the dolomite (table 1) indicate hypersaline conditions at the time of its formation. The AMS age of the crust is 17,250 ^{14}C yr BP (20.3 ka) (table 2; figure 2b). Dolomite crusts are the oldest samples so far reported for near surface sediments of the carbonate platform.

3.3 *Vengurla - Mangalore*

Grey carbonate nodules (figure 4b) were recovered abundantly between Vengurla and Goa and sparsely between Goa and Mangalore. High-magnesium calcite, carbonate fluorapatite and quartz are present in order of abundance. These nodules contain up to 10% P_2O_5 (Rao and Lamboy 1996). Polished and thin sections indicate that the nodules are dominated by foraminiferal (*Gypsina*) encrustations (figure 6a) with intermittent thin coralline algal laminations (figure 6b–c). *Mesophyllum* (figure 6c), *Lithothamnium, Archaeo-lithothamnium, Sporolithon, Lithoporella* and *Porolithon* are the different genera of coralline alga present intermittently in different nodules. These associations represent moderate to deeper depths at the time of their formation (see Rao *et al* 2002a; Taberner and Bosence 1985; Adey 1986; Reid and Macintyre 1988; Minnery 1990). Siliciclastic detritus trapped between the laminations has been phosphatized. These nodules also show a succession of encrusters and are represented by alternate laminations of foraminifera and coralline algae, or repeated succession of foraminifera, coralline algae and encrusting corals (figure 6d). The age range of the nodules off Vengurla-Goa is narrow and lies between 7,000 ^{14}C yr BP (7.9 ka) and 8,940 ^{14}C yr BP (10 ka), while that of Goa - Mangalore is slightly higher (10,980 ^{14}C yr BP) (12.9 ka) (table 2). Corals overlain by encrusted foraminiferal laminae occur at 70 m water depth off Mangalore (SK65/2). The age of the coral is 7,780 ^{14}C yr BP, while that of the foraminiferal encrustation is 7,590 ^{14}C yr BP. Coral polyps at 59 m depth are dated at 2,390 ^{14}C yr BP (2.5 ka) (table 2).

3.4 *Mangalore - Cape Comorin*

The ages of the *Porites* corals off Mangalore at 105 and 110 m water depths are 12,610 ^{14}C yr BP and 11,520 ^{14}C yr BP, respectively (table 2). Spherical carbonate nodules $\sim$ 5 cm diameter (figure 4c) occur abundantly at 90 m off Cape Comorin. Thin sections of the nodules indicate dense coralline algae (figure 7a) belonging to *Lithothamnium* and *Lithophyllum* with thin veneers of encrusting foraminifera. Solution features, alteration of skeletal material and micritisation of algal material (figure 7b) are common in these nodules. These features indicate shallow water conditions at the time of their formation. These nodules are dated at 11,650 ^{14}C yr BP (13.5 ka). Sandy sediments comprising of a mixture of benthic foraminifers and mollusks were recovered at the inner shelf around Cape Comorin. The age of these sandy sediments at 49 m is 7,600 ^{14}C yr BP (8.4 ka) while those at 18 m depth is 6,390 ^{14}C yr BP (7.3 ka) (tables 1–2; figure 2c).

4. Discussion

4.1 *Evidence of sea level during isotope stage 3*

The oldest samples recovered are sheet limestones from the Gulf of Kachchh. They are dominated by both low- and high-magnesium calcite. Their ages (table 2) provide evidence for sea level in the Gulf prior to the Last Glacial Maximum (LGM), i.e., in isotope stage 3 (50–26 ka), during which the global sea level was within −40 to −80 m (Labeyrie *et al* 1987; Bard *et al* 1990).

4.2 *Sea level during LGM*

Dolomite crusts from the carbonate platform are the second oldest on this margin. The cyanobacterial mats, trapping and binding of sediments by microbial mats and their direct dolomitization (figure 5a–d) indicate that these dolomite crusts were similar to dolomite stromatolites. The origin and environmental conditions of the crusts in detail were discussed elsewhere (Rao *et al* 2002b), suggesting that the dolomite formed in the crusts is primary, microbially mediated and in shallow (subtidal to intertidal) hypersaline conditions. The other carbonate phase – high-magnesium calcite associated with the crust is also of marine origin. The AMS age of the crusts at 64 m is 17,250 yr BP. Contrastingly, the glacio-eustatic sea level at about 18,000 yr BP was at −120 m (Fairbanks 1989). This implies, unlike other continental shelves of the world oceans or continental shelf between Mangalore-Cape Comorin (see below) which were subaerially exposed during the last glacial maximum (LGM – 18,000 yr BP), the carbonate platform was at shallow depths or pockets of lagoons may have existed on the platform in which the dolomite crusts were formed. Hypersaline conditions revealed by stable isotopes of the crusts (table 1) point to the existence of lagoons on the carbonate platform. Since these crusts were collected by Peterson Grab, the lagoons may not have been too deep. In other words, the platform was

