Review Article

Estimation of Long-term Catchment Scale Denudation Rate Using ^{10}Be : Past Studies and Challenges

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This review focuses on the use of cosmogenic radio nuclides (CRNs), in particular ^{10}Be ($T_{1/2} = 1.387\text{Ma}$) as geochronometer and tracer to estimate long-term catchment scale denudation rate. The half-lives of CRNs are appropriate for tracing a number of surficial processes and to understand landscape evolution. This technique has been widely applied for studying exposure ages, erosion rates and burial history etc. despite some associated limitations and uncertainties. History of CRN studies in India shows that most of the studies are concentrated in the Himalayan region whereas peninsular region has been less studied due to lower *in situ* CRN production rate. Latitudinal and altitudinal dependence of CRN production rate instigate to develop regional production rate data, which can be used for the CRN dating studies more effectively. In this review, applications of CRNs in paleo-glaciations, landscape evolution, paleoclimate reconstruction, sediment transport and its dynamics are discussed from the Indian perspective. Basics of AMS techniques for CRN measurement, chemical processing and ^{10}Be analysis from natural samples are also described, citing the challenges and solutions offered by AMS.

Keywords: CRNs; AMS; ^{10}Be ; Denudation Rate; Himalaya

Introduction

Geomorphological evolution of landscape and elemental cycle is controlled by different surface and subsurface earth processes such as tectonics, upliftment, physical and chemical denudation. Way back in 1899, Chamberlin hypothesized that the rock uplift favors rapid chemical denudation rate and influence carbon cycle. However, the link between mountain building processes and global climate is still a hot topic of debate in the field of climate studies. The Himalayan region witnessed major glacial and interglacial cycles during Quaternary period, which led to change of denudation rate in different Himalayan river basins (Clift *et al.*, 2008; Rahaman *et al.*, 2009; Lupker *et al.*, 2013; Tripathy *et al.*, 2014). River basins might have responded differently to the global climatic change depending up on their location and the tectonic regime (Olen *et al.*, 2015). These spatial and temporal variations among different basin can be

evaluated effectively using a suitable proxy like cosmogenic radionuclides (CRNs). Radioactive nuclides produced in nature through the interaction of cosmic rays with stable nuclei are termed as Cosmogenic Radionuclides. Use of CRNs in denudation rate calculation has helped geomorphologists to study landscape evolution at an intermediate age range; between the short term changes calculated from historical record and long term changes on tectonic time scale calculated from different luminescence methods (Burbank *et al.*, 1996). Integration period of CRNs derived catchment wide denudation rates are on the order of 10^2 - 10^5 years and this makes it a suitable proxy to study the response of climatic variations in the catchment area than regional scale tectonic perturbations (Olen, 2015). These types of denudation rate estimations are acceptable for slow sediment transport and intermediate sediment storage spanning thousands of

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years (Hippe *et al.*, 2012). Topographic change is related with long term denudation rate (Kober *et al.*, 2015) and this rate has positive correlation with the amount of sediments transported from land to ocean. In India, few studies were conducted on estimation of catchment scale denudation rate using CRNs (Barnard *et al.*, 2001; Barnard *et al.*, 2004b; Lupker *et al.*, 2012; Vassallo *et al.*, 2015; Lupker *et al.*, 2017; Dhal *et al.*, 2018). Considering the potential use of CRNs for long-term denudation studies, an attempt has been made to review the earlier studies to understand the technique and associated limitations/challenges faced during the process of sample collection, sample processing, measurement, data analysis and interpretation.

