Radiocarbon as isotope chronometer and tracer in hydrological sciences

The potential & diverse dating and tracing applications of radiocarbon using Accelerator Mass Spectrometer

Pankaj Kumar
pkb@iuac.res.in

Radiocarbon (^{14}C) acts as an "isotope chronometer" allowing to determine the age of carbon-bearing materials based on its predictable radioactive decay. ^{14}C is formed naturally in the upper atmosphere through interactions between cosmic ray neutrons and nitrogen. By measuring the remaining ^{14}C in a sample and comparing it to the initial levels, scientists can date the samples up to ~50,000 years of age. This makes radiocarbon a powerful chronometer for dating archaeological, geological, and environmental samples, helping reconstruct past events and processes across a range of scientific fields. Additionally, during 1950s-1960s, ^{14}C has been formed anthropogenically due to sudden increase of neutrons in the atmosphere caused by on surface testing of nuclear bombs. This article showcases the potential and diverse dating and tracing applications of radiocarbon using Accelerator Mass Spectrometer (AMS), helping reconstruct past events and processes in paleoclimatology and marine sciences.

Discovery of radioactivity was one of the highly significant gifts to the human kind. Out of the known 3349 isotopes, 3303 isotopes are radioactive and only 246 isotopes are stable. These isotopes have played a vital role in the modernization of healthcare, environmental research and many other domains of the human life. Carbon is one element with three isotopes ^{12}C, ^{13}C (both stable) and ^{14}C (radioactive) which plays a vital role being ubiquitous on the planet earth (Fig.1A). The half-life of 5730 years make radiocarbon a unique isotope as it is the most ideal isotope to characterize not only the development of human civilization but also to understand the climate, sea level and environmental changes in recent geological past called Holocene and beyond, upto ~50ka. Radiocarbon as a dating tool was discovered by Willard F. Libby in 1946 (Libby et al. 1949) for which he was awarded Nobel Prize in 1960, and at that time it brought revolution in establishing accurate chronology in archaeology and related domains, and even now perhaps ^{14}C is the most used radionuclide in studying the all spheres of our environment. Invention of AMS in 1977 out of nuclear physics research laboratories brought second revolution in radiocarbon dating as it drastically reduced the required sample size and measurement time and increased sensitivity and accuracy of age estimation.

Radiocarbon is produced in the upper atmosphere by the interaction of cosmic rays with ^{14}N. Following production, ^{14}C is oxidized to $^{14}CO_2$ and quickly dispersed throughout the atmosphere, then transferred to other carbon reservoirs like the biosphere and oceans through processes like photosynthesis and air-sea exchange of CO_2. This production channel in nature has been since time immortal with some fluctuations depending on the availability of cosmic ray neutrons and ^{14}N. However, very recently this, natural ^{14}C levels were disturbed by large amounts of bomb ^{14}C; produced during atmospheric nuclear weapons tests in the 1950s and 1960s. Peak concentration of ^{14}C in atmosphere, in 1963 was 1000 times higher than the natural cosmogenic background. This bomb ^{14}C has moved throughout the environment, including into organic matter present on land and sea. Being a recent phenomenon, Bomb carbon has been measured in various archives at land and sea and it is well documented for regions of southern and northern hemispheres. Bomb pulse dating and tracing is highly useful in forensic, biological in oceanography research. Thus, radiocarbon became a powerful tool for investigating water circulation on regional and global scales in marine environment. Isotopic fractionation occurs naturally during processes like photosynthesis and air-sea CO_2 exchange, measured ^{14}C concentrations are typically corrected using $\delta^{13}C$ values.

Inter-University Accelerator Centre (IUAC), New Delhi has established India's first facility for AMS measurement of various isotopes viz. ^{10}Be ($T_{1/2}$= 1.38Ma), ^{14}C ($T_{1/2}$= 5730a) and ^{26}Al ($T_{1/2}$= 0.75 Ma) radioisotopes (Kumar P et.al 2015, Sharma et.al, 2019) by modifying its 15UD Pelletron Accelerator and later with a dedicated 500kV ion accelerator system. The recent developments in Accelerator Mass Spectrometry (AMS) have significantly advanced oceanic and environmental investigations that were previously limited by sensitivity or sample availability. AMS allows for the analysis of long-

