Radon anomaly in the soil of Taal volcano, the Philippines: A likely precursor of the M 7.1 Mindoro earthquake (1994)

P. Richon,[1] J.-C. Sabroux,[2] M. Halbwachs,[3] J. Vandemeulebrouck,[4] N. Poussielgue,[4] J. Tabbagh,[5] and R. Punongbayan[6]

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[1] The soil-gas ^{222}Rn concentration had been monitored almost continuously from June 1993 till November 1996 on Taal volcano, Luzon Island, the Philippines. During this measurement period, a singular Mb 7.1 earthquake occurred on November 15, 1994, between Luzon and Mindoro, 48 km south of the volcano. Twenty-two days before the earthquake, an anomalous increase in soil-gas radon (peak to background ratio = 6) was recorded, unique in the whole time series. The possible generation of this anomaly by typhoon *Teresa*, which struck Luzon Island a few days before, was ruled out one year later when super typhoon *Angela*, the most powerful storm to hit the Philippines in ten years, crossed Luzon Island along almost the same track without triggering a similar disturbance in the radon signal. Consequently, there is strong evidence that the Taal radon anomaly originated in stress accumulation preceding the Mindoro earthquake. *INDEX TERMS:* 7223 Seismology: Seismic hazard assessment and prediction; 9820 General or Miscellaneous: Techniques applicable in three or more fields; 8494 Volcanology: Instruments and techniques; 9320 Information Related to Geographic Region: Asia; *KEYWORDS:* radon, precursor, earthquake, volcano, strain, stress. **Citation:** Richon, P., J.-C. Sabroux, M. Halbwachs, J. Vandemeulebrouck, N. Poussielgue, J. Tabbagh, and R. Punongbayan, Radon anomaly in the soil of Taal volcano, the Philippines: A likely precursor of the M 7.1 Mindoro earthquake (1994), *Geophys. Res. Lett.*, 30(9), 1481, doi:10.1029/2003GL016902, 2003.

1. Introduction

[2] Since the great Tashkent earthquake of 1966 [*Sadovsky et al.*, 1972], numerous studies have suggested that the measurement of radon (mainly its isotope 222) concentrations in well water and soil gas could be an effective tool for the prediction of seismic events, still at comparatively long distances from the epicenter [*Wakita*, 1996]. For example, in measurements carried out in Japan, variations of soil-gas radon concentrations were recorded two weeks before the M 6.8 western Nagano Prefecture earthquake, at 65 km from the epicenter [*Hirotaka et al.*, 1988]. The wealth of such anomalies supports the assumption that radon is a possible precursor of earthquakes, potentially effective for an early warning, even though the mechanism connecting distant seismic events and the variation of soil-gas, or groundwater, ^{222}Rn concentrations, remains controversial [*Toutain and Baubron*, 1999]. Indeed, the diffusion length of ^{222}Rn in soil does not exceed a few meters, making it necessary to put forward another mechanism of radon migration. Moreover, superficial meteorological factors (mainly rainfall, temperature, wind and barometric pressure) act upon soil-gas radon concentration, and may hinder variations arising from depth. Radon transport in soil occurs by two processes: diffusion, driven by radon concentration gradients, as described by Fick's law, and advection, driven by pore fluids (water, carbon dioxide, etc.) pressure gradients, following Darcy's law. Both mechanisms are dependent on the porosity and the permeability of the soil, which in turn vary as a function of the stress field [*King*, 1978; *Holub and Brady*, 1981].

[3] In June 1993, we installed an automatic measuring station of soil-gas ^{222}Rn concentration on Taal volcano, the Philippines. The first goal of this experiment was to test such a station under demanding environmental conditions, in order to validate the ARGOS transmission system associated with the radon probe and, eventually, to obtain a soil-gas ^{222}Rn concentration record on an annual basis. The volcanic and tectonically active area chosen for this experiment was regarded as a zone of abnormal permeability, with significant advective fluid transfers. Taal volcano is routinely monitored by *PHIVOLCS*, with a complementary instrumentation by Université de Savoie. Considered as one of the most dangerous volcanoes of the Philippines, it had shown alarming signs of increasing activity since March 1993. The precise spot for radon measurement, located in the north of the central cone of Taal volcano (Figure 1), was selected after a soil-gas radon survey which aimed at identifying a zone with conspicuously high concentrations [*De Luna*, 1993].