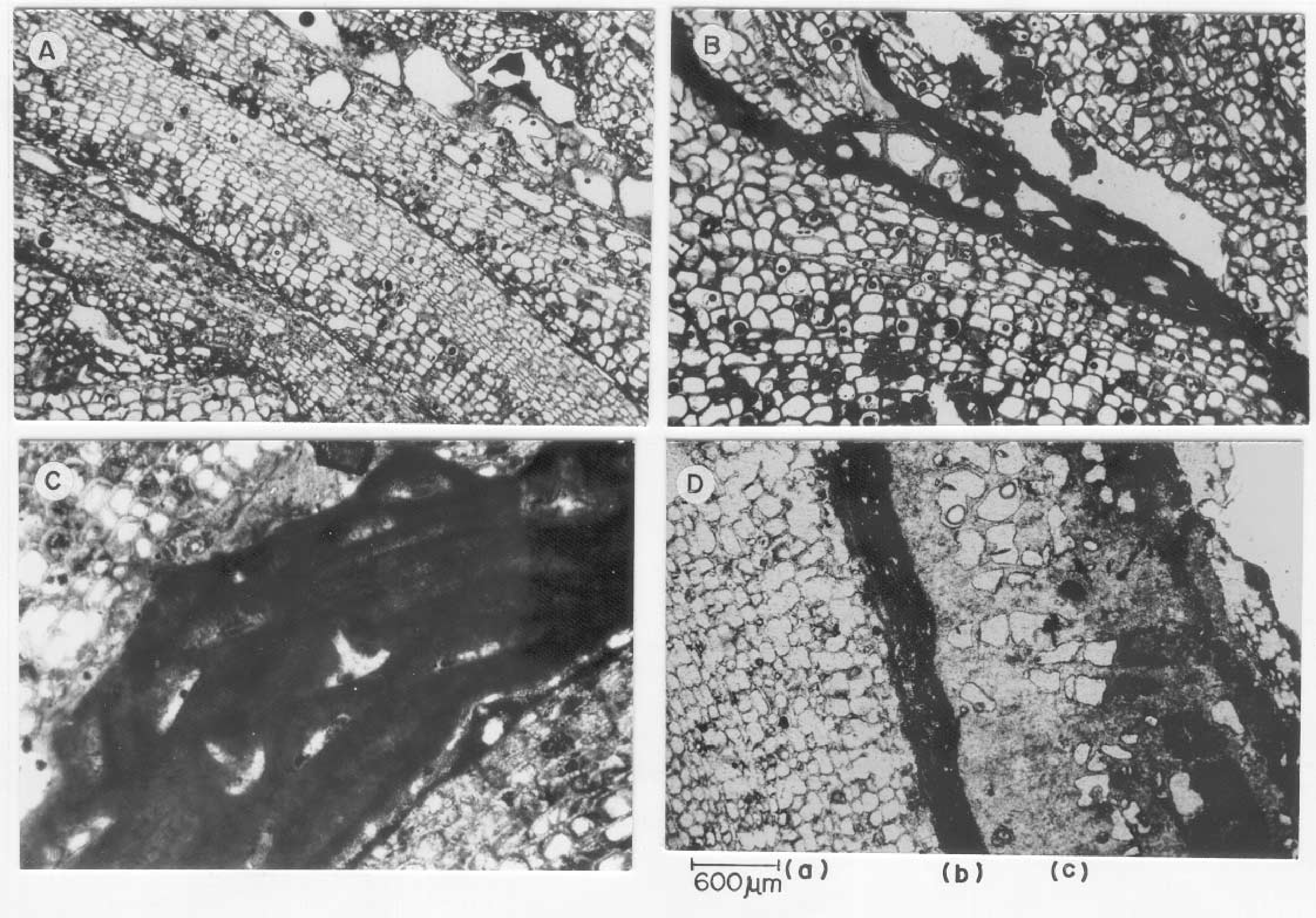

Figure 6. Thin section photomicrographs of carbonate nodule off Vengurla showing abundant foraminiferal **(A)** with intermittent coralline algal laminae **(B)**; **(C)** a mesophyllum encrustation between foraminiferal encrustations; **(D)** alternate laminations of foraminifera (a), coralline algae (b) and encrusted corals (c) in a nodule. Scale is same for all.

