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Radon tides on an active volcanic island: Terceira, Azores

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RESUMEN

Se usaron 12 estaciones de monitoreo de radón sincrónicas, de registro continuo de radón en el volcán Pico Alto, en la isla Terceira, Azores, el cual se encuentra geotérmica y tectónicamente activo. Estas estaciones se utilizaron para identificar y cuantificar los movimientos subterráneos de radón. Se encontraron los siguientes resultados:

(1) Las variaciones meteorológicas tienen efectos despreciables en las emanaciones subterráneas de radón.
(2) Las emanaciones de radón en función del mes lunar generan patrones repetitivos en tiempo y magnitud para varios meses consecutivos (al menos un año). Las desviaciones del patrón establecido indican eventos adicionales no sistemáticos en las emanaciones de radón.
(3) En radón del subsuelo se comporta como un cuerpo continuo, en gran parte como un acuífero. El radón presenta "mareas" distintas de la mareas marinas y terrestres. Las edades de las mareas de radón tienen una magnitud negativa, con máximos de emanación ocurriendo algunos días antes de la conjunción luni-solar y/o en oposición. Los máximos absolutos de radón están asociados con la Luna Llena, en contraste con el máximo de la marea marina, que ocurre en la Luna Nueva.
(4) Las emanaciones de radón tienen dos máximos por día, uno al amanecer y otro al anochecer. Las separaciones y tiempo de los picos varían con la estación, en función de las variaciones en la extensión del día.
(5) Las mareas marinas influyen en el cuerpo de radón a lo largo de fallas conectadas directamente al mar. Estos efectos de mareas están en forma de una acción física de bombeo en acuíferos y "masas" de radón.
(6) Las estaciones de la isla de Terceira responden ya sea al sistema tectónico regional de esfuerzos Azores/Gibraltar (NO-SE), o al régimen local NE-SO del volcán Pico Alto. Se observó que los máximos de emanación cambiaron de un sistema al otro conforme predominaban diferentes regímenes tectónicos.

PALABRAS CLAVE: Mareas de radón, mareas marinas y terrestres, fuerzas gravitacionales luni-solares, predicción de sismos.

ABSTRACT

Twelve synchronous, continuously recording underground radon monitoring stations on the geothermally and tectonically active volcano Pico Alto, Terceira Island, Azores, are used to identify and quantify underground radon movements. Findings include:

(1) Meteorological variations have negligible effects on underground radon emanations.
(2) As a function of lunar month, radon emanations generate repetitive patterns in time and magnitude for several consecutive months (at least one year). Deviations from the established pattern indicate that additional, non-systematic events influenced radon emanations.
(3) Underground radon behaves as a continuous body, much like an aquifer. It exhibits "tides", distinct from marine and earth tides. Radon tidal "ages" have a negative magnitude, with emanation maxima occurring some days before the luni-solar conjunction and/or opposition. Absolute radon maxima are associated with the Full Moon in contrast to marine tidal maxima, which occur at New Moon.
(4) Radon emanations give rise to two maxima per day, one at dawn, the other at sunset. Peak times and separations vary with the season, depending on variations in the length of day.
(5) Marine tides influence the radon body along faults directly connected to the sea. These tidal effects are in the form of physical pumping action on buried aquifers and radon "masses".
(6) On Terceira Island, stations respond either to the stress system of the regional Azores/Gibraltar tectonic regime (NW-SE), or to the local NE-SW Pico Alto Volcano regime. Emanation maxima were seen to shift from one system to another as different tectonic regimes came into play.

KEY WORDS: Radon tides, marine and earth tides, Luni-Solar gravitational forces, earthquake prediction.

INTRODUCTION

Terceira Island, part of the Azores archipelago in Mid-Atlantic, forms the setting for the unique radon monitoring experiment described below. Terceira is active both tectonically, volcanically and geothermally. Tectonically Terceira is influenced by the triple junction between the North American, the African and the European plates: here one finds the interaction between the regional Azores-Gibraltar fracture zone, locally in the form of the Gloria Fracture Zone, the Terceira Rift and the Lajes Graben, running approximately NW-SE to almost W-E, and a more local system, approximately parallel to the axis of the Mid-Atlantic Ridge, oriented NE-SW. Volcanically, Terceira is still active: although the last land based eruption occurred in 1761 from Pico Alto volcano, currently there is a new, active underwater volcano (Serreta) just a few km offshore to the NW of the island, which in recent times has built up an edifice which is now but a few meters below the surface of the sea. Geothermally, there is an active, quite shallow and exploitable high temperature geothermal field beneath Pico Alto volcano.

