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Magma Wagging at the Conduit as a Result of Forced Oscillations created by Periodic Magma in the Chamber

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Abstract: The paper is dedicated to *Pele* (Fig.0) the revered Goddess of Earthquakes and Volcanoes and begins with a historical account of convection. The magma chamber as a general topic has been extensively discussed. Beginning with ordinary convection, the author has considered the paths of convection of magma in the magma chamber by comparing them with paths traced out by pendulums both having relation with rotation of Earth. It is shown graphically that the convective motion of magma in the chamber is periodic. The Rayleigh number for magma in the chamber has been worked out from first principles. Computerized pictures of convective motion for various Rayleigh numbers are shown the higher numbers referring to convective vigor. The state of magma convection in the chamber due to the composition of many periodic motions is compared with magma turbulence in the chamber; Magma just entering the conduit before the process of magma wagging; Frequency of magma wagging obtained by eminent geophysicists, David Bercovici and Mark Jellinek is given without derivation. The eruption is shown at resonance. The main paper ends with a conclusion.

Unlike other research papers, the author at the end has added an "*Epilogue"* wherein few photographs of the author's visit to Geological Institutions and related subjects in US are shown.

As this research paper is prepared during the global outbreak of the Corona Virus, the author has made the final end of the paper by adding a write-up looking like a Poem based on Physics on the deadly Virus.

Key Words

Main Paper: Convection, Convective vigor, Double Pendulum, Electrically-operated Tuning Fork, Eruption, Faucault's Pendulum, Forced Oscillations, Magma Chamber, Magma Turbulence, Magma Wagging, Magma Wagging Frequency, Pele (Goddess of Earthquakes and Volcanoes), Pendulums, Periodic Motion, Rayleigh number, Rayleigh Benard Convection, Rayleigh Benard Convection Cells, Resonance, Rotation of Earth.

Epilogue: Calpine Geothermal Power Station, Laboratory for the Geophysical Sciences at University of Chicago, Poem on Corona Virus, Thomas Chrowder Chamberlin bust at University of Chicago, Volcano Lassen Peak, Volcano Mount Shastha.

Philosophy "The Idea that Mathematics is the rightful interpreter of Nature originated with the Pythagoreans and doubtless with Pythagoras himself." Sir Edmund Whittaker [5]

Dedication: This Research Paper is dedicated to Goddess Pele (Fig.0) [7] the revered Goddess of Volcanoes, Earthquakes and the creator of the Hawaii Islands in the Pacific of the US

Fig.0 The volcano goddess Pele (credit: Prayitno/CC by 2.0)
Picture by Jane Palmer of Washington university]

I. INTRODUCTION

1.1 Historical: A brief historical account of convection is given by this author Nair V.C.A[11, p.11]. The theory of „Convection" dates back to the 19th century. In Figures 1 to 8 are shown pictures in chronological order of some scientists who were involved in the research on Convection. The phenomenon of convection was first recognized by Count Rumford (1870) (Fig.1) and James Thomson (1882) (Fig.3) brother of Lord Kelvin. Exactly at the beginning of the 20th century Henry Benard (1900) (Fig.5) noticed that as one surface of the liquid is open to the atmosphere, effect of surface tension has to be considered in addition to thermal convection. The results obtained were in agreement with what was shown later by Lord Rayleigh (Fig.4) in 1916. Lord Rayleigh was the first to consider a linear problem of the onset of thermal convection in a horizontal layer. It was Arthur Holmes (Fig.7) in 1931 who correctly identified convection as the ultimate driving force for continental motion. A more comprehensive analysis of the problem was given by Pellew (Fig.2) and Southwell (Fig.6) in the year 1940. Later in the year 1961 S. Chandrasekhar (Fig.8) considered the effect of magnetic field and rotation of the Earth in a monograph. As the extensive pioneering work was done by both Lord Rayleigh and Henri Benard, the convection what we deal with is legitimately called "Rayleigh-Benard Convection" or Benard-Rayleigh convection or simply Rayleigh convection.

1.2 Preamble: Looking upon the Title of the Paper, I have first dealt with a Magma Chamber and factors that cause Convection. As the Wagging starts before and during an eruption, situations occurring in the Chamber during this period are taken into account. The Convection of magma in the Chamber is considered as a periodic motion by taking temperature, T_1 at the bottom (near top of

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upper mantle) and temperature, T_2 at the top of the Chamber near starting of the conduit with $T_1 > T_2$.


Fig.1 Count Rumford (1753-1814)


Fig.2 Sir Edward Pellew (1757-1833)

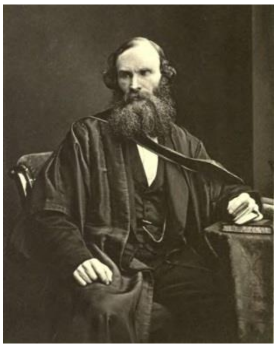
Fig.3 James Thomson (1822-1892)


Fig.4 Lord Rayleigh (1842-1919)


Fig.5 Henri Benard (1874-1939)

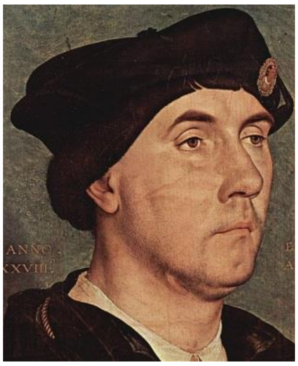
Fig.6 Richard Southwell (1888-1970)


Fig.7 Arthur Holmes (1890-1965)

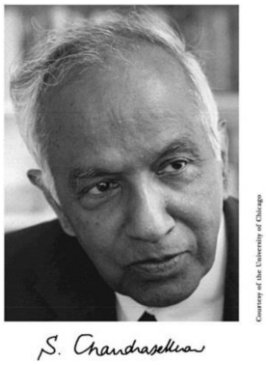
Fig.8 S. Chandrasekhar (1910-1995)

II. THE MAGMA CHAMBER

2.1 The Shape and Size: What is unclear to Volcanologists as on today is the exact shape and size of a Magma Chamber. Ken Jorgustin [10] Author of Modern Survival Blog, New Hampshire, USA (Jan.11, 2011) has given a vague, but believable, information regarding the size of many volcanoes of different strengths. Accordingly, the size of a VE-8 volcano is shown in Fig.9. That, the Chamber under the Earth's crust stretches from San Jose to Sacramento a distance of about 190 km in the San Francisco Bay of Californian coast of the western USA.

Giving an example for India, the Chamber may stretch from city of Mumbai to northern end of Palghar district of Maharashtra, India.

2.2 Assumption for the size: The shape can be legitimately assumed to be a rectangle or better as an ellipse even though in some of my previous papers, I have assumed it to be a sphere. In this paper I have taken it as an Ellipsoid (Fig.10) because I can include many things in that.

