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Helium/radon precursory anomalies of Chamoli earthquake, Garhwal Himalaya, India

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Abstract

In the Garhwal Himalaya, the Bhagirthi and Alaknanda valleys were rocked respectively by two major earthquakes; the Uttarkashi earthquake of magnitude $m_b = 6.5$, $M_s = 7.0$ on 20 October, 1991 and the Chamoli earthquake of $m_b = 6.8$, $M_s = 6.5$ on 29 March 1999, during this decade only. Both these seismic events are associated with ongoing deformation along the main central thrust (MCT) of the Himalayas. The helium and radon anomalies on 24 and 27 March 1999, respectively, were recorded at Palampur which is about 393 km from the Chamoli earthquake epicentre. A helium/radon ratio anomaly was recorded on 20 March, 9 days before the Chamoli earthquake. The precursory nature of radon and helium anomalies is a strong indicator of the physical basis of earthquake prediction and a preliminary test for the proposed conceptual helium/radon ratio model.

1. Introduction

The Bhagirthi and Alaknanda valleys of Garhwal Himalaya in N-W Himalayas is a good example of tectonically active area. The region has suffered several major and minor earthquakes of magnitude 5–7, including the Badrinath earthquake (1803), Gangotri earthquake (1816) and the Mussoorie earthquake (1865) (Oldham, 1883). During this decade two major earthquakes have occurred in the Garhwal Himalaya; the Uttarkashi earthquake of magnitude $M_s = 7.0$ occurred on 20 October 1991 and the Chamoli earthquake of $M_s = 6.5$ on 29 March 1999. Both earthquakes (Fig. 1) were followed by severe aftershocks for many days. It shows that the Bhagirthi and the Alaknanda valleys and areas around MCT are tectonically active.

Studies of geochemical and hydrological anomalies preceding significant earthquakes had been reported from China, Japan, Uzbekistan (Tashkent), Mexico, Italy, India and Germany (Liu et

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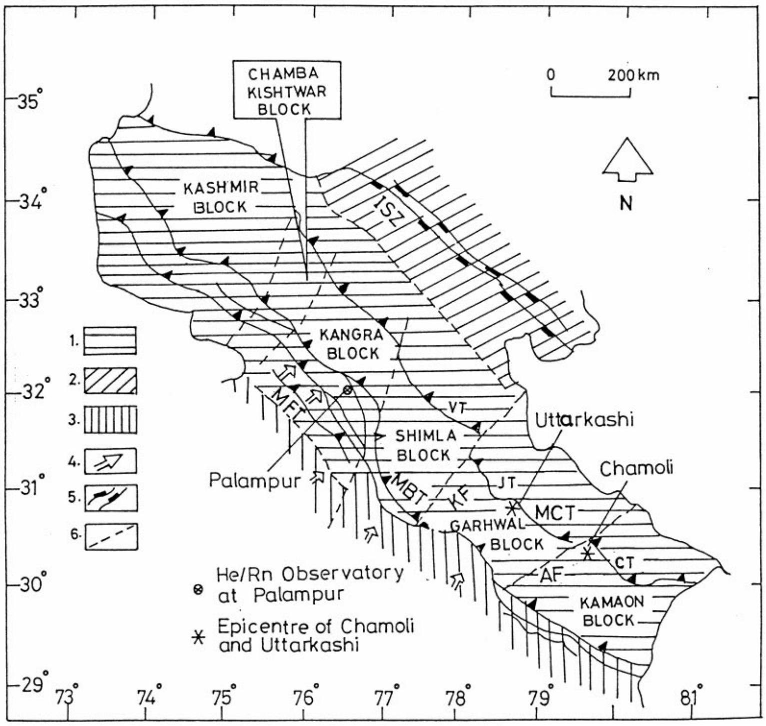

