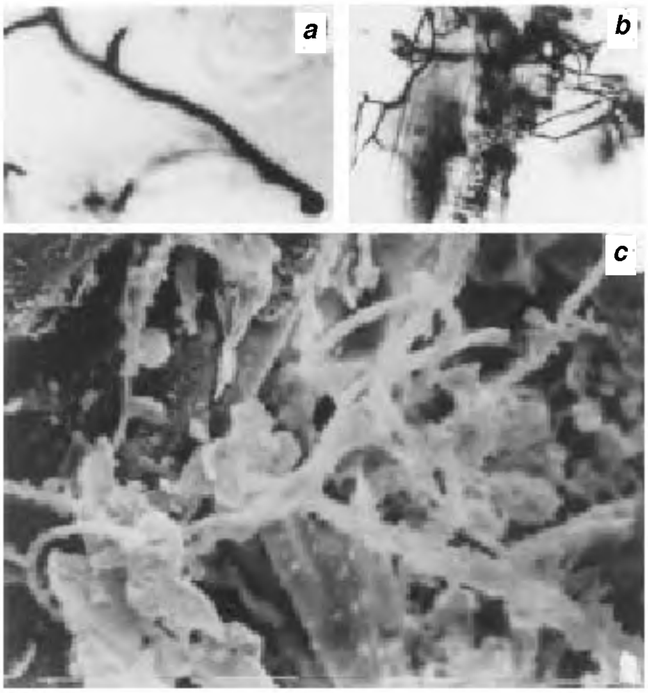

Figure 3. Growth and germination of chlamydospores of *C. subvermispora* on wood chips after 48 h incubation at 25°C. (***a***) Germ-tube formation from the chlamydospore and (***b***) mycelium formation and colonization as observed under light microscope (40 ×). (***c***) Chlamydospore germination and mycelium formation as observed under scanning electron microscope (5000 ×).

These spores could efficiently colonize wood chips and other agro-wastes which are used for paper manufacture. Thus, there is immense practical feasibility of the procedure for the production of chlamydospores in this fungus. First, their mass production is essential for the preparation of starter cultures for biopulping and biobleaching. Secondly, they can be transported in large quantities, remain viable for a long period of time and can be handled easily. Finally, since the spores formed are thick-walled, they have a prolonged shelf-life and are resistant to contamination.

1. Eriksson, K. E. and Kirk, T. K., *Comprehensive Biotechnology* (ed. Murray Moo-Young), Pergamon Press, 1985, vol. 3, pp. 271–294.
2. Blanchette, R. A., Burnes, T. A., Leatham, G. F. and Effland, M. J., *Biomass*, 1988, **15**, 93–101.
3. Blanchette, R. A., Burnes, T. A., Eerdmans, M. M. and Akhtar, M., *Holzforschung*, 1991, **46**, 109–115.
4. Akhtar, M., *Holzforschung*, 1994, **48**, 199–202.
5. Akhtar, M., Attridge, M. C. and Blanchette, R. A., *Biotechnology in the Pulp and Paper Industry* (eds Kuwahara, M. and Shimada, M.), UNI Publishers Co. Ltd, Tokyo, 1992, pp. 545–560.
6. Ruttimann, C., Salas, L., Vicuna, R. and Kirk, T. K., *Appl. Environ. Microbiol.*, 1993, **59**, 1792–1797.
7. Saxena, R. K., Khurana, N., Kuhad, R. C. and Gupta, R., *Mycol. Res.*, 1992, **96**, 490–494.
8. Monreal, J. and Reese, E., *Can. J. Microbiol.*, 1969, **15**, 689–696.
9. Saxena, R. K., Ph D thesis, University of Delhi, 1976.
10. Turian, G., *Annu. Rev. Phytopathol.*, 1974, **12**, 129–137.
11. Ordentlich, A., Elad, Y. and Chet, I., *Phytopathology*, 1988, **78**, 84–87.
12. Gupta, R., Saxena, R. K., Chaturvedi, P. and Virdi, J. S., *J. Appl. Bacteriol.*, 1995, **78**, 378–383.

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Late Quaternary changes in sea level and sedimentation rate along the SW coast of India: Evidence from radiocarbon dates

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We determined the ^{14}C dates of carbonized wood/peat and organic matter from two cores from the southwestern inner continental shelf of India, to understand late Quaternary changes in sea level and sedimentation rate. The ^{14}C ages of carbonized wood/peat samples from the two cores range from 10,760 ± 130 to 9,280 ± 150 yr BP, corresponding to Late Pleistocene–Early Holocene. These ages suggest that the sea level was much lower (> 50 m) than the present level during the Late Pleistocene–Early Holocene, when there was a luxuriant growth of mangrove vegetation and rainfall in the region. Later, due to transgression during Early Holocene, the mangrove vegetation was submerged and buried under a thick column of sediment, giving rise to carbonized wood/peat. The ^{14}C ages reported for the present-day onshore peat and shell material at various depths along the SW coast of India reveal that after 6400 yr BP, the sea level receded and stabilized at the present level. The results indicate that: (1) the present-day sedimentation rates in the study area are generally comparable to those reported for similar water depths off the Karnataka coast, but higher than that reported for the Kerala coast; (2) sedimentation rate at a site is controlled by its proximity to river mouths and it decreases offshore; and (3) sedimentation rate during the Pleistocene–Holocene transition period is 6–7 times higher compared to the Holocene.