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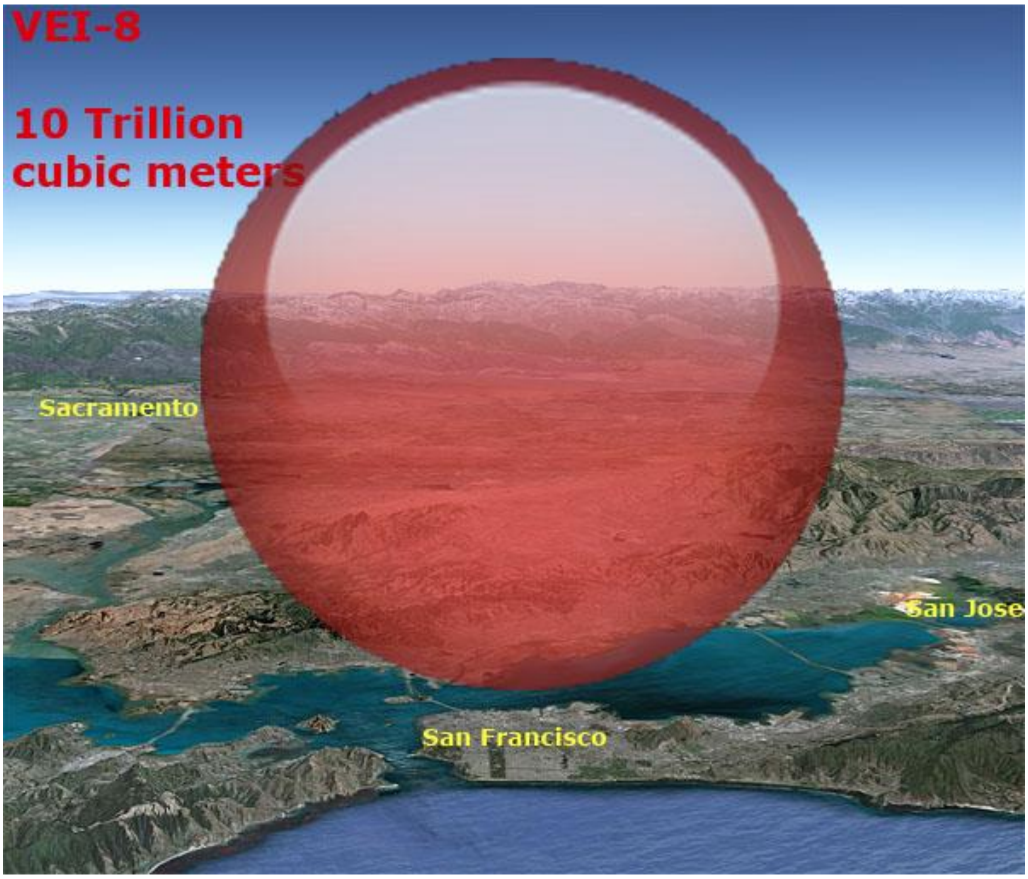

Fig.9 The size of a Magma Chamber of a VE-8 Volcano [10]

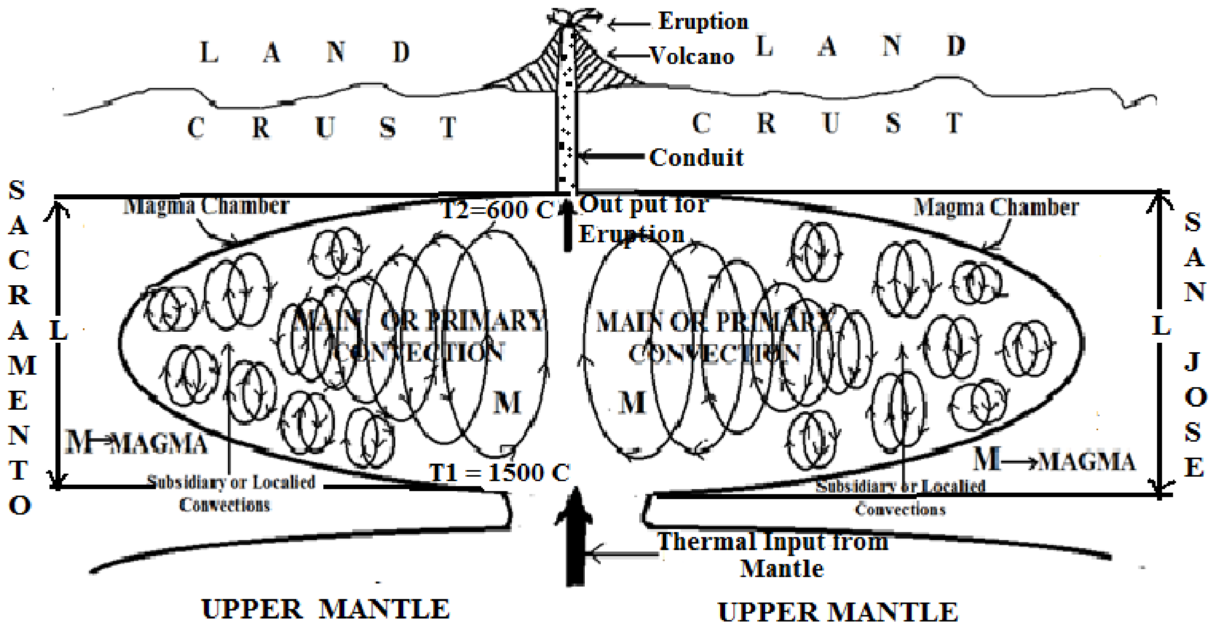

Fig.10 An idealized and assumed shape of a Magma Chamber showing details

III THE CONVECTION

3.1 Preamble: P. Bergé & M. Dubois [2]: The authors mention in their 'introduction' of their paper that Convection is a very common phenomenon in nature, and has fascinated many people for a very long time. Its study and understanding have fundamental importance in meteorology,

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oceanography, geophysics and astrophysics. Moreover thermal instabilities and related transport processes are involved in practical applications such as power engineering, combustion, material science, and space technology. More precisely, phenomena as diverse as solar granulation, atmospheric structuring of planets, continental drift, striations in crystal growth, flame structure, atmospheric circulation, etc. are all related to thermal convection. The origin of the term ‘convection’-from the latin ‘conuectio’-gives an idea of ‘carrying with‘. It seems to have been applied first to denote the transportation of heat through fluid motion. Thermal convection arises when a thermal inhomogeneity exists in a fluid. This thermal inhomogeneity is the source of motion through different mechanisms (such as surface tension etc.); but, on the other hand, stabilizing effects (such as viscosity) tend to dampen these motions. Then, generally, the competition between these two opposite effects leads to an instability.

3.2 Ordinary Convection: Following the historical aspects mentioned in section 1.1 and as we have to strictly stick on to the title of the paper, we may have to specifically deal with the path traced out by the particle. Let us look at the ordinary convection taking place in water when heated in a vessel as shown in Fig.11 in which the possible paths of convection are shown colored. If the vessel is shallow and if there is uniform heating at the bottom, the convection forms cells as shown in Fig.12.