Interaction of high energy cosmic rays with target nuclides present on the earth surface produces *in situ* CRNs. Quartz is a suitable target mineral for the study of *in situ* ^{10}Be and ^{26}Al . Inverse relationship between denudation rate and CRN concentration of an eroding surface shows that the cosmogenic nuclide concentrations measured are based on physical processes that can be quantitatively related to time (Lal, 1991; Nishiizumi *et al.*, 1993). Buried quartz grains in the sediment archives are shielded from cosmic rays and the CRN concentrations in quartz grain may be used for the estimation of burial age after correcting for the decay. CRNs measurements on the exposed rock and sediments are also used to infer long-term erosion rate, denudation rate and soil production rate (Lal, 1991; Brown *et al.*, 1995 and references therein). CRNs like ^{10}Be and ^{26}Al are widely used as a proxy to calculate long term denudation rate in mountain belts (Olen, 2015). Wide abundance of target nuclides for the formation of the CRN in common rock forming minerals provides broader application compared to the radiocarbon and luminescence dating techniques where sample collection constraints are generally encountered (Cockburn and Summerfield, 2004). Development in the Accelerator Mass Spectrometry (AMS) measurement technique provides ample scope to apply CRNs as a proxy to decipher temporal and spatial variation of earth surface processes. Advancement in the measurement techniques and apposite half-life of ^{10}Be (1.387 Ma, Korschineck *et al.*, 2010) for dating various surficial processes have helped earth scientists to use these nuclides as a geochronometer and tracer.

Application of CRNs technique in India indicate that majority of the work has been carried out in the Himalayas where researchers estimated the timing and extent of the Himalayan glaciers (Owen *et al.*, 2001) and tried to link the findings with the global climate (Table 1). *In situ* CRNs were also used as proxy for paleoclimate reconstruction, landscape evolution, sediment transport and its dynamics in the Himalayan region (Table 1). It is relatively easy to apply CRN technique in the Himalayan region, thanks to the higher production rate. At higher elevation and latitude, production rate of CRN is higher. Therefore, very less attempts were made from peninsular region of the country to use *in situ* CRNs for surface exposure dating and landscape evolution (Gupta *et al.*, 2007; Mandal *et al.*, 2015; Dhal *et al.*, 2018). Some of the important studies are highlighted in the next section.

Previous Studies

Himalayan Region

In the Himalayan region, CRN dating technique was used to understand catchment scale denudation rate; to identify glacial events and its possible link with global climate (Benn and Owen, 1998); and uplift rate and its link with tectonic events. ^{10}Be derived denudation rate of the Central Himalayan range has an average value of 1.3 mm yr^{-1} (Lupker *et al.*, 2012). CRN was used by Scherler *et al.*, 2014 to understand the catchment scale averaged erosion rates in the Yamuna River, Garhwal Himalaya. Significant variability in ^{10}Be derived erosion rates, analyzed from the larger mainstream river is connected with the non-proportional supply of sediments and their incomplete mixing. In the Garhwal Himalayan region, Barnard *et al.*, 2001, have applied CRN dating technique to study the role of landslide in total denudation rate. For this study, strath terraces along the Alaknanda River were dated using ^{10}Be and ^{26}Al , for calculation of regional denudation rate and the contribution of landslide to overall regional denudation rate. In the Lahul Himalaya, Owen *et al.*, 2001, used CRN for dating of moraines, drumlins, and glacially polished bedrocks to estimate exposure age. These ages turned out to be more precise compared to the OSL age of the sample collected from the vicinity of moraines. Study of 'Be' exposure dating on moraine boulders of the Western Garhwal region helped in identifying five

Table 1: Summary of selected studies carried out in the Himalaya using *in situ* ^{10}Be

