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Using Underground Radon To Detect Inactive Geological Faults

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USING UNDERGROUND RADON TO DETECT INACTIVE GEOLOGICAL FAULTS

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Master’s Program in Physics

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2017
Dedication

I want to dedicate this work to my mother because without her immense effort and patience to help me in my education I would not be here.
USING UNDERGROUND RADON TO DETECT INACTIVE GEOLOGICAL FAULTS

by

GERMÁN RODRÍGUEZ ORTIZ, B.S.

THESIS

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Abstract

This thesis presents the results of an investigation of the concentration of radon in soil around a fault in the East Franklin Mountains in the El Paso area in West Texas. The connection between underground radon exhalations near active faults has been known for decades, but possible similar increases of underground radon levels around inactive faults have not been studied as thoroughly. Arguing that the dilatancy-diffusion model used to explain the phenomenon near active faults does not apply to the case of inactive faults, a hypothesis is formulated under which increased levels of underground radon must be present near inactive faults.

To test the hypothesis a series of measurements of underground radon gas were performed around a fault in the Franklin Mountain of El Paso, Texas. The measurements found that the in-soil production of radon is indeed correlated to the existence of a fault even if it has not had any recorded activity in recent geological times.

This finding seems to indicate that in non-active faults the radon production is due mainly to the radioactivity of the top soil and to the transport properties of the medium, and not to deeper seismic activity. These results open the possibility of using in-soil radon gas concentrations as an examination tool of dormant faults in inhabited areas where no other fault-detecting methods can be used.
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Chapter 1: Introduction

Radon (Rn-222) is a gas produced by the radioactive decay of 238U, which includes 230Th, 234Th, 234Pa and 234U and other elements; all of these elements exist abundantly in most types of rocks and sediments and, thus, radon is present in all types of soil. Since radon has a short half-life of 3.8 d, it cannot travel far since its creation and, thus, its concentration near the surface depends on the presence of its parent nucleus, 226Ra, and the transport properties of the medium. As the transport properties of the soil vary near geological faults, it is expected that underground and surface radon gas concentration will increase near faults [5].

The increase of radon concentrations near active faults has been used to predict tectonic activity. The explanation of this phenomenon is based on the dilatancy-diffusion model of earthquake occurrence [20]. Synoptically, changes of elastic strain that occur before earthquakes can cause rocks to dilate rupturing and forming open fractures, this in turn allows the flux of underground gases including Rn. Since radon has a very short half-life it would not be expected to propagate upwards long distances before decaying, however, the existence of rising fluids such as underground water, carbon dioxide, nitrogen and methane produced by the tectonic activity can enhanced the upward speed of radon [4]. Such increase of Rn flow is expected to last for as long as the fault continues being active.

Without the outward flow of other gases, the concentration of radon near the surface depends solely on the existence of its parent nucleus Ra-226. Since there are wide variations of the levels of this solid material throughout the surface of the Earth, the in-soil concentrations of radon vary widely and no precise averages exist. Most measurements reported are near active faults and are connected to seismic activities; increments ranging up to 3.233% over local mean backgrounds of radon level have been reported at the Bad Nauheim fault in Germany [12], where peak signals of
over 1,000 kBq/m³ were measured around a region with a mean background level of 30 kBq/m³. On the other hand, similar increments of radon concentration have also been reported around less active faults [4, 14, 23]. Therefore, it is possible to think that enhanced levels of radon gas could be found in non-active faults, i.e. in fault that have not registered any recent tectonic activity.

1.1 Hypothesis

In this thesis, we test a complementary hypothesis, namely, that fractures create enlarged paths for Rn gas flow even in the absence of any tectonic activity. That is, in-soil radon concentration should increase near faults as compared to the background levels of the immediate neighborhood. In this scenario, without the help of seismically-released gases, the underground radon gas found near the surface must have been produced near the surface and not at greater depths. Radon, at a difference from tectonic gases, is produced at all depths but its slow diffusion and short half-life forces it to migrate only short distances before decaying.

We base the previous hypothesis on the following facts:

i) Radon’s parent nucleus, 226Ra, exists in all types of rocks and sediments and, thus Rn-222 is bound to be produced continuously in all types of rocks and sediments. [Indeed 226 Ra is produced by the decay chain of 238U, 234U, and 230Th all of which have long half-lives and exist in granite, igneous rocks, sedimentary rocks, metamorphic rocks, etc.]

ii) Rn-222 has a very brief half-life of only 3.82 days.

iii) Rn has slow diffusivity in soils.

iv) Points ii) and iii) imply that the mean distance displacement of Rn in soil is relatively short. For example, taking the diffusion coefficient of radon in dry soil as 5×10⁻⁶ m²/s, the average diffusion length in 3.82 days is found to be 1.6 m [15]).
It must be emphasized that the expected increase of Rn levels near a dormant fault would not be due to the extra flow given by tectonic gases; indeed we are proposing to look for a phenomenon that is independent of the dilatancy-diffusion model.

Furthermore, we also remark that any underground Rn gas detected near the surface is bound to have been produced in the top few meters of soil; any Rn gas produced at much larger depths would not live long enough as to reach the surface through dry soil.

Indeed, the proposed increase of underground Rn levels near dormant faults is expected to be solely due to the existence of fractures that could increase the diffusivity near the surface.

As a proof of principle, in this thesis we test whether radon concentration increases noticeable near a dormant fault, i.e. around a fault that has not had any recorded activity in recent geological times.

In this thesis we present a preliminary study of Rn-222 measurements along a dormant fault in the Franklin Mountains in the El Paso Area in West Texas, and contrast it with studies that identify fractures and faults through the general area. If proven correct, this hypothesis would open the possibility of using in-soil radon gas concentrations as a passive detection tool of dormant faults.