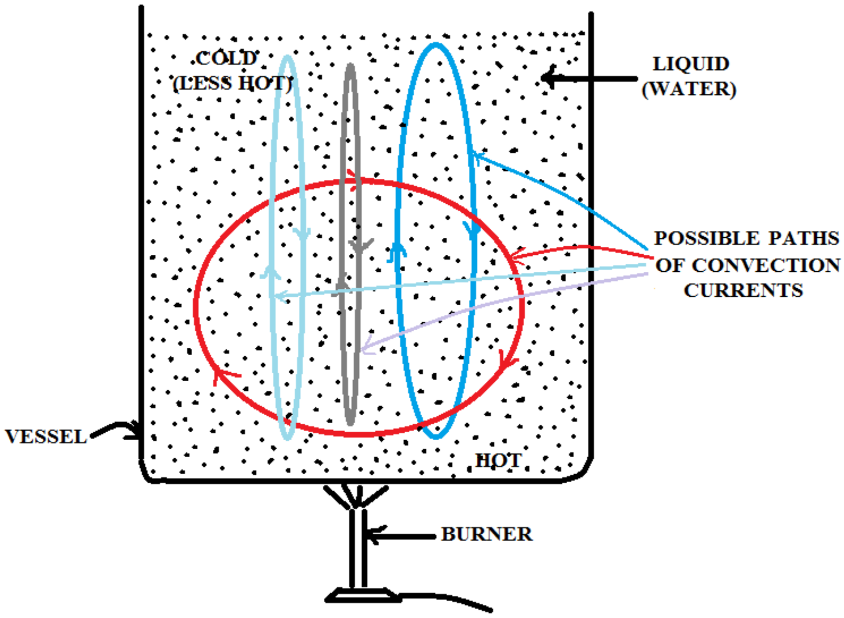

Fig.11 Water being heated in a vessel

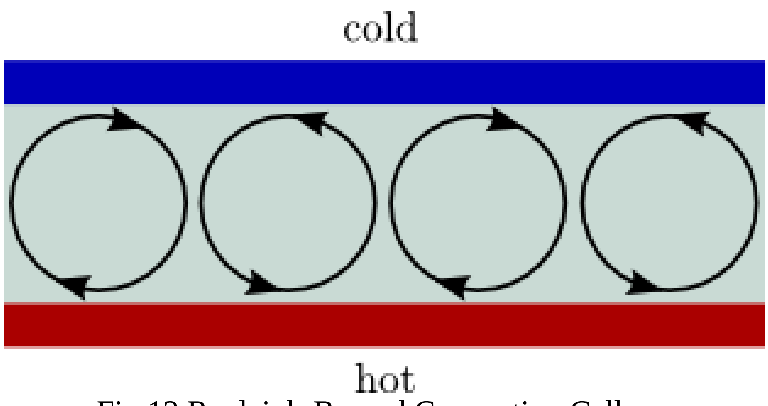

Fig.12 Rayleigh-Benard Convection Cells

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3.3 The paths traced out by Pendulums: Lookng upon the paths of convection as shown in Fig.11, let us compare various paths traced by Pendulums specially that of a Conical Pendulum. A simple pendulum is associated with Galileo (Fig.13) in the measurement of acceleration due to gravity. A Conical Pendulum tracing the path of an ellipse the trajectory of planets around the Sun as shown by Johannes Kepler (Fig.14) a contemporary of Galileo. At this juncture, I would like the readers to go through a Research Paper, by Germain Rousseaux, Pierre Coullet and Jean-Marc Gilli [6(a)] wherein the conversation of Robert Hooke (Fig.15) with Sir Isaac Newton (Fig.16) in the discussion of planetary motion had mentioned the path traced by a Conical Pendulum. Another pendulum of importance is the Faucault's Pendulum the behavior of which is also related to the Earth's rotation. This pendulum first designed by Jean Bernard Leon Faucault (Fig.17) (1819-1868) in 1851 are at display at few places in the world among which the author happened to visit (Fig.18) the one at California Academy of Sciences on 21 July 2001.

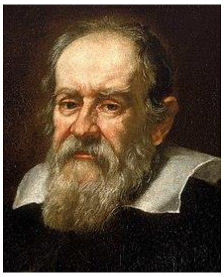


Fig.13 Galileo Galelei (1564-1642)

Fig.14 Johannes Kepler (1571-1630)

Fig.15 Robert Hooke (1635-1703)

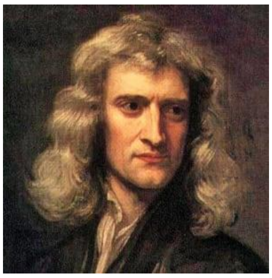
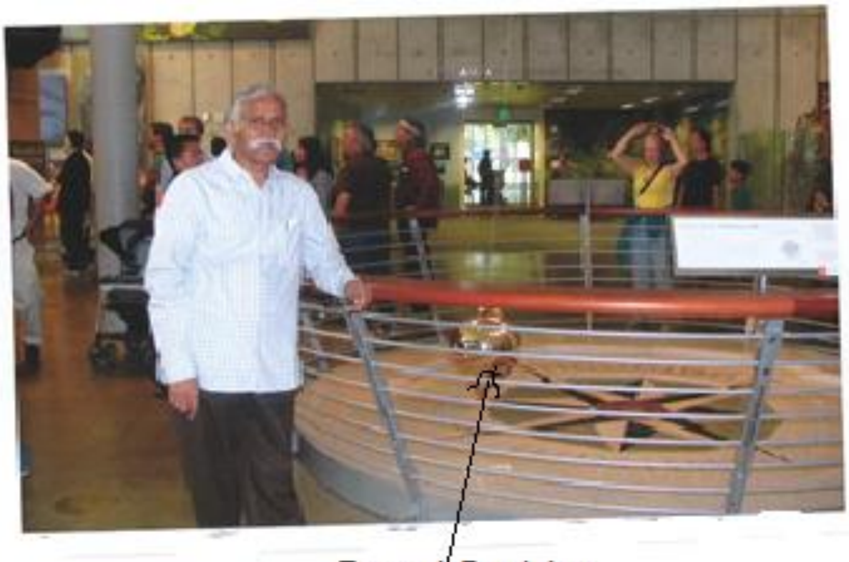


Fig.16 Isaac Newton (1642-1727)

Fig.17 Leon Faucault (1819-1868)



Faucault Pendulum
Author with the oscillating Faucault Pendulum on his left at the California Academy of Sciences, US - 21 July 2001

18 Author standing near the Faucault's Pendulum

It is not our aim to discuss pendulums, but, what is of interest to note is that pendulums have something or other connected with the Earth especially with its rotation. It is like the motion of the pendulum is related with the rotation of the Earth or the rotation of the Earth has something to do with the motion of the pendulum. The author, Nair V.C.A[(11) p.20, Fig.14] has published a part of the Research Paper by Shuping Chen [16] where it is diagrammatically shown (Fig.19) the effect of rotation of Earth on the magma of the Mantle. Shuping Chen in his research paper has represented the relationship between convection and Earth‟s rotation by a cartoon model, called the "Earth‟s Dynamic Car" in which the convection is shown as Power Source similar to engine of the car responsible for plate breaking and the Steering Wheel corresponds to rotation of the Earth determining the direction of plate movement is shown Fig.19. The author further says in his paper that mantle convection is relevant to heat-content of the Earth and where the convection actually takes place, there is a redistribution of interior substance of the Earth resulting the rotational angular speed of the Earth getting altered. This develops an increment in Earth's rotation inertia force. This along with the force of mantle convection decides the orientation or direction of plate movement. The geometric shapes of the plate boundaries adjust the direction of plate movement. The Shuping Chen‟s argument is further supported by geophysicists Carlo Doglioni and Roberto Sabadini [3]. These authors are of the view that mantle convection alone seems not able to generate plate tectonics. A more robust contribution in combining mantle convection with Earth's rotation could be envisaged. The Earth's rotation is also able to generate a possible polarity in the kinematics of the core, mantle and lithosphere, a sort of railway path, they say. Shuping Chen's argument is related to mantle convection. In the literature that follows, I have shown the same to be true for convection of magma in the chamber also.

3.4 A corollary: In the beginning of the paper we have been saying that the motions of the pendulums are related with the rotation of the Earth and according to Shuping Chen who has mathematically shown that the rotation of the Earth affects mantle convection. Our topic of magma convection in the Chamber is a rider to the convection of magma in the mantle. Volcanologists are aware that the magma chamber of each volcano is connected to the top of the mantle. Imagine the magma chambers of nearly 1500 volcanoes of the planet forming a part of the mantle. That is to say that the mantle is like the trunk of a huge tree and the magma chambers are its branches. The question of Earth's rotation affecting the convection of magma in the chamber gets automatically answered.

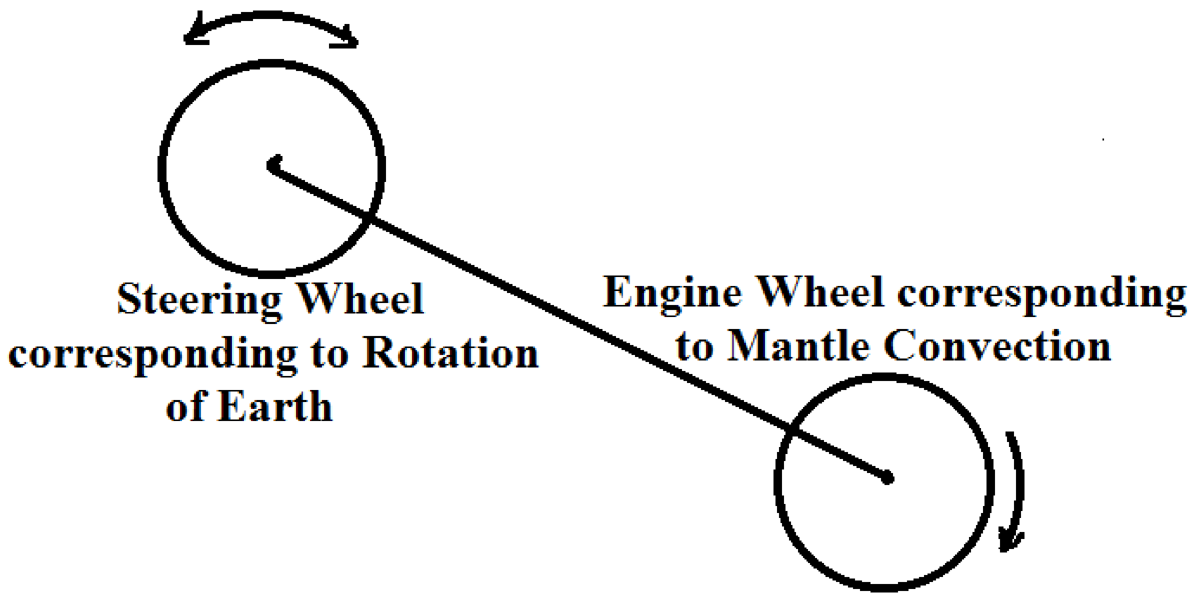


Fig.19 Principle of Shuping Chen's Dynamic Car [16]