S.No.	Application	Location of study	Reference
1.	Glacial chronology: Assessment of glacier's response to the regional and global forcing factors	Shyok valley, Ladakh Punga valley, Zaskar Gangotri, Garhwal Himalaya, Nun Kun, India Nubra and Shyok valley Ladakh range, India Western Garhwal Himalaya Lahul Himalaya Garhwal Himalaya Chandra valley, Spiti valley, Middle Yunam valley NW Himalaya	Hedrick <i>et al.</i> , 2011 Barnard <i>et al.</i> , 2004a Lee <i>et al.</i> , 2014 Dortch <i>et al.</i> , 2010 Owen <i>et al.</i> , 2006 Scherler <i>et al.</i> , 2010 Owen <i>et al.</i> , 2001 Sharma and Owen 1996 Saha <i>et al.</i> , 2016
2.	Paleoclimate reconstruction: Inferring global and regional trend in climate change during different time periods	Central Grahwal, NW India Nubra and Shyok valley, Ladakh Chandra valley NW Himalayas Hunza valley (Karakoram Mountains), the Lahul and Garhwal Himalaya, and the Khumbu Himalaya Central Karakoram Chandra valley, Spiti valley, Middle Yunam valley, NW Himalaya	Murari <i>et al.</i> , 2014 Dortch <i>et al.</i> , 2013 Eugster <i>et al.</i> , 2016 Benn and Owen, 2002 Seong <i>et al.</i> , 2007 Saha <i>et al.</i> , 2016
3.	Landscape evolution: Determining the role of surface and tectonic process in the evolution of mountain topography	Gori Ganga valley of Nanda Devi, NE Garhwal Jammu and Kashmir, India Ladakh, India Garhwal Himalaya, India	Barnard <i>et al.</i> , 2004b Vassallo <i>et al.</i> , 2015 Brown <i>et al.</i> , 2002 Barnard <i>et al.</i> , 2001
4.	Sediment transport and its dynamics: To constrain denudation rates across the catchment and to quantify the impact of rapid erosion based on cosmogenic nuclide budgets and signals	Tsangpo-Brahmaputra catchment, Eastern Himalaya, Pasighat, NE India Ganga Basin, India	Lupker <i>et al.</i> , 2017 Lupker <i>et al.</i> , 2012

glacial episodes of decreasing magnitude, where the oldest glaciation was dated back to 16 Ka. Other stages are ~11-12 Ka, ~8-9 Ka, ~5 Ka and youngest stage was at <1 Ka (Scherler *et al.*, 2010).

Application of cosmogenic nuclides in the tectonic study is evident from the Himalayan region where average slip rate ($4 \pm 1 \text{ mm yr}^{-1}$) along Karakoram fault has been calculated using ^{10}Be age of boulders from debris flow. Field observation indicates the displacement of $40 \pm 5 \text{ m}$ of this debris flow due to the strike slip fault. Apart from this, the Himalayan river strath terraces were dated using cosmogenic nuclides to understand river incision rate and bedrock uplift rate, which has an important role in determining equilibrium or transient conditions in the landscape evolution (Dortch *et al.*, 2011). In the Gori Ganga valley of Nanda Devi, north east Garhwal, sedimentological study along with geomorphological analysis and ^{10}Be surface exposure dating indicate a

rapid landscape evolution during periods of deglaciation (Barnard *et al.*, 2001). Saha *et al.*, 2016, has applied cosmogenic ^{10}Be in NW Himalayas to study streamlined subglacial landforms. Geomorphic, sedimentological and geochronological analysis of subglacial landforms in the Chandra Tal, the upper Spiti valley and the middle Yunam valley of the NW Himalaya of India have been studied to develop glacial chronostratigraphy and glacial dynamics of the region.

Peninsular Region

In situ ^{10}Be dating technique is used to estimate the minimum age of the gorge development in the Narmada River at Dadri falls (Gupta *et al.*, 2007). In this study significance of the method in understanding regional morphology and bedrock incision were evaluated. In the Cauvery river catchment, analysis of *in situ* produced ^{10}Be concentrations in river sediments and exposed bedrocks are used to

understand the landscape evolution across passive margins of the Western Ghats (Mandal *et al.*, 2015). This study provides bedrock erosion rate and subsequent changes in regional morphology. In southern peninsular India, the application of cosmogenic nuclides has been limited to local bedrock erosion rate calculation, where regional scale studies on erosional dynamics are rare (Gunnell and Fleitout, 1998). This method is also applied in an archaeological site at Attirampakkam, Tamil Nadu, where direct burial dating of stone artifacts using $^{26}\text{Al}/^{10}\text{Be}$ was carried out. Study shows that the Acheulian Hominons occupied India even before middle Pleistocene (Pappu *et al.*, 2011). Application of meteoric $^{10}\text{Be}/^9\text{Be}$ ratio sediment on core samples of Cauvery river delta shows an inverse relationship between paleodenudation rates and Indian summer monsoon (Dhal *et al.*, 2018). Low CRN production rate at peninsular region make the study difficult as precise knowledge of local production rate is important in CRN dating (Stone, 2000). Disparity in the number of studies associated with geographic location is supposedly by the variation in CRN production rate.