Fig. 1. Tectonic map of NW Himalaya showing main thrustal blocks: 1. main Himalayan seismic zone; 2, high Himalayan seismic zone; 3, foot hill seismic zone; 4, direction of crustal shortening; 5, Indus suture zone; 6, block boundary based on geological/geophysical/tectonic attributes. MBT, main boundary thrust; MCT, main central trust; MFT, main frontal thrust; ISZ, Indus suture zone; AF, Alaknanda Fault; KF, Kaurik Fault; CT, Chail Thrust; JT, Jautogh thrust; VT, Vaikrita thrust (adotopted from Narula et al., 2000).

al., 1984/1985; Igarashi and Wakita, 1990; Heinicke et al., 1995; Segovia et al., 1995; Virk, 1996). However, studies of these pre-seismic phenomena have been controversial for several reasons (Silver and Wakita, 1996; Wakita, 1996). During the last decade some highly useful data on the correlation of radon anomalies with seismic events which occurred in the N-W Himalaya have been reported (Virk, 1986, 1990, 1995; Ramola et al., 1990; Virk & Singh, 1992, 1993, 1994; Virk et al., 1995, 1997; Virk and Sharma, 1997). Radon monitoring started in 1989 at Palampur in the Kangra valley using plastic detectors and emanometry. Radon anomalies in soil-gas and groundwater were correlated with seismic events in N-W Himalaya. The apparent postdiction of the Uttarkashi earthquake (Virk, 1998) at our radon network in Kangra valley encouraged us to set up five more stations using alpha-logger probes for continuous monitoring of radon in real time. Time series radon data in soil-gas and groundwater during 1992–1998 have established that more than 50% of radon anomalies are correlatable with microseismic events of 2–4 M (Virk and Sharma, 1997).

Helium monitoring was started at Palampur during 1997. The global value of helium concentration in soil-gas is 5 ppm only. In general, helium is emanated from deeper layers of the crust than radon in the earthquake preparation zone during the strain build up. Hence helium is a better precursor than radon and the conceptual He/Rn ratio model (Virk et al., 1998) is proposed to be tested in N-W Himalaya. To date, we have only two events, the Sundarnagar earthquake of $M_s = 5.1$ on 29 July, 1997 (Virk, 1999) and the Chamoli earthquake of $M_s = 6.5$ on 29 March, 1999, where both helium and radon anomalies were precursory. This suggests that helium responds to seismic events of $M = 5$ or higher but its signatures are not visible for microseismic events of 2–4M. In fact, this is a preliminary study to test the novel idea for forecasting of earthquakes.

2. Experimental techniques

Radon is monitored in soil-gas and groundwater by using an emanometry technique. An emanometer (model RMS-10) manufactured by the Atomic Minerals Division, Department of Atomic Energy, Hyderabad is used to measure the alpha emanation rate from radon in the gas fraction of a soil or water sample by pumping the gas into a scintillation chamber using a closed-circuit technique (Ghosh and Bhalla, 1996). This technique gives instant values of radon concentration and is therefore highly suitable for quick radon surveys.

In this method, the auger holes, each 60 cm in depth and 6 cm in diameter, are left covered for 24 h so that soil-gas radon and thoron become stable. The soil-gas probe is fixed in the auger hole forming an air-tight compartment. The rubber pump, the soil-gas probe and the alpha detector are connected in a closed-circuit. The soil-gas is circulated through a ZnS coated chamber (110 ml) for a period of 15 min, allowing the radon to uniformly mix with air. The detector is then isolated by clamping both ends, and observations are recorded after 4 h when equilibrium is established between radon and its daughters. Alpha particles emitted by radon and its daughters are recorded by the scintillation assembly consisting of photomultiplier tube and a scaler-counter unit.

Radon monitoring in water is also carried out by using the closed-circuit technique. Groundwater samples are collected daily from a 'bauli' (natural spring) in a 250 ml sample bottle. The air is circulated in the closed-circuit containing a hand-operated rubber pump, the water sample bottle, a drying chamber and a ZnS(Ag) detector cell for 10 min. The alpha counts are recorded after 4 h during which the equilibrium between radon and its daughters is established.