Our radon experiment took place in the Pico Alto/ Lajes Graben area, initially as a support to geothermal exploration. One year was spent carrying out geological and geotectonic mapping of the area, assisted by aerial, satellite and Shuttle imagery (including radar), deep magnetotelluric soundings, and over 900 SSNTD integrating ground radon and 100 helium stations. By the end of this preliminary phase, the area and its underlying geothermal field were well understood: the locations of active faults and fractures and upwelling cells were well defined. Some of these “leaked” radon to the surface along narrow conduits in concentrations of up to 40 000 Bq/mc. Subsequently, we installed twelve synchronous, recording radon monitoring stations over a number of these open conduits in three distinct tectonic settings:

1 – over clearly delineated NW-SE fractures (the Azores-Gibraltar Fracture Zone system), unaffected by the younger intersecting NE-SW fractures. Three such stations were deployed along the Lajes Graben boundary fault, within the compound of the Lajes Air Force Base. This gave us the added advantage of access to continuous meteorological data (temperature, humidity, pressure, wind velocity and direction, and rainfall) throughout the period of the experiments.

2 – over clearly delineated NE-SW and NW-SE fractures belonging to the younger Pico Alto System (as at Farroco, on the low-lying northern slopes of the volcano).

3 – at the intersection of the two fractures systems, such as at Agualva Caldera, half way up the northern slopes of Pico Alto.

Detectors at all stations were of the ultra-thin windowed geiger tube type, particularly sensitive to α radiation, buried in PVC tubes one metre below the surface, shielded from lateral and surface radiation by lead cupolas. Data was recorded continuously using small computers every sixty seconds, which filed average values at 10 minute intervals. All computer clocks were synchronised to better than 5 minutes, so that peak times and other events at different stations could be compared directly. Stations had an autonomy of 30 to 40 days, more when power packs were substituted by solar panels. In all cases, data from each station were downloaded at monthly intervals and forwarded electronically to the base laboratory.

RESULTS

1 - Atmospheric influences

On occasion, daily meteorological variations (temperature, pressure, humidity and wind) were seen to influence overall radon emission intensities by a small fraction of total emissions, whereas other factors, described below, caused variations in orders of magnitude size. Statistical comparisons of meteorological variations against emission intensities showed insignificant correlation factors. We concluded that in a geologically active situation like that of Terceira, atmospheric variations have negligible effects on underground radon emanations in comparison to other influencing factors, to the extent that they can be disregarded.

2 – Radon peaks

As our recording techniques and data handling improved, it became apparent that at all stations, even those with low signal/noise ratio, daily radon emissions were in fact made up of either two distinct peaks, or of one broad peak with two maxima. These two daily maxima occur at dawn and at sunset (Figure 1). During the night and early morning, when the Sun is still below the horizon, the first radon pulse begins to build up strength, reaching its maximum just as the Sun appears over the horizon. It should be noted here that none of the stations were illuminated by the morning Sun. As the Sun rises in the morning sky, the radon peak diminishes, reaching a minimum value at around Noon – 14:00 hours. Thereafter, as the Sun begins its descent in the afternoon sky, radon emissions again increase, reaching the second daily maximum within a few minutes of sunset. Consequently, peak times and separations vary with the season, following variations in the length of the day. Their controlling factor appears to be the Sun and its gravitational forces: i.e., the Principal Semidiurnal **S2** and the Diurnal **P1** Gravitational forces with periods of 12 and 24 hours respectively, when measured at the Ecliptic. At higher latitudes, the two periods making up the 24 hours are distributed unequally, depending on the season (Figure 2).

