A study of fluctuation in radon concentration behaviour as an earthquake precursor

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Before, during and after many large earthquakes significant change in concentration of radon has been observed in China, Japan and India. To establish this behaviour as a potential earthquake precursor, it is important to understand the phenomenon in terms of geodynamics. Here I propose a geodynamic model to establish a correlation between precursory radon concentration fluctuations and an impending earthquake. The model has been validated by field data collected from Japan and China. Further investigation with this model also helps to find a possible explanation for abnormal variation in the geomagnetic field intensity observed before, during and after some earthquakes.

LARGE earthquakes (M 5.5 or more) are the most devastating of all natural calamities to human life and property. Therefore, scientific research leading to successful prediction of large earthquakes, sufficiently in advance, has great significance to mankind. Unfortunately, to this date, no reliable method for successful earthquake prediction with precise timing, location and intensity has been developed. Nevertheless, based on long-time studies, some earthquake precursors like change in ion concentration in water, variation in concentration of He, Ne, Ar, Rn and N2 in the environment of the affected zone, abnormality of behaviour in some animals, occurrence of milder fore shocks before a large earthquake, sudden water-level change in some wells, ground deformation, stress build-up in the ground rocks (which may in turn alter electric resistance of the rocks), etc. have been identified. But most of these precursors behave erratically and therefore have been poorly understood so far and earthquake prediction has become a controversial issue.

To understand the exact relationship of a precursor with an impending large earthquake, it is essential to know the geodynamical reason behind the occurrence of that precursor. Erratic change in radon concentration has been observed in many earthquake-prone zones a few months before, during and after a large earthquake. Such behaviour has been observed in deep wells where inducement of radon concentration fluctuations from the environment can virtually be ruled out. Therefore, it is tempting to consider a sudden erratic fluctuation in radon concentration, for days on end, particularly in deep wells in an earthquake-prone zone, as a potential omen for an impending large earthquake. Here an analysis of the precursory radon concentration behaviour during the Izu-Oshima-kinkai earthquake (M 7.0) during 1978 in Japan will be undertaken, and based on this a geodynamic model will be proposed, which has been validated by data collected during some other earthquakes.

Let us try to find an explanation for the erratic fluctuations in radon concentration recorded in an artesian well in Izu peninsula of Japan, before, during and after the 14 January 1978 Izu-Oshima-kinkai earthquake (M 7.0, Figure 1).

Most of the rocks in the earth's crust, as well as soil and alluvium derived from it, contains uranium. About 99.3% of this uranium is the isotope U-238. Decay of an U-238 atom marks the beginning of a series of 14 decays that ends at the isotope Pb-206. Rn-222 (half-life 3.82 days, directly derived from Ra-226) is an intermediate radioactive, inert, odourless, colourless, gaseous daughter isotope in the decay of U-238 to Pb-206. Because of the short half-life of Rn, it is generally believed that most of the naturally occurring Rn in the environment comes from only within a few metres of depth in the earth's crust. The continental crust has an average thickness of 30 km, reaching its highest value of 70 km in the Tibetan plateau, and minimum at the spreading plate boundaries. A standard argument for the variation in dissolved gas concentration in water wells before, during and after an earthquake in that zone, is the variation in release of the gases entrapped in crustal rocks due to pore collapse and/or crack build-up caused by variation in stress. Being an inert gas, radon concentration cannot be varied due to chemical reaction with other substances exposed due to crack build-up in the rocks. Normally, its source on the earth is U-238 in the near-surface crustal rocks, whose typical concentration level is 1 to 4 parts per million (ppm). To explain the erratic precursory radon concentration behaviour in Figure 1, I propose the following model.

Figure 1. Precursory radon concentration fluctuations of 1978 Izu-Oshima-kinkai earthquake observed in an artesian well, 25 km away from the epicentre. The heavy dotted line shows the average annual variation calculated from data for eight years. (After Wakita et al.*)

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The pattern of convection beneath the earth's surface plate, on which the plate tectonics and therefore earthquakes depend, remains one of the main unsolved problems in geophysics. Because both seismic earth models and mineral physics studies suggest that any present-day chemical density heterogeneity in the mantle cannot exceed 1–2%, the mantle is often assumed to be homogeneous for the purposes of dynamic modelling. Clearly, this is only an approximation. The upper mantle, near the subduction zones, where subducted lithospheres with strong chemical heterogeneity on the scale of tens of kilometres are slowly being recycled back into the mantle, must bear the signature of this heterogeneity. In fact, chemical segregation is favoured over homogenization by kinematic mixing.