1.2 Objectives and thesis content

The main goal of the work presented in this thesis is to carry out a series of measurements of the underground radon concentration in order to demonstrate the feasibility of the proposed hypothesis. As all proof-of-principle investigations, our study if necessarily limited in scope and time, but –we believe— will suffice to demonstrate the possibility of implementing Rn measurement as a viable tool for detecting faults.

We begin the narrative of thesis in Chapter 2 with a description of radon, its impact on health and its connection to earthquakes. We continue in Chapter 3 with a description of the geological area under study, followed in Chapter 4 with a theoretical study of the mobility of radon in underground
soils, and in Chapter 5 with a presentation of the measurements of the underground radon gas concentrations. The thesis closes in Chapter 6 with a summary of the findings and a list of ideas for future work.
Chapter 2: Radon

Radon was discovered in 1900 by Friederich Ernst Dorn (Fig. 2.1) while studying radioactivity. Originally radon was initially named “radium emanation”, and later “niton”, after the Latin word for shining, but since 1923 has been known as radon.

Figure 2.1: Radon discoverer Friederich Ernst Dorn.

Radon is the heaviest noble gas [16], and it comes from the uranium 238 decay chain (Fig. 2.2). In nature, there are several Rn isotopes ranging from Rn-195 to Rn-229 and with half-lives lasting from nanoseconds to days. Most of these isotopes are synthetic (manmade) and only a few exist in nature but only trace abundances. The longest living isotope is Rn-222 (with a half-life of 3.82 days) which decays mainly through alpha emission into Po-218: $^{222}\text{Rn} \rightarrow ^{218}\text{Po} + ^{4}_2\text{He}$.

The Rn-222 concentration is estimated by measuring its radioactivity, i.e. by capturing the alphas produced in its decay. Each alpha counted signifies an Rn decay, thus its concentration is measured in becquerels, Bq, i.e. in disintegration per second; the concentration of radiation in the atmosphere
is measured in becquerels per cubic meter of air, Bq/m$^3$, and that of underground radon in Bq/m$^3$ of soil air.

The element radon is present in all types of rocks and soil, however different concentration levels are found in different kind of soils. Classifying soil by radon concentration we find the following ranking, from maximum to minimum, granitic (G), volcanic (V), sedimentary (S) and metamorphic (M) [15]; that is, it is most likely to find higher Rn concentrations in a soil composed of granite than in one composed of metamorphic rocks. As an example, granite countertops have been found to exhale radon to levels of 100 pCi/L [27], which is about 100 times the safe levels set by The Environmental Protection Agency.

Figure 2.2: Decay chain of U-238.
2.1 Health and radon

Rn-222 at room temperature (32 °C) has no odor nor color and, because of this, it is difficult to detect and quantify without the use of special equipment. Radon gas enters into houses from the ground through cracks in concrete floors and walls, or it is exhaled by cement blocks on walls, etc. The higher levels of radon and polonium are encountered on basements and closed places where air is not renewed constantly. Because Rn-222 and its daughter Po-218 are gases, they are easily combined with normal air which, when breathed in is deposited into the lungs where the emitted alphas can damage the lung cells; people exposed regularly to this kind of radiation may develop lung cancer. It is estimated that 20,000 lung cancer deaths per year are caused by exposure to radon gas.

Background levels of radon in outdoor air are about 0.003 to 2.6 pCi of radon per liter of air. The amount of radon needed to produce on picocurie is $28 \times 10^{-18}$ grams. Indoor locations have higher levels of radon of about 1.5 pCi/L. Water can also carry radon dissolved in it (as water from wells), with levels of about 350 pCi per liter of water. The Environmental Protection Agency recommends to take action whenever indoor levels of radon exceed 4 pCi/liter of air [27].

The danger of radon exposure is only to the lungs, no damage to the skin is known to occur from the alpha radiation in air. The damage to the lungs, however, is due to long term exposure. Workers in mines exposed to radon levels of 50 to 150 pCi/L of air for about 10 years have shown an increased frequency of lung cancer [33].

2.2 Radon in soil

As uranium is present in all rocks and soils, radon is also present. Inside of rocks and soil, radon is produced by the decay of a nucleus of radium into an alpha particle (two neutrons and two protons) and a nucleus of Rn. By conservation of momentum, the alpha particle and the radon
nucleus atom ae produced with opposite velocities, this initial push provides the kinetic energy that makes the new nucleus of radon start migrating. The creation location of the radon nucleus and the direction of the initial velocity determine if the newly formed radon nucleus moves in the right direction to escape from the rock or soil, or if it will be trapped for the remainder of its short life (3.82 d). If a radon nucleus is produced deep within the rock or soil, it will not become free regardless of the direction of its velocity. And even when a radon nucleus is produced near the surface of a grain, half of the time the initial velocities will have the wrong direction preventing the Rn nucleus from escaping.

This situation is substantially different when fluids are present. For instance, if water or a flow of gases are present in the pore space, the moving radon nuclei will quickly be absorbed and follow the fluid flow.

This flow mechanism limits the amount of radon in mineral pores to only 10 to 50 percent of the radon produced. Quantitatively, soils contain between 200 to 2,000 pCi or 7.4 to 74 Bq of radon per liter of soil air (one Curie is $3.7 \times 10^{10}$ Bq).

2.3 Radon and earthquakes

Several studies have been performed all across the world measuring the concentration of Rn-222 in soil and water before, during and after earthquakes. These investigations have shown that there are temporal and spatial variation in the Rn-222’s concentrations right before a geological event like an earthquake [17].
Figure 2.3: Radon concentration observed as a function of time in a well in the southern part of Nishinomiya city, Japan. The spike in January 1995 preceded a 7.5 earthquake.

Taken from Igarashi et al., 1995.