Apart from temperature differences standing as the basic cause for convection which is a thermal motion of the fluid, the mechanical displacement of convection which is periodic as will be shown in the next section. The plane of convection is vertical slightly getting tilted due to revolution (not rotation) of the Earth for different observers.

IV. CONVECTION AS A PERIODIC MOTION

4.1 The need for two temperatures*:* There cannot be convection without supply of heat. The supply of heat comes from the upper mantle near the bottom of the Magma Chamber. The heated magma being lighter rises above and reaches the top of the Chamber and get cooled and become heavier and come down and get further heated and rise above creating a process known as Convection which essentially is a mode of transmission of heat.

As mentioned in sec.1.2 Preamble, we should get values for temperatures T_1 (Hot) and temperature, T_2 (Cold). Values given by various authors differ and even the values chosen by me in some of my previous papers also may differ. What is to be seen is that there is proper matching of values. Wikipedia [22] is a general reference widely referred by authors and hence we stick on to it.

4.2 Wikipedia: Wikipedia [22] gives the following statement (in italics) "*Temperatures of most magmas are in the range 700 °C to 1300 °C (or 1300 °F to 2400 °F), but very rare carbonatite magmas may be as cool as 490 °C, and komatiite magmas may have been as hot as 1600 °C. At any given pressure and for any given composition of rock, a rise in temperature past the solidus will cause melting. Within the solid earth, the temperature of a rock is controlled by the geothermal gradient and the radioactive decay within the rock. The geothermal gradient averages about 25 °C/km with a wide range from a low of 5–10 °C/km within oceanic trenches and subduction zones to 30–80 °C/km under mid-ocean ridges and volcanic arc environments".*

The temperature of 490°C can be approximated to 500 °C. This with the other low temperature 700 °C, makes an average of 600 °C. The higher temperatures, 1300 °C and 1600 °C makes an average of 1450 °C which can be rounded off to 1500 °C. Thus the Convection can be assumed to take place between temperatures 600 °C and 1500 °C. As there is a large variation in temperatures given by different authors, we permit such approximations. Thus, starting from 600 °C to 1500 °C, the mean temperature works out to be 1050 °C and make it rounded off to 1100 °C. Let us make a Table of observations with a change of temperature 100°C for each arbitrary unit of time and the same is shown in Table No. 1.

Table No.1

No	Unit Time t	Temp. T°C	No	Unit Time t	Temp. T°C	No	Unit Time t	Temp. T°C	No	Unit Time t	Temp. T°C
1	0	1100	6	5	1400	11	10	900	16	15	800
2	1	1200	7	6	1300	12	11	800	17	16	900
3	2	1300	8	7	1200	13	12	700	18	17	1000
4	3	1400	9	8	1100	14	13	600	19	18	1100
5	4	1500	10	9	1000	15	14	700	20	19	1200

Now plot a graph of arbitrary units of time (x-axis) versus temperature T on the y-axis and the same is shown in Fig.20. The nature of graph obtained is a Sine curve, $T = A \sin \omega t$ where A is an arbitrary constant which can be the amplitude and ω the angular frequency.

4.3 Size of the Magma Chamber: For various shapes and sizes of magma chambers, readers may refer to [Nair V.C.A (12) Fig.15, p.122]. What is known for certain is the temperature at the bottom and top of the Chamber. As the units of time are not correctly known so are the units of distances from the bottom to the top of the Chamber. If the length of the Chamber is taken as the distance from San Jose to Sacramento of the Californian coast of the US, the width of the Chamber can be legitimately taken to be at least 10 km. The temperature variation, if taken for each km, we may even get a graph similar to Fig.20. Thus, we may conclude that the convection is periodic both spatial and temporal.

For readers the readings shown in the Table may appear to be imaginary whether it is arbitrary units of time or arbitrary units of distance from bottom to top of the chamber, but the fact remains that there is convective motion with respect to both time and space. There can be some doubt and dispute over the exact values shown in the Table, but the variation of values shown is a real fact.

In support of my argument that the convection is periodic, I shall present here excerpts of some work of some researchers.

I would like to quote the Abstract of Joseph B. Keller [9]

"Periodic oscillations are found in a one-dimensional model of thermal convection. The model consists of a fluid-filled tube bent into rectangular shape and standing in a vertical plane. The fluid is heated at the center of the lower horizontal segment and cooled at the center of the upper horizontal segment. When a certain parameter exceeds unity, a periodic motion of the fluid is found in which the flow is always in the same direction but in which the speed varies. Inertia is unimportant for this oscillation, which depends upon the interplay between frictional and buoyancy forces" Italics credit: [9]

It has now been firmly established that the convection of magma in the chamber is periodic.

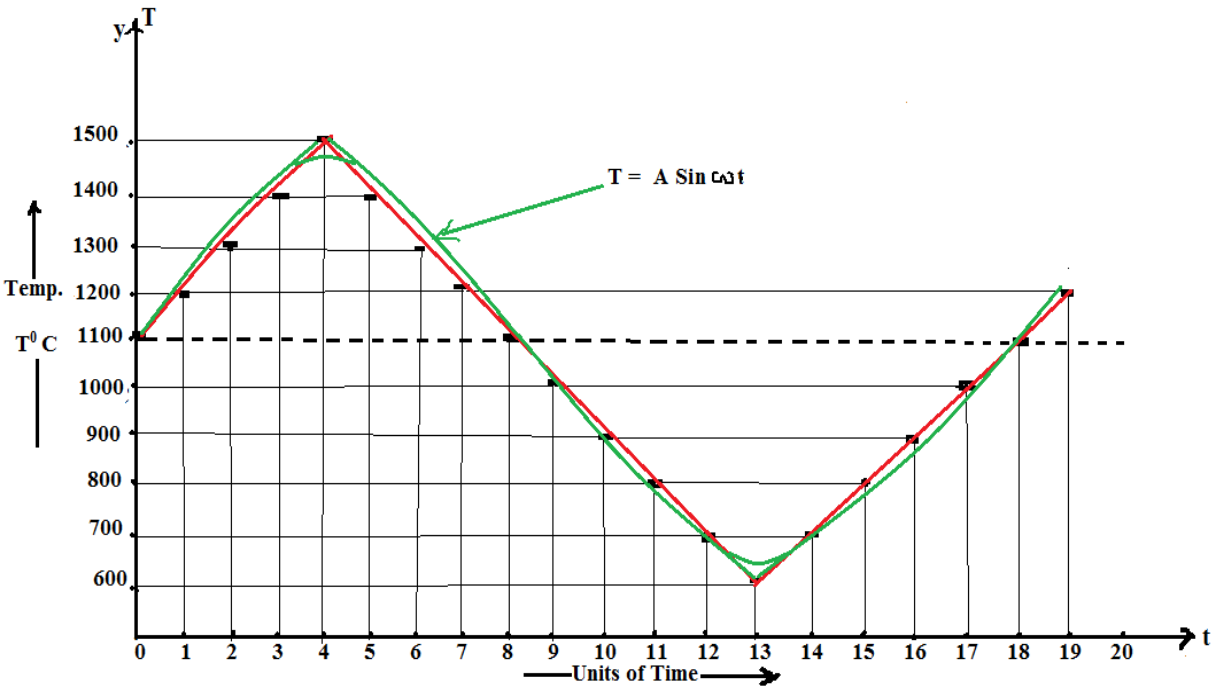


Fig. 20 Graph showing periodicity of magma in the Chamber
(Graph drawn freehand by Author)

Let us now come back to Fig.10. I would like to instruct the readers regarding my philosophy of experience in dealing with such topics. I give my experience in Italics:

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"*The reader should note that a subject like Physics is built on reasonable assumptions whereas a subject like Geophysics is developed more on imaginations, of course based on facts, rather than realization. The common link between these two subjects is their language which is Mathematics.*" (See Philosophy at the start of the Paper).