SEDIMENTS of the western continental shelf of India may be categorized as: (1) modern clayey silt and silty clay

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sediments on the inner shelf, and (2) calcareous sand/relict sand of Late Pleistocene–Early Holocene age (9000–11,000 yr BP) on the outer shelf[1,2]. Based on ^{14}C ages, it has been suggested that the submerged terraces at – 92, – 85 and – 75 m off Mumbai and Karwar may correspond to still stands of global sea level during the Holocene[3]. Sedimentological and SEM studies have shown that the outer shelf sands off Mangalore were deposited in a beach environment[4]. The sea rose by as much as 6 to 10 m above the present level around 6000 yr BP, along the west coast of India, which later regressed and stabilized at the present level[5]. Although carbonized wood/peat beds have been reported from various bathymetric levels from many parts of the south-western continental shelf of India, only those off Karwar and Taingapatnam have been dated[6–8]. Moreover, ages of different layers in a single core, which are necessary to determine long-term sedimentation rate, are lacking from the south-western inner shelf of India. In this paper we present new ^{14}C data for carbonized wood/peat layers and organic matter in sediment cores off Karwar and Honnavar (Figure 1). We have used these radiocarbon ages to understand Late Quaternary changes in sedimentation rate and sea level along the south-west coast of India. Two sediment cores, SK-148/13 and SK-148/14, were raised from the inner shelf off Karnataka (Figure 1) during the 148th cruise of ORV *Sagar Kanya*. The locations and other details of the cores are shown in Figure 1 and Table 1. The cores were sub-sampled at 1 cm interval in order to get radiocarbon dates of sharply-defined depth intervals.

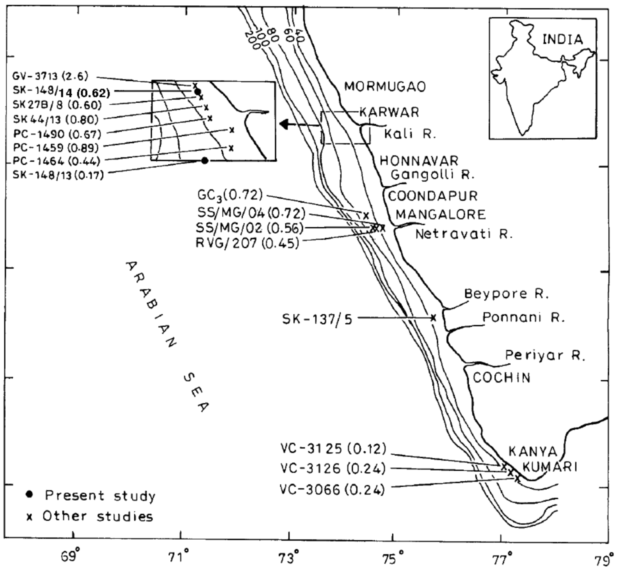

Figure 1. Map showing the location of cores used in this study (SK-148/13 and SK-148/14) and those referred to in the text. Bathymetic contours are in metres and sedimentation rates (in parentheses) in mm/yr.

Core SK-148/13 (Figure 2) is composed broadly of three litho-units: calcareous sand (0–199 cm), carbonized wood/peat (199–222 cm) and clay (222–486 cm). The first litho-unit consists predominantly of calcareous sands (50–80 wt%) up to 153 cm depth, with abundant shell fragments. Below 153 cm depth, the calcareous sand content decreases through 20–40 wt% (153–191 cm) to < 10 wt% (191–195 cm) and is absent at 199 cm depth. This litho-unit contains a two-cm thick carbonized wood/peat layer at 167–169 cm depth.

The second litho-unit (199–222 cm) mainly consists of carbonized wood/peat, with intercalation of clay from 208 to 218 cm.

The third litho-unit (222–486 cm) of clay has two zones: (a) black clay (222–276 cm) that is enriched with fine organic material and rootlets; and (b) sticky clay (276–486 cm).

Core SK-148/14 (Figure 2) is composed primarily of clayey material. It may be demarcated into three zones: (a) Dark-green clay (0–68 cm) with several layers of shell pieces; (b) sticky clay (68–193 cm) with intercalation of

Table 1. Details of sediment cores, type of material dated and radiocarbon ages

Core no. (core length)	Location (water depth)	Sub-sample no.	Depth in core (cm)	Material dated	Measured ^{14}C age[a] (yr BP)	Calibrated age[b]
SK-148/13 (466 cm)	14.4°N; 74°E (50 m)	PRL-2096	167–169	Carbonized wood/peat	9790 ± 120	BC 8360 (8330) 7970
		PRL-2097	199–200	Carbonized wood/peat	9990 ± 120	BC 8655 (8375) 8330
		PRL-2098	220–222	Carbonized wood/peat	10,010 ± 120	BC 8675 (8380) 8340
		PRL-2099	272–274	Sediment enriched with black, fine organic material	10,760 ± 130	BC 9955 (9410) 8925
SK-148/14 (537 cm)	14.84°N; 74°E (22 m)	PRL-2100	258–259	Organic matter in sediment	4190 ± 110	BC 2300 (2140) 1990
		PRL-2101	535–536	Pieces of peat and fine organic matter-enriched sediment	9280 ± 150	BC 7885 (7670) 7200