The pioneer on these investigations was a Hatuda, who measured the Rn-222 concentration during 2 years over an active fault, he noticed anomalous Rn-222 concentrations right before the Tōnankai earthquake with a magnitude of 8 on the momentum magnitude scale [17].

Japan is the country that has the biggest network of groundwater radon monitoring, it has been operated by the University of Tokyo and Geological Survey of Japan, on Figure 2.3 we can see a radon anomaly that was reported by Igarashi in 1955, the authors performed a measurement of the radon concentration in a well 17 m deep from November 1993 to March 1995, we can appreciate how the radon concentration starts rising on November of 1994 followed by a pike in January of 1955 then a sudden decrease seven days before an earthquake [17].

To understand the increase of radon gas before and during a seismic activity near a fault is necessary to review the Dilatancy-Diffusion theory of earthquake precursors.
2.3.1 The Dilatancy-Diffusion theory of earthquake precursors

The dilatancy-diffusion theory of earthquakes was developed in the 1970's [30]. In a nutshell, the theory explains the precursory steps leading to an earthquake:

1. First an external elastic strain causes rocks to dilate, which makes them increase in volume.
2. Whenever the stress reaches about half of the rock strength, microcracks form and multiply.
3. Isolated pores in the rocks connect to one another creating paths for the flow of water allowing water to diffuse and saturate the rock.
4. The wetting of the rock reduces its strength and eventually leads to failure producing an earthquake.
5. The earthquake opens paths for the water and gases to diffuse reducing the fluid pressure and the stress on the rocks.

The theory is based on the observation of changes of the physical properties of rocks with dilatant strain in laboratory tests. Indeed it is known that rocks “dilate” under stress, i.e. increase their volume during deformation; this occurs by an increase in pore volume and pore distribution, changes in cracks, rotation of grains, etc. If the theory is true (and doubts exist as it is not clear that lab observations are valid in the field) tracking these changes could provide information about an imminent earthquake; this, however, is easier said than done.
Figure 2.4: Predictions of anomalies in geophysical signals associated with elastic loading, dilatancy, diffusion, earthquake and post-seismic periods [31,32].

Although the changes in geophysical properties of the rock modify the speed of both the P and S waves, measuring any other precursor rapidly and accurately has been difficult to do; Figure 2.3 shows the theoretical predictions of the changes that can occur to physical variables. For instance,
Bakun et al., Jordan et al. and others have tested seismic velocity, seismicity, electrical conductivity or radon release as precursors without finding any direct evidence for detectable precursory behavior [24,26]. The absence of significant precursory strain was confirmed more recently by satellite interferometry recorded before and during the 2009 L’Aquila earthquake in Italy [23]. But not all is negative evidence, Niu et al. observed pre-seismic speed changes in the travel-time data 10 and 2 hours before two earthquakes of magnitude 3 and 1, respectively, at the San Andreas Fault [29], and suggested that the speed changes may be related to pre-rupture stress-induced changes in crack properties, as predicted by the dilatancy-diffusion theory. Although the dilatancy-diffusion theory has not been proven wrong, its impracticality has made it fall out of favor in geophysics circles.

2.3.2 Radon and the Dilatancy-Diffusion theory

The connection of the dilatancy-diffusion theory to the topic of this thesis is, precisely, precursory steps 2 and 3 of the theory, namely, the formation of microcracks and the growth of interconnectivity of the previously isolated pores in the rocks, which create pathways for the flow of water and gas. These newly formed pathways and the liquids and gases in them are responsible for the creation of an upward draft that carries the existing radon to the surface of the ground, travelling way much higher than what the radioactive gas would have travelled by itself before decaying.

Upon decaying from a mineral, radon nuclei must first migrate from the grains into the air-filled pore space. Although the diffusion of gases in solid materials is slow, upon creation the radon nuclei has a relatively large kinetic energy (86 keV) to move away from where it is generated. It is known that the range of Rn-222 is between 20 to 710 nm in solids, 100 nm in water and 63 μm for air [34]. Some emanated radon nuclei can penetrate the pores of a material and reach the surface
before decaying. The probability for this to happen depends basically on the transport properties of the medium. This diffusive transport makes radon flow in a direction opposite to the radon concentration gradient according to Fick’s law.

The soil-air exhalation rate depends on atmospheric meteorological parameters, such as the moisture content, temperature, wind speed and atmospheric pressure. Representative values of the radon activity concentration are $C_{Ra} = 40 \text{ Bq/m}^3$, flux rate of radon emerging at the Earth’s surface is $J_D = 0.026 \text{ Bq/m}^2 \text{s} \ [25]$.

2.4 Radon in inactive faults

The plausibility of the Dilatancy-Diffusion theory in what respects to the increase of production of radon exhalations at the surface of the ground before and during earthquakes is demonstrated by the long series of measurements listed in Chapter 1, and shown in Figure 2.3. However, for the purpose of this thesis, which deals with inactive faults, the Dilatancy-Diffusion theory is not applicable.

In the case of dormant faults, no precursory steps 2 and 3 will occur, i.e. there will not be any formation of microcracks, nor an increased interconnectivity of pores, and no formation of new paths for the flow of water and gas which would help radon reach the surface. Indeed in dormant faults, the increased of radon exhalations near a fault predicted by the hypothesis of this thesis, would be solely due to radon produced locally and propagated through existing fractures.