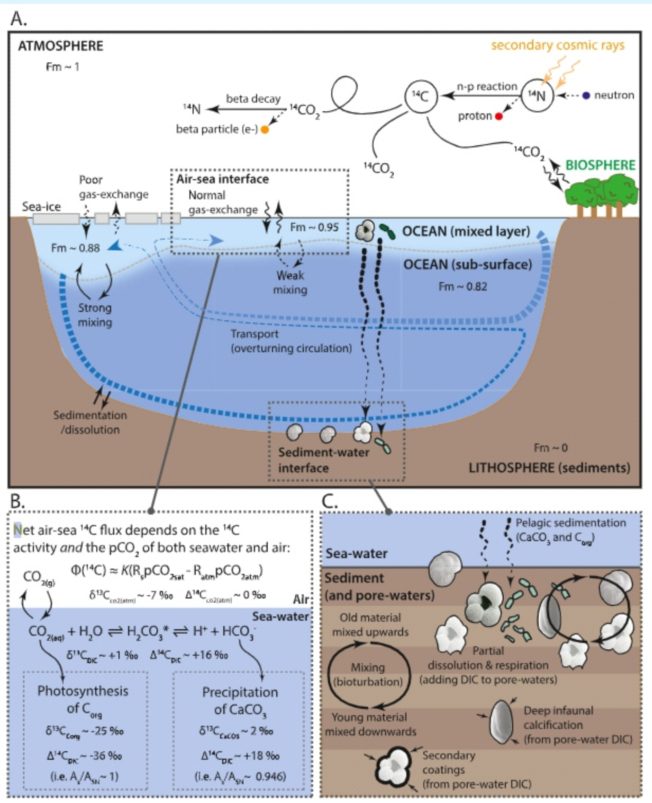

Fig.1: Pictorial representation of radiocarbon production mechanism in the atmosphere and its transport into the marine radiocarbon cycle (A), including chemical processes happening at the air-sea interface (B) and the sediment-seawater interface (C). (taken from Skinner, L. C., & Bard, E., 2022).

THE RECENT DEVELOPMENTS in Accelerator Mass Spectrometry (AMS) have significantly advanced oceanic and environmental investigations that were previously limited by sensitivity or sample availability.

lived natural and anthropogenic radionuclides at ultra-low levels. Few applications of radiocarbon in marine science research are presented in Fig.1.

Sea Level Rise Research

Climate change driven sea level rise is major cause of concern for the coastal population across the globe. The behaviour of sea level in past specially the Holocene has been investigated and contributing factors could be global as well local. The global factors are those related to the change in the global ocean volume affected by the melting of the ice at polar regions as well as other ice reservoirs (e.g. Himalaya) feeding the large quantity of water into ocean through rivers. Local factors are responsible for the change in costal morphology driven by the tectonics and cause the sea level change due to upliftment or subsidence. Both factors are time-dependent and the accurate reconstruction of sea-level variations requires the use of suitable sea-level indicators, whose age can be ascertained by proper absolute dating methods. Most of the times these indicators are carbonaceous and siliceous materials such as shells, foram aggregate, coral, wood materials and peat etc. and have been given importance as they are the good indicators of sea level as well as datable with radiocarbon. V.J. Loveson and R. Nigam (2019) have complied 75 radiocarbon dates performed on several sea level indicators and have generated Holocene Sea level curve for the east coast of India (Fig.2).

Submerged speleothems have also been used as past sea level indicators and in these cases ^{14}C dating is performed on the last layer formed in aerial continental conditions. In sea-level rise research, radiocarbon plays an important role to provide an absolute date to the sea level markers (Antonioli, F., et.al 2021).

Tracing Global Ocean Movement

Radiocarbon enters the ocean from the atmosphere via air-sea CO_2 exchange at the sea

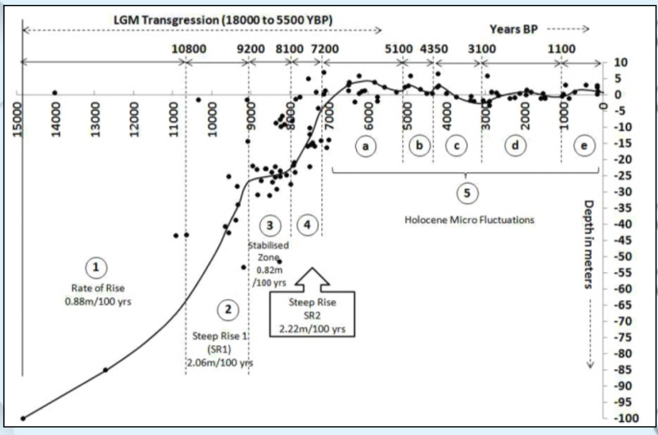

Fig.1: Holocene sea level curve for the east coast of India based on the ^{14}C age data

surface, which in turn is influenced by temperature and salinity effects on CO_2 solubility, once radiocarbon has entered the surface ocean, it is re-distributed within the "mixed layer" relatively quickly (the top ~100 m or so of the water column is mixed on a timescale of order ~years), and can then be transported into the ocean interior via advective and diffusive processes, with radiocarbon decaying away over time as this occurs (Fig.1B). Through continuous exchange with the atmosphere the ocean surface water approximately reflects the atmospheric $^{14}C/^{12}C$ ratio, whereas the deep ocean water shows a reduced ratio depending on how long it had been disconnected from exchange with the surface (Fig.1C). In order to obtain better insights into the ocean circulation and to validate ocean circulation models (Broeker, 1991), a dedicated AMS facility The National Oceanographic Sciences AMS (NOSAMS) at Woods Hole USA was set-up in 1990, with the goal to map the world oceans with ^{14}C measurements in an unprecedented way. As compared to the first mapping performed in the 1980s with beta-counting, which required 250 L water samples, but now 0.5 L of water provides sufficient carbon for a ^{14}C AMS measurement. As a result, over 20,000 water samples have been measured for ^{14}C within the World Ocean Circulation Experiment project (WOCE), literally mapping the world oceans in three dimensions (McNichol, 2000) and supplying a wealth of information on global ^{14}C and $\delta^{13}C$ distributions.