2. Investigation Area

[4] Taal volcano, located on the Island of Luzon at 60 km south of Manila, is a very active stratovolcano of the Philippines archipelago. It consists of a 16 × 27 km prehistoric caldera, partly filled by Lake Taal at sea level. A 5 km diameter volcanic cone occupies the center of this lake and concentrates, principally on its SW flank, the historical activity of Taal. A lake (Main Crater Lake) fills the crater of this comparatively small volcanic edifice, which culminates at 311 m a.s.l. This lake has a surface of 1 km^2 and a volume of *ca.* 40 × 10^6 m^3.

[1] Département Analyse Surveillance Environnement, Commissariat à l'Energie Atomique, Bruyères-le-Châtel, France.
[2] Institut de Radioprotection et de Sûreté Nucléaire, Gif-sur-Yvette, France.
[3] Institut National de Recherche Pedagogique, Université de Savoie, Le Bourget du Lac, France.
[4] Centre National de la Recherche Scientifique, Laboratoire de Géophysique Interne et Tectonophysique, Université de Savoie, Chambéry, France.
[5] Université Pierre & Marie Curie, Paris, France.
[6] Philippine Institute of Volcanology and Seismology, Manila, Philippines.

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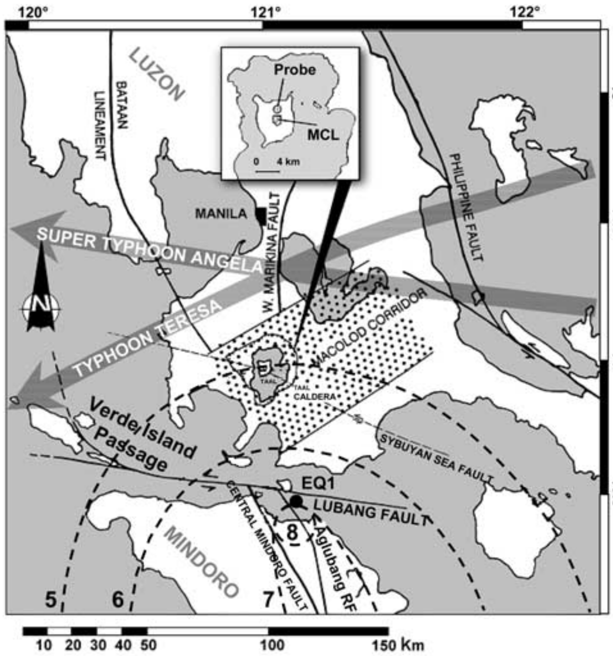

Figure 1. Geographical setting of Taal volcano, Lubang and Aglubang River faults, Macolod Corridor and epicenter of the 1994 Mindoro earthquake (EQ1). The iso-intensity lines of this earthquake, according to the 9-point Adapted Rossi-Forel scale, are also displayed [*PHILVOCS*, 1994], together with the approximative typhon tracks [*Etro and Bassi*, 1994, 1995]. In inset, the more detailed map of Taal volcano displays the radon probe location, north of Main Crater Lake (MCL).

[5] The Philippines archipelago is transected by three parallel NW-SE geological lineaments. Two convergent oceanic plates undergo subduction beneath the Philippines, generating an oceanic trench along the western and eastern coast. The archipelago is dissected by numerous left lateral strike-slip faults, including the Lubang and Aglubang River faults in the Verde Island passage, between Luzon and Mindoro, 50 km south of Taal. The Taal area forms an integral part of the ''Macolod Corridor'' (Figure 1), which is a zone of SW-NE extension and includes, beside Taal, several basaltic volcanoes [*Föster et al.*, 1990].

3. Methods

[6] The BARASOL™ probe (*Algade*, *Bessines-sur-Gartempe*, *France*) measures radon gas by diffusion. It includes a silicon junction, a preamplifier, an amplifier, a window for energy discrimination and a microprocessor which deals with data acquisition and storage. The ^{222}Rn diffuses through the filters placed in a geometrically optimised measurement chamber. The discrimination window (from 0.7 MeV to 6.1 MeV) makes it possible to eliminate any contribution of ^{220}Rn and of the ^{222}Rn short-lived daughters deposited on the detector and on the wall of the chamber. Therefore, in the following paragraphs, the term ''radon'' designates exclusively ^{222}Rn. The detector has an active surface of 470 mm^2 and a biasing voltage of 5 V, leading to a sensitivity of 1 count.h^{-1} = 50 Bq.m^{-3}. Entirely autonomous during at least ten months, the probe allows long continuous recordings with a sampling interval as short as 15 minutes. The probe is buried directly in the ground, with its measuring end at a depth of one meter.