In the following chapter we address the propagation of radon through dry soil by diffusion forces solely, that is, by the forces produced by the radon concentration gradient according to Fick’s law. We will see that under normal expected conditions, radon will propagate merely a few meters from its place of formation.
Chapter 3: Diffusion Theory

The diffusion theory was developed at the beginning of the eighteenth century by Jean-Baptiste Joseph Fourier. Fourier started to work in a heat conduction problem at the beginning of the nineteenth century when potential and differential equations theories were being developed. Fourier began working in the heat conduction problem in 1802 trying to the problem as an N-body problem using the Biot’s work of action at a distance theory, but in 1804 started to work the problem as a continuum body idealizing the macroscopically behavior of matter assuming that the temperature in an infinitesimal infinite lamina depended only in the conditions of the upstream or downstream element of it. In 1807 Fourier summited his “Partial differential equation for transient heat conduction in solids” where he formulated the heat conduction in terms of partial differential equation and its solution in trigonometric series.

\[ K \nabla^2 T = c \frac{\partial T}{\partial t} \]  

(1)

Where K is the thermal conductivity, T the temperature, t time and c the heat capacity per unit of volume. Physically, the equation tells us how the temperature changes as a function of time depending on K and c; parameters that Fourier noticed that they are fundamental characteristics of a solid.

After the French Academy refuse to publish his article, Fourier continued to work on the topic and in 1822 he published his Analytic Theory of Heat.

His theory of heat conduction was later used to model electricity, molecular diffusion in liquids and solids, diffusion of gases and diffusion of heat. Investigation of the flow of water through
porous materials led to the adoption of Fourier's heat conduction model to the flow of fluids in geologic media [28].

3.1 Fick’s law of diffusion

Adolf Eugen Fick was born in 1829 at Kassel, studied physics and mathematics, and earned a doctorate in medicine from the University of Marburg in 1851. At age 25 years worked on a experiment of diffusion in liquids. Noticing noticed an analogy between heat diffusion and liquid diffusion he adopted Fourier’s heat conduction equations as his underlying model for diffusion. In 1855, he published his paper called “Fourier’s model applied to molecular diffusion”, where he presented what it is now known as Fick’s laws.

Figure 3.1: Adolf Eugen Fick.
3.1.1 Fick’s first law

Fick’s first law explains how the concentration and the flux are related by making the assumption of a steady state. In order to derive Fick’s first law, we will work only in one dimension and we are going to assume that the particles are moving randomly in the x-direction.

Let’s suppose that there are \( N(x) \) particles in the left-hand side of the area \( A \) and \( N(x+dx) \) particles in the right-hand side of the area \( A \) (Figure 4.2). We are going to assume that the probability that a particle crosses the area \( A \) from left to right is equal to 50% and the same for one particle moving from the right side to the left side of the area \( A \). This means that \( 0.5N(x) \) particles are going to move to the right and \( 0.5N(x+dx) \) are going to move to the left.

Therefore, the net number of particles crossing the area \( A \) in any way is:

\[
-\frac{1}{2} (N(x + \Delta x) - N(x))
\]  

(2)

Figure 3.2: Illustration showing \( N(x) \) particles in the left-hand side of the area \( A \) and \( N(x+dx) \) particles in the right-hand side of the area \( A \).
Now, we will count how many particles cross that area in a short period of time and we are going to call that flux.

\[ J = \frac{1}{2} \frac{(N(x + \Delta x) - N(x))}{A \tau} \]  \hspace{1cm} (3)

Now, we are going to define the concentration \( C \) and then we are going to rewrite the equation (3) in terms of it.

\[ C(x) \equiv \frac{N(x)}{A \Delta x} \]  \hspace{1cm} (4)

So,

\[ J = -\frac{\Delta x^2}{2\tau} \frac{(C(x + \Delta x) - C(x))}{\Delta x} = -D \frac{\partial C(x)}{\partial x} \]  \hspace{1cm} (5)

When we take the limit of \( \Delta x \to 0 \), the flux \( J \) will be equal to the gradient of the concentration multiplied by the constant \( D \), where \( D \) is the so-called diffusion constant of the medium and it is defined as \( D = \frac{\Delta x^2}{2\tau} \). The equation (5) is known as Fick’s first law.

### 3.1.2 Fick’s second law

Fick’s second law can be derived directly from the first law just by making the assumption that the number of particles that enters into a volume is the same as the number of particles that come out from it, this means that no particles are created nor destroyed inside of the volume.

In order to start with the derivation, we need to consider a volume \( A\Delta x \) and a flux \( J(x) \) that comes in at the left side of the volume and a flux \( J(x+dx) \) that comes out from it (Figure 4.3). Because our assumption of conservation of matter, the rate of change of the concentration inside the volume during a short time is given by
\[
\frac{dc}{dt} = - \frac{1}{\tau} \left( \frac{J(x + \Delta x, t) - J(x, t)A\tau}{A\Delta x} \right) = \frac{J(x, t) - J(x + \Delta x, t)}{\Delta x}
\]  

(6)

In the limit when \(\Delta x\) goes to zero, we have

\[
\frac{\partial c}{\partial t} = - \frac{\partial J}{\partial x}
\]  

(7)

Figure 3.3: Area A with flux \(J(x)\) from the left and flux \(J(x+dx)\) moving to the right.

Now, using Fick’s first law (5) that relate us the flux with the change in the concentration, we are going to substitute the flux into equation (7).

\[
\frac{\partial c}{\partial t} = - \frac{\partial}{\partial x} \left( -D \frac{\partial c}{\partial x} \right)
\]  

(8)

This equation is called Fick’s second law of diffusion, notice that this equation is written in one dimension but it can be rewrite in 3D by using the Laplacian operator. This equation describes us how the concentration is varying in the special and temporal “dimensions”.

18
\[ \frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} \quad (9) \]

As we can see, equation (9) is a second order partial differential equation (PDE), where \( c \ (kg/m^3) \) is the concentration and \( D \ (m^2/s) \) is diffusivity constant and it changes depending on the medium, we need to keep in mind that sometimes \( D \) is not a constant, it can be a function of the concentration, function of the temperature, for anisotropic material can be function of the direction, etc.