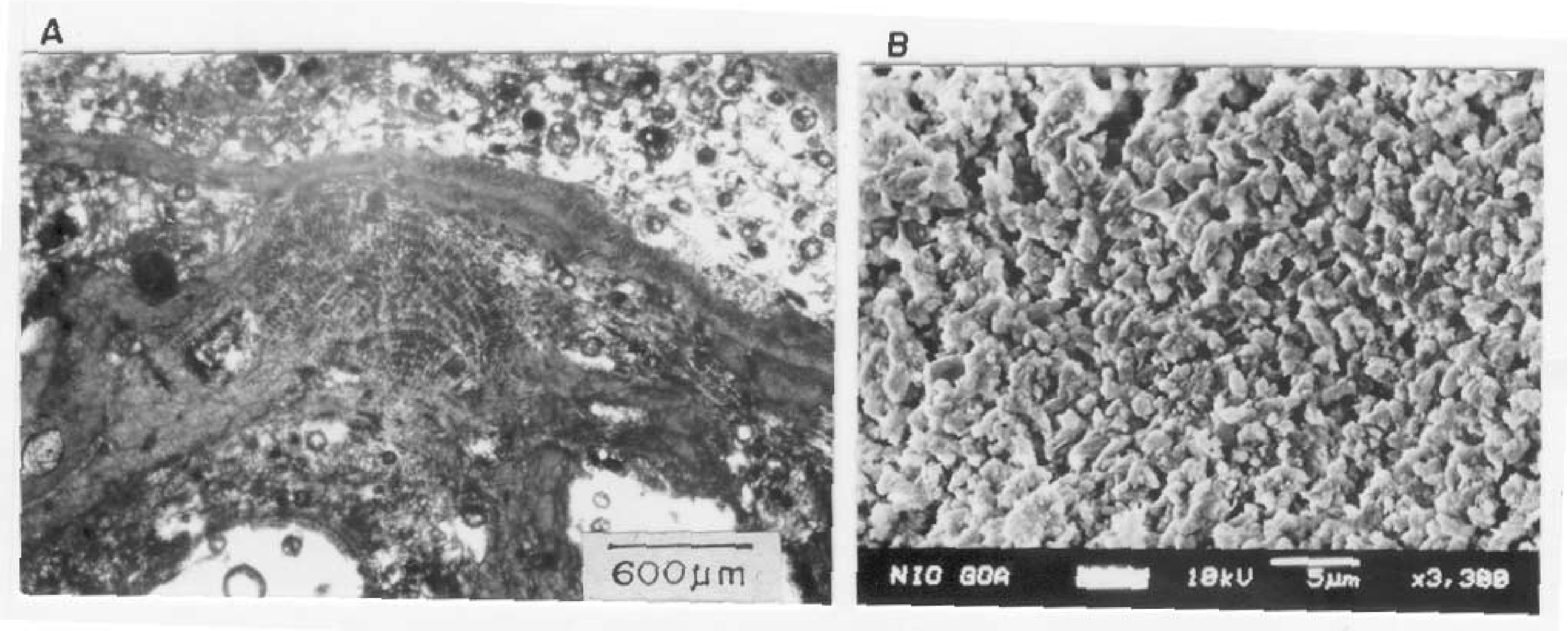

Figure 7. Thin section photomicrograph **(A)** and SEM photograph **(B)** of the coralline algal nodules off Cape Comorin. *Lithothamnium* overlain by lithophyllum **(A)** and, micritisation of algal material **(B)**.

at shallow depths during the LGM and explanation is needed for the difference of sea level of ~ 50 m at about LGM between the global position (-120 m) and the platform position (-64 m). The next higher or older age (12,440 ^{14}C yr BP) comes from the aragonite sands of the platform. Since both (dolomite crust and aragonite sands) are near surface sediments and are separated by $\sim 5,000$ years in age, we presume that the carbonate production was low on the platform between 17,250 and 12,440 ^{14}C yr BP. Beck *et al* (2001) reported decreased atmospheric Δ^{14}C values from ~ 700 to ~ 100 per mil between 26 and 11 ka and suggested substantially slower or shallower thermohaline circulation and/or reduced carbonate sedimentation rates are necessary to explain these values.