All stations but one gave peaks whose times were clearly Sun-controlled. At the anomalous site, Farroco “A”, on the

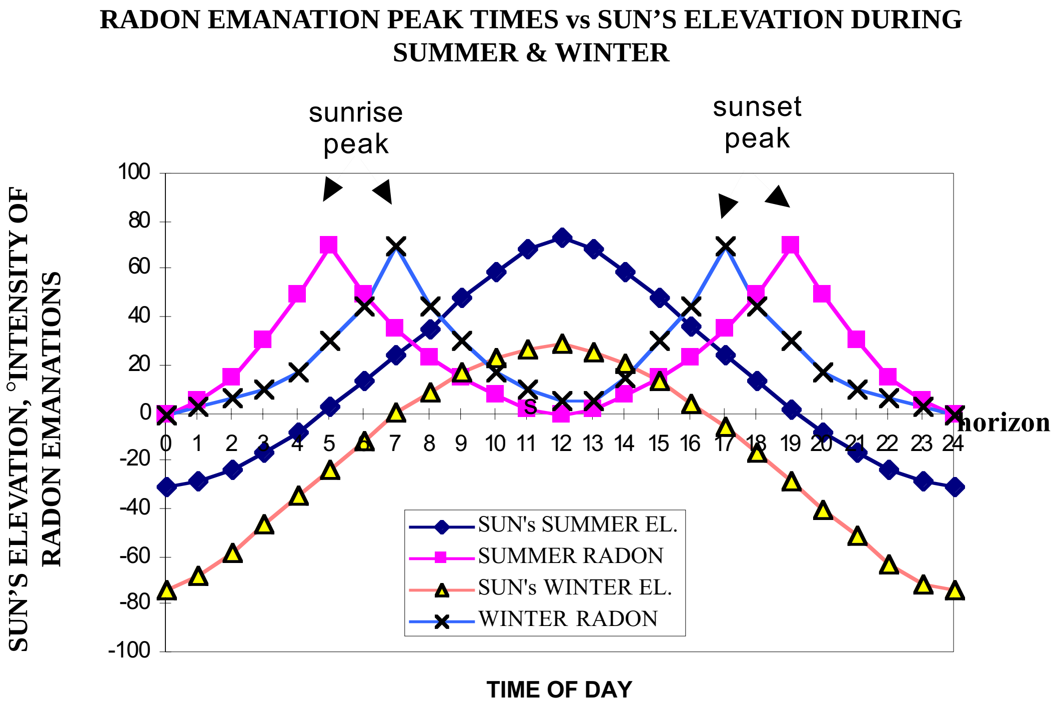


Fig. 1. Radon emanation peak times vs Sun's elevation during summer and winter.