### 3.1.3 Solution of Fick’s second law

Fick’s diffusion equation is a parabolic PDE, we are going to solve this equation by making an analysis of the case of one-dimensional non-steady state conditions.

Starting with the equation (9), let us make the assumption of a constant \( D \) and then we are going to define a new function \( u(x, t) \) as follows,

\[ u(x, t) = \frac{x}{2\sqrt{Dt}} \quad (10) \]

Thus, now we are going to take the partial derivatives of (10), this is,

\[ \frac{\partial u}{\partial x} = \frac{1}{2\sqrt{Dt}} \quad (11) \]

And

\[ \frac{\partial u}{\partial t} = -\frac{x}{4\sqrt{Dt^3}} \quad (12) \]

Now, using the chain rule, we have,
\[ \frac{\partial c}{\partial t} = \frac{\partial c}{\partial u} \frac{\partial u}{\partial t} = -\frac{x}{4\sqrt{Dt^3}} \frac{\partial c}{\partial u} \quad (13) \]

And

\[ \frac{\partial^2 c}{\partial x^2} = \frac{\partial}{\partial x} \left[ \frac{\partial c}{\partial u} \frac{\partial u}{\partial x} \right] = \frac{1}{4Dt} \frac{\partial^2 c}{\partial u^2} \quad (14) \]

Now, substituting equation (11) and (12) into (9) yields to,

\[ \frac{\partial c}{\partial u} = -\sqrt{Dt} \frac{\partial^2 c}{x \partial u^2} \quad (15) \]

And if we combine the equation (9) and (10) give us

\[ \frac{\partial c}{\partial u} = -\frac{1}{2u} \frac{\partial^2 c}{\partial u^2} \quad (16) \]

Now, in order to make this equation (16) easier to solve, we are going to define a new variable

\[ z = \frac{\partial c}{\partial u} \quad \text{so (16) becomes,} \]

\[ z = -\frac{1}{2u} \frac{\partial z}{\partial u} \quad (17) \]

\[ -2 \int u \, du = \frac{\partial z}{z} \quad (18) \]

Then,

\[ -u^2 = \ln z - \ln B \quad (19) \]

Where B is the integration constant, now we are going to rearrange the terms of equation (19),
\[ z = \frac{B}{\sqrt{t}} e^{-u^2} \quad (20) \]

And

\[ \int dc = \frac{B}{\sqrt{t}} \int e^{-u^2} du \quad (21) \]

The function \( e^{-u^2} \) is part of a family of the so-called “Bell shape curves” equations. The solutions of this integrals are based in the boundary condition that we have for a determined problem.

Let’s consider a case where we are having an element \( c \) diffusing into an element \( D \), with the constraint that the amount of the concentration \( c \) is fixed, this means.

\[ \int dc = \int_0^\infty c(x, t) \, dx = \frac{B}{\sqrt{t}} \int_0^\infty e^{-u^2} \, du = N = \text{Constant} \quad (22) \]

Now, let’s recall our definition of \( u = \frac{x}{2\sqrt{Dt}} \) and plug it into equation (23) yields,

\[ B \int_0^\infty e^{-u^2} \, du = \frac{B}{\sqrt{t}} \int_0^\infty e^{-\left(\frac{x}{2\sqrt{Dt}}\right)^2} \, d\left(\frac{x}{2\sqrt{Dt}}\right) \quad (24) \]

Then we have,

\[ 2\sqrt{Dt} \frac{B}{\sqrt{t}} \int_0^\infty e^{-u^2} \, du = N \quad (25) \]

We already know the value of that integral, it is a pretty known function and it is called error function and by definition we have that,

\[ \int_0^\infty e^{-u^2} \, du = \frac{\sqrt{\pi}}{2} \]

Then, solving the equation for \( B \), we have,

\[ B = \frac{N}{\sqrt{\pi D}} \]

And now plugin in that \( B \) to the equation (25), we have,
\[ c(x, t) = \frac{N}{\sqrt{\pi Dt}} e^{-\left(\frac{x}{2\sqrt{Dt}}\right)^2} \]  

(26)

### 3.1.4 Infinite reservoir solution

We are going to consider the special case when we have a surface that is in contact with an infinite reservoir of fixed concentration \( c_r \), where we have a diffusion towards the right. In figure 4.4 we can notice that the concentration in \( x \) is due to the contribution of every slab \( dy \) from \( c_r \) to \( x = 0 \), now let’s recall equation (26).

\[ c(x, t) = \frac{N}{\sqrt{\pi Dt}} e^{-\left(\frac{x}{2\sqrt{Dt}}\right)^2} \]

Because our initial conditions we know that we have a fixed amount of concentration,

\[ c_r \, dy = N \]  

(27)

![Figure 3.4: Area A with flux J(x) from the left and flux J(x+dx) moving to the right.](image)

Plugging in equation (27) in (26), we get,
\[ c(x, t) = \int_x^\infty dc(x, t) = \int_x^\infty \frac{c_r}{\sqrt{\pi Dt}} e^{-\frac{y^2}{4Dt}} dy \]

Now let’s recall our definition of \( u \),

\[ u = \frac{y}{2\sqrt{Dt}} \]

Then,

\[ c(x, t) = \int_x^\infty \frac{2c_r}{\sqrt{\pi}} e^{-u^2} du = \frac{2c_r}{\sqrt{\pi}} \int_x^\infty e^{-u^2} du \quad (28) \]

Now, we are going to rearrange the terms on (28) to make it easy to solve,

\[ c(x, t) = \frac{2c_r}{\sqrt{\pi}} \int_x^\infty e^{-u^2} du - \frac{2c_r}{\sqrt{\pi}} \int_x^{2\sqrt{Dt}} e^{-u^2} du \quad (29) \]

