First results from the PRL Accelerator Mass Spectrometer

Accelerator mass spectrometry is a highly sensitive technique developed nearly four decades ago primarily for the measurement of cosmogenic radionuclides with half-lives exceeding a few hundreds of years. Long-lived isotopes having low abundance are not detectable by radiometric counter and sensitivity of the commonly used mass spectrometer is low. Therefore, long-lived isotopes with low abundance were not detectable. Advantage of the above-mentioned technique is that nuclides in the ionic state achieve high energies and hence stripping of multiple electrons is possible. This is used to reduce the isobaric and molecular interference considerably, permitting identification and measurement of isotopes with very low natural abundance (10^{-10} to 10^{-16}) such as ^{14}C (half-life = 5730 yrs), ^{10}Be (1.51 Myr) and ^{26}Al (0.705 Myr) (ref. 1). A much reduced analysis time[2] and very small amount of sample are the additional advantages gained in the method, opening new avenues of research in earth sciences, viz. carbon sequestration, climate change, geo- and biosciences.

A new generation, compact 1 MeV Accelerator Mass Spectrometer (AMS) designed for the measurement of ^{14}C, ^{10}Be and ^{26}Al (Figure 1) has been installed at the Physical Research Laboratory (PRL), Ahmedabad, India. This facility has been acronymed as PRL-AURiS (Physical Research Laboratory-Accelerator Unit for Radioisotope Studies), manufactured by High Voltage Engineering Europa B.V. (HVEE), the Netherlands. The facility comprises (a) ion source, (b) low energy mass spectrometer, (c) 1 MeV Tandetron, (d) high energy mass spectrometer, (e) 120° electrostatic analyser (ESA), (f) low background magnet and (g) gas ionization detector for the measurement of rare isotopes. AURiS has been tuned to the desired precision and background for the measurement of ^{14}C, ^{10}Be and ^{26}Al. To ascertain the quality assurance and ensure the laboratory procedures, radiocarbon samples supplied as part of the International Radiocarbon Intercomparison exercise were measured with AURiS[3,4] (Table 1). Results show good agreement with the reported consensus values[3,4], proving authenticity of the radiocarbon measurement procedures followed at AURiS and demonstrate its ability to provide reliable results.

At AURiS high-resolution chronology of northern Andaman marine sediment core using radiocarbon dating on selected foraminiferal species was developed[5,6]. The sediment core: SK/304B-18 (12°35.022′N; 93°52.127′E, core length ~2 m) was collected in 2013 from a water depth of 2332 m on-board *ORV Sagar Kanya* during the cruise SK/304 (Figure 2). The Andaman Sea receives freshwater influx primarily from Irrawaddy River with an annual discharge of 428 km^3 from the catchment mainly during Indian summer monsoon[7]. Several studies covering late Quaternary period for deciphering sediment provenance and climate perturbation have been undertaken earlier, however, with a minimal

Table 1. AURiS results of reference standards obtained during international intercomparison programmes[3,4]. Errors quoted are standard error of mean at 1σ level estimated based on five runs of each sample

Reference	Unit	Consensus ^{14}C value	PRL-AURiS ^{14}C value*
IAEA-C1	pMC	0.00 ± 0.02	0.06 ± 0.01
IAEA-C2	pMC	41.14 ± 0.03	41.92 ± 0.21
FIRI-E	BP (yr)	11780 ± 7	11600 ± 50
VIRI-U	pMC	23.07 ± 0.02	22.78 ± 0.07

IAEA-C1 and IAEA-C2, Carbonate; FIRI-E and VIRI-U, Humic acid.
*AURiS values are based on 4 or 5 runs.