4.3 *Sea level during 12,610 – 11,650 yr BP*

The sediments (or sedimentary rocks) with radiocarbon ages between 12,610 ^{14}C yr BP (14.8 ka) and 11,650 ^{14}C yr BP (13.5 ka) were spread along the margin in the form of different deposits (figure 2a–2c; table 2). They occur as dolomite crusts in the Gulf of Kachchh, coralline algal nodules, aragonite sands or oyster shells (figure 4a) on the carbonate platform, *Porites* corals off Mangalore and coralline algae-dominated nodules (figure 4c) off Cape Comorin (tables 1 and 2). These deposits, however, occur in the depth range of 85 – 110 m between Cape Comorin and Ratnagiri and on carbonate platform, but at 35 m in the Gulf of Kachchh (table 1). Interestingly, some of these are shallow water deposits and serve as sea level indicators. For example, live *Porites* corals with a cap of < 10 m water are found abundantly in the Indo-Pacific region (Done 1982; Veron 1986). Dense coralline algae and its alteration to micrite (figure 7a–b) in the nodules off Cape Comorin are indicative of shallow marine conditions at the time of their formation (see Logan *et al* 1969; Winland 1969; Bosence 1985; Rao *et al* 2002a). Similarly, oyster shells (figure 4a) were reported at intertidal to subtidal depths and have been used as sea level indicators (Merrill *et al* 1965; Meldhal and Cutler 1992). These imply that the sea level reached about 85 m by about 13.5 ka along the western margin of India between Cape Comorin and Mangalore. Since dolomite crusts dated 17,250 yr BP and different deposits (oyster shells, aragonite sands and algal nodules occupying different latitudes) having age $\sim 12,000$ yr BP (table 2; figure 2c) are present on the platform, it is difficult to envisage the water depth on the platform during this time. Although the depth of the shell zone off Ratnagiri (southern part of the platform) coincides very well with glacio-eustatic sea level position, the depth and age of the aragonite sands do not correspond (see below). At present we are unable to answer this discrepancy. Relic reefs at about 100 to 90 m containing sediments/reefs of $\sim 12,000^{14}$C yr BP were reported off Caribbean Islands, Comoro Islands and Red Sea (Dullo *et al* 1998; Montaggioni 2000). Our findings for this period of time between Cape Comorin and Ratnagiri are consistent with other margins.

The depth and ages of the samples from the Gulf of Kachchh are in contrast with that on the glacio-eustatic sea level. Dolomite crusts dated at 14.3 ka occur at 35 m in the Gulf. Dolomite usually forms under evaporative conditions and at shallower depths on the continental shelf, where large volumes of normal sea water/brines are pumped through the sediments (Patterson and Kinsman 1982; Carballo *et al* 1987). Moreover, laminated microbial mats with intermittent sediment particles (figure 3a–d) are considered to form at shallow depths (Logan *et al* 1969; Walter 1976). Dolomite encrustations occur on large sheet limestones and are formed by dolomitization of microbial filaments. We, therefore, consider that these crusts were developed *in situ*. Rugged topography with pinnacles as high as 10 m is characteristic of the sea floor at the mouth of the Gulf of Kachchh ruling out the possibility of transportation. Since miliolite limestones are spread along the Saurashtra, one would argue that the detrital carbonates from these limestones may have transported and mixed up with these dolomites and diluted the age of the dolomite crust. The dolomite crusts consist of abundant dolomites of primary origin formed by microbial mediation (figure 3a–d) and high-magnesium calcite, both formed in hyposaline conditions (see stable isotopes). Since low-magnesium calcite (major mineral of the miliolite limestones on land) is not present in the crusts, contamination from older carbonate detritus may not be a major factor. Furthermore, the ages of *Favia* corals (aragonite in composition) (10.8 ka) and dolomite crust (12.5 ka) at 28 and 25 m, respectively at the mouth of the Gulf (see tables 1 and 2) also do not correspond with the glacio-eustatic sea level (see below). Aragonite crust dated at 13.7 ka occurs in a core (at 100–105 cm interval) collected at 55 m depth on the shelf off the Gulf of Kachchh (V P Rao unpublished data). These suggest that not only dolomite crusts but also other types of samples (aragonite crusts and corals) collected from the Gulf and in its vicinity showed similar older ages. We, therefore, consider that the ages of the crusts are reliable. Since the oldest age of the sample (dolomite crust) is 14.3 ka the Gulf must have inundated much before, because for initiation of dolomite formation (or for the growth of corals) one would expect a lag period after flooding of the Gulf. Davies and Montaggioni (1985) reported a lag period of 1200 – 2000 years between initial flooding and start-up phase for the coral settlement in the Great Barrier Reef (GBR). Keeping this in view, we suggest that after the Last Glacial Maxima (LGM), the Gulf must have inundated atleast by ~ 15 ka. Corals of the *Faviidae* family are characteristic of turbid water and occur at shallow depths (1–6 m) (Veron 1986). These corals occur at 28 m in the Gulf and are dated at 10.8 ka. The glacio-eustatic sea level was, however, at ~ 70 m by 11 ka (Fairbanks 1989). This implies that the Gulf of Kachchh was uplifted atleast by ~ 40 m sometime after 10.8 ka.