If we look closely to the first integral we are going to notice that it is a Gaussian equation and we have already defined the values for that kind of integrals, by definition we have,

\[ \int_0^\infty e^{-u^2} du = \frac{\sqrt{\pi}}{2} \quad (30) \]

Using (30) on (29), we have,

\[ c(x, t) = \frac{2c_r}{\sqrt{\pi}} \left( \frac{\sqrt{\pi}}{2} - \int_0^{\frac{x}{2\sqrt{Dt}}} e^{-u^2} du \right) = \frac{2c_r}{\sqrt{\pi}} \left( 1 - \int_0^{\frac{x}{2\sqrt{Dt}}} e^{-u^2} du \right) \]

\[ c(x, t) = c_r \left( 1 - \operatorname{erf} \left( \frac{x}{2\sqrt{Dt}} \right) \right) \quad \ldots (31) \]

Where \( c_r \) is the initial concentration and \( \operatorname{erf} \left( \frac{x}{2\sqrt{Dt}} \right) \) is the so-called error function, defined as,
After plotting the solution (31) (Figure 4.5), we can see that when we are at x=0 we are going to have the initial concentration $c_r$, in this case is equal to 1 because we used that as our initial concentration. In order to plotted this graph, we used three different times (100 000 s, 200 000 s and 330 000 s), as we can see, we have three different graphs of three different colors, the blue one corresponds to 100 000 s, the orange one is for 200 000 s and finally the green one is for 330 000 s. We used 330 000 s as our final time because is the Rn-222’s half-life (3.82 d) and we used D as $6.8 \times 10^{-6} \text{ m}^2/\text{s}$, that is the diffusion constant for dry soil according to Koike, Katsuaki [15].

If we take a closer look at 5 m in the x-axis on the green graph (Figure xxx2) we have a concentration of almost zero, this means that 5 meters away from the starting concentration $c_r$, we are not going to be able to measure any Rn-222 concentration, at least in a model that does not take into account any other transportation phenomena aside the diffusion itself.

Other important quantity of our solution is the so-called “Diffusion Length”, this quantity is defined as the average distance that a molecule moves in a determinate time, mathematically has the following form,

$$L = \sqrt{D\lambda}$$  \hspace{1cm} (32)
Figure 3.5: Concentration graph for a fixed time 100,000 (blue), 200,000 (orange) and 330,000 (green), using a diffusion constant of $6.8 \times 10^{-6} \text{ m}^2/\text{s}$.

Where $L$ is the diffusion length, $D$ the diffusion constant and $\lambda$ is the half-life of the radioactive material. If we plot the diffusion length we are going to be able to know how much distance the Rn-222 travels before it decays, in figure 4.6 we can see the diffusion length from the concentration graph perspective, we can notice that it is measured from half of the concentration and it is increasing with the time as expected, it goes from 70 cm in 100 000 s to close to 1.5 m at Rn-222’s half-life.

Now looking at the diffusion length vs time graph figure 4.7, there we have three diffusion lengths, one for $D = 6.8 \times 10^{-6} \text{ m}^2/\text{s}$, one for $D = 5 \times 10^{-6} \text{ m}^2/\text{s}$ and $D = 1.5 \times 10^{-6} \text{ m}^2/\text{s}$ respectively, those are the minimum and maximum values for dry soil according to [15]. Looking
at the graph we can clearly see the maximum diffusion length for the Rn-222 in a dry soil with a $D = 6.8 \times 10^{-6} \text{ m}^2/\text{s}$ is almost equal to 1.5 meters, this means that when we are taking measurements of the Rn-222 concentration in dry soil we are measuring just the near surface Rn-222.

Figure 3.6: Concentration graph zoomed in for a fixed time 100,000 (blue), 200,000 (orange) and 330,000 (green), using a diffusion constant of $6.8 \times 10^{-6} \text{ m}^2/\text{s}$. 
Figure 3.7: Diffusion length from the concentration graph perspective for a fixed time 100,000 (blue), 200,000 (orange) and 330,000 (green), using a diffusion constant of $6.8 \times 10^{-6} \text{ m}^2/\text{s}$. 
3.2 In summary

In this chapter, we have seen how to deduce Fick’s laws of diffusion, that leaded us to equation (5) and (26). We also learned how to solve equation (26) for a special case of infinite reservoir or constant concentration of Rn. We used a constant of diffusivity for a dry soil of $6.8 \times 10^{-6} \text{ m}^2/\text{s}$ to get figure 3.5 that gave us an idea how the concentration will change with the distance for a given time. Also, we determined an important quantity to describe the diffusion “so-called” diffusion length, equation (32). Figure 3.8 gave us the most important part of this chapter,
this is, in absence of any seismic activity in the fault we can expect a maximum diffusion length of 1.5 m, this is the case for a dry soil, using a final time equal to the 222Rn’s half-life (3.82 days) and a constant of diffusion for a dry soil equal to $6.8 \times 10^{-6} \text{ m}^2/\text{s}$. This value of the diffusion length (1.5 m) tells us that when we measure the Rn concentration due merely to just diffusion and not any activity in the fault, we are going to measure only the concentration of the near surface Rn.
Chapter 4: Geographical area of study

Measurements of radon concentrations were taken on the east side of the Franklin Mountain in El Paso, Texas in the United States of America. These are tilted block-fault mountains formed by fractures of the Earth’s crust produced by near-vertical faults which thrusted and tilted the landmass upward producing diagonal rock layers which expose layers of Precambrian rock 1.25 billion years old. The area of study (see Figure 1) is located at the east flank of the Franklin Mountains, which constitutes a small range trending north-south between south New Mexico and the western tip of Texas. Although the Franklin Mountains are mainly composed of Cretaceous sedimentary rock units formed when the region was covered by water, there are also tertiary igneous intrusions and Precambrian crystalline rocks.