[a]Based on half-life ($t_{1/2}$) of 5730 years for ^{14}C; [b]Calibrated ages are at 1σ (one standard deviation) level and are written in the following format: Maximum (cal. age) minimum.
Organic carbon present in peat and organic matter in sediments was radiocarbon-dated by liquid scintillation spectrometry. The organic carbon was converted to benzene. Preparation of benzene, ^{14}C detection and other details of the method followed are described elsewhere[33]. Radiocarbon activity of benzene was detected and registered in a LKB-Quantulus ultra-low level detector. The ages estimated from ^{14}C activity measurements (conventional radiocarbon ages) were converted to calibrated ages using the CALIB 4.0 computer program based on INTCAL98 data[34].

shell pieces at different depths. In fact, shell pieces constitute ~ 90% of the sediment in the 190–193 cm interval; and (c) sticky and compact clay (193–537 cm), also interspersed with shell pieces, and pieces of carbonized wood/peat with fine organic material in the 530–536 cm zone.

Carbonized wood/peat deposits in marine sediments are indicators of extremely shallow water conditions and of palaeo-coastline. Mangroves are the most common producers of peat in coastal regions. Mangrove peat generally occurs in the inter-tidal zone. Hence, they are directly related to the sea level at the time of their formation. The radiocarbon dates of peat beds may be used to find out the time of marine transgression. Carbonized wood/peat layers occur at several depth intervals of the cores studied. For this, it is important that they satisfy the condition of having formed *in situ* to qualify as good candidates for studying changes in sea level and palaeo-coastline. We list below some features which indicate that the peat layers indeed formed *in situ*:

(1) Reports of extensive peat layers (a few cm to 0.6 m thick) in sediment cores from all along the SW continental shelf of India[4,6–10].

(2) Occurrence of peat of the same age at similar depths in cores that are as much as ~ 300 km apart from the SW continental shelf: at 318–323 cm in core SK-137/5 (unpublished data) and at 312–320 cm in core VC-3126 (ref. 8).

(3) Fibrous nature of the peat and the occurrence of numerous rootlets.

(4) Stratigraphically correct positions of the different peat layers in sediment cores which is also confirmed by ^{14}C dates obtained on organic matter in sediments from above/below the peat layers (see the following section).

(5) Occurrence of peat (in core SK-148/13) below relict sand/palaeo-beach sand[4,8,9] that formed during the Pleistocene low stand of sea level may indicate that the peat formed *in situ* in marsh/protected environment during Late Pleistocene.

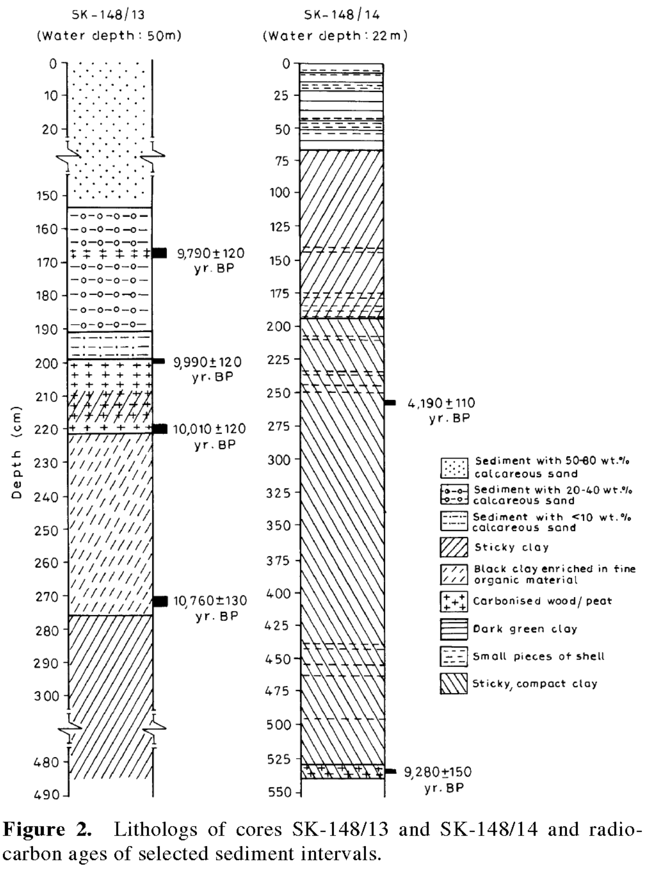

Figure 2. Lithologs of cores SK-148/13 and SK-148/14 and radiocarbon ages of selected sediment intervals.