A helium leak detector ASM 100 HDS (Alcatel Company, France) based on a sniffing technique has been used for helium analysis in soil-gas at Palampur using discrete sampling at a fixed site daily. The detector is comprised of a helium gas analyser with a pumping system. The main component of the helium leak detector is a spectro-cell which acts as a mass spectrometer. In soil-gas, helium is estimated directly by a sniffing probe from an auger hole. The helium ion analysis is based on the partial pressure of helium in the system which is calibrated to yield the helium concentration in ppm. The calibrated logarithmic scale displays the helium concentration in ppm. The whole operation is fully automatic and helium values from 0.1 ppm to 100% helium can be measured.

3. Geodynamics of Garhwal Himalaya

The Himalayan mountain range, an outcome of the compressional process ensued by the India-Asia collision (70–40 Ma) has been undergoing extensive crustal shortening along the entire 2400 km long range. A series of major thrust planes; the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT) have been formed as a result of these processes (Gansser, 1964). The evolutionary model of Himalayas (Le Fort, 1975) considers the MCT to be the older thrust plane that was more active in the early phases of the Himalayan orogeny and MBT is a younger one that is more active currently. The steady-state model (Seeber and Armbruster, 1981) treats both the MCT and MBT to be contemporaneous and merging at depths with a common detachment surface where the great Himalayan earthquakes are believed to originate. The seismicity of the Himalayas, therefore, needs to be understood in terms of the relative roles of these thrust faults.

Tectonically, the MCT represents a ductile shear zone at depth, comprising a duplex zone with three distinct thrust planes: MCT I, MCT II and MCT III from south to north. Based on the degree of metamorphism, lithostratigraphy and tectonic setting, these thrust planes are also referred to as *Chail* (MCT I, lower thrust), *Jutogh* (MCT II, middle thrust) and *Vaikrita* (MCT III, upper thrust) (Valdiya, 1980). The Chamoli earthquake appears to be associated with the ongoing deformation along the youngest *Chail* thrust (MCT I).

Narula (1992) divided the main longitudinal Himalyan seismic zone into discrete seismotectonic segments with well defined transverse boundaries marked by interpretative fundamental faults. These segments are the Kashmir block, Chamba-Kishtwar block, Kangra block, Shimla block, Garhwal block and Kumaon block (Fig. 1). Narula and Shome (1992) suggested that transverse features have a significant role in the generation and modification of some parameters. The segmentation boundaries might act as earthquake nucleation sites with rupture propagation only in one direction along the longitudinal seismic source. Macroseismic surveys conducted for earthquakes in the NW Himalaya have indicated that most of the isoseismals attenuate very rapidly in one direction resulting in asymmetrical pattern.

The Garhwal seismic block, defined by the *Kaurik* fault in the west and the *Alaknanda* fault in the east constitutes one of the highly active seismic zones. The energy release in the region bounded by latitude (29.5°N–31°N) and longitude (70°E–81°E) has been of the order of 10^{23}ergs/decade (Narula et al., 1995). Two catastrophic events have occurred within a decade in the form of the Uttarkashi (1991) and Chamoli (1999) earthquakes with manifestation of large seismic energy release which took a toll of about 2000 human lives and damaged a hundred thousand houses.

Fault plane solution of the Chamoli main shock as reported by US Geological Survey (USGS) with two nodal planes striking at 282 and 97° is shown in Fig. 2. The parameters given by USGS and IMD (Indian Meteorological Department, N. Delhi) are as follows:

Parameters	USGS	IMD
Magnitude	M_w 6.4, m_b 6.4, M_s 6.6	M_b 6.8, M_s 6.5
Origin time	19:05:10.0 (UT)	19:05:13.4 (UT), 00:35:13.4 (IST)
Epicentre	30.550 N, 79.424 E	30.48 N, 79.416 E
Depth	15 km	21 km
M_o	5×10^{25} dyne.cm	–
Half-duration	4.0 s	–
Fault-plane	strike 282°, dip 9° N, slip 95°	–

Geological map of the area indicates the presence of an anticlinal structure very close to Chamoli. A sharp contact of MCT I with recent deposits was located on the southern flanks of this anticline.