The Kachchh region is seismically active and controlled by a series of normal and low-angle reverse faults, which are exposed in certain regions. Several $\mathrm{Th}^{230}/\mathrm{U}^{234}$ ages on miliolite limestones of Saurashtra and Kachchh indicated three episodes of uplift and miliolite deposition during the Pleistocene (Baskaran *et al* 1989). Recent regional studies have shown the uplift of the northern Kachchh at different times in Holocene, including 8,500 yr BP, 5,000 yr BP and 2,500 yr BP (Parkash *et al* 2000) and subsidence of Bet Dwarka sometime after 3,870 yr BP (Rao 1996; Vora *et al* 2002). Although the uplift time at 8,500 yr BP (9.6 ka) on land is close to the younger age of the sample (coral – 10.8 ka) from the Gulf of Kachchh, other regional uplift times and subsidence time of the Bet Dwaraka cannot be accounted with our data. Palaeoseismological studies further indicate that the Kachchh region experienced large and moderate earth quakes, including the ones in the most recent years (1891, 1956 and 2001). Some of these earthquakes are caused by blind faults and induced surface deformation and widespread liquefaction including lateral spreading (see Rajendran *et al* 2001). We, therefore, suggest that the Gulf of Kachchh was subjected to complex tectonic movements (including uplift and subsidence at different times) during the late Pleistocene and Holocene and it is difficult to quantify the rate of uplift/subsidence.

4.4 *Sea level between 10,000 and 7,000 yr BP*

The age of the aragonite sands (oolites and aragontic faecals) from 15 stations on the carbonate platform (figure 2b) ranges between 12,440 and 6,730 yr BP implying that carbonate sedimentation continued until 6,730 yr BP. The colour differences of these sands from east to west of the platform suggest that there is no mixing of sands from different depths. If one considers that oolites form in shallow marine conditions and serve as sea level indicators (Illings 1954; Loreau and Purser 1993), it is necessary to envisage intertidal to subtidal conditions on the platform during their formation. This seems unlikely here, because the glacio-eustatic sea level rose by ~ 80 m between 12,000 and 7,000 yr BP. This implies that oolites may not be considered as sea level indicators and can even form at deeper depths (Kump and Hine 1986; Rao *et al* 1996). Rao *et al* (1994) suggested that some of these sands are aragonitic faecals and, *Halimeda* bioherms acted as the source of aragonite mud for the formation of faecals. It is also difficult to explain the continued growth of Halimeda bioherms with the rise of sea level by about 80 m.

The limestones (G72/1459, G72/1479) collected at 95 m and 85 m water depth on the platform show solution features, needle fibre aragonite and drusy calcite cements indicating vadose diagenetic conditions of the platform. The age of the limestone at 85 m depth is about 8,785 ^{14}C yr BP (Rao *et al* 1994) (table 2; figure 2b). The glacio-eustatic sea level at 9,000 yr BP was ~ -37 m (Fairbanks 1989) implying that a difference of sea level of about ~ 50 m have to be explained.