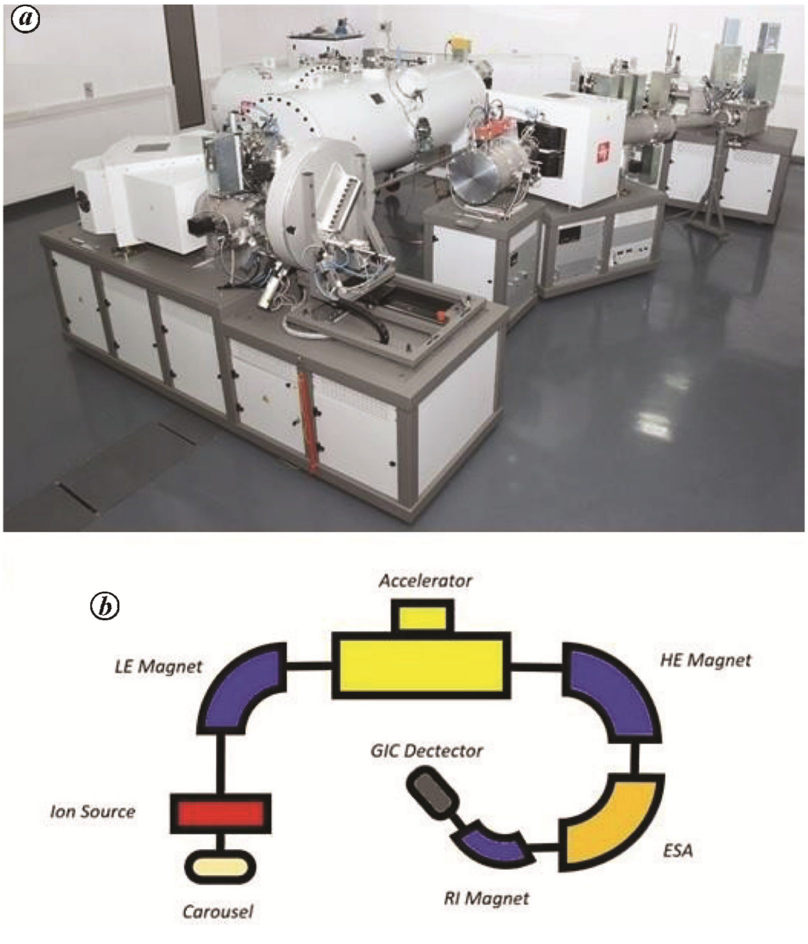

Figure 1. ***a***, Photograph of Accelerator Mass Spectrometer (AMS) facility at PRL, Ahmedabad; ***b***, Schematic of the PRL-AURiS.

Table 2. Calibrated radiocarbon ages and sedimentation rates obtained for the Andaman Sea sediment core SK-304/18. Measurement was done at +2 charge state

Sample ID	Depth (cm)	Lab ID	^{13}C beam current range ($\times 10^{-7}$ A)	^{14}C/^{13}C ($\times 10^{-11}$)	σ ^{14}C/^{13}C ($\times 10^{-11}$)	Radiocarbon age (yrs BP)	Calibrated age range (cal yrs BP)	Sedimentation rate (cm/kyr)
SK-304/18-1	8.5	AURIS-00053	2.34–3.62	8.83028	0.02760	979 ± 32	500–640	–
SK-304/18-2	19	AURIS-00054	2.16–3.05	8.20652	0.06017	1555 ± 62	950–1250	20
SK-304/18-3	38.5	AURIS-00055	2.60–3.30	7.56635	0.04145	2214 ± 48	1640–1940	28
SK-304/18-4	59	AURIS-00056	2.69–3.15	6.69162	0.03641	3204 ± 48	2830–3160	17
SK-304/18-5	79	AURIS-00057	1.93–3.20	5.60005	0.03859	4644 ± 40	4640–5040	11
SK-304/18-6	99	AURIS-00058	3.07–3.60	5.07079	0.02133	5443 ± 40	5670–5910	21
SK-304/18-7	138.5	AURIS-00059	2.39–3.16	4.51612	0.01860	6358 ± 39	6670–6940	39
SK-304/18-8	159	AURIS-00060	2.88–3.04	4.12530	0.04389	7108 ± 88	7410–7760	27