Denudation Rate Calculation Using ^{10}Be : Theory, Application and Challenges

Primary cosmic rays of solar, galactic and anomalous origin interact with earth's atmosphere and produces secondary cosmic rays. Secondary cosmic rays further interact with the atmosphere as well earth's surface to produce meteoric and *in situ* CRNs respectively. At the earth surface, 98% of *in situ* CRNs are produced by the secondary cosmic ray's interaction (Masarik and Beer, 1999). Meteoric cosmogenic nuclides reach earth surface via dry and wet fallout, and subsequently gets adsorbed on to surface materials. This is also referred as 'garden variety' CRNs (Nishiizumi *et al.*, 1986). However, for some CRNs like ^{10}Be , *in situ* and meteoric origin nuclides can be separated chemically from the sediments/rocks and used independently. Production rate of CRNs primarily depends on the flux and energy of primary cosmic rays entering into earth's atmosphere, earth's magnetic field strength, abundance of target nuclides, altitude and latitude. Earth's magnetic field act as a filter, which deflects the cosmic radiation, therefore production rate is higher at regions where this filtering/shielding effect is negligible. This effect is higher at the equator, while

it is lower at latitudes greater than 55° (Lifton *et al.*, 2008 and references therein). Therefore, production rate is higher near polar region and it decreases towards low latitude (Shea *et al.*, 1987). Attenuation length of energetic particle is another important controlling factor for the production rate of CRNs (Hatton, 1971). Particles lose their energy with each interaction with atomic nuclei resulting in lower energy particles and having shorter attenuation lengths (Lifton *et al.*, 2014). One of the important advantages of beryllium is that we need to calculate the ^{10}Be production from oxygen only. Whereas in the case of other nuclide like ^{36}Cl , the production rate has to be determined separately from different atoms such as Ca, K and Cl (Fifield, 1999).

Geomagnetic latitude, altitude, and topographic shielding control the CRN production rate at a given site. Interpretation of landscape evolution became more reliable with the introduction of cosmogenic nuclides, as it provide better estimation of long term erosional and denudation rate (von Blanckenburg, 2006). Quantifying denudation rate is important in geochemical studies, because it influences the fresh mineral surface available for chemical weathering and controls the solute fluxes in river system (Riebe *et al.*, 2000). ^{10}Be concentration measured in river sediments at the outlet of the basin can provide catchment scale averaged denudation rate, under the assumption that the river sediments are well mixed, the denudation is in steady state, and the process has been taking place for a longer period compared to the denudation time scale (Z^*/ϵ) (von Blanckenburg, 2006; Lupker *et al.*, 2012). At the surface, removal of nuclides due to denudation is same as the production of nuclides. Hence denudation rate (ϵ) of an eroding surface is inversely proportional to the CRN concentration (von Blanckenburg, 2006)

$$c = p0 / \left(\lambda + \frac{\epsilon}{Z^*} \right)$$

c = Nuclide concentration on the surface of an eroding bedrock or soil (atoms g^{-1})

$p0$ = Production rate at the surface in a mineral of known composition (atoms $\text{g}^{-1} \text{ year}^{-1}$)

λ = Decay constant (year^{-1})

Z^* = Absorption depth scale

$Z^* = \Lambda/\rho$ (Λ absorption mean free path, ρ – density of the material,

ϵ - denudation rate

Unlike the physical calculation of chemical weathering, the CRN based chemical weathering rate calculation is not done at a discrete points on earth surface and it is based on a mixture of material derived from the entire basin (Bierman and Steig, 1996). High chemical weathering rate is associated with a rapid denudation rate, supposedly regulated by tectonic forcing (Riebe *et al.*, 2004). Spatial variation in denudation rate can be applied in paleoclimate studies. This relation between paleoclimate and associated denudation rate can be used to understand the variation in the process of chemical weathering. This will also help to establish the relationship between climate, physical erosion and chemical weathering (Riebe *et al.*, 2001). Comparison of ^{10}Be concentration in Pleistocene terrace samples with the Holocene sediments to understand the effect of variation in precipitation pattern on denudation rate in the Western cordillera, Peru is an example, which shows how this method has been used globally in interpreting tectonic and climatic induced landscape evolution (McPhillips *et al.*, 2013).