The ^{14}C ages of the dated materials from core SK-148/13 range from 10,760 ± 130 to 9790 ± 120 yr BP (Late Pleistocene–Early Holocene; Table 1). The 535–537 cm layer of core SK-148/14 has an age of 9280 ± 150 yr BP, which corresponds to Early Holocene. This date suggests that the entire sequence of clay in core SK-148/14 was deposited during Early Holocene. In tune with this pattern of sedimentation, the 258–259 cm interval has a ^{14}C age of 4190 ± 110 yr BP.

Based on these radiocarbon ages, we discuss below changes in sedimentation rate and sea level in the SW continental shelf coast of India.

Figure 3 *a* is a plot of ^{14}C age versus depth for core SK-148/13. Peat occurs at three depths in this core (167–169 cm, 199–200 cm and 220–222 cm). The texture of sediments that occur between the peat layers is nearly uniform. Assuming uniform sedimentation between the dated layers, the sedimentation rate works out to 1.6, 11 and 0.69 mm/yr, respectively for the time slices 9790–9990 yr BP, 9990–10,010 yr BP and 10,010–10,760 yr BP. The pre-10,760 yr BP sediment (below 274 cm) is sticky clay that extends up to the bottom of the core. Hence, a sedimentation rate of 0.69 mm/yr could be tentatively assigned to the rest of the core, as no datable material was found below 274 cm depth. A sedimentation rate of 0.17 mm/yr is obtained by extrapolating the data to the origin in Figure 3 *a*. However, the sediment corresponding to this interval is relict sand that has been dated to 9000–11,000 yr BP, by several workers[1–3]. The sedimentation rate during the Pleistocene–Holocene transition period (11 mm/yr) is 6–7 times high when compared to Early Holocene (1.6 mm/yr; Figure 3 *a*). Higher sedimentation rates have been reported for the nearby Laccadive Trough also for the transition period, when compared to Holocene[11].

The two radiocarbon dates for core SK-148/14 yield sedimentation rates of 0.62 and 0.54 mm/yr, respectively for the periods 4190 yr BP-present and 9280–4190 yr BP (Figure 3 *b*). The uniform character of sediment in this core suggests constant sedimentation between the dated layers and up to the core top. The two rates are more or less uniform and the slope of the regression line passing through the points (Figure 3 *b*) provides an average sedimentation rate of 0.58 mm/yr for Holocene.

Some features of the spatial variations in sedimentation rate on the SW continental shelf of India are:

(1) The sedimentation rate of 0.62 mm/yr at 22 m water depth off Karwar is comparable to that reported for two cores raised from almost the same location[12] (Figure 1; Table 2). It is also comparable to the sedimentation rate reported for 34 m water depth off Karwar[6] and for 41 m water depth off Mangalore[13]. However, the higher sedimentation rates of Caratini *et al.*[12] based on the ages of deeper layers in core SK-27B/8 may be due to the inverse ^{14}C ages obtained for that core (Table 2). A much higher sedimentation rate of 2.6 mm/yr at 20 m water depth off Karwar has been reported[14]. This may be because the core[14] is located close to the Kali river mouth.