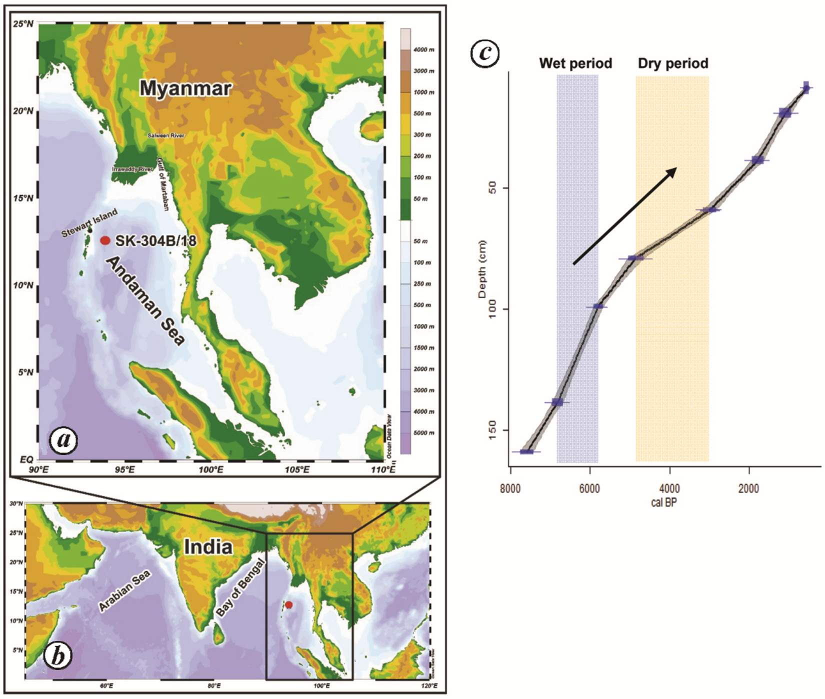

Figure 2. ***a***, ***b***, Sediment core location of SK-304B/18 in the northern Andaman Sea. ***c***, Age–depth plot using linear interpolation model showing wet and dry periods.

focus on Holocene climate and estimation of sedimentation rates. Planktonic forams >150 μm in size were handpicked from the sediment core for depths between 6 and 160 cm. The foram samples were hydrolysed to CO_2 with 85% phosphoric acid and converted to graphite in the presence of hydrogen with iron as a catalyst at 600°C using AGE3 Graphitization system[8,9]. Isotopic ratio of sample carbon $^{14}C/^{13}C$ was estimated at AURiS. Radiocarbon ages were estimated following the expressions and approaches as described in Donahue *et al.*[10] and Burr *et al.*[11]. The $\delta^{13}C$ values of foram samples were calculated using measured values of sample $^{13}C/^{12}C$ and required fractionation corrections as inferred from several runs of oxalic-II standard (known to have $\delta^{13}C$ value of –17.8‰)[12]. Radiocarbon ages thus obtained were calibrated using Calib 7.1 (refs 13, 14) with a reservoir age correction ΔR as 12 ± 34 years, a value applicable for Steward Island near northern Andaman Sea[15]. Table 2 shows the radiocarbon age of the foraminifera samples and the respective calibration age range (1σ) along with median calibration age values.

The calibrated ages showed increasing age with depth. Sedimentation rate was determined using a linear interpolation age–depth model of the clam software that uses Monte Carlo sampling of calibrated age distribution[16]. Calendar age point estimates for depths were taken as weighted average of all age–depth curves (Figure 2).

The estimated sedimentation rates were found to vary between 11 and 39 cm/kyr, with the lowest sedimentation rate during 2995–4770 cal yrs BP and maximum sedimentation rate during 5800–6745 cal yrs BP. Low sedimentation rate can be attributed to reduced detrital influx due to weakened monsoonal activity, while enhanced monsoonal activity can be ascribed to high sedimentation rates. The high sedimentation rate of 39 cm/kyr between 5800 and 6744 cal yrs BP resulted as function of monsoon intensification triggering high terrestrial flux in the region. This period of high sedimentation is known for warm climate and has been termed as Holocene megathermal maxima (HMM). HMM has been identified based on various proxy data from the Arabian Sea and Bay of Bengal[17–19]. A gradual shift in climate from wetter to drier conditions from 10000 to 4000 yrs in the Bay of Bengal has been ascribed to gradual weakening of summer monsoon[20]. Subsequently, drier conditions with increased aridity between 4000 and 1700 cal yrs BP have been attributed to reduced summer monsoon[20] from which low sedimentation rates between 2995 and 4770 cal yrs BP have been identified for the northern Andaman Sea sediment core. A multiproxy approach on a sediment core retrieved from the northern Andaman Sea near Landfall Island demonstrated intensification of Indian Summer Monsoon (ISM) during 6400 cal yrs BP, while dry climate prevailed since 3200 cal yrs BP (ref. 21). On the basis of oxygen isotopic studies on foraminifera from the sediment core of Andaman Sea, depleted $\delta^{18}O$ of sea water during early Holocene (11.5–5.5 ka) has been observed than at present, which has been interpreted as the wettest period during the last 25 ka as a result of ISM strengthening[22].

The present study suggests that change in sedimentation in the northern Andaman Sea is a function of changing monsoonal activity and the detrital influence, whereas a previous study has shown that the overhead productivity and upwelling events persist as a result of winter monsoon and winds[22]. Further analysis and detailed multiproxy approach will provide a good platform to decipher the effects of summer and winter monsoons on the Andaman Sea basin during the Holocene.