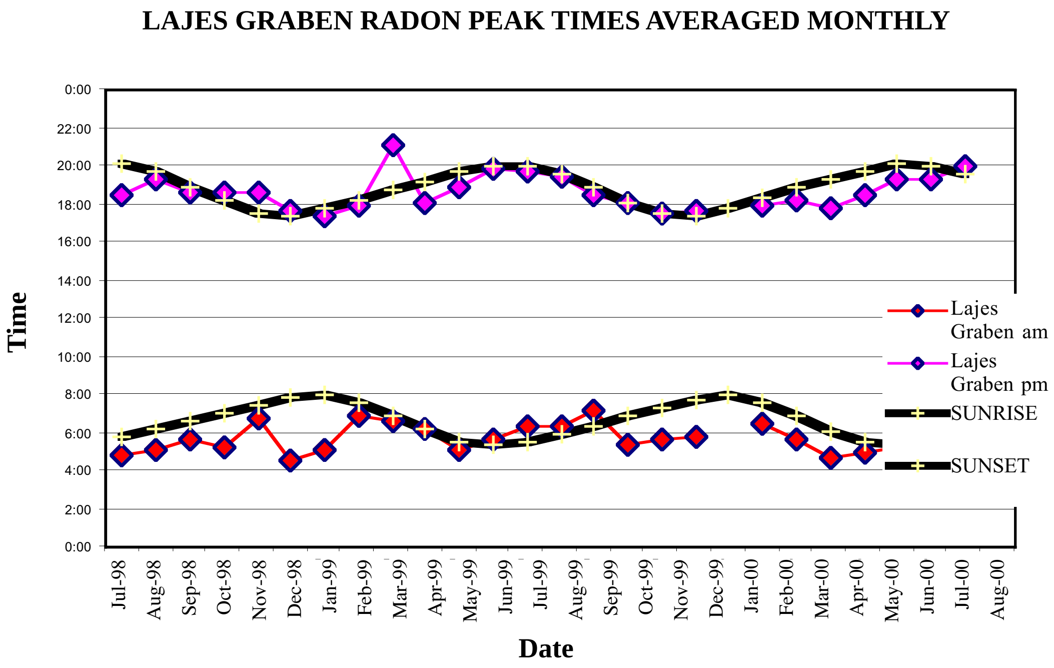


Fig. 2. Lajes Graben radon peak times averaged monthly.

lower slopes of Pico Alto volcano (not far from the sea), not only did a single, broad peak replace the twin daily peaks, but the timing of this peak did not show any correlation with either the Sun or marine tides (Figure 3): the peak occurred later in the day as the days went by, at an average rate of one hour's delay per month. This delay continued for approximately one year when, from one day to the next, the peak time shifted by twelve hours, returning to its original time at the beginning of the previous year (Figure 4).

3 – The lunar month

For the first two years, all data recorded at the different stations were plotted against calendar months. These generated confusing graphs, from which few valid observations and correlations could be made. Eventually, it became apparent that radon emissions and their variations were highly dependent on the phases of the Moon. All data were replotted as units of Lunar Months, each plot starting with the day, hour and minute of the occurrence of that month's New Moon, and terminating with the time of the following New Moon some 29 days later (Figure 5 and in more detail in Figure 6). When examined this way, radon emanations immediately exhibited orderly, correlateable patterns. Most strikingly, emissions form repetitive patterns which are perfectly coincident both in time, magnitude and overall characteristics month after month (at least one year). This makes it possible to sum the radon emanation patterns over several lunar months, the resulting graph being an enhanced emission pattern over any one single lunar month. Occasional, marked deviations from these established patterns do occur, sometimes in most pronounced, drastic ways; there are taken to indicate that additional, non-systematic events (possibly volcano-tectonic) influenced radon emanations at these particular moments. In fact, the clearest emissions integrated over time were from stations recording over single tectonic lineaments; those at the intersections of two lines of tectonism gave more confused patterns, subject to greater tectonic disturbances.

4 – Radon tides

Examining the radon emanations/lunar phases correlations further, we attempted to correlate radon emanations with marine tides. The correlations between the latter and luni/solar alignments are well known: marine tides reach their maxima just after the New and Full moons; this time delay, known as the "Tidal Age", due to the viscosity of water retarding water's response to gravitational forces, is of the order of a day and a half or so. Absolute marine tidal maxima occur associated with the New Moon (the moment of luni-solar conjunction, when both celestial bodies are "pulling" from the same direction).

Radon also follows the gravitational variations associated with luni-solar movements; as such, the behaviours of underground radon can be considered locally to be comparable to that of a continuous body, much like an aquifer or sea water. The rhythmic emissions it exhibits are not the result of pumping action of seawater or local aquifers (a different effect described in a following section). The radon body exhibits its own "tides", which we refer to here as **Rnm**, quite distinct from marine and earth tides. The resultant emissions form a clear cycle during the lunar month, emission maxima occurring some days before the luni-solar conjunction and/or opposition (Figure 7). Consequently, radon tidal "ages" have a negative magnitude; the latter is of the order of two days. Absolute maxima are associated with the Full Moon (i.e., luni-solar opposition) in contrast to marine tidal maxima, which occur at New Moon (luni-solar conjunction).

Therefore, we observe that the luni/solar gravitational field affects different terrestrial masses in different ways, dependent of their mass and viscosity. The solid Earth itself, being a rigid body, responds almost instantly to luni/solar gravitational changes, such that earth tides have a very small tidal age. Seas and oceans are made up of more viscous fluid which delay gravitational effects on the movements of water masses. These give rise to positive tidal ages of more than one day. In complete contrast, we suggest that radon, being a noble, very mobile gas, reacts so readily to gravitational changes that it exhausts its potential source of supply prior to the moment of luni/solar conjunction climax; by the time this event takes place, the radon body has already given its maximum pulse; having exhausted its primary supply, subsequent emanation intensities begin exhibiting a gradual reduction.