4.5 *Age vs depth relation of the samples*

Forty-six of the 62 data points from table 2 were plotted on the glacio-eustatic sea level curve of Fairbanks (1989) (see figure 8). The age/depth of the samples which are outside the limits of the curve, duplicate analyses, age of the samples from the gravity cores, age of the corals from the Angria Bank and ages of the polyp corals (see table 1) were not plotted on this curve. The samples from the Gulf of Kachchh fall distinctly on the right of the curve (figure 8). As explained earlier, this is due to early flooding of the Gulf atleast by 15 ka after the Last Glacial Maxima and subsequent uplift and/or subsidence. The dolomite crusts from the platform also fall on the right of the curve. All other samples plot on or left of the curve. There are a few data points at depths < 60 m. Only 8 samples were dated from the continental shelf between Cape Comorin and Mangalore. Of these, five samples at water depths from 110, 90, 58, 49 and 18 m having their ages between 12,610 and 6,390 yr BP fall on or, very close to the glacio-eustatic sea level curve. On the other hand, the ages of the oyster shells and a few coralline-algal limestones from the platform also fall very close to the sea level curve, but all other samples from the platform fall away from the curve (figure 8). In other words, the samples dated 12,000 – 6,900 yr BP from the carbonate platform spread at depths between 105 and 65 m, whereas the samples of the same age range from the shelf between Cape Comorin and Mangalore occur at depths between 110 and 18 m. This suggests that carbonate sedimentation continued on the platform despite the glacio-eustatic sea level rise by about 80 m (between 12,000 and 7,000 yr BP) or, the platform was subjected to