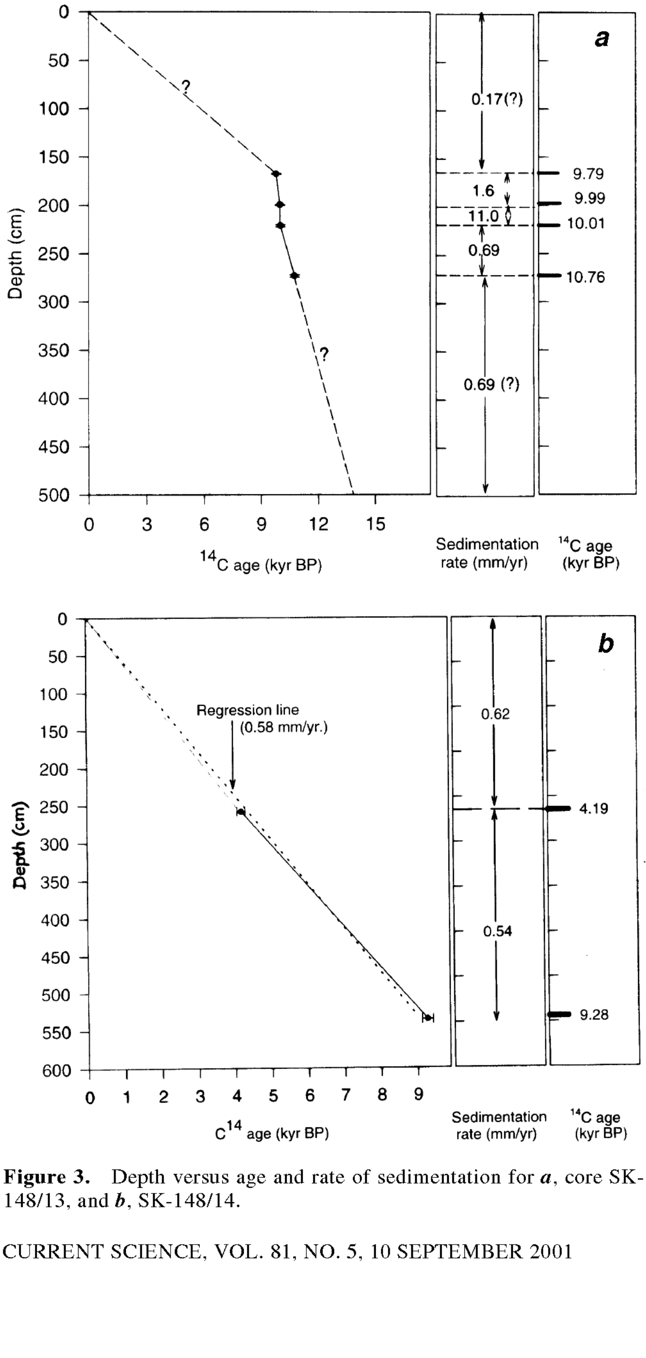

Figure 3. Depth versus age and rate of sedimentation for ***a***, core SK-148/13, and ***b***, SK-148/14.

(2) It appears that sedimentation rate is also controlled by proximity to the river mouth: Cores GV 3713, SK-148/14, SK-27B/8 and SK-44/13, that are located near the Kali river mouth, have recorded relatively higher rates of sedimentation (Table 2). In fact core PC-1490, which is comparatively closer to the Kali river mouth, has recorded a higher sedimentation rate of 0.67 mm/yr in spite of its location in deeper water depths, when compared to 0.44 mm/yr recorded by core PC-1464.

(3) Sedimentation rate seems to decrease in the offshore direction. In the cores studied by us, the sedimentation rate decreases offshore from 0.62 mm/yr at 22 m water depth to 0.17 mm/yr at 50 m water depth. Off Karwar, cores from shallow water depths (17.7–20 m) have documented higher sedimentation rates (2.6–0.89 mm/yr) than those from greater water depths (Table 2). This decrease is understandably due to the waning terrigenous influx with increasing distance from the coastline. On the outer shelf, there is hardly any sedimentation[4,15]. This has been attributed[4,17] to the negligible amount of sediment delivered by the west-flowing rivers, entrapment of sediments by the estuaries, landward transport of coastal sediment, etc.

(4) There also appears to be a north–south trend in sedimentation rate on the SW continental shelf of India. At ~ 22 m water depth, the sedimentation rate decreases from 0.62 mm/yr off Karwar to 0.12–0.24 mm/yr off Taingapatnam[8]. However, a similar trend is not discernible for ~ 40–50 m water depth off Mulki[16] and Mangalore[13,17] because these sediment cores are located off the Mulki–Pavanje and Netravati–Gurpur rivers. A southerly decrease in sedimentation rate has also been reported for the western continental shelf of India[17]. This has been attributed to differences in the discharge and suspended particulate matter concentrations of rivers in the northern and southern sectors of the west coast of India.

The sedimentation rate in the area of study has changed temporally also. The sedimentation rate during the Pleistocene–Holocene transition period (11 mm/yr; Figure 3 *a*) is 6–7 times high when compared to Early Holocene (1.6 mm/yr; Figure 3 *a*). The high sedimentation rate of 11 mm/yr during Late Pleistocene–Early Holocene may be related to the input of higher sediment quantities during this period. This may be related to relatively higher rates of weathering and erosion in the hinterland as a result of high rainfall. A more intense SW monsoon during Late Pleistocene–Early Holocene has been suggested by several workers[18–23]. Higher sedimentation rates in the Laccadive Trough during the transition period when compared to Holocene has been attributed to sediment slump or turbidite emplacement[11]. The sedimentation rate decreased from 1.6 mm/yr during Early Holocene, i.e. 9990–9790 yr BP (Figure 3 *a*) to 0.58 mm/yr in the post-9280 yr BP period.

The occurrence of different litho-units in the cores (Figure 2) may be explained in terms of Late Pleistocene–