Denudation studies in the Himalayas are important as this region has been proposed as a location where tectonic-climatic coupling might occur (Thiede *et al.*, 2005). General evolution of the Himalaya has been similar from west to east; however, the northern and southern part of the Himalayas marks different denudation histories. Southern greater Himalayan denudation rates were highest ($\sim 1.5\text{--}3\text{ mm yr}^{-1}$) between ~ 10 and 2 Ma and lower rates ($0.5\text{--}2.6\text{ mm yr}^{-1}$) observed over the last 2 Ma . In the northern Himalaya, slower denudation ($< 1\text{ mm yr}^{-1}$) observed between 10 and 4 Ma followed by a large increase ($1.2\text{--}2.6\text{ mm yr}^{-1}$) in the last $\sim 4\text{ Ma}$ (Thiede and Ehlers, 2013). This suggests that the denudation history of these two regions at different times might have controlled by other mechanisms than orogeny.

Factors influencing denudation rate in the Himalayas are under debate. The Indian Summer Monsoon (ISM) intensification in early Holocene is associated with an increase in sediment flux in the north-west Himalaya and frequent landslides (Goodbred and Kuehl, 2000). Stronger ISM in the

early Holocene compared to LGM and the present day indicate that the impact of climate on sediment flux and topography might have stronger in the past (Goodbred and Kuehl, 2000). However, scientists argue that the landscape evolution in the Himalayan region is mainly controlled by tectonic deformation and uplift (Godard *et al.*, 2014; Scherler *et al.*, 2014) and the climatic influence is considered secondary.

In the Himalayas, the denudation pattern is proposed to have influenced by both tectonic factors and precipitation gradients. However, coupling between climate, tectonic and denudation in the Himalayan region during different geological time periods is highly debatable (Herman *et al.*, 2010). CRN based studies in the Himalayan region shows location dependent trend in the correlation between denudation rate and climatic and tectonic factors.

Despite the wide range of applicability of this technique, there are a number of theoretical, practical and analytical concerns associated with *in situ*-produced ^{10}Be dating techniques. Fundamental challenges are associated with the assumptions made during the calculation of denudation rates from *in situ* produced concentrations of ^{10}Be in fluvial sediments. One of the assumptions is that between the point of sediment production and deposition, there is a short transit or the sediment rapidly transported with no intermediate storage points (von Blanckenburg, 2006). Storage and remobilization of alluvial sediment can either cause underestimation or over estimation of CRN concentration. However the extent of the uncertainty associated with this assumption can be constrained in the field. Sampling is done under the assumption that the basin is in isotopic steady state and the collected sediment is well mixed (Bierman and Steig, 1996). For long term study, uncertainty associated with the isotopic steady state of a basin is less. Whereas, it is difficult to get a well-mixed sample representing the entire basin to obtain an average value for CRN concentration. There is a chance that the calculated erosional rate for a region may show ambiguous result due to mixing of sediments derived from extreme erosional regime.

Calculation of cosmogenic nuclide production rates at a sampling site requires some background/standard information such as a reference production rate and a scaling scheme based on the location of

study. Hence, some of the common assumptions made during the dating of cosmogenic nuclides are a) production rates are well known; b) sampling location has been perfectly exposed to cosmic rays with no history of multiple exposures; and c) sample has been in a closed system with neither loss nor contamination has occurred. These assumptions fails when there is temporal variation in production rate due to magnetic and atmospheric effects, which will alter the CRN production rate and the unrecognized shielding by snow, sediment and/ or vegetation. In that case the constraints related to the shielding of the sampling location or erosional effects have to be separately scaled/normalized. Although scaling factors are applied to reduce the sources of errors, uncertainty may remain because of ambiguity in spatial scaling, temporal variation, inheritance, muonic contribution on CRN production and attenuation length.