5 – Radon and marine tides

In the previous section it was stated quite categorically that radon tides were independent from marine tides (for example, as in Figure 3). However, marine tides also affect the radon body when close to faults directly connected to the sea. They interfere on both the intensity and timing of radon pulses. These tidal effects are in the form of physical pumping action of marine tides on buried aquifers and radon "masses". At these specific sites (the Lajes Boundary Fault, for example), during the twice monthly days of maximum marine tides (close to luni/solar conjunctions and oppositions), marine tides succeed in forcing radon peak times away from solar time control and to comply with the Principal Lunar Period **M2.** A few days later, as marine tidal magnitudes diminish, peak times quickly revert to Solar time control. This temporary, superimposed marine tidal control is not encountered over faults/fractures not connected to the sea.

6 – Radon, tectonics and volcanism

Although there were several instances of coincidences between anomalous radon emissions and the large number of M<2 earthquakes recorded in the region, statistical correlation between these events and radon did not produce a convincing story. However, for more significant events, radon stations could be seen to respond either to the stress system

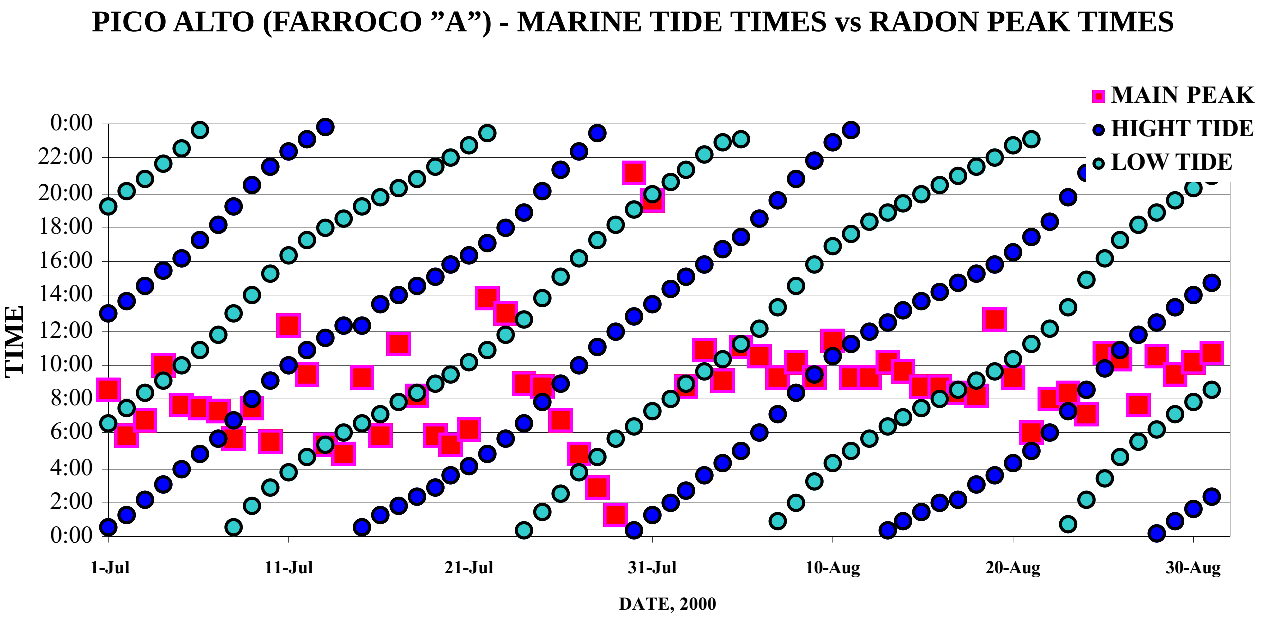


Fig. 3. Pico Alto (Farroco) – Marine Tide times vs radon peak times.