Table 2. Rate of sedimentation on the south-western continental shelf of India

Area	Water depth (m)	Core no.	Depth in core (cm)	Material dated	Dating technique	Age (yr BP)	Sedimentation rate (mm/yr) (during the period)	Reference
Off Karwar	20	GV 3713		Sediment	Excess ^{210}Pb		2.60	13
	22	SK-148/14	258–259	Organic matter in sediment	^{14}C	4190 ± 110	0.62 (4190 yr BP to present)	Present study
			535–536	Pieces of peat and organic matter in sediment	^{14}C	9280 ± 150	0.54 (9280–4190 yr BP)	
	22	SK-27B/8	130–135	Organic matter in sediment	^{14}C	2220 ± 40	0.60 (2220 yr BP to present)	14
			140–145	Organic matter in sediment	^{14}C	2020 ± 40	0.70 (2020 yr BP to present)	
			225–230	Shell	^{14}C	2220 ± 70	1.02 (2220 yr BP to present)	
			300–305	Organic matter in sediment	^{14}C	3510 ± 60	0.86 (3510 yr BP to present)	
			445–450	Organic matter in sediment	^{14}C	4325 ± 65	1.03 (4325 yr BP to present)	
	25	SK-44/13	300–304	Organic matter in sediment	^{14}C	3780 ± 210	0.80 (3780 yr BP to present)	
			450–455	Organic matter in sediment	^{14}C	6370 ± 170	0.58 (6370–3780 yr BP)	
			455–460	Organic matter in sediment	^{14}C	6200 ± 90	0.73 (6200 yr BP to present)	
	33.7	PC-1490	578–580	Carbonized wood	^{14}C	8620 ± 300	0.67 (8620 yr BP to present)	6
	17.7	PC-1459	302–310	Shell	^{14}C	3410 ± 90	0.89 (3410 yr BP to present)	
	25	PC-1464	420–438	Carbonized wood	^{14}C	9630 ± 120	0.44 (9630 yr BP to present)	
Off Honnavar	50	SK-148/13	167–169	Carbonized wood/ peat	^{14}C	9790 ± 120	0.17 (9790 yr BP to present)	Present study
			199–200	Carbonized wood/ peat	^{14}C	9990 ± 120	1.60 (9990–9790 yr BP)	
			220–222	Carbonized wood/ peat	^{14}C	10,010 ± 120	11.0 (10,010–9990 yr BP)	
			272–274	Organic matter in sediment	^{14}C	10,760 ± 130	0.69 (10,760–10,010 yr BP)	
Off Mulki	50	GC_3	0–9	Sediment	Excess ^{210}Pb		0.72	16
Off Mangalore	45	SS/MG/02	0–7	Sediment	Excess ^{210}Pb		0.56	17
	35	SS/MG/04	0–6	Sediment	Excess ^{210}Pb		0.72	
	41	RVG/207/	50–60	Organic matter in sediment	^{14}C	1330 ± 80	0.45 (1330 yr BP to present)	13
			90–100	Organic matter in sediment	^{14}C	2090 ± 80	0.53 (2090–1330 yr BP)	
Off Taingapatnam	21	VC-3066	224–240	Carbonized wood	^{14}C	9390 ± 150	0.24 (9390 yr BP to present)	8
	21	VC-3125	107–117	Carbonized wood	^{14}C	8850 ± 140	0.12 (8850 yr BP to present)	
	22	VC-3126	312–320	Carbonized wood	^{14}C	8420 ± 160	0.24 (8420 yr BP to present)	
			340–350	Carbonized wood	^{14}C	8750 ± 130	0.88 (8750–8420 yr BP)	

Table 3. Onshore peat and shell deposits and their ^{14}C ages along the west coast of India

Location	Depth below surface (m)	Material dated	^{14}C age (yr BP)	Reference
Colva, Goa	6.5	Peat	6430 ± 110	28
Idythra (near Baindur), Karnataka	5.5	Sediment with peat material	6430 ± 120	
		Shells	6410 ± 110	29
Payyanur, Kerala	~ 2.0	Lime shell	4370 ± 100	
			4490 ± 90	
Tellicherry, Kerala	2.0	Peat	7230 ± 120	
Tannisseri (Irinjalakuda), Kerala	2.0	Peat	6420 ± 120	30
Muhamma (Vembanad Lake), Kerala	~ 2.0	Lime shell	3130 ± 100	
Vechur (Vembanad Lake), Kerala	~ 2.0	Lime shell	3710 ± 90	
Wellington Island, Kerala	16.75	Peat	8080	31
Iranimangalam (Changanacherry), Kerala	–	Peat	7050	32

Early Holocene transgression. The sticky clay and peat layers were deposited when the coring site had a marshy environment during Late Pleistocene–Early Holocene, as indicated by the ^{14}C dates. There are several examples of similar occurrences of marsh deposits in the western continental shelf of India[4,6–10,24] and elsewhere too[25]. As the sea level rose due to the Pleistocene–Holocene transgression, the coastal mangroves were submerged, giving rise to carbonized wood/peat deposits. Simultaneously, the marshy environment changed to beach environment, which is recorded in the form of increasing calcareous sand content in the top of core SK-148/13. With a further rise in sea level during Early Holocene, the beach conditions changed to inner shelf conditions when clayey sediments, as recorded in core SK-148/14, were deposited. The radiocarbon ages of peat layers (Table 2) show that the present inner shelf that was subaerially exposed during Late Pleistocene was inundated by the sea during Early Holocene (8400–10,000 yr BP).

The widespread occurrence of peat in the inner shelf sediment cores shows that peat formation was a regional phenomenon along the south-west coast of India during Late Pleistocene–Early Holocene. Age data indicate that there was a luxuriant growth of vegetation in the area during Late Pleistocene–Early Holocene. Oxygen isotope/ pollen records from a core off the SW coast of India[19] have revealed that there was maximum mangrove vegetation and rainfall around 11,000 yr BP in the region, when the sea level was much lower.