In laboratory experiments, under much more simplified conditions compared to the actual mantle, 'doming' regimes have been observed at a layer of viscosity stratification in a thermochemical flow model. The Rayleigh numbers of the experiments are comparable to those of the actual mantle flow. Hot plumes come out from a small neighbouring area centering the uppermost point of the dome. In a recent study, four high-viscosity stratification layers in the mantle have been identified, the uppermost being only 220 km deep. Chemical heterogeneity near a subduction zone, coupled with this viscosity stratification, should also give rise to smaller (only of the order of a few thousand cubic km), shortlived blobs (existing only for a few tens of years before being mixed-up in the mantle), unlike the megablobs in existence for hundreds of million of years, as inferred by Davaille. Hot, cylindrical, axisymmetric plumes of diameter only from a few hundred metres to a few kilometres will reach up to just below the plates. There is a region of upper mantle, 50 to 150 km deep, with low viscosity and low seismic velocity (i.e. with low density) over which plates glide, like rafts floating on sea. Hot-plume injection in this region near a subduction zone will expedite plate motion, by reducing viscosity and/or increasing negative buoyancy (by density reduction), which may lead to the advancement of an earthquake. In this regard, it is interesting to note the excellent correlation observed between seismic activity of an earthquake-prone zone with artificial injection of water in the rocks, although the two mechanisms and effects are completely different.

Studies carried out clearly indicate that the flow inside the mantle is turbulent, in the sense that (i) the velocity field is random and (ii) vortices occur chaotically. Turbulent flow and temperature variations in the upper mantle may occasionally increase the pressure inside the blob, leading to a sudden increase in plume discharge from it. This, in turn, will increase the plate motion sometimes (but not always) leading to an earthquake. Alternatively, the conduit through which the plume is upwelling may get choked for sometime, leading to a pressure build-up inside the blob. When the pressure level becomes sufficiently high the conduit may burst, much like a blocked pressure cooker valve, ejecting greater amount of plumes than usual for sometime, till the pressure level inside the blob returns to normal. This process may expedite the plate motion more than it has initially slowed down depending on the duration of choking and the magnitude of the upwelled magma after the blast.

To explain the precursory erratic radon concentration behaviour of Izu-Oshima-kinkai earthquake (Figure 1), let us note that the high annual average radon concentration cannot be due to a source from near the surface of the earth, but rather from much deeper underground. It is actually coming out of the Moho through a conduit across the plate. The Moho in this region got its supply (steady at least for several years) of U-238 from a blob just underneath, through upwelling plumes. Just a few months before the 14 January 1978 event, the magma upwelling conduit above the blob got choked-up, leading to an intermittent release of smaller-than-usual amount of uranium. (The uranium concentration is diluted fast through mixing in the low viscosity and low density region, where the velocity of ejection is much higher than the usual convection speed in that layer.) The average concentration of U-238 in the interior of the earth is $30.8 \times 10^{-8}$ kg/kg and that at the uranium ore is $10^{-4}$ kg/kg, as characterized by sudden step-like lowering in the rate of radon emission in Figure 1. When the burst occurred, it cleared the block at the magma upwelling conduit leading to a greater-than-usual uranium supply at the Moho just above, which in turn increased the radon emission rate just before and after the 14 January event, as shown in Figure 1. The hypothesis is further bolstered by the data presented in Figure 2 in conjunction with the above-mentioned radon emission rate (see Figure 2 a). In Figure 2 b, water-temperature variation in a 500 m well, at an epicentral distance of 30 km, has been recorded. In Figure 2 c and d water-level variation at the well of (Figure 2 b) and the ground strain variation (at a borehole strain-meter placed at an epicentral distance of 50 km) have respectively been recorded. From the data of Figure 2, it is apparent that the water in the well (Figure 2 b) is directly being heated by hot gas emanating from the plume under the plate and reaching the well by diffusion through small cracks across the plate (unfortunately, no chemical analysis data of the well-water at that time is available to further confirm or reject this assumption). As the plate slowly subducts, the ground strain is relaxed leading to crack enlargement, which decreases the water level in the well (by 0.3 m) by consuming some of it. But since the plume has ceased to upwell due to temporary choking of the plume conduit over the blob in the upper asthenosphere region, the water temperature falls instead of increasing even after enlargement of the cracks. This is compatible with a similar fall in the radon emission rate level at the well (Figures 1 and 2 b). The subsequent
rise in radon emission rate level (Figure 2a) and water-temperature increase (Figure 2b) are also compatible. It is worthwhile to note that during observation of radon concentration in the well of Figure 1 from May 1977 to August 1986, no significant change was observed due to other earthquakes of magnitude greater than $M_5$ within an epicentral distance of 100 km and greater than $M_6.5$ within 600 km