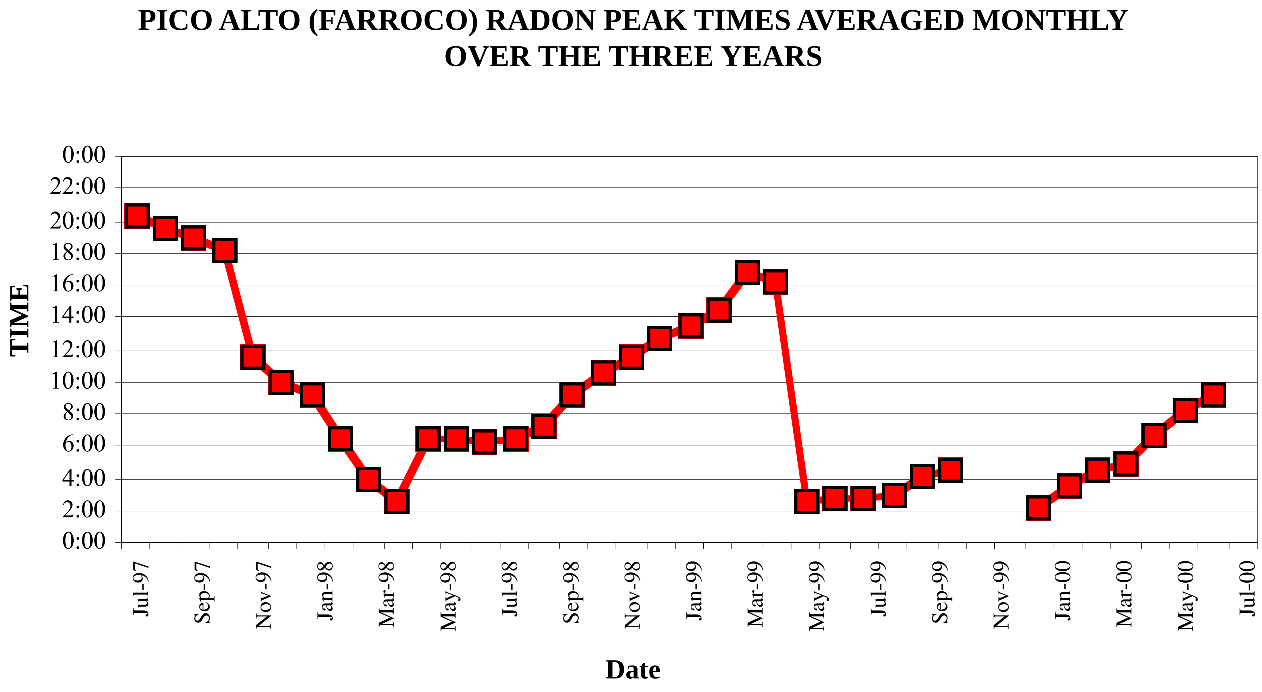


Fig. 4. Pico Alto (Farroco) radon peak times averaged monthly over three years.