Core SK-148/13, from a water depth of 50 m, is ~ 45 km seaward of the present coastline. This indicates that the sea level was at least 50 m below the present level during Late Pleistocene–Early Holocene. Sea level curve for the west coast of India[26] also shows that the sea level was much lower (by 60–70 m) 10,000 years ago and that there was a steep rise in the sea level during 10,000–8000 yr BP. The eustatic sea level rise was rapid (23 m/1000 years) during 10,000–9000 yr BP[27]. The sea level curve by Fairbanks[27], which is widely used as a reference curve, reveals that the eustatic sea level was at – 90, – 65, – 40 and – 30 m during 12,000, 10,400, 9200 and 8340 yr BP, respectively. Our data on sea level are in tandem with the eustatic sea level curve.

There are reports of peat deposits from various onshore locations which are up to 0.5 km landward of the present-day high tide line along the south-west coast of India (Table 3). Their ^{14}C ages[28–32] range from 8000 to 6400 yr BP, indicating that the sea level was much higher than the present level during that period. During the period of higher sea level, the coastal vegetation was inundated to give rise to onshore peat deposits. Most of the onshore peat deposits are overlain by calcareous sand[28–30], which represents a regression event. These calcareous shell deposits, dated to 5000–3000 yr BP, were formed by the accumulation of shells after the organisms were trapped in their ecological habitats which were destroyed by regression[29]. These observations reveal that after 6400 yr BP, the sea level receded and stabilized at the present level.

Sedimentation rates in the study area are controlled by terrigenous input, proximity to river mouths and distance from coastline. The present-day sedimentation on the outer shelf is negligible. Very high sedimentation rate during Late Pleistocene–Early Holocene may be due to relatively higher rates of weathering and erosion in the adjacent hinterland as a result of high rainfall, resulting in higher input of sediment to the inner shelf region. The sea level was much lower during Late Pleistocene–Early Holocene, when there was maximum mangrove vegetation along the SW coast of India. The Holocene transgression resulted in the formation of the present-day onshore and offshore peat deposits.

1. Hashimi, N. H., Kidwai, R. M. and Nair, R. R., *Indian J. Mar. Sci.*, 1978, **7**, 231–238.
2. Nair, R. R., Hashimi, N. H. and Gupta, M. V. S., *J. Geol. Soc. India*, 1979, **20**, 16–18.
3. Nair, R. R., *Proc. Indian Acad. Sci.*, 1974, **79**, 197–203.
4. Shankar, R. and Karbassi, A. R., *J. Geol. Soc. India*, 1992, **40**, 241–252.
5. Merh, S. S., *Proc. Indian Natl. Sci. Acad.*, 1992, **58**, 461–472.
6. Nambiar, A. R., Rajagopalan, G. and Rao, B. R. J., *Curr. Sci.*, 1991, **61**, 353–354.
7. Nigam, R., Report submitted to DST, New Delhi, 1991, p. 78.
8. Nambiar, A. R. and Rajagopalan, G., *Curr. Sci.*, 1995, **68**, 1133–1137.
9. Rajan, T. N., Ramachandran, K. V. and Michael, G. P., Vol. of Abstr., National Seminar on Recent Geoscientific Studies in the Arabian Sea off India, Geol. Surv. of India, Marine Wing, Mangalore, 1987, p. 72.
10. Mascarenhas, A., Paropakari, A. L. and Prakash Babu, C., *Curr. Sci.*, 1993, **64**, 684–687.
11. Shankar, R. and Manjunatha, B. R., *J. Geol. Soc. India*, 1995, **45**, 689–694.
12. Caratini, C., Bentaleb, I., Fontugne, M., Morzadec-Kerfourn, M. T., Pascal, J. P. and Tissot, C., *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 1994, **109**, 371–384.
13. Pandarinath, K., Narayana, A. C. and Yadava, M. G., *Curr. Sci.*, 1998, **75**, 730–732.
14. Nigam, R., Khare, N. and Nair, R. R., *J. Coast. Res.*, 1995, **11**, 1099–1107.
15. Rao, P. C. and Wagle, B. G., *Curr. Sci.*, 1997, **73**, 330–350.
16. Karbassi, A. R., Ph. D. thesis (Unpubl.), Mangalore University, 1989, p. 96.
17. Manjunatha, B. R. and Shankar, R., *Mar. Geol.*, 1992, **104**, 219–224.
18. Van Campo, E., Duplessy, J. C. and Rossignol-Strick, M., *Nature*, 1982, **296**, 56–59.
19. Van Campo, E., *Quat. Res.*, 1986, **26**, 376–388.
20. Prell, W. L., Marvil, R. E. and Luther, M. E., *Paleoceanography*, 1990, **5**, 447–457.
21. Naidu, P. D. and Malmgren, B. A., *Paleoceanography*, 1996, **11**, 129–140.
22. Rajagopalan, G., Sukumar, R., Ramesh, R., Pant, R. K. and Rajagopalan, G., *Curr. Sci.*, 1997, **73**, 60–63.
23. Naidu, P. D., *J. Geol. Soc. India*, 1998, **52**, 257–272.
24. Manjunatha, B. R. and Shankar, R., Vol. of Abstr., Joint Oceanogr. Assembly, Acapulco, Mexico, 1988, p. 65.