A simple mathematical model of elliptic spreading of hot magma (for clue see Figure 1b of Manga), in the Moho, ejected through the plume conduit on top of a blob is being proposed. According to this model, the two-dimensional magma flow in the Moho is turbulent at any point of time. According to some opinion, turbulent flows cannot be modelled by the Navier–Stokes equations. Here I propose the following set of equations for modelling the two-dimensional magma spreading through the Moho. (Equations (1) and (2) represent a general form of flow in a plane. By choosing the values of $v_i$, $A_i$, $m_i$ and the form of the functions $f_i$, any flow in a plane can be modelled by eqs (1) and (2), as shown here in case of an elliptical flow.)

$$u_1(x_1, x_2, t) = v_1(x_1, x_2, t) + A_1 e^{-m_1 f_1(x_1, x_2, t)}$$  \[1\]

$$u_2(x_1, x_2, t) = v_2(x_1, x_2, t) + A_2 e^{-m_2 f_2(x_1, x_2, t)}$$  \[2\]

$u_i$ is the total velocity component along $x_i$, $v_i$ is the linear velocity along $x_i$, $A_i e^{m_i f_i(x_1, x_2, t)}$ is the curvilinear (spiral) component of velocity along $x_i$, for $i = 1, 2$. $A_i$ and $m_i$ are constant numbers whose values lie in some closed, bounded intervals of the real line. (The absolute value of $m_i$ is an increasing function of Rayleigh number and determines the angular shape of curving, $A_i$ determines the radius of the curving), $f_i$ is a function giving the angular span of curving. $A_1$ and $A_2$ are of the order of tens of kilometres. Moreover, if the flow is approximately elliptical, then we should take

$$f_1 = \frac{1}{m_1} \log(\sin t)$$  \[3\]

$$f_2 = \frac{1}{m_2} \log(\cos t)$$  \[4\]

where $t$ is of the order of years and therefore $\sin t$ and $\cos t$ can be taken as positive in a few months to few years range. Since here I am concerned with the curvilinear spreading of flow only, keeping the centre of propagation (the hole of plume ejection) fixed, $v_1 = v_2 = 0$.

Geochemical heterogeneity within the upper mantle is not limited to the subduction zones alone. Due to existence of diverse isotopic suits throughout the upper mantle, the upper mantle has been modelled like a ‘plum pudding’. So blobs can also form below, deeper inside the plate. Ejection of plumes from such blobs may affect the intraplate stress build-up, expediting an intraplate earthquake.

In a two-layer mantle convection model, the concentration of radiogenic heat sources (U-238, U-235, Th-232 and K-40) in the lower mantle is only about 1.5% of the average heat-source concentration in the entire mantle. In a more detailed model, the upper mantle itself is subdivided, according to viscosity stratification, into two zones separated by a high-viscosity layer at 220 km depth. The density variation is the highest in the whole mantle above this layer, possibly forming the continental and the oceanic crusts at the surface, like accumulation of cream over boiled milk after cooling. Mantle flow through the high viscosity barriers (at least four) is

\[\text{Figure 2. Precursory changes of the 1978 Izu-Oshima-kinkai earthquake.} \]

\[\text{a. Radon concentration change observed at the well of Figure 1.} \]

\[\text{b. Water-temperature variation observed at a 500 m well (epicentral distance 30 km).} \]

\[\text{c. Water-level variation at the well of (b).} \]

\[\text{d. Strain change measured by a borehole strainmeter at the tip of the peninsula (distance 50 km). After Wakita et al.} \]
maintained through upwelling of plumes in a smaller scale, compared to the ones in Hawaii, which gradually depletes the lower parts of the mantle of radiogenic heat producing materials and enriches the upper parts of the mantle with their deposit. This process becomes the richest in radiogenic substances through the uppermost high-viscosity layer at 220 km depth. The spike-like fluctuation in the precursory radon concentration behaviour before several earthquakes of intensity $M \geq 5.5$ or more, as recorded in Guza station (located at the intersection of three major fault systems) in China (Figure 3), is directly related to this phenomenon. The smaller plume conduits, where plume strength varies in time and possibly deformed by other motions in the flow, often tend to get choked-up. Due to radiogenic heating inside the blob, the pressure keeps building up. When the pressure becomes sufficiently high, the choke in the conduit is blown up, releasing a sudden spurt of U-238-rich plume for some-time before being choked-up again. This may affect the strain build-up in the plate directly above by expediting the plate motion, sometimes (but not always) leading to an intraplate earthquake. Radon, produced by U-238 decay, might be reaching the station through some cracks across the plate and after the plume conduit chokes up, the uranium concentration below the plate is diluted fast through rapid mixing in the low-viscosity and low-density region.