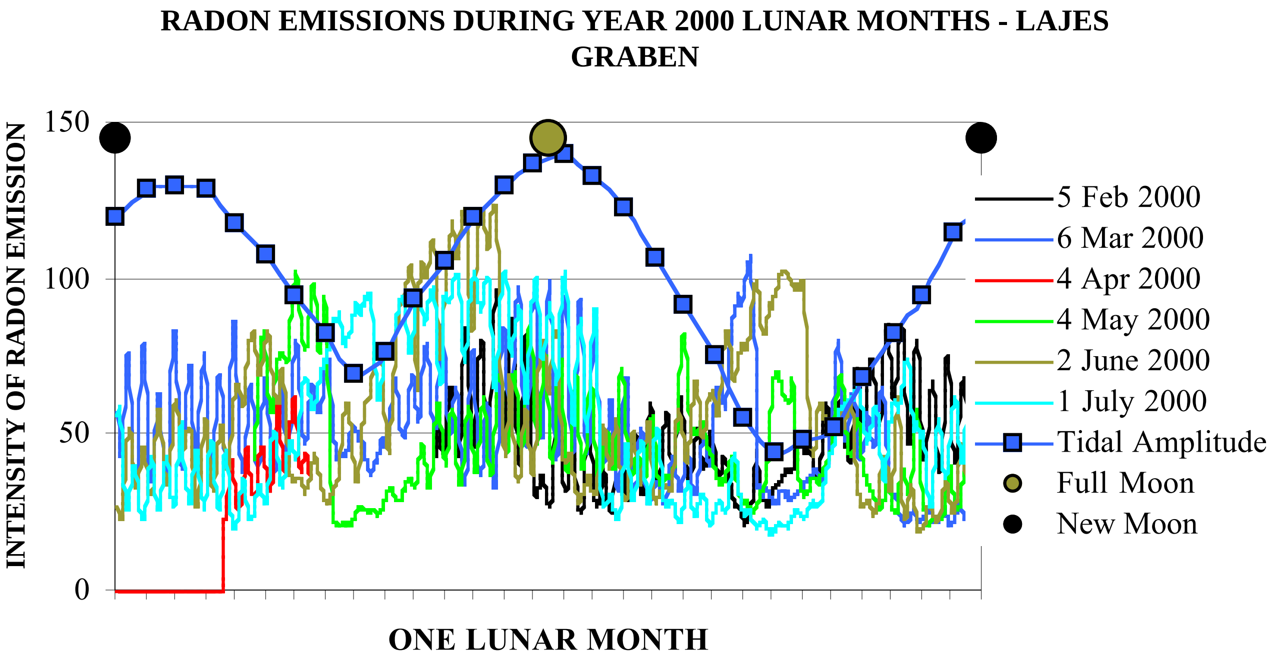


Fig. 5. Radon emissions during year 2000 Lunar Months – Lajes Graben.

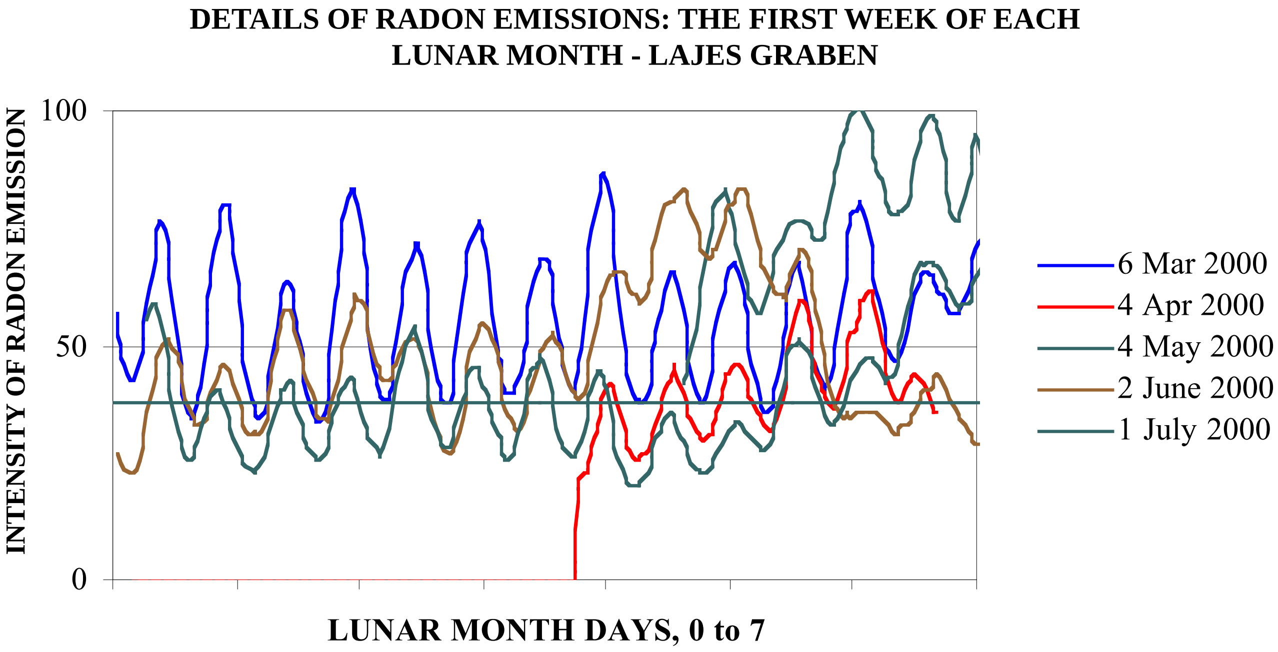
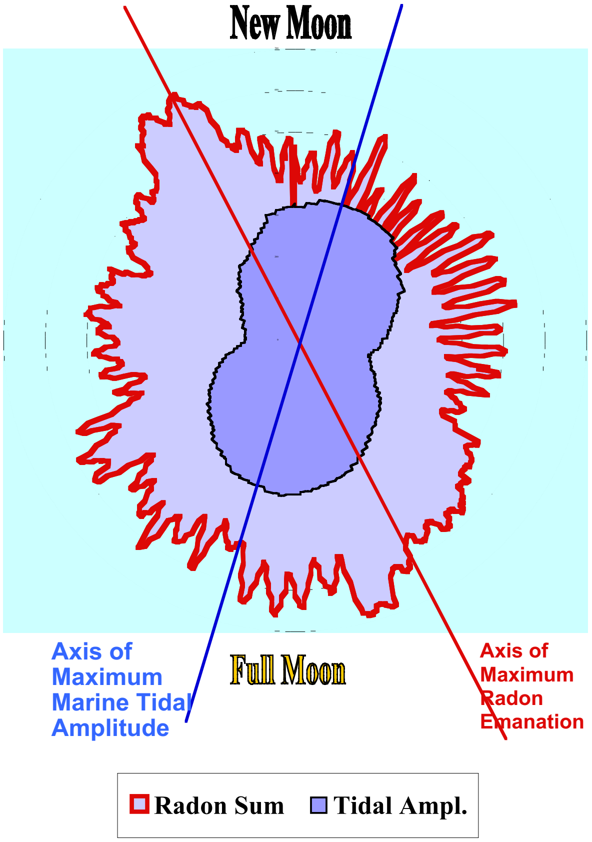