25. Monteillet, J. and Evin, J., *Bull. Assoc. Senegal. Etud. Quat.*, 1977, **50**, 23–29.
26. Hashimi, N. H., Nigam, R., Nair, R. R. and Rajagopalan, G., *J. Geol. Soc. India*, 1995, **46**, 157–162.
27. Fairbanks, R. G., *Nature*, 1989, **342**, 637–642.
28. Kale, V. S. and Rajaguru, S. N., *Curr. Sci.*, 1983, **52**, 778–779.
29. Caratini, C. and Rajagopalan, G., *Indian J. Mar. Sci.*, 1992, **21**, 149–151.
30. Rajendran, C. P., Rajagopalan, G. and Narayanaswamy, *J. Geol. Soc. India*, 1989, **33**, 218–222.
31. Agarwal, D. P., Gupta, S. K. and Kusumgar, S., *Curr. Sci.*, 1970, **30**, 219–222.
32. Powar, S. D., Venkataramana, B., Mathai, T. and Mallikarjuna, C., Progress Report (unpublished), Geol. Surv. of India, Thiruvananthapuram.
33. Yadava, M. G. and Ramesh, R., *J. Sci. Ind. Res.*, 1999, **58**, 339–348.
34. Stuiver, M. *et al.*, *Radiocarbon*, 1998, **40**, 1041–1083.

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Seismically-induced soft-sediment deformational structures around Khalsar in the Shyok Valley, northern Ladakh and eastern Karakoram, India

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Soft-sediment deformation structures occur in the ~ 150 m thick Pliocene–Quaternary fluvio-lacustrine sediments exposed around Khalsar and Tirit area in the Shyok Valley, eastern Karakoram, India. Occurring at different stratigraphic horizons, these structures vary in morphology and pattern and satisfy criteria for correlating with seismic events. The deformation structures are thus interpreted as resulting from earthquake-induced liquefaction that happened at ~ 5 Ma and were associated with the tectonic activity along the Karakoram Fault.

THE various deformation structures attributed to seismic activity include ball-and-pillow[1], pseudo-nodules or cycloids[2], pinch-and-swell bedding and lenticular boudins, pocket and pillar structures[3], flame-like structures[4] and sedimentary dykes. The soft-sediment deformational structures involving escape of pore fluids in fine sediments are linked to seismic shocks[5,6]. These structures play an important role in identifying the distribution and intensity of ancient tectonic activity[7].

The continued post-collisional convergence of the Indian plate and the Asian landmass causes intense seismicity[8,9] and attendant topographic changes in the Himalaya and the Tibetan Plateau. The 2500-km long east-west trending Himalaya is cut by several major north dipping thrusts, such as the Main Boundary Thrust (MBT) and the Main Central Thrust (MCT)[9] (Figure 1). In the extreme north-west lies the seismically active knot of the Hindukush, the Karakoram and the Pamir (Figure 1). Seismological studies in the Hindukush show that earthquakes of intermediate depth are abundant at depths between 70 and 300 km[10]. The usually high *P*- and *S*-wave velocities observed, indicate that the lithospheric material is being subducted beneath the Hindukush range[10]. While there is some palaeoseismite-documentation of historic and prehistoric earthquakes in the Himalayan region[11–13], no such records of pre-historic earthquakes are available from northern Ladakh and eastern Karakoram. Studies carried out in the belt of the Altyn Tagh Fault (Figure 1) by Molnar *et al.*[8], Peltzer *et al.*[14] and Avouac and Tapponnier[15] show that two earthquakes of magnitude 7.2 occurred in 1924 near the western end of the fault and one earthquake of magnitude 6 occurred near its eastern end in 1951 (ref. 16).

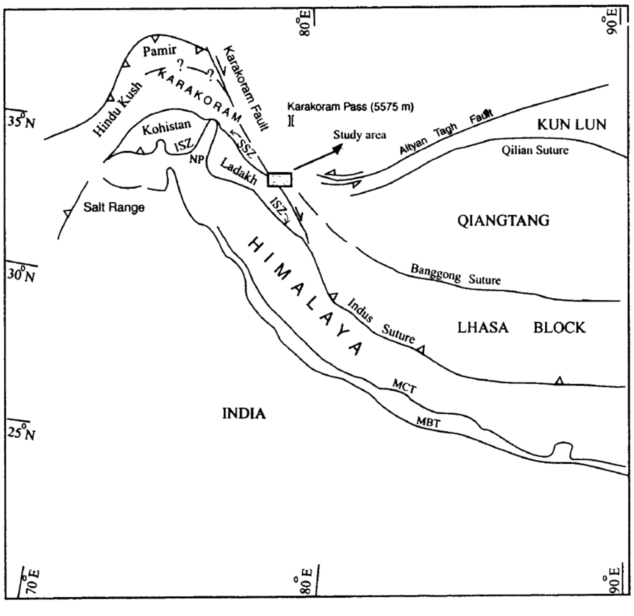

Figure 1. Simplified tectonic sketch map of Central Asia (modified after Searle[20]). Shaded box, Study area; SSZ, Shyok Suture Zone; ISZ, Indus Suture Zone; MCT, Main Central Thrust; MBT, Main Boundary Thrust; NP, Nanga Parbat.

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