The simulation given in Figure 4 will help analyse the precursory change in geomagnetic field intensity during some moderate-to-large earthquakes in China and Mongolia (Figure 5).

The propagation of hot magma as shown in Figure 4, is in general turbulent, due to numerous collisions with the subsolidus rock. But if the radioisotope-rich magma at some portion gets an average angular velocity, as shown in Figure 4, then the emitted $\alpha$, $\beta$ and $\gamma$ rays due to radioactive decay ionize some of the neighbouring materials and release free electrons. The circulation of free electron-rich magma in a path indicated by arrows in Figure 4, will produce a magnetic field. According to its orientation, it may increase or decrease the geomagnetic field intensity as experienced on the surface of the earth.

Magma upwelling below a plate near the boundary may help plate subsistence due to negative buoyancy (upwelled magma is hotter and therefore less dense than the surrounding). This may expedite an interplate strike-slip earthquake, like the one that occurred on 12 June 1897 in Assam, India ($M = 8.1$)\(^1\). Radon concentration fluctuation monitoring has been going on for about two decades in the Himalayan region also\(^6,16\). Here too, the correlation between erratic fluctuations in radon concentration and seismic activity is clear\(^6,16\). It has been demonstrated that

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**Figure 3.** Spike-like changes in radon concentration observed at Guza station, Sichuan Province, China before several earthquakes of magnitude $M \geq 5.5$ or more, within an epicentral distance of 320 km. After Wakita et al.\(^4\).

**Figure 4.** Magma propagation below the plate after upwelling through an axisymmetric plume at the centre (diameter 2 km). In reality, the upwelled magma will collide with the subsolidus rock in the Moho and the velocity vector will be random at each point. A more complicated calculation of eqs (1) and (2) at a finer resolution will give a more realistic simulation. But even the present simple simulation will help explain phenomena like precursory change in geomagnetic field intensity\(^4\). If the radioisotope-rich magma in certain regions gets an average angular velocity as indicated by the arrows, it will affect the geomagnetic field intensity.
even in case of small earthquakes (M 4.5 or less), erratic fluctuations in radon concentration is clearly observable before, during and after an earthquake\(^\text{16}\). Radon concentration fluctuation data collected from Chamba station (in Himachal Pradesh, India) during March 1995 have been presented in time series form (see figure 3, Virk et al.\(^\text{6}\)). An earthquake of M 5.1 occurred in Chamba on 24 March 1995. Here too, several days before the quake, radon concentration level went down (possibly because of choking as described above) and then suddenly shot up abnormally (because of the sudden burst of the choked conduit) a few days before the earthquake. Right at the time of the quake, it reached almost the usual level. But the earlier events had already expedited the plate motion, leading to the 24 March earthquake, or at least some advancement of it.

Validating an earthquake precursor through an acceptable geodynamic modelling and accounting for its occurrence is a challenging task. Earthquakes are seen as consequences of plate tectonics. Plate motions are controlled by the complex dynamics of mantle flows, which depends on the thermal states and chemical composition of the mantle. Upwelling of hot plumes and downwelling of colder, denser materials keep running the cycles of vertical mantle flow over geologic time. Therefore, it is only natural to expect that plume upwelling and propagation below the plates may have significant effects on the seismic activities. Based on the findings of some recent research\(^\text{9,10}\), here a model has been proposed for upwelling and spreading of radioisotope-rich magma below the plates, which leaves its signature in the erratic radon concentration fluctuations, as observed before, during and after some earthquakes in China, Japan and India. With this model, the geomagnetic field intensity change as a precursor to some earthquakes can also be explained. Based on the validity of the model, radon concentration and geomagnetic field intensity variation give a direct measure of the velocity field and chemical composition of magma upwelling and propagation below the plate, from which the prospect of an intermediate-term prediction of an impending large earthquake can sometimes be improved.

This should be viewed as a complementary and not competitive effort for earthquake prediction in addition to the existing ones like the measurement of rupture propagation\(^\text{3,17}\). Further testing of this model with more diverse datasets is needed.


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