Fig. 6. Details of radon emissions: The rirst week of each lunar month: Lajes Graben.

of the regional Azores/Gibraltar tectonic regime (NW-SE) or to the more local NE-SW Pico Alto volcano regime. Peak intensities were seen to shift from one system to another as different tectonic regimes came into play. For example, immediately after a major earthquake on the adjacent island of Faial in July 1998, caused by movement on the regional NW-SE system, radon intensities measured over said system were observed to drop steadily for several weeks. Subsequently,



RADON EMANATIONS SUMMED OVER 12 LUNAR MONTHS, LAJES GRABEN BOUNDARY FAULT, TERCEIRA, AZORES

Fig. 7. Radon emanations summed over 12 Lunar Months, Station "S", Terceira, Azores.

as underwater eruptions from the nearshore Serreta volcano picked up in intensity, whose activity was associated with the younger NE-SW fault system, radon stations over these lineaments showed marked increases in emissions.

7 – Radon as a geothermal fluid tracer

Previous investigations have shown that on Pico Alto volcano radon reaches surface levels along vertical conductive cells through open faults/fractures from the underlying geothermal field, the centre of which lies below the eastern flanks of the volcano. Each day, the systematic twin radon peaks are first detected at the station nearest the source, at Agualva Caldera (550 m elevation); these peaks occur close to sunrise/sunset times, as described above. Subsequently, as radon migrates along interconnecting open fractures/faults, the same radon pulses are recorded sequentially, with ever increasing delay, at the numerous down-slope stations (such as Agualva Pump Station, Pico dos Loiros). Finally, the last appearances of radon pulses appear over faults at Farroco, close to sea level. Through careful synchronisation of the stations involved, with a precise knowledge of the active fault patterns in the area at hand, as well as a three dimensional view from magnetotelluric investigation of the below ground distribution of extremely low conductivity layers (>3Ωm), one can visualise the movement of pulses of radon gas as they follow open faults/fractures down to the sea, picking up time delay and gradually losing intensity as they travel away from the source. With continuous monitoring over long periods of time, one can observe that the open channels available for the migration of radon sometimes shifts from fracture to fracture in response to telluric activity, resulting in modified radon flow paths.

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