4. Results

[7] The radon probe had recorded data for two years and a half, with a sampling interval of one hour (Figure 2). Several disruptions occurred during the acquisition period, essentially due to the failure of the lithium batteries supplying the radon probe, and to data transmission gaps. The available meteorological record are also displayed in the same figure. A comparative analysis between local meteorology and radon signal does not show any obvious correlation. This is true as well for the conspicuous radon anomaly (up to 30000 Bq.m^{-3} in October 1994), strikingly above the yearly averaged background (*ca.* 6000 Bq.m^{-3}).

[8] We shall now focus on the almost continuous time series including this anomaly (September to December 1994, see Figure 3). An analysis by Fast Fourier Transform (FFT) clearly reveals a diurnal and semidiurnal peak, the 12-hour amplitude being the highest in the so-called ''Section 1'' of the time series, before the onset of the anomaly (Figure 4). It has been demonstrated [*Ferry et al.*, 1996] that this semidiurnal soil-gas radon oscillation originates in the thermally driven atmospheric tide, the amplitude of which is a little over 1 mb in equatorial regions [*Craig*, 1965]. The phase delay between pressure lows and induced radon highs is a small fraction of the 12-hour oscillation period. Consequently, it turns out that the site selected for our radon experiment was sensitive to atmospheric pressure changes, and that strong disturbances in the radon signal were to be expected during the typhoon season. Nevertheless, on October 21, 1994, the typhoon *Teresa* (minimum pressure 963 mbar, intensity 80 knots) passed closest to Taal volcano (Figure 3), without noticeable change in radon soil-gas concentration. Indeed the peak radon anomaly was recorded only three days after the typhoon-induced pressure drop (the duration of which being typically of the order of ten hours), whereas it should be almost synchronous.

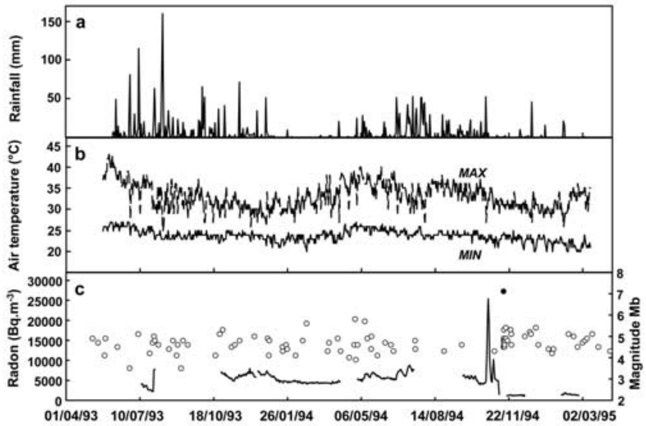

Figure 2. Daily rainfall (a), maximum and minimum air temperatures (b), daily ^{222}Rn in soil-gas and earthquakes (c): ○ earthquake, — radon, ● Mindoro earthquake. Meteorological data by PHIVOLCS, earthquake data by USGS (Iris DMC Event Search). Mindoro earthquake stands clearly as a singular event throughout the time window selected.

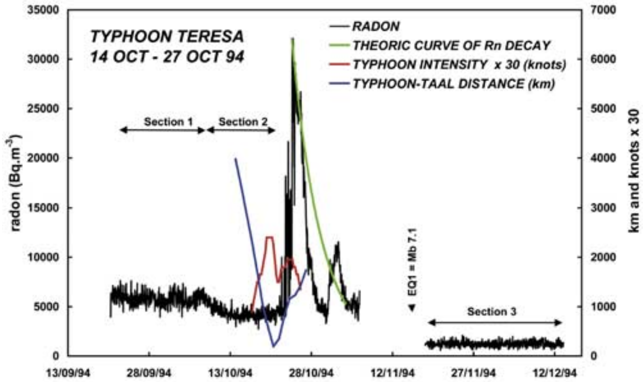

Figure 3. Radon anomaly and typhoon *Teresa* (October 1994): intensity of the typhoon (knots) and distance (km) between typhoon and Taal volcano are displayed together with radon concentration in soil gas. Green curve is the theorical radioactive decay of radon starting at the peak of the anomaly.