A close study of the figure10 reveals many things. Even though the temperature of magma at the bottom is 1500℃ and that at the top 600℃, the variation of temperature from either bottom to top or top to bottom is not uniform. Due to the irregular inner shape of the Chamber, temperatures of magma at far left or at far right in the chamber and the type, especially the paths, of convection are left to imagination for the volcanologists. The quantity of magma at a particular place in the Chamber decides the type of convective motion. Accordingly, the convection at the central part of the Chamber has been designated as Main or Primary convection. At the extreme ends of the Chamber, due to irregular temperature differences and uneven quantity of magma, minor convections exist and they are being designated as Subsidiary or Localized convections. It should be remembered that whatever convections that take place inside the Chamber are periodic. Imagine the situation when a large number of periodic motions, small and big, taking place in a closed space, they all get added according to "Summation or Composition of Periodic Motions". The resultant motion of magma in the chamber becomes erratic and irregular, but periodic as only periodic motions get added with a resultant period, $(\frac{2\pi}{\omega})$ which in the present case can be taken as a natural free periodic motion and it can force or induce similar motion on other bodies in the neighborhood.

V. REVIEW OF PAST WORK OF THE AUTHOR RELATED TO THIS PAPER

5.1 The Rayleigh Number, R_a: In the topic of convection, Rayleigh number, R_a read as "R suffix, a" in honor of the great physicist, Lord Rayleigh (Fig.4) is of importance. Convection, though the word appears simple, is very complicated when dealt with Mathematics. We are not talking of the simple convection observed in the heating of water, but the convection in the atmosphere, the convection in the water of the oceans, the convection of magma in the Earth's Mantle and the convection of magma in the magma chamber of a volcano. In such cases, one has to deal with non-linear differential equations of Fluid Mechanics. The readers are advised to go through the following papers, Nair V.C.A [11], Nair V.C.A [12] and Nair V.C.A [13] wherein the author has extensively dealt with this topic and also some of the following sub topics.

5.2 The Definition: The Rayleigh number has been defined by many authors in different ways. I would like to give a simple and appropriate definition by Arunn Narasimhan [1]. The Rayleigh number is the buoyant force divided by the product of the viscous drag and the rate of heat diffusion. The statement of definition appears to be very simple. But, getting a formula in the form of an equation, is a herculean task.

5.3 The Formula for Rayleigh Number: The author of this paper, Nair V.C.A. [11] following Fluid Mechanics of B.M. Smirnov [17 Eqn.11, p.17] has given a formula as

$$R_a = [\frac{(\beta\ \Delta\theta\ c_v\, g\ \rho^2\ D^3)}{\eta\chi}] \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where β is the coefficient of volume expansion of magma, θ stands for the temperature, c_v the specific heat, ρ the density, g the acceleration due to gravity, η the shear viscosity, χ the thermal conductivity and D the distance between the bottom and top or rather the width of the chamber. What is actually required in the formula is the kinematic viscosity, $\nu = (\frac{\text{Shear Viscosity},\eta}{\text{Density},\rho}) = (\frac{\eta}{\rho})$ and

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the thermal diffusivity, $K = [\frac{(\text{Thermal conductivity}, \chi}{(\text{Specific heat}, c_v)(\text{Density}, \rho)}] = (\frac{\chi}{c_v \rho})$. Now, coming to our symbols, temperature, T for θ and distance L for D, the equation, (1) becomes

$$R_a = [\frac{(\beta\ \Delta T\ g\ L^3)}{\nu\ K}] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1a)$$

This is the equation of Nair V.C.A [13, Eqn. (13a) p.12]

5.3.1 The Values for R_a: Looking upon equation, (1a) the only variable quantity in the numerator of the equation is ΔT. In the denominator, there is no much change in the thermal conductivity, χ and hence in the thermal diffusivity, K. Thus, the value of R_a exclusively depends on the ratio ($\frac{\Delta T}{\nu}$) as is well known that as temperature increases, the viscosity decreases. Researchers, Nair V.C.A [(11), p.18] on theoretical considerations given by Smirnov [17] have given a minimum value, R_{am} = 658 for convection of magma just to begin and a critical value, R_{ac} = 1708 in order to sustain the convection.

Let us substitute the values for the physical quantities in Equation, (1a) and find out our value for the magma in the chamber. The value for β as given by David Bercovic [8] is 3 X 10^{-5}/℃; $\Delta T = (T_1 - T_2)$ = 1500 ℃ − 600 ℃ = 900 ℃ (See Fig.10); g = 9.8 $ms^{-2} \approx 10\ m\ s^{-2}$; L = 10 km = 10000 m as assumed by us in Sec. 4.3; ν = 10^{12} Pa s and K = $1.59 \times 10^{-7}\ \frac{m^2}{s}$ [Values as per Nair V.C.A [13, p.13]. Thus, equation (1a) becomes

$$R_a = [\frac{(\beta\ \Delta T\ g\ L^3)}{\nu\ K}] = \frac{(3 \text{ X } 10^{-5})(900 \text{ X } 10 \text{ X } (10000)^3}{(10^{12})(1.59 \text{ X } 10^{-7})} = \frac{27 \text{ X } 10^{13}}{1.59 \text{ X } 10^5} = 16.981 \text{ X } 10^8 \approx 1.7\text{X}10^9$$

$$\therefore \quad R_a = 1.7\text{X}10^9$$

Stephen Clark, et.al [18] has obtained a value for the Rayleigh number for magma as lying between 10^9 and 10^{17} and hence the value obtained is reasonably correct.

5.3.2 Other values for R_a: As is known that the Rayleigh number depends on the ratio, ($\frac{\Delta T}{\nu}$), values higher than R_{am} = 658 and R_{ac} = 1708 has been found by researchers. We shall consider just two Rayleigh numbers of value around 3000 and some higher value around 9000 and see their corresponding convective paths. Our aim is to finally show readers that the convective path is periodic. Oceanography-540 [15, Part of Fig.8-3] has shown the paths of convection for R_a= 3000 and the same is shown in Fig.21. Nair V.C.A [13, Fig.14, p.10] has shown the paths of convection for R_a= 9215 and the same is shown in Fig.22. Very high values of R_a leads to instabilities of convection of magma in the chamber ultimately leading to magma turbulence as shown in Fig.23 [Nair V.C.A [(13) Fig.16, p.11] which is the basic cause for eruption. To summarize we can say that the value of R_a decides the *convective vigor* of magma in the chamber and hence the cause for turbulence. Figures (10) and (23) are just two processes bringing out the same result.