Presence of low *in situ* ^{10}Be concentration in the sample due to lower production rate on the earth surface (~ 6 atoms per gram of quartz yr^{-1} at $>50^\circ$ latitude) demand a highly sensitive instrument to quantify the isotope concentration (Nishiizumi *et al.*, 1990). Measurement of radionuclides could be performed either by measuring the radiation emitted in radioactive decay (decay counting) or by counting the number of radionuclide atoms (atom counting). Reliability of these methods depends on various factors such as half life, sample amount etc. For radionuclides with long half life ($>10^3$ years) will have lower decay rate therefore, decay counting will not be reliable. On the other hand, for radionuclide with shorter half life decay counting is preferred.

Atom counting can be performed with conventional mass spectrometers (MS) as these were followed to measure stable as well as very long lived radioisotope (Kutschera, 2005). Mass spectrometry is an important tool to measure the abundance of elements by ionic separation and detection based on their mass and charge. However, the detection of low abundant elements with prominent isobaric interferences remained as a challenge and that can be tackled with the accelerator based mass spectrometry (AMS).

AMS is an extension of MS with an accelerator involving much higher energies ($\sim \text{MeV}$). At this energy, several ion filtering techniques such as

magnetic/electric filters and nuclear detection techniques become more effective, which enables suppression of isobaric and isotopic interferences to a very low level. Molecular or atomic isobaric interference during conventional mass spectrometer analysis cause high background and reduce sensitivity. Use of accelerator improves the sensitivity of measurement as well as reduces the sample size and measurement time in comparison to the decay counting (Hellborg and Skog, 2007). For measurement of cosmogenic radionuclide from natural samples, AMS techniques is used and it eliminates isobaric interference to great extent and it could measure isotopic ratios of a specific element (e.g. $^{10}\text{Be}/^9\text{Be}$) up to a level of 1 in 10^{15} (Tuniz *et al.*, 1998).

Table 2 summarizes the challenges of ^{10}Be measurement and their solution through AMS system. Followings are the major component of an AMS system and their uses help to tackle challenges of ^{10}Be measurement.

1. Ion sources: capable of producing negative ions as well as pre-acceleration of $\sim 10\text{-}100$ keV energy. Prominently, Cs based sputter ion sources are used in AMS systems. In some cases, isotope of interest has low or negative electron affinity and therefore, does not form sufficient negative ions. In such cases a molecular ion is chosen and molecular ions (oxides, fluorides etc.) are extracted out of the ion source. Electron affinity of Be is 0.195 eV and therefore, BeO^- is used for its measurements. BeF_2 has also been used by researchers to suppress ^{10}B during AMS measurement (Grajcar *et al.*, 2007), however, handling of BeF_2 in the ion source is tedious and required certain precautions. During sample analysis, quick change from sample to standard cathode and *vice-versa* is required to minimize the effect of machine parameter fluctuations on result. Therefore, AMS facilities are typically equipped with the multi-cathode ion source having bidirectional movement of the cathode wheel (Pattanaik, 2010; Pattanaik *et al.*, 2011, Kumar *et al.*, 2015, 2014, and 2011). Optimizations of ion source parameters are crucial for higher and stable ion current.
2. Accelerator and stripping system: Ions extracted

from the ion source are mass analyzed with a dipole magnet (ME/q^2 analysis) and injected into the accelerator. Tandem type of accelerators are predominant in AMS mostly due to the fact that it involves stripping process inside high voltage area at the middle of accelerator to convert injected negative ions into positive ions so that dual acceleration could be achieved. Stripper (gas/foil) not only converts negative ions into positive, but also dissociates molecular interferences which are later on removed by electric and magnetic filters. Selection of foil and/or gas stripper for stripping of molecular ion is important to reduce scattering and yield of atomic ions. In lower energy AMS systems thinner stripper medium (N_2 gas of $\sim 6\mu\text{m}$) is good enough to dissociate BeO^- ion and to strip Beryllium to Be^+ ion. At higher energy AMS systems combination of gas and foil stripper helps in better transmission through accelerator.