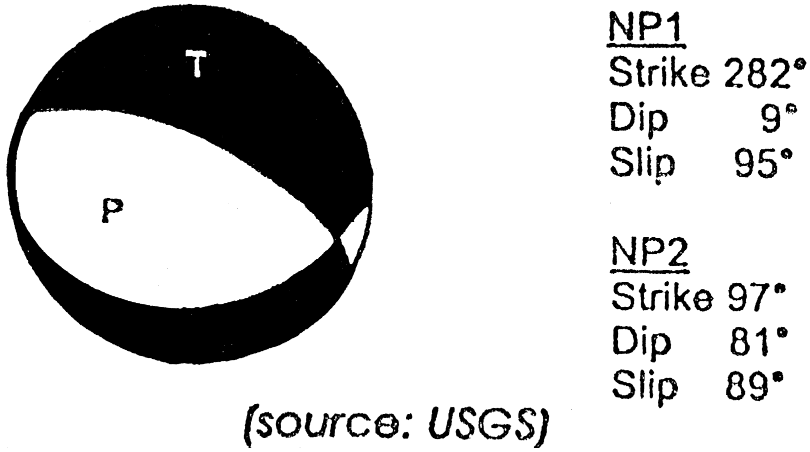

Fig. 2. Fault plane solution of the Chamoli main shock recorded on 29 March 1999.

The tight compressional folding in the Berinag quartzite and the stretching lineation in mylonitic quartzite observed at these localities are suggestive of the intense shortening along this contact. These observations are significant because the contact of the thrust plane occurs very close to the epicentral zone of the Chamoli earthquake.

4. Helium/radon ratio model

It is felt that radon abundance alone may not be relied upon as an earthquake precursor but should be correlated with a deep origin gas like helium. Radon coming from deep layers of the crust ($>$ 500 m) may not be detectable at the surface due to its short half life of 3.8 days. Helium, on the other hand consists of two stable isotopes, ^{3}He and ^{4}He with a ratio $(11–14)\times10^{-6}$, 2×10^{-8} and 1.4×10^{-6} in the mantle, crust and air, respectively (Zhignan, 1997). ^{3}He is primordial in origin and occurs in traces in mantle-derived magma. ^{4}He is a highly mobile gas and originates at deeper layers of the crust ($\geqslant$ 5 km) from the decay of U/Th series. It is highly stable and diffuses through interstitial spaces in rocks during strain build up prior to an earthquake. The presence of radon and helium anomalies in geothermal springs of N-W Himalaya indicates the depth distribution of radioactive elements in the deep crustal layer (Virk et al., 1998). However there is utter lack of isotopic geochemical studies to determine gradient of U/Th distribution in the crust. Most U/Th anomalies occur as pockets in the form of sandstones and conglomerates in the sedimentary rocks. The situation is further complicated by the well established 'Inverted' metamorphism of Himalayan rocks (Kaul et al., 1993).

A hypothesis based on the mobility of radon and helium gases in crustal layers may prove more useful in earthquake prediction studies. Groundwater helium content has been used as a pathfinder of fault systems and a precursor to some of the earthquakes (Biagi et al., 1999; Quattrocchi et al., 1999). But the idea of helium/radon ratio as an earthquake precursor has never been tried before.