5.3.3 Comparison of Figures (10), (21) and (22): Readers have to closely look at the directions shown by arrows of Fig. 21 and Fig.22. What type of pendulum can be assigned to such a motion? They are photographs obtained with the help of computers. The directions given by those figures can be of either circular or elliptical motion. If the required result is eruption, turbulence of magma due to instability of convection in the chamber is one way for causing eruption and the other way is to achieve the same by composition of several periodic motions taking place rigorously and vigorously in the chamber as shown in Fig.10 with a period given by

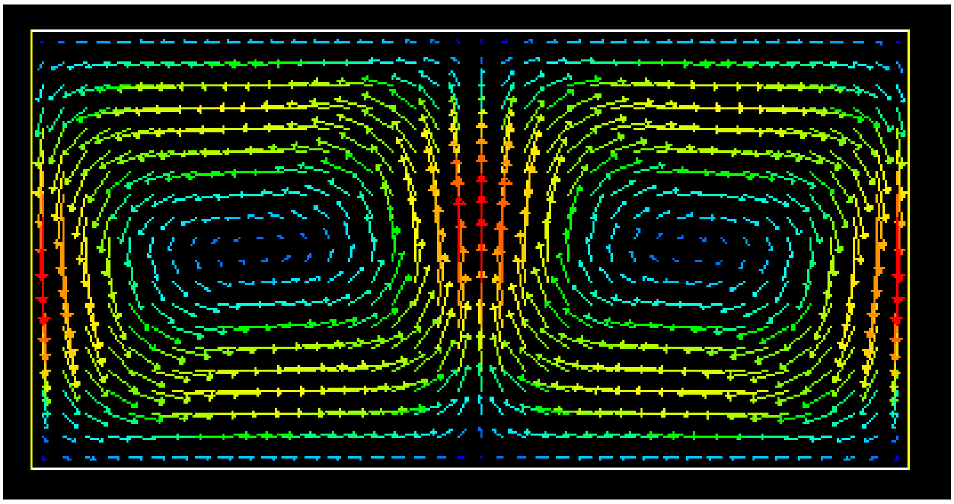

Fig.21 Diagram showing the velocity vectors and the computerized convection for $R_a = 3000$ [15]

$(\frac{2\pi}{\omega})$ where ω is the angular frequency of the system. The oscillations of magma created in the chamber has tremendous energy proportional to square of its natural frequency, n and if A is theoretically taken as the amplitude of the system, then the intensity is proportional to square of amplitude. What is meant by this is that the system can induce oscillations in other bodies in the neighborhood.

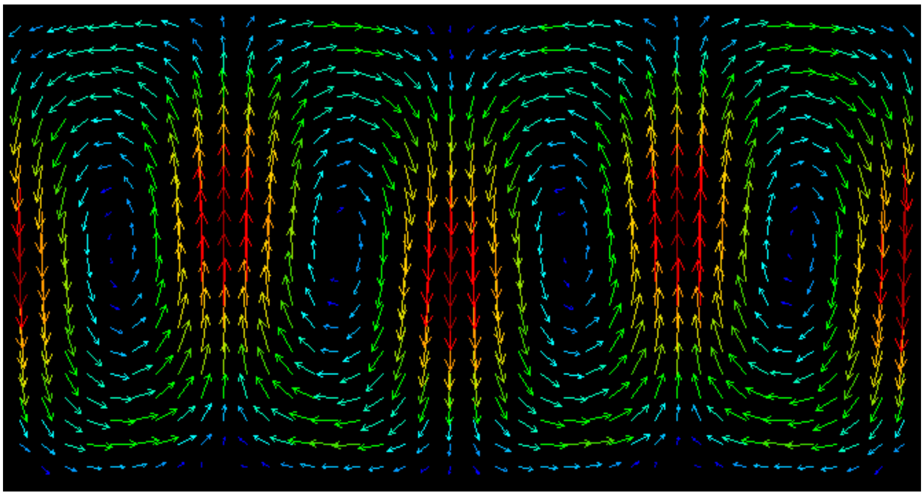

Fig.22 Convective paths for $R_a = 9215$ [Reference unrecorded]

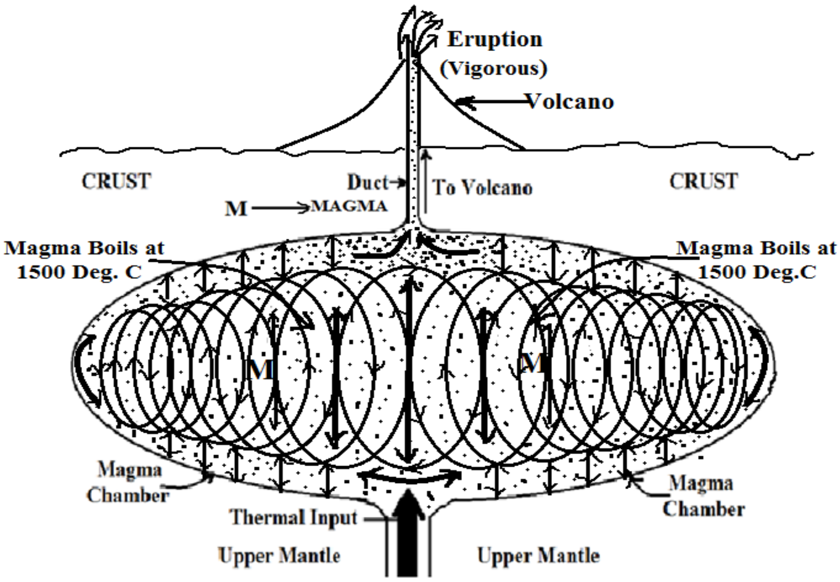

Fig.23 The Turbulence of Magma in the Chamber [13]

5.3.4 The magma just enters the Conduit: When the periodic motion of magma in chamber is vigorous due to the composition of the primary and localized periodic convections with some fresh magma at a high temperature entering the chamber from the upper mantle, the situation forces some magma of the chamber enter the conduit. After the entry, even though it is in thermal contact with the magma of the chamber, there is a slight change in its physical characteristics. For example, its top surface being open, its temperature is less than the average temperature, T= $(\frac{T_1 + T_2}{2})$ = $(\frac{1500+600}{2})$ = $\left(\frac{2100}{2}\right)$ = 1050℃ of magma in the chamber and further its viscosity is less and the formula gets compensated by a low value of ΔT and hence has a low Rayleigh number and it remains almost stationary for variable lengths of time in the conduit as shown in fig.24.

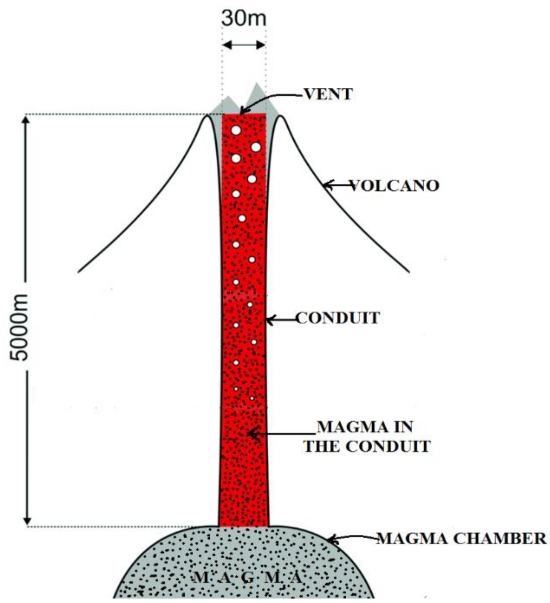

Fig.24 The Geometry of the Conduit slightly and suitably modified by author.
(Original Picture Credit: [20]

5.4 The Right Conjecture for Forced Oscillations: From elementary theory on oscillations, it is known that the total energy of the combined composite oscillations of magma in the chamber is equal to the square of its linear frequency and hence the energized magma can induce forced oscillations in the neighboring bodies. The chamber being very huge and of irregular size, the frequency also called the natural frequency of the periodic magma in the chamber has not been worked out.

M.E. Thomas, J.W. Neuberg and A.S.D. Collinson [20] has given data from Soufrière Hills Volcano (Barclay et al. 1998; Sparks et al. 2000), placing minimum depth constraints of 5–6 km for the position of the magma chamber and width estimates of 30–50 m for the conduit and the same is shown in Fig.24 with magma in the conduit shown red.