Tectonically, two major pulses, the Laramide orogeny (85-45 My) and the Cenozoic Rio Grande Rift, have shaped the geological landscape around the area of study. However, the major structural control on the uplift and tilting of this range is the Late Cenozoic crustal extension process associated with the Rio Grande Rift, which has resulted on a well-defined horst and graben classic rift architecture.

The Bolson del Hueco, located at the eastern upskirts of the Franklin Mountains is an extensional basin developed as consequence of the Neotectonic displacement of the basement by more than 2,700 m in depth along a series of quaternary age of the Late Miocene [13]; there are normal faults bounding the basin between the Franklin Mountains and the Hueco Tanks [6].

The main fault evidenced by surface geology is the East Franklin Mountain Fault (EFMF), which has been dated as 8-12 ky [16], with scarps ranging between 2 m and 60 m [16, 6], and with average displacements of 0.18 mm/yr [17]. This 52.7 km length fault [17] is considered, assuming and equivalent surface rupture, with potential to trigger a 7.1 Richter scale earthquake ([23], normal
fault data). The EFMF is also clearly evidenced by the strong gradient on the tilt derivative map of the gravity corrected Bouguer anomaly (Figure 4.1, inset a), derived from the gravity data base of the University of Texas at El Paso.

Figure 4.1: Location of the Franklin Mountains, the area of study, collected points and approximate location of the East Franklin Mountain Fault. The inset (a) shows the tilt derivative map derived from the Corrected Bouguer Anomaly to infer the trace of the EFMF.
Although the East Franklin Mountain Fault surface location is mapped and available through the USGS quaternary fault database [13], the fault attributes are not detailed. Fault anatomy can be found on more recent studies which have not only mapped the quaternary faults in the El Paso Texas - Ciudad Juarez metroplex area, but also modeled gravity 2D profiles [2, 3, 18, 7].

The study of Ávila [3] shows two profiles located nearby the study area of this research. Figure 4.2, modified from such study, shows the fault trace location and 2D profiling of the zone. In particular profile B-B’, located 6 km north to the radon field collection area, shows how the gravimetric signature can be properly fitted with a 2000 m heave, and a throw of nearly 2600 m. This quasivertical displacement of the Precambrian basement is associated with the EFMF. Ávila
et al. also shows the gravity forward modeling correlated to a north located seismic reflection section [8] providing both geophysical and geological constraints that support the normal fault controlled horst-and-graben basin architecture. The gravity forward model also reveals the outcropping Precambrian basement that might be acting as radioactive source.

In this study we connected the EFMF along Ávila’s profiles BB and CC. Since the radon decay products are expected to occur across faults and nearby presence of crystalline rock units, the fault trace was mapped and identified on the terrain to collect a series of radon concentration readings on the field as shown in Figure 4.1.
Chapter 5: Radon measurements

Although the natural radon family has among their members the isotopes 222, 220 and 219, the most often measured is the radioactive inert gas Rn-222 that has a half-life of 3.82 days and belongs to the 238U chain. The world average exhalation flux at the soil surface is 22 mBq/m2s which corresponds to about 40 Bq/m3 indoors; however, depending on the subsurface gas permeability, the flux can be much larger.

5.1 Equipment

Measurements of radon content in ground air were carried out using a Markus 10 portable instrument manufactured by Gammadata in Sweden, figure 5.1. The instrument operates by pumping out gas from the ground through a probe inserted in the soil at a relaxation depth of ~35 to 70 cm during 30s. The gas is stored for 10 min. in a measuring chamber, time during which 218Po decays into its progeny 214Pb through alpha radiation detected with a silicon surface barrier detector operating under a strong electric field (~600 VDC), then the measures are amplified and passed by a filter that only count alpha particles that have kinetic energy between 5.5 and 6.5 MeV’s, figure 5.2. The readings are converted by the device into volume concentrations (i.e. an average radon concentration in the air-filled part of soil-pores) in kBq/m3.
Figure 5.1: Rn concentration detector Markus 10 from Gammadata.

Figure 5.2: Markus 10’s work principle.
5.2 MEASUREMENTS

Table 1 shows the radon measurements obtained at the 16 points selected. The nominal measuring error established by the factory calibration is of 1.7% of the measurement, but the readings are additionally rounded off by the LED readout of the device to tenths of kBq/m3; this sets the average uncertainty to a minimum of 50 Bq/m3 and as high as 1.7% of the measurement. For this reason, we take all readings as being in the middle of each 100 Bq/m3 bin and list the uncertainty as the maximum of 1.7% or 50 Bq/m3. For instance, the reading at point C, which was recorded by the Makus 10 as 8.7 kBq/m3, could indeed correspond to any value between 8.700 and 8.799 kBq/m3, thus in Table 1 it is listed as 8.75 kBq/m3 with a 1.7% error of 0.149 kBq/m3. The first observation is that the overall scale of measurements is in the same range as observed in many active faults as reported, for instance, by [19] (see Table 1); indeed these readings are higher than those obtained near the active fault of Dead Sea Transform in Jordan (1.8 – 3 kBq/m3) [1] and the Johnson Valley Fault in Landers, California (4 kBq/m3) [19], similar to those on the North Anatolian Fault in Turkey (9.8 kBq/m3) [10], and not too distant to those measured on the North and Northwestern Greece Fault (13 kBq/m3) [11]. This immediately appears to support the hypothesis that radon production is not related to seismic activity. Overlaying the values of concentration of Table 1 over the geographic map of the EFMF it is possible to obtain a contour map of the concentration levels of the inspected area; Figure 3 shows such contour map using a color scale ranging from 1.1 kBq/m3 to 9.1 kBq/m3. Although the lack of information at the far edges of the map distorts a bit the information presented, the map clearly shows that the highest concentration levels, namely points C (8.7 kBq/m3), H (9.3 kBq/m3) and N (7.7 kBq/m3), coincide with the expected location of the EFMF. Furthermore, the concentrations are observed to die down very rapidly for points merely meters away from the fault.
Table 5.1: Location of points and radon concentrations obtained.