1. Tuniz, C., *Radiat. Phys. Chem.*, 2001, **61**, 317–322.
2. Larsson, M., *Mass Spectrom. Rev.*, 2008, **27**, 397.
3. Scott, E. M., Cook, G. T. and Naysmith, P., *Radiocarbon*, 2010, **52**, 859–865.
4. Rozanski, K. *et al.*, *Radiocarbon*, 2006, **34**, 506–519.
5. Broecker, W., Mix, A., Andree, M. and Oeschger, H., *Nucl. Instrum. Methods Phys. Res. Sect. B*, 1984, **5**, 331–339.
6. Heier-Nielsen, S. *et al.*, *Radiocarbon*, 1995, **37**, 119–130.
7. Milliman, J. D. and Meade, R. H., *J. Geol.*, 1983, **91**(1), 1–21.
8. Wacker, L., Němec, M. and Bourquin, J., *Nucl. Instrum. Methods Phys. Res. Sect. B.*, 2010, **268**, 931–934.
9. Wacker, L., Fülöp, R. H., Hajdas, I., Molnár, M. and Rethemeyer, J., *Nucl. Instrum. Methods Phys. Res. Sect. B*, 2013, **294**, 214–217.
10. Donahue, D. J., Linick1, T. W. and Dull, A. J. T., *Radiocarbon*, 1990, **32**, 135–142.
11. Burr, G. S. *et al.*, *Nucl. Instrum. Methods Phys. Res. Sect. B*, 2007, **259**, 149–153.
12. Mann, W. B., *Radiocarbon*, 1983, **25**, 519–527.
13. Stuiver, M., Reimer, P. J. and Braziunas, T. F., *Radiocarbon*, 1998, **40**, 1127–1151.
14. Reimer, P. J. *et al.*, *Radiocarbon*, 2013, **55**, 1869–1887.
15. Dutta, K., Bhushan, R. and Somayajulu, B. L. K., *Radiocarbon*, 2001, **43**, 483–488.
16. Blaauw, M., *Quat. Geochronol.*, 2010, **5**, 512–518.
17. Prell, W. L. and Van Campo, E., *Nature*, 1986, **323**, 526–528.
18. Sirocko, F., Sarnthein, M., Erlenkeuser, H., Lange, H., Arnold, M. and Duplessy, J. C., *Nature*, 1993, **364**, 322–324.
19. Overpeck, J., Anderson, D., Trumbore, S. and Prell, W., *Climate Dyn.*, 1996, **12**, 213–225.
20. Ponton, C. *et al.*, *Geophys. Res. Lett.*, 2012, **39**, 1–6.
21. Achyuthan, H., Nagasundaram, M., Gourlan, A. T., Eastoe, C., Ahmad, S. M. and Padmakumari, V. M., *Quaternary Int.*, 2014, **349**, 232–244.
22. Rashid, H., Flower, B. P., Poore, R. Z. and Quinn, T. M., *Quaternary Sci. Rev.*, 2007, **26**, 2586–2597.

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First record of parrotfish bite mark on larger foraminifera from the Middle Eocene of Kutch, Gujarat, India

Larger foraminifera are excellent recorders of shallow marine sclerobionts (*sensu* Tayler and Wilson[1]) in low sedimentation regimes[2,3]. The range of sclerobionts may include cemented or organically anchored sessile taxa, borers and vagile organisms that live on or habitually visit the live or dead foraminiferal tests. In India, body fossil and ichnofossil (mostly bioerosion) of sclerobionts that subsisted on the larger foraminifera have been systematically recorded from the Paleogene of Kutch, Gujarat[4–10]. These sclerobionts comprise acrothoracican cirriped, worm, bivalve, gastropod, green algae, scleractinian coral, other foraminifera and bryozoa. Here we document a new sclerobiont in the form of bite marks of nectobenthic parrotfish (class Actinopterygii, family Scaridae) preserved in the Middle Eocene larger foraminifera *Assilina exponens* (Sowerby, 1840). It may be noted that the lectotype of *A. exponens* (a microspheric specimen) illustrated by Samanta[11] (plate 26, figure 1) also bears the characteristic parrotfish bite mark, but the same was overlooked by the past workers. To the best of our knowledge, there have been no previous studies regarding parrotfish bioerosion on the Tertiary larger foraminifera of India.

Palaeocene–Pliocene sediments are well preserved in the Tertiary basin of Kutch[12]. The examined specimens of *A. exponens* were collected from Jhadwa, Guvar and Lakhpat areas of Kutch basin (Figure 1). This foraminiferal species, characterized by feebly involute planispiral chambers and involute spiral wall[13], occurs in rock forming abundance in the lower part of Fulra Limestone (Middle Eocene)[12]. The protist is represented by dimorphic forms; diameter of microspheric and megalospheric test ranges from 20 to 28 mm and 6.5 to 9.5 mm respectively. The parrotfish bite marks are predominant on the large microspheric specimens of *A. exponens*. The present study is based on examination of 51 microspheric and 4 megalospheric bioeroded specimens of *A. exponens* under a