We shall take some values slightly less than what is quoted by Thomas [20]. And see how the periodic motion of magma in the chamber can influence or force periodic motion in the magma of the conduit. Let the height or length of the conduit be 5 km even though it is 6 km as shown by author. The diameter of the conduit we take as 30 m even though the maximum shown by author is 50 m. Now work out the volume of magma in the conduit.

$$\text{Volume} = \pi\ (\text{radius})^2\ \text{X height} = 3.14\ \text{X}\ (15)^2\ \text{X}\ 5000 = (3.532\ \text{X}\ 10^6\ )m^3$$

We have now to compare this volume with that of any standard magma chamber. Nobuo Geshi, et.al [14] have given the volume of a VE-8 volcano equal to Sacramento, San Jose and San Francisco put together as 10 trillion cubic meter. As 1 trillion = 10^{12}, 10 trillion = 10 X 10^{12} = 10^{13}. Taking the ratio of the volumes, we find the ratio, $\frac{10^{13}}{3.532\ \text{X}\ 10^6}$ = 2.83 X 10^6 which means that the volume of the chamber is some 3 million times larger than the volume of magma in the conduit. It is like a large continent with an adjacent small island. The chamber is the continent and conduit is the island. Oscillations of magma in the chamber as explained in section 4.3 can very well rattle magma in the conduit, induce or rather force oscillations on it and it starts vibrating with certain frequency. These vibrations are named "Magma Wagging", a term very much used by authors [8] which is a major and important part of the research paper we are dealing with.

VI. MAGMA WAGGING

6.1 Ideal and Appropriate Illustrations: With my experience of teaching Applied Physics for nearly half a century (46 years) under the Department of Technical Education, Government of Maharashtra, India, I would like to present things more understandable to readers (whom I take as my students because I am around 81of age). Readers may closely study Figures 25 and 26.and the same must be clear for any physicist. Fig.25 is a double pendulum in which the smaller one on the right corresponds to magma wagging as it derives energy from the larger pendulum corresponding to magma of the chamber. We came back again to the pendulum which is not leaving us. Fig.26 is an illustration of an electrically operated tuning fork. The AC circuit is periodic corresponding to the periodic magma of the chamber. The vibrations of the prong of the fork are forced oscillations which die out the moment the switch is put off.. There is no other simpler and better way of explaining the phenomenon of magma wagging.

6.2 Earlier Work: In the earlier days of research on volcanoes, volcanologists did not pay attention to such phenomenon as magma wagging even though it existed for centuries. What was really interested those days was the process of eruption, which according to me is one of the most beauty of Nature, and protection from it.

Theresa Oei [19] Volcanic tremors occur before the eruption of a volcano and may last for few minutes or several days. The tremors are defined by a low frequency shaking, about 0.5 to 5 and sometimes to 15 Hertz.. The universality of this tremor frequency was puzzling to geologists, who sought to create mathematical models that could predict volcanic eruptions.

A model developed by another team considers tremors created by columns of magma within a volcano that wag back and forth within its main conduit like a metronome rod.

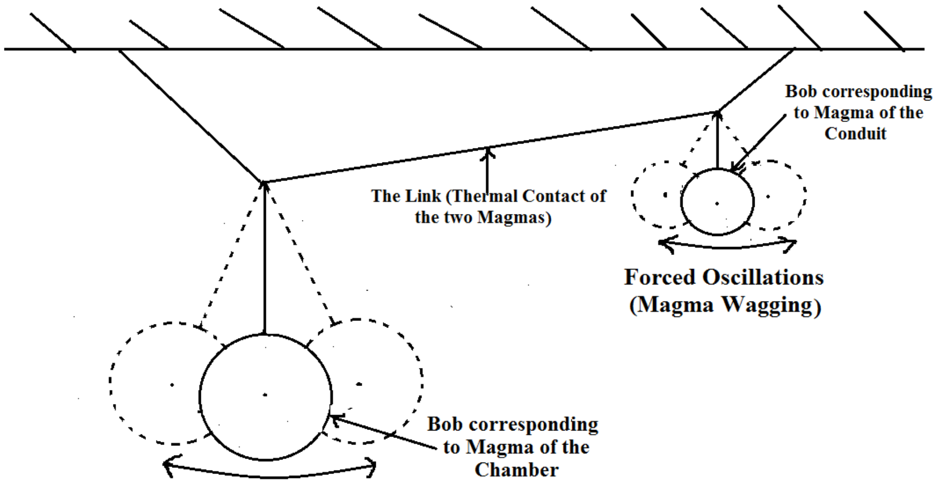

Fig.25 The Double Pendulum illustrating Forced Oscillations, Resonance and Magma Wagging (Figure drawn freehand by author

Charles Q. Choi [4] reports in the Scientific American that Volcanic Tremors may help predict massive eruptions.

Recent studies and research by some stalwarts like David Bercovici, Department of Geology and Geophysics, Yale University, US and Mark Jellinek, Professor, Earth Ocean and Atmospheric Sciences, University of British Columbia, Canada and few others have done extensive research on volcanoes. In this paper I shall present some excerpts from their research on Magma Wagging.

The authors begin by mentioning that "*A Volcanic Tremor is an ubiquitous feature of any erupting volcano".*

The type of words and the language used by David Bercovici is: *Explosive eruptions are some of the most spectacular and destructive phenomena in nature. Tremor is very mysterious, most notably because it shakes at pretty much the same frequency in almost every explosive volcano, whether it's in Alaska, the Caribbean, New Zealand or Central America. That it's so universal is very weird because volcanoes are so different in size and character," he said. "It would be like blowing on five different musical wind instruments and having them all sound the same The tremor, Bercovici said is both a warning of the event and a vital clue about what is going on in the belly of the beast.* (Italics Credit: [8])

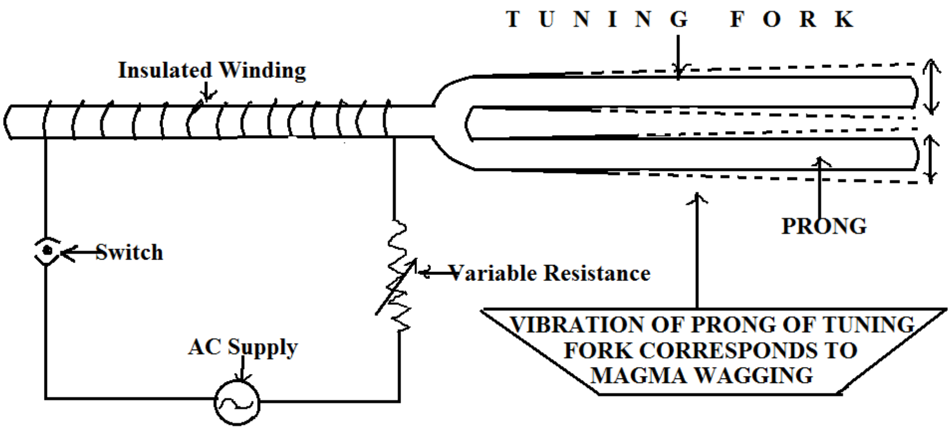

Fig.26 The vibrations of the prong of an electrically operated Tuning Fork is similar to Magma Wagging (Figure drawn freehand by author)

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What is of importance is the behavior of magma column in the conduit. They have considered a simplified version of the model in which the annulus of diameter, u (Fig.27) contains a compressible but impermeable gas-magma foam of disconnected bubbles that rises with the magma column. The behavior of a column of very viscous magma surrounded by a foam-spring of fixed mass is similar to an unforced damped harmonic oscillator. The primary model prediction for the volcanic tremor is the frequency of wagging magma. The equations to obtain the frequency are non-linear and hence trivial. The authors, David Bercovici, et.al and excerpts from the same published by Nair V.C.A [(11, p.126-127)] have shown the angular frequency, ω_0 for the magma wagging as

$$\omega_0 = \sqrt{\left[\frac{2\,\rho_0\, C^2}{\varphi_0\, \rho_m\, (R_c^2 - R_m^2)}\right]} \quad \dots\dots\dots\dots\dots\dots\dots (2)$$