The various stages of the conceptual model (Fig. 3) of the mobility of helium and radon gases prior to an earthquake (Sharma, 1997; Virk, 1999) may be described as follows:

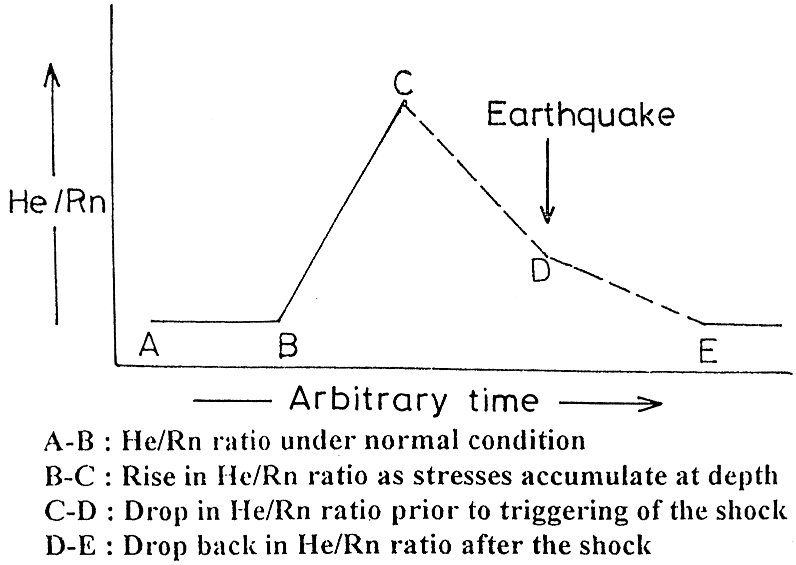

Fig. 3. A conceptual He/Rn ratio model as a predictive tool for earthquakes.

i. Under normal stress/strain conditions, the helium to radon ratio may have some constant value depending on the geology and meteorological conditions at the monitoring site (Segment AB).

ii. Stress build up around the hypocentre, eventually causing an earthquake. During this phase, first helium is affected at deeper layers and its emanation rate increases. As a result, the He/Rn ratio rises sharply (Segment BC).

iii. When the stress reaches the elastic limits before the rupture, radon emanation is enhanced from upper crustal rocks under excessive strain and hence He/Rn ratio falls suddenly (Segment CD); this is an alarm signal for the impending earthquake.

iv. After the earthquake, both Rn and He drop down to normal values after relaxation of strain as the ground conditions stabilise (Segment DE).

5. Results and discussion

The Chamoli earthquake of magnitude 6.5 M_s occurred at 00:35.50 (IST) on 29 March 1999 with epicentre at 30.2°N, 79.5°E. The epicentre was situated about 13 km northwest of Chamoli town in the Garhwal Lesser Himalaya, with a focal depth of 15/21 km as reported by USGS/IMD. A radon anomaly (defined as radon spike crossing $\bar{X}$ by 2σ, where $\bar{X}$ is the average value and σ, the standard deviation) was recorded simultaneously in both soil-gas and groundwater on 27 March at Palampur (32.10°N, 76.51°E) which is about 393 km from the Chamoli earthquake epicentre, with radon activity crossing the 2σ level above the average value. Temporal variations of radon in soil-gas and in groundwater recorded during March 1999 at Palampur are shown in Fig. 4. The average radon values recorded during 1999 at Palampur in soil-gas and groundwater were 24.31 and 56.69 Bq/l with a standard deviation of 10.4 and 4.66 Bq/l, respectively. The radon anomalies were recorded in both the media on 27 March, with the peak values of 46.63 and