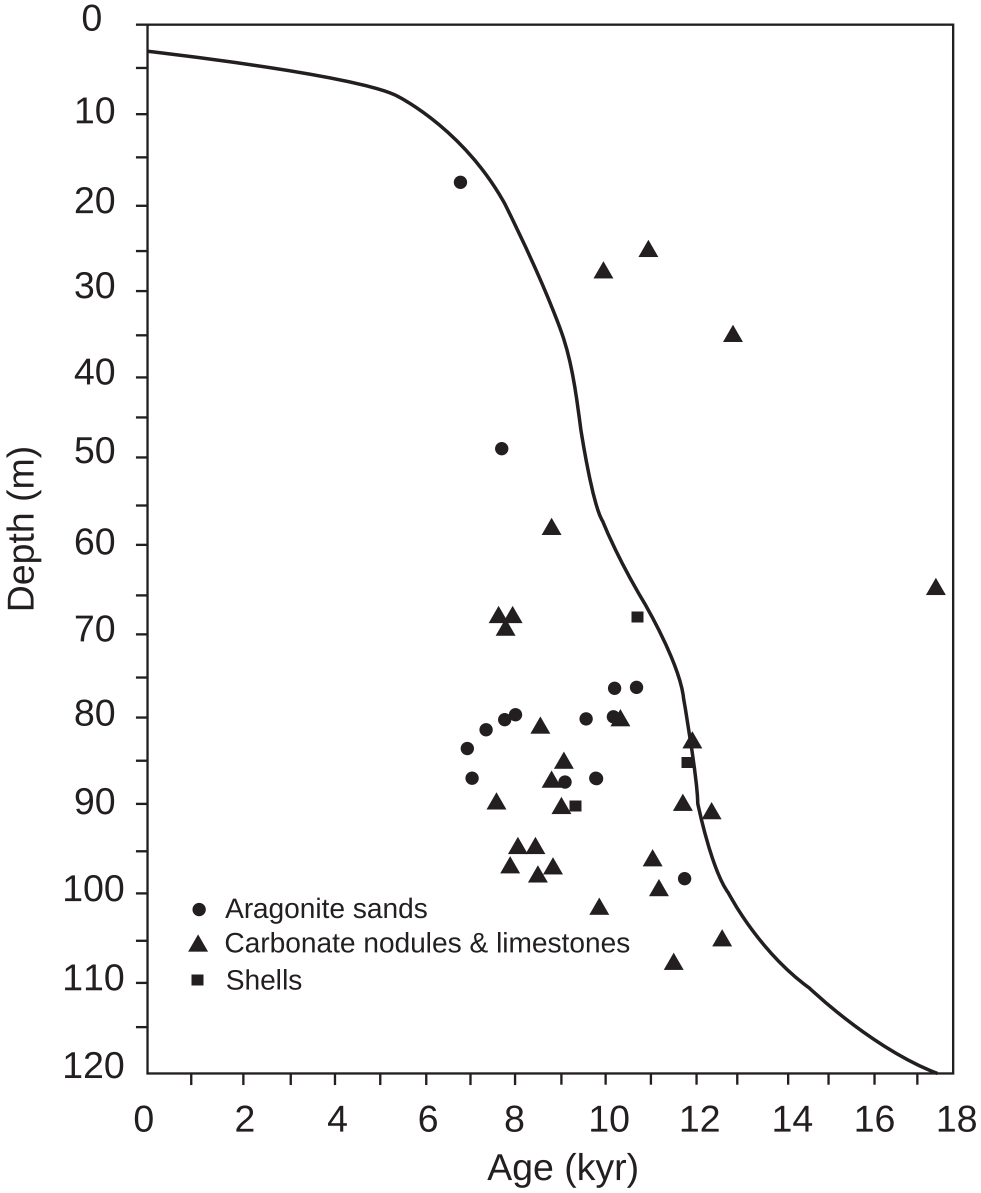

Figure 8. A plot of corrected radiocarbon ages and depth of the samples on a glacio-eustatic sea level curve of Fairbanks (1989).

intermittent neotectonic activity and then carbonate growth continued. We are indeed concerned and careful about documenting the neotectonic activity on the platform, as many do not believe this possibility on the passive margins such as Indian margins. However, evidences such as **(a)** deeper water terraces (Rao and Veerayya 1996), **(b)** limestones of early Holocene age showing vadose diagenetic textures (see Rao *et al* 1994), **(c)** dolomite crusts dated 17,250 yr BP at 64 m depth and **(d)** age of the aragonite sands (12,440 – 6,730 yr BP) on the platform cannot be explained by any other single mechanism. Even considering that aragonite on the platform is of biogenic origin (derived from *Halimeda* bioherms), it is difficult to envisage a massive carbonate production with the rise of sea level about 90 m, between 12,440 yr and the present. It is known that the glacio-eustatic sea level reached its present position at about 6000 years BP. If one assumes aragonite forms even in deeper water, the controlling factor for the cessation of aragonite sands after 6,730 years BP, and absence of terrigenous sediments, between 12,440 yr BP and the present, on the platform despite its position off the rivers need explanation. Keeping these in view, we believe that the platform may have been at a different elevation during LGM and subsequently subsided during the Holocene. The exact time/times and rate/rates of subsidence are unknown and it is difficult to quantify the phases of subsidence with the existing data. Since aragonite cemented vadose diagenetic limestones (G72/1459) were formed at 8.85 ka, we presume that atleast one phase of subsidence of the platform must be after 8.85 ka. The carbonate platform was an isolated feature during the Eocene. The sediments originated from the River Indus accumulate abundantly on the western slopes of the platform and sediments from the Narmada and Tapti on the eastern slope of the platform and in the Dahanu depression (inner shelf) since Eocene. The sediments thus accumulated on the slopes of the platform acted as load on the platform. The combined effect of water and sediment load may have been responsible for the subsidence of the platform.

4.6 *Inferred environmental conditions*

The relic ages of the *Porites* reefs (14.8 to 13.4 ka) off Mangalore indicate reef development stopped after 13.4 ka. There may be two reasons for their demise. The reefs may have been affected by the rapid changes in sea level caused by the main phase of deglaciation and to the melt water pulse (MWP) 1 A (Fairbanks 1989) or catastrophic rise events (Blanchon and Shaw 1995) occurred at about 14 ka. Palaeoclimate records from several sites of the western margin of India suggest enhancement of monsoonal precipitation about 15 ka (Thamban *et al* 2001) and intensified precipitation between 11 and 9 ka (Van Campo 1986). Such intensification could have resulted in large flux of fresh water and sediment into coastal water thereby reducing water transparency, salinity and increasing nutrient flux and creating eutrophic conditions. Such conditions are considered to inhibit coral growth (Hallock and Schlager 1986). The rapid sea level rise also interrupts sedimentation and starving of sediments, that would correspond to diastem recording a typical drowning unconformity. Hardground conditions are indeed evident at about this time (13.1–12.3 ka) on the relict deposits occurring at the seaward edge of the carbonate platform and are represented as indurated aragonite muds, serpulid encrustations on algal nodules or *Halimeda* or pelletal/oolitic limestones with several borings (tables 1 and 2; figure 2b).

Patches of coral fragments dated 7,780 ^{14}C yr BP and 2,550 ^{14}C yr BP or polyp corals dated 2,390 ^{14}C yr BP occur at depths between 60 and 70 m off Mangalore, carbonate platform and Vengurla (tables 1 and 2). These indicate intermittent oligotrophic conditions (atleast locally) on the shelf during which corals were formed. Present day corals (dated 240 yr BP) at 22 m on the Angria Bank (SK111/1), located away from the continental shelf, indicate suitable conditions for reef development in the shallow offshore banks.