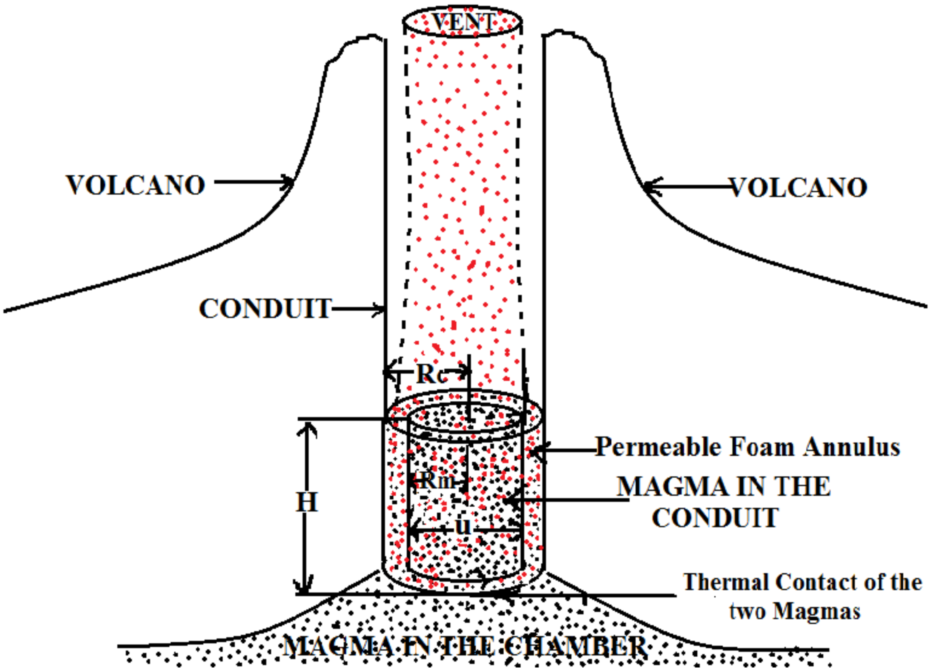

Fig.27 Sketch (*re-drawn from original*) of the Magma Wagging model of Volcanic tremor (Picture credit: [8]

where the linear frequency is $\frac{\omega_0}{2\pi}$, C is the speed of sound in gas given by $C = \sqrt{(\frac{R\,T}{m_g})}$ where R is the universal gas constant, T the absolute temperature lying between 1000 and 1300 degree Kelvin and m_g, the molar mass of water which is the dominant volatile in the erupting gas and its value is 18 x $10^{-3}\,\frac{kg}{mol}$. The value of C is found to be about 700 $\frac{m}{s}$. ρ_0 and φ_0 are the density and volume fraction of the undisturbed gas in the annulus, The volume fraction is the porosity equal to 0.7. ρ_m the magma density, R_c and R_m are the radii of the conduit and magma column respectively.

It is found that oscillations persist longer for taller columns. The critical height, H_c required for wagging, however, is

$$H_c = \frac{\pi}{2}\left[\sqrt{\left(\frac{\mu_m}{2\,\rho_m\,\omega_0}\right)}\,\right] \dots\dots\dots\dots\dots\dots\dots\dots (3)$$

where μ_m is the magma viscosity. This, on substitution of values, is found to be 40 meter. A typical H is about 1 km. From the above equation (3), the longest dimensional damping time, t is given by

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$$t = \left(\frac{2\,H}{\pi}\right)^2 \left(\frac{2\,\rho_m}{\mu_m}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

For a column of height 1 km, $\rho_m = 2500\ \frac{kg}{m^3}$, and taking minimum value of viscosity 10^5 Pa s, we get the damping time as

$$\left(\frac{2 \times 1000}{3.142}\right)^2 \left(\frac{2 \times 2500}{10^5}\right) = \left(\frac{2000}{3.142}\right)^2 (5 \times 10^3 \times 10^{-5}) = (636.54)^2 \times 5 \times 10^{-2} = 405183 \times 0.05$$

$$= 20259 \text{ second} = \frac{20259}{3600} = 5.63 \text{ hours}$$

which is slightly less than 6 hours

VII. THE RESONANCE AND THE ERUPTION

7.1 Frequency of magma in the chamber: The Magma wagging in the conduit with whatever frequency is the result of a *"Cause and Effect"* formalism on which certain or some of the physical processes are built up. I do not know whether some of the readers might take me as cunning or shrewd or rather more cunning than shrewd. That is because nowhere in the paper I have mentioned regarding the frequency of the periodic magma in the chamber except mentioning that the geometry and the structure of the magma chamber does not suit for a calculation. But, the herculean task with rigorous Mathematics by the Volcanologists, David Bercovici, and Mark Jellinek have successfully worked out the frequency, ω_0 of magma wagging. By obtaining the frequency of magma wagging, the geophysicists, David Bercovici and Jellinek have solved not my problem but that of many others in this regard. If the frequency of the magma wagging lies between 0.5 Hz and 7 Hz, the periodic magma in the chamber should also have a frequency in this range.

7.2 The Resonance and the Eruption: The magma wagging may continue from minutes to days and weeks and behave as a precursor for the prediction of an eruption. The oscillations have their own characteristic behavior. At some stage known only to the volcano, the frequency of the periodic motion of magma of the chamber may coincide with that of the magma of the conduit. The two may resonate each other as per phenomenon of Resonance. The amplitude is maximum leading to turbulence that sets in the magma chamber with very high values of the Rayleigh number as per literature shown in the text, magma fragmentation starts making it of high fluidity. The molten magma being of low density rises above to the surface through the vent. The eruption will continue depending upon the quantity of magma in the chamber facilitated by additional new entry of magma from the upper mantle. An explosive eruption will only take place if the pressure within the magma exceeds the strength of the surrounding rock. These explosive eruptions are driven by the thermal energy stored in the magma. The thermal energy is transferred into kinetic energy of the eruption column through the expansion of gases into growing vesicles (air bubbles)

VIII. CONCLUSION

In conformity with the title of the research paper, it has been firmly established that the convection of magma in the chamber is periodic both with respect to space and time. Each physical quantity in the title of the paper has been extensively dealt with. The frequency of magma wagging worked out by David Bercovici and Mark Jellinek, the US and Canadian physicists respectively brought an end to this lengthy paper.

As a picture speaks thousand words, pictures of scientists are given at appropriate places. The figures, other than those of the scientists, are drawn free hand by author.

ACKNOWLEDGEMENT

Through this paper I wish to acknowledge the excellent work of both **David Bercovici** and **Mark Jellinek** the geophysicists of Yale University US and University of British Columbia respectively. In fact, without referring to their work, the main objective of this paper would not have been achieved. I offer my sincere thanks to both of them.

I also acknowledge the research publications of others which helped in the completion of this paper.

BIOGRAPHY

Dr.(Prof.) V.C.A. Nair* (b.15th Aug. 1939) is an Educational Physicist, Counselor, Research Guide and Consultant. He did his Masters in Physics from Mumbai University, India and Ph.D. from Shri. JJT University, Rajasthan also in India He is a Research Guide and distinguished alumnus of JJT University. He is also a Chancellor designated Resource Person in the area of Physics of the University. He has to his credit over 4 decades of teaching Applied Physics in eminent Polytechnics in Mumbai and having taught nearly 16,000 students since 1965. He has published a number of research papers in Physics and Geophysics in International and $UGC^{\#}$ recognized Journals some of which can be seen in the net 'Google Search' when the name of the author or his e-mail is clicked in that style. He is a Life Member of Indian Society for Technical Education which is an all India body. He had been to USA a number of times and visited eminent Universities such as Stanford, Harvard, MIT, 3 Universities of California at Berkeley, Los Angeles and also at Davis, University of Princeton at New Jersey, Roosevelt University at Chicago, University of Chicago and University of San Francisco. At present Dr. Nair is a Research Guide for Physics at Shri JJT University, Rajasthan-333001, India . He is a member of the Editorial Board of this Journal. His Ph.D. Thesis is in Geophysics and he is working on topics such as Volcanoes, Earthquakes, Tides, Clouds, Global