[9] Then, it makes sense to attempt correlating the Taal radon time series with local, or regional earthquakes. Seismic data obtained from U.S.G.S. include 80 seismic events being recorded between May 1, 1993 and April 31, 1995, within the latitudes 11.0° and 16.5°N and the longitudes 118.5° and 124.0°E. They are displayed in Figure 2, with their reported magnitude. Event EQ1 (Mb 7.1, Figure 1) occurred on November 14, 1994 at 19:15:30 UT (15 November, local date), with an epicentre located on the Aglubang River fault, 48 km south of Taal, at a depth estimated between 7 and 12 km. Remembered as the Mindoro earthquake, responsible of 78 casualties, it caused ground ruptures around the fault zones, numerous landslides, a tsunami and widespread phenomena of soil liquefaction [*PHILVOCS*, 1994]. The seismic stations recorded 2350 aftershocks in two days. They were all located in two preferential areas, one in the neighbourhood of Verde Island and the other along the Aglubang River and Central Mindoro faults. Superficial effects of the main shock were conspicuous in the north of Mindoro, whereas no ground phenomena were visible in Southern Luzon, which does not exclude extensive ruptures at depth.

[10] The radon anomaly (Figure 3) occurred 22 days before the Mindoro earthquake, with an overall duration of 7 days. This anomaly was surrounded with three quite distinct phases of the time series. The already mentioned section 1 is a sample of the "flat" radon signal: it integrates conspicuous diurnal and semi-diurnal FFT peaks (Figure 4). The anomaly itself displays a steep rise and a comparatively

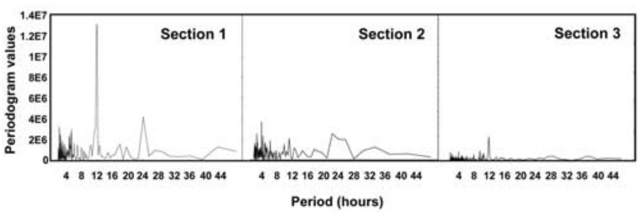

Figure 4. FFT over three representative periods of the radon anomaly (see Figure 3).

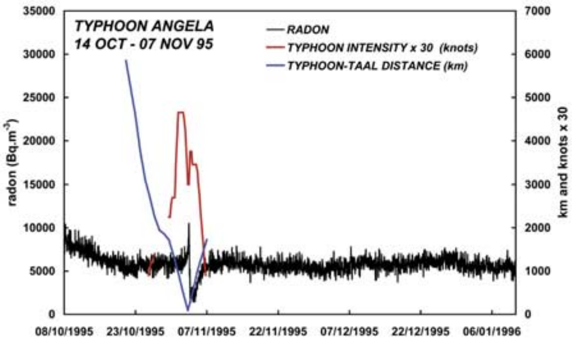

Figure 5. Radon anomaly and super Typhoon *Angela* (October 1995). The scale of this figure and Figure 3. are the same, allowing a straightforward comparison between typhoon characteristics and amplitude of the radon anomaly.

smoother decrease, indicating a vertical motion of soil-gas with advective transport of radon. Section 2 shows a slight fall of the radon signal during the two weeks preceding the anomaly, with a complete disappearance of the 12-hour FFT peak. A few days after Mindoro earthquake, section 3 shows a significant reduction of the soil-gas radon concentration (2000 Bq.m^{-3}), with a weak 12-hour FFT peak. Disruption of data logging in early November, 1994, precludes any observation of a co-seismic radon signal, if any. On the other hand, the radon anomaly recorded on Taal volcano stands clearly as a likely precursor of the Mindoro earthquake. Measurement resumed in August 1995: radon concentration was then back to its 6000 Bq.m^{-3} pre-seismic value. The experiment ended in January 1997. A sample of this time series is displayed in Figure 5.

5. Discussion

[11] As already mentioned, radon concentrations in soil gas are strongly dependant on meteorological parameters. Due to the disturbances generated by a tropical storm (heavy rainfall, barometric pressure drop and gales), it is necessary to scrutinize the possible generation of soil gas radon anomalies by such disturbances. We already ruled out typhoon *Teresa* as the cause of the Taal radon anomaly, on the sole basis of the time lag between both events. One year later, however, a typhoon struck the same area, fortuitously allowing to strengthen our hypothesis. On 3 November 1995, the "super" typhoon *Angela* (minimum pressure 879 mb, 155 knots) passed closest to Taal volcano (Figure 1). Although much more powerful than *Teresa*, it correlated with a smaller radon anomaly (twice, instead of five times the background level), incipient at the very minimum of typhoon distance from Taal volcano (see Figure 5), and with a completely distinct signature.