AMS measurements of CRNs are carried out with respect to their stable isotopes. To minimize the effect of accelerator parameter change during AMS measurement, simultaneous injection of stable and CRN isotope is preferred over the sequential injection (Kumar *et al.*, 2011). However, now a days, fast bouncing system attached with injector magnet allows sequential injection of stable and CRN with a very small time interval ($\sim \mu\text{s}$) to minimize the accelerator parameter fluctuations, if any.

3. Post acceleration analysis system composed of various filters such as magnetic dipole (ME/q^2 filter), electrostatic analyser (E/q filter) and or velocity selector (E/M filter) help in removing unwanted scattered ions, molecular fragments, isotopic background coming out of the accelerator. In certain cases, post stripper foils (mostly silicon nitride foil) are used prior to E/q or E/M filters to create energy difference between radionuclide and its isobar. Due to energy difference, E/q or E/M filters help reducing isobaric interferences. In low energy AMS systems ($\sim 500\text{kV}$ - 1MV) this technique is used to reduce ^{10}B during ^{10}Be measurements. In medium and high energy AMS systems (3MV - 10MV), passive gas cell absorber is employed prior to detector to stop

^{10}B entering the detector, while ^{10}Be still left enough energy to be counted by the detection system. This technique is useful to suppress ^{10}B up to 7-10 order magnitude and thereby the detection limit is increased up to 10^{-15} for the $^{10}\text{Be}/^9\text{Be}$ ratio (Klein *et al.*, 1982; Grajcar *et al.*, 2007).

4. Detection system to identify the radionuclide on the basis of atomic number and atomic mass. The unwanted ions either do not reach the detector or identified as unwanted signal. Predominantly, multi anode gas ionization detectors are used for radionuclide counting, while off axis or retractable faraday cups are used for the counting of stable isotope.

Table 2: Challenges and their solution during AMS measurement of ^{10}Be from natural samples

Challenges	Solution
Low electron affinity of Be	BeO^- or BeF_2^- is extracted from the ion source
^{10}B – isobar removal	Chemical processing steps, BeF_2^- extraction from source, post accelerator strippers in combination with E/q and ME/q^2 filters, gas cell absorber, gas ionization detector
Isotopic interferences originating from injection of ($^9\text{Be}^{16}\text{OH}^-$, $^{12}\text{C}^{13}\text{CH}^-$, $^{13}\text{C}_2^-$ etc.)	Stripping system and subsequent ME/q^2 and E/q filters

In India, AMS facility at Inter University Accelerator Center (IUAC), New Delhi routinely measure ^{10}Be from natural samples (Kumar *et al.*, 2015 and 2011). IUAC started ^{10}Be measurements with 15MV Pelletron Tandem accelerator with ^{10}Be beam energy of about 34MeV. In this energy range, isobar ^{10}B was being stopped entering detector by employing a gas cell absorber. Recently, IUAC has started using 500kV AMS system for ^{10}Be measurements, where 75nm silicon nitride foil is used to create energy difference between ^{10}B and ^{10}Be and subsequent E/q , ME/q^2 filters helps reducing ^{10}B counts entering the detector.

Prior to the AMS measurement, a rigorous chemical processing is required with an objective to

pre-concentrate the element of interest and to avoid any contamination during sample handling. For *in situ* ^{10}Be analysis, care must be taken during mineral separation and purification, leaching of atmospheric ^{10}Be from the surface and fractures, dissolution and removal of fluoride complexes (if formed), column chromatography to isolate 'Be' element followed by precipitation of Be-hydroxide at suitable pH. Finally, Be-hydroxides are converted in to the BeO oxides (Pattanaik *et al.*, 2007; Pattanaik 2010; Pattanaik *et al.*, 2011; Kumar *et al.*, 2015, 2014, and 2011). Mixing of Nb powder with BeO is a common practice followed at various AMS lab to enhance the beam current and its stability. Above chemical procedure needs to be carried out in an ultra-clean lab using purified acids and water, to reduce the procedural blank and isobaric effects. During chemical procedure, optimal amount of Be-carrier needs to be added in the sample for easy handling and to know the yield of the chemical procedure.