A LARGE POPULATION OF INDIA (~65%) is dependent on monsoon rainfall driven agriculture and it is imperative to model the future trends of Indian monsoon for better preparedness and policy formulation to maintain sustainable development, supported by long term temporal and spatial monsoon variation data.

Paleomonsoon reconstruction

A large population of India (~65%) is dependent on monsoon rainfall driven agriculture and it is imperative to model the future trends of Indian monsoon for better preparedness and policy formulation to maintain sustainable development of the country. For this purpose, it is required to have long term temporal and spatial monsoon variation data. There have been numerous studies taken up on land and marine archives to create such a dataset in Indian subcontinent (Sengupta et.al, 2025, Palar et.al, 2025). Marine environments, especially Oceans offer long, uninterrupted and continuous records and therefore, for paleomonsoon studies, sediment cores collected from high sedimentation rates zones (e.g. Bay of Bengal) are studied to generate sub-centennial to decadal resolution paleo-monsoonal records. Often microfossils, like foraminifera, radiolarians, diatoms, ostracodes, coccolithophores, pollens, spores, alkenone, corals and other microfossils are picked up from sediment cores and studied. Radiocarbon dating of these microfossils (sea water derived ^{14}C present in $CaCO_3$) collected from different depths in the sediments cores helps in establishing absolute chronology up to 50 Ka.

Tracing anthropogenic radionuclides

Beyond bomb ^{14}C, anthropogenic radionuclides released from sources like, nuclear reprocessing facilities and the Fukushima accident are used as tracers. ^{14}C enrichment from Sellafield has been tracked in the Irish Sea and West of Scotland, showing higher levels in mussels and shells above background, though decreasing over time with reduced releases (Tierney, K.M., et.al , 2016, Muir, G.K.P., et.al 2015). Elevated ^{14}C has also been found in sediments, where the enrichment appears to be increasing. Studies confirmed a detectable, though relatively small (9% above global fallout), contribution of ^{14}C from the Fukushima accident to the sea (Povince, P.P., et.al, 2017, Kaizer J., et.al 2023)

Tsunami periodicity

The 26th December 2004 tsunamigenic earthquake took more than 280,000 lives and post this event, there have been efforts (Malik et.al, 2019, J. Sanwal et.al, 2023) to find out paleo tsunami events and their recurrence interval, if any, so to better plan the infrastructure activities near the densely populated coastal areas in India. In order to understand the tsunami periodicity, if any, by analysing the sediment cores collected from the southern Andaman Island. Several cores and trenches at Badabalu along the south cost of Andaman were dug and 7 tsunami events were identified ranging over past 8000 years. Radiocarbon dating of charcoal, coconut clast, root, buried wood and foraminifera, confirmed the presence of Paleo-tsunami events occurred in 2004CE (recent), historic tsunami in 1881, 1762, 1679CE, prehistoric tsunami in 1300-1400CE, in 2000-3000BCE and 3020-1780BCE and before 5600-5300BCE. This study suggested a recurrence of 420–750 years for mega-earthquakes having different source, and a shorter interval of 80–120 years for large magnitude earthquakes.

Conclusion

Radiocarbon is a potential dating tool having wide applications in hydrological, archaeology, paleoclimatology, and marine sciences. Accelerator Mass Spectrometry (AMS) is a well-established and absolute dating technique for measuring radiocarbon in small sample sizes with fast measurement times and it also provides accurate and precise measurements. However, site specific marine reservoir correction and calibration are essential to deduce accurate calendar ages. A few research studies presented in the article showcases diverse applications of radiocarbon dating using AMS in oceanography.

Dr. Pankaj Kumar, Senior Scientist in IUAC (Delhi), is a physicist with research interest in geochronology and isotope research using accelerator mass spectrometer and low energy mass spectrometers. He has played a key role in advancing India's capabilities in geochronology and environmental radionuclide analysis by establishing MoES funded National Geochronology Facility at IUAC. He has published more 110 publications in peer reviewed journals. Dr. Kumar is a recipient of S.N. Seshadri Memorial Award-2020 by Indian Physics Association (IPA), in recognition of his key role in developing Accelerator Mass Spectrometry (AMS) facility at IUAC. He is a Life-Member of IPA, NASI and Indian Society of Particle Accelerator. He has been selected member of Indian National Young Academy of Science (INYAS) of INSA and served as a national core committee of INYAS. Currently, he is executive council member and joint secretary of IPA.