[12] Another experiment, carried out on Taal volcano during the same period, sheds light on the possible mechanism generating the radon anomaly. A hydrophone was installed at a depth of 40 m in the Main Crater Lake, 19 days before the Mindoro earthquake [*Poussielgue*, 1998]. Underwater noise in the crater lake of an active volcano is, indeed, a powerful means to monitor the volcanic activity, and in particular the gas flow-rate from fumaroles located on the crater floor [*Bercy et al.*, 1983]. The method proved successful before the 1990 Kelut eruption in Indonesia

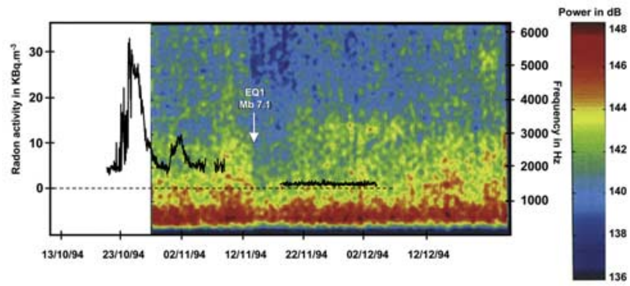

Figure 6. Temporal correlation between soil-gas radon concentration (black curve), and the sonogram of intermediate frequency (<12.5 kHz) underwater noise originating in gas bubbles rising through MCL. Hydroacoustic monitoring started October 27, 1994. The co-seismic decrease of underwater fumarolic gas flow is clearly visible in the sonogram, and correlates with the post-seismic low radon concentration level.

[*Vandemeulebrouck et al.*, 2000]. The Taal hydro-acoustic station samples the acoustic signal over 15-minute intervals in three different frequency bands: low frequencies (<500 Hz), intermediate frequency (<12.5 kHz) and high frequencies (<500 kHz). The outcome is a time-frequency diagram exemplifying, through the bubble noise in the 500 to 2000 Hz band, the flow rate of the fumarolic gas through the crater floor (Figure 6). The co-seismic drop of gas-flow in the lake shows clearly the tectonic control of the permeability in the volcanic edifice and, thus, of the fluid transport within.

[13] A similar control has been noted in other tectonically active settings, such as the Kobe region, Japan, where radon changes in groundwater were interpreted as precursory phenomena of the disastrous January 1995 earthquake [*Igarashi et al.*, 1995]. The Kobe radon event is strikingly similar to the Taal anomaly, including a radon decrease before the onset, a sharp rise and comparatively smoother decrease before the earthquake, a radon stable at low level in the aftermath. The peak to background ratio is 5 at Kobe and 6 at Taal, for the same base width of the anomaly. The peak is dated 7 days before Kobe earthquake (30 km distant from the monitoring station), and 22 days before Mindoro earthquake (48 km). The morphology of the anomaly itself seems typical of a stress-induced radon exhalation, as was observed in a tunnel close to a reservoir dam [*Trique et al.*, 1999], suggesting a common mechanism of radon release associated with stress changes in fractured rocks (changes being generated by variations of lake level, in this latter case).

6. Conclusion

[14] Radon in the soil-gas of Taal volcano appears to be strongly controlled by permeability variations correlated with the regional crustal stress. These permeability changes (sealing or fracturing of the bedrock) modify soil-gas advection, a very effective mechanism for radon transport within an active volcano. Indeed, the Taal radon event preceding the 1994 Mindoro earthquake shows that active volcanoes, being anomalies in both permeability and gas seepage, could be very sensitive sites for the search of geochemical earthquake precursors.

[15] **Acknowledgments.** This experiment had been carried out within the framework of the co-operation program between PHIVOLCS and several French universities and research agencies, launched in 1990 by the Centre International pour la Formation et les Echanges Géologiques (CIFEG).

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M. Halbwachs, INRP, U. Savoie, F-73376 Le Bourget du Lac, France.

N. Poussielgue and J. Vandemeulebrouck, CNRS, LGIT, U. Savoie, UMR C 5559, F-73376 Chambéry, France.

R. Punongbayan, PHIVOLCS, Manila, Philippines.

P. Richon, DASE, CEA, BP12, F-91680 Bruyères-le-Châtel, France. (Patrick.Richon@cea.fr)

J.-C. Sabroux, IRSN, BP68, F-91192 Gif-sur-Yvette Cedex, France.

J. Tabbagh, UMR Sisyphe case 105, U. Pierre & Marie Curie, 4 place Jussieu, F-75252 Paris Cedex 05, France.