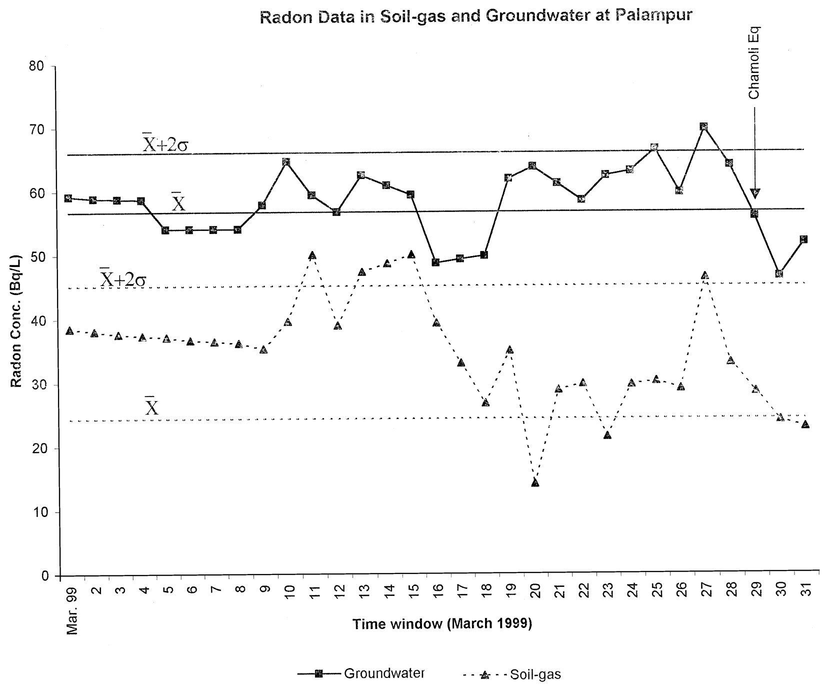

Fig. 4. Radon anomalies in soil-gas and groundwater at Palampur as a precursor to Chamoli earthquake.

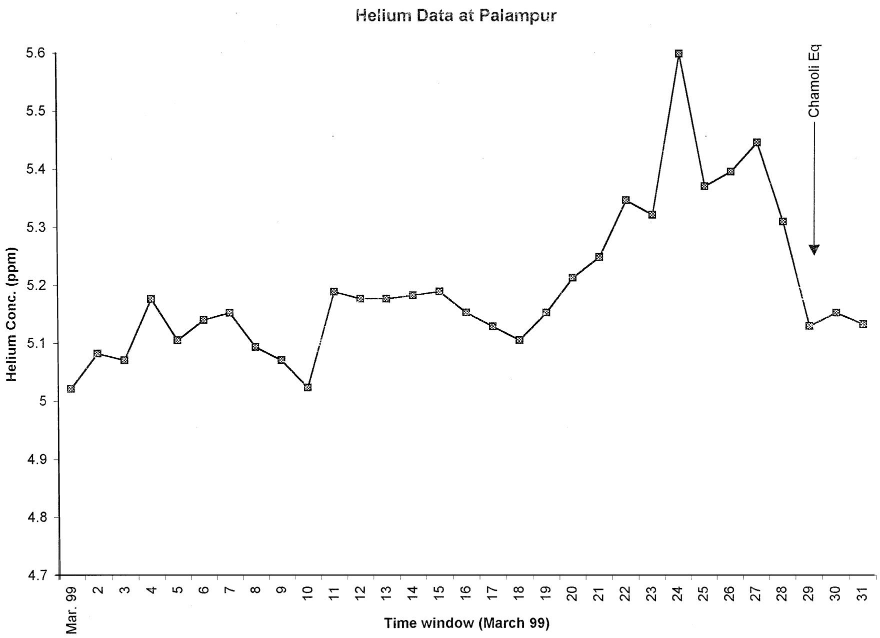

Fig. 5. Helium anomaly in soil-gas at Palampur as a precursor to Chamoli earthquake.

69.66 Bq/L, crossing the $\bar{X}$ 2σ level (Fig. 4). In fact, radon fluctuations started on 10 March with some highs and lows (Fig. 4) attaining its minimum value on 20 March and the final peak on 27 March. This appears to show the stress behaviour of crustal rocks.

The epicentres of both the Uttarkashi and Chamoli earthquakes lie along MCT (Fig. 1). Helium variations in soil-gas during March 1999 at Palampur are shown in Fig. 5. Helium concentration starts rising in March and an anomaly was recorded on 24 March, 3 days before the radon anomaly and 5 days before the Chamoli earthquake. This clearly shows that helium is influenced by strain build-up prior to radon. The same trend is observed in He/Rn ratio (Fig. 6). On 19th March, there was a sharp rise in He/Rn ratio, with a peak value on 20 March, followed by a sudden fall with a minimum recorded on 27 March. This sudden rise and then fall in the He/Rn ratio seems to be a precursory signal for the impending earthquake which occurred near Chamoli in Garhwal Himalaya.