It is indeed amazing how carbonates developed when one considers the geographic settings of the platform, age of the sediments on it and environmental conditions during the early Holocene. Firstly, the platform is located off the river mouths of Narmada and Tapti, which debouch 58.7 million cu. m. of water and several tons of suspended and bed load annually through the Gulf of Khambat (Rao 1975). The water depths on the platform range between 60 and 110 m. Since the glacio-eustatic sea level at 10,000 yr BP was at 60 m (Fairbanks 1989), one would expect the platform at or slightly below the sea level at this time and river discharged sediments transported right onto the platform. Secondly, enhanced monsoonal conditions have been reported during 13,000 − 6,000 yr BP (Van Campo 1986; Sarkar *et al* 2000; Thamban *et al* 2001). As a consequence, one would expect large fresh water and siliciclastic flux during this time. Thirdly, it is well known that carbonate sedimentation rates are inversely proportional to the siliciclastic flux. In view of the above, one would expect abundant terrigenous flux and, as a result cessation of carbonate growth on the platform. However, carbonate sedimentation continued until 6,730 yr BP and the platform sediments contain only $< 10\%$ terrigenous flux. This implies the riverine flux delivered either filled the innershelf – Dahanu Depression – wherein sediments are being accumulated since Eocene, and/or diverted southwards under the influence of southwest monsoon current (Banse 1968). If the latter is the case, one would expect a high degree of turbidity in the water column on the shelf south of the carbonate platform. The age of the foraminiferal-dominated nodules (figure 4b) (9,400 and 7,500 yr BP) off Vengurla - Goa (figure 2b) (south of the platform) indicates their formation during intensified monsoonal conditions. The constituents of the nodules indicate their deeper water origin. We therefore propose that these nodules are characteristic of turbid waters and support our argument that the riverine flux was directed southwards for the reasons given below.

- Hottinger (1983) and Plaziat and Perrin (1992) reported well-developed abundant foraminiferal-dominated nodules and indicated that they even survive in turbid conditions, unfavourable for encrusting corallines.
- The intermittent micro-laminations of coralline algae probably represent seasonal growth (figure 6b–c) when waters were more transparent under non-monsoonal seasons. During monsoonal months foraminifera are favoured due to excess turbidity which excludes coralline algae (see Reid and Macintyre 1988).
- Phosphatized sediment detritus trapped between laminations indicate abundant flux to the region

and suboxic conditions at or closer to the sea bed at the time of their formation. Intensified monsoons and associated upwelling brings large nutrient input and reduces the temperature and dissolved oxygen contents at subsurface depths and these conditions are not conducive for corals and coralline algal growth. The cyclic bands of foraminifera, coralline algae and corals (figure 6d) in the nodules may indicate improvement in environmental conditions in the water column from turbid to eutrophic to clearer and oligotrophic at the time of their formation.

5. Conclusions

- Relic carbonate deposits on the western margin of India occur as dolomite crusts, aragonite sands, vadose diagenetic limestones, coralline algal and foraminiferal-dominated nodules, oyster shells, *Faviidae/Porites* corals and benthic foraminifera/mollusk-dominated sediments.
- The relic deposits dated $\sim 12,000 - 6,390$ ^{14}C yr BP spread on the outer and inner continental shelf at depths of 110 – 18 m between Cape Comorin and Mangalore, but occur within a narrow depth range (105 – 65 m) on the carbonate platform of the northwestern margin of India. Relic deposits of the Gulf of Kachchh (25 – 35 m) are dated at 12,550 – 9,630 ^{14}C yr BP. Relic deposits of the isotope stage 3 also found in the Gulf.
- The age vs depth plot of the samples indicates that the Gulf of Kachchh was uplifted and the carbonate platform subsided during early Holocene. A few samples were dated on the shelf off Cape Comorin-Mangalore. Of these five samples plot on or, close to the glacio-eustatic sea level.
- Occurrence of *Porites* corals at 12,610 to 11,520, $\sim 7,780$ and $\sim 2,550$ ^{14}C yr BP indicate intermittent oligotropic conditions. Ecological succession from corals to coralline algae and to foraminiferal encrustated nodules, indicates changing water column conditions with respect to the nutrients and turbidity, probably due to intensified monsoons during the early Holocene.
- The sediments of the Narmada and Tapti were largely deposited on the inner shelf or, diverted southwards during the early Holocene, facilitating carbonate growth on the platform and foraminiferal nodules off Vengurla-Goa.

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