<table>
<thead>
<tr>
<th>Point</th>
<th>Easting (m)</th>
<th>Northing (m)</th>
<th>Radon Concentration Bq/m^3</th>
<th>Point</th>
<th>Easting (m)</th>
<th>Northing (m)</th>
<th>Radon Concentration Bq/m^3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>361731</td>
<td>3525816</td>
<td>1.05 ± 0.050</td>
<td>I</td>
<td>361553</td>
<td>3526166</td>
<td>2.75 ± 0.050</td>
</tr>
<tr>
<td>B</td>
<td>361883</td>
<td>3525823</td>
<td>8.05 ± 0.137</td>
<td>J</td>
<td>361555</td>
<td>3526062</td>
<td>3.75 ± 0.064</td>
</tr>
<tr>
<td>C</td>
<td>361586</td>
<td>3525789</td>
<td>8.75 ± 0.149</td>
<td>K</td>
<td>361606</td>
<td>3526056</td>
<td>1.35 ± 0.050</td>
</tr>
<tr>
<td>D</td>
<td>361660</td>
<td>3525801</td>
<td>4.05 ± 0.069</td>
<td>L</td>
<td>361819</td>
<td>3526143</td>
<td>4.35 ± 0.074</td>
</tr>
<tr>
<td>E</td>
<td>361436</td>
<td>3525831</td>
<td>4.35 ± 0.074</td>
<td>M</td>
<td>361706</td>
<td>3526041</td>
<td>1.75 ± 0.050</td>
</tr>
<tr>
<td>F</td>
<td>361286</td>
<td>3525855</td>
<td>5.75 ± 0.098</td>
<td>N</td>
<td>361787</td>
<td>3526655</td>
<td>7.75 ± 0.132</td>
</tr>
<tr>
<td>G</td>
<td>361716</td>
<td>3526156</td>
<td>5.75 ± 0.098</td>
<td>O</td>
<td>361830</td>
<td>3526632</td>
<td>6.05 ± 0.103</td>
</tr>
<tr>
<td>H</td>
<td>361632</td>
<td>3526159</td>
<td>9.35 ± 0.159</td>
<td>P</td>
<td>361733</td>
<td>3526659</td>
<td>7.05 ± 0.120</td>
</tr>
</tbody>
</table>

The noticeable exceptions are the points J, K and M which show much lower levels of radon concentration: 3.7, 1.3 and 1.7 kBq/m^3 respectively. These points, fortuitously, are located on a dirt road that was excavated next to a wash which, undoubtedly, removed and eroded soil and deposited extraneous debris of several feet of depth that affected both the radon production (compared to neighboring terrains) and the structure of the uppermost soil and its gas transport properties.
Figure 5.3: Concentration of radon gas measured on the area studied; the color scale varies from 1.1 kBq/m³ (blue) to 9.1 kBq/m³ (pink). The solid line approximates the location of the EFMF.

Seen from the positive side, the low readings obtained at the dirt road and wash seem to confirm that the in-soil radon concentration is produced mostly by the top soil and not by the deeper undergrounds which, in this case, were covered by dirt and debris of the erosion. [A second possible conclusion, not explored in this thesis, is that the reduction of radon gas could indicate a segmentation of the fault. This would be welcome news for the El Paso Area population as a 52.7
km fault carries a risk of 7 in the Richter scale while two faults of 26 km would reduce the risk to 5 in the same scale; further analysis would be needed to test this possibility.

As pointed in other studies [9], the soil-gas concentrations of radon are expected to vary in time due to several factors (temperature, precipitation, humidity, pressure, tectonic activity), thus, to fully substantiate the hypothesis presented in this thesis a continuous long-time monitoring of this and other faults is necessary. It must be pointed out that, to support the hypothesis, the levels at the fault would only have to peak with respect to the background of the immediate neighborhood and not attain specific levels. Such spatiotemporal study is currently underway [20].
Chapter 6: Conclusions

By studying the production of radon in soil around the East Franklin Mountain Fault in El Paso, Texas, we determine a strong correlation between the in soil concentration of radon gas and the location of the fault. The fact that the fault has not had any activity in recent geological times serves as a proof of principle that enhancement of radon production near a fault is not due to seismic activity as predicted by the dilatancy-diffusion model of earthquake occurrence, but to the inherent radioactivity of the soil and to the enhanced gaseous transport properties of the soil due to the existence of the fault.

Since the in-soil radon concentration is observed to decrease where extraneous dirt and debris have been deposited on top of the fault, this supports the idea that the in-soil radon concentration is produced mostly near the top soil and not deeper in the ground. We conclude that the use of non-invasive measurements of radon gas concentrations to detect non-active faults appears as a real possibility that deserves further study. If proven correct by further studies, this method of fault detection has distinct advantages when used in populated areas. For instance, it does not rely on the production of shear and compressional waves, such as the method of seismic tomography, nor needs to produce electrical signals which can interfere with the urban electrical network as does the method of electrical resistivity tomography. These advantages are especially useful in determining the location of faults inside cities.
References


Vita

Germán Rodríguez Ortiz is from Juárez, México. He did his bachelors in Juárez at the “Universidad Autónoma de Ciudad Juárez” and he earned his masters from The University of Texas at El Paso. He did his research on a method to use the underground Radon radiation to find inactive faults under Dr. López supervision and successfully publish a research paper called “Correlation Between Underground Radon Gas and Dormant Geological Faults”. He served as a teacher assistant while doing his masters. In future, he plans to continue with his education by earning a doctoral degree.

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