Limitations are also associated with the experimental procedure including the requirement of a large quantity of pure, coarse-grained quartz for the analysis, which is difficult to get in a continuous sedimentary record (Willenburger and von Blackenburg, 2010). It is particularly challenging to use cosmogenic radionuclides to determine denudation rates and exposure ages in rapidly evolving landscapes and recently exposed bedrock surfaces. Occurrence of landslide or debris flow events may result in admixing and short exposure time will resulted in lower ^{10}Be concentration in samples (Licciardi *et al.*, 2009). Presently, the method is best applied in areas undergoing long exposure (5ka – 5Ma) and low erosion rates (0.1mm/ka to 10 mm/ka) (Tuniz *et al.*, 1998). Sensitivity of AMS is an important limiting factor as it determines the lower limit of the exposure date. Therefore, the technical improvement of AMS measurement technique will help to expand the use of this method.

However, the limitations can be taken care to some extent if the sample collection, processing and analysis are done systematically. For *in situ* ^{10}Be dating, preferably sandstones or granites are to be collected with the aim of obtaining 10 to 50g of pure quartz after mineral separation. Parameters such as latitude, longitude and depth below the surface of the sample need to be recorded for calculating ^{10}Be

production rate. The sample has to be collected in such a way that the prior exposure is negligible and free of debris and snow cover since exposure. Hence, large boulders or sloping bedrock surfaces are preferred (Fifield, 1999). However while sample collection it is important to mark the details about surrounding relief features, snow or debris coverage, large scale erosion, orientation/change in orientation and inherited cosmogenic content of the sampling to make sure the accuracy of the results.

Drawback associated with the sample taken for ^{10}Be extraction is that compared to other CRN, ^{10}Be has lowest production rate in quartz. However, almost all the studies are based on the ^{10}Be concentration in pure quartz crystal. Little work has been done in exploring ^{10}Be production rates in other mineral systems such as olivine solid solution series (Gosse and Philips, 2001). Considering the CRN based erosion rate calculated from outcrops and alluvial sediments, the latter is more complicated as the minerals in sediment can accumulate cosmogenic nuclides not just during exhumation but also during storage and transportation (Granger *et al.*, 1996). Another important source of uncertainty in the CRN concentration occurs when the outcrop undergoes multiple exposures and variable thickness of over burden prior to its present depositional setting. Analytical errors are associated with the presence of cosmogenic nuclides not as a result of spallation reaction but radiogenic.

Concluding Remarks

Denudation is a complex mass transport process that controls the rates of sediment supply to a depositional site. Temporal variation in catchment scale denudation rate has various applications ranging from biogeochemical cycles to understanding the evolution of the basin morphology and associated river system. Local geomorphic parameters, lithology of the area and morphology of the basin are supposed to control the spatial variability in denudation rate (Hippe *et al.*, 2012). Establishment of geomorphologically and lithologically controlled spatial denudation rate will be helpful to compare different river basins with time. Apposite half-life of ^{10}Be and abundant target mineral like quartz is helpful to use *in situ* ^{10}Be as proxy for denudation study. Advantage of using ^{10}Be is that it provides average denudation rate of a river basin over

longer timescale, which will mask the short-term changes. Hence, understanding of long-term geomorphic processes is promising using this technique (von Blackenburg, 2006). Progress in the understanding of cosmic rays interaction with the earth surface has helped in the practical applications of CRN in surficial process studies.

Different theoretical, practical and analytical uncertainties do exist with the method, where the limitations are reduced by using AMS and making some assumptions and standardizations. History of CRN studies in India shows that most of the studies are concentrated in the Himalayan region and peninsular region has been less studied due to lower *in situ* production rate. Latitudinal and altitudinal dependence of CRN production rate shows the need of regional production rate which can be used as a calibration data for the CRN dating studies.

Considering the potential of the method, we need to apply other exposure dating techniques along with CRN to compare and calibrate in the lower *in situ* production regime so that the acceptability of this technique will be improved. In Indian scenario, application of this technique should also be encouraged in archeology and neotectonic studies. As neotectonic history of a region is very important for risk assessment study.

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