The stresses causing an earthquake develop closer to the focal depth would affect the upper layers of the crust at a later phase (Fig. 3). This would increase the emanation of helium from depth while the radon emanation from the upper crust may remain unchanged. Thus a rise in helium/radon ratio is a natural consequence, which would increase progressively as the stresses build up. The continuous rise in He/Rn ratio is thus a precursory signal of an earthquake event. During the next phase when strain reaches closer to the surface, the radon emanation would also increase and He/Rn ratio would drop, which would be the alarm signal. The observed trend (Fig. 6) follows the He/Rn ratio model and may be considered as a preliminary test of this time predictive tool for future earthquake prediction.

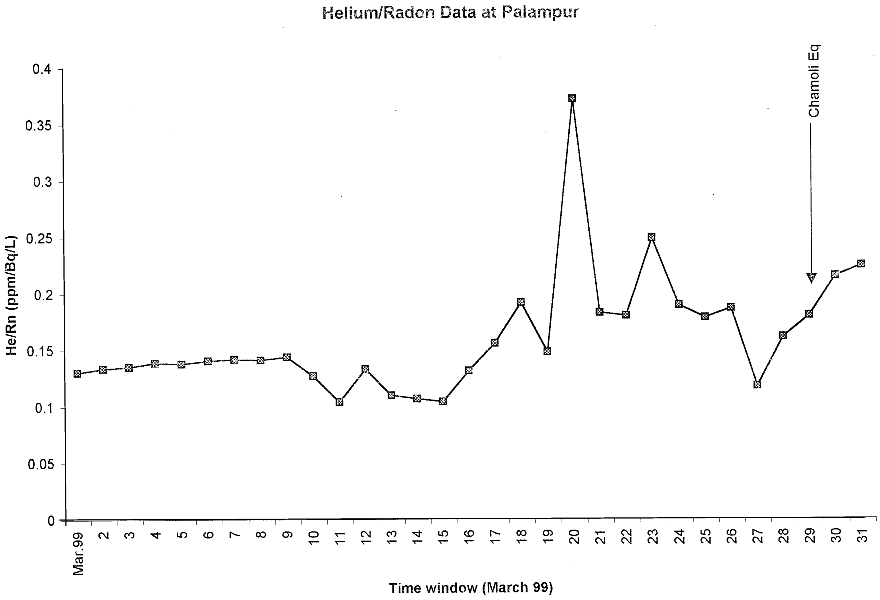

Fig. 6. Helium/radon ratio anomaly in soil-gas at Palampur as a precursor to Chamoli earthquake.

6. Conclusions

1. The preliminary study reveals the validity of conceptual helium/radon ratio model as a predictive tool for earthquakes in N-W Himalaya.
2. To date, we tested our hypothesis on two events only; hence the result is not statistically significant.
3. The seismic gap between the great Kangra earthquake ($M = 8.6$) of April 1905 and the Bihar-Nepal earthquake ($M = 8.4$) of 1934, viz. Garhwal seismic gap, needs careful monitoring as it may rupture causing wide spread damage to life and property in the region. The accumulation and release of seismic energy is witnessed by two major earthquakes which occurred in a short span during this decade.
4. The steady-state model of Himalayan orogeny (Seeber and Armbruster, 1981) is vindicated. According to the evolutionary model (Le Fort, 1975) and on the basis of focal mechanism, it has been argued that MCT is probably aseismic and the current acivity is due to the MBT. However, Chamoli earthquake proves that the most recent activity is associated with the MCT.
5. The helium/radon ratio is not sensitive to microearthquakes as Chamoli aftershocks are not recorded in the form of helium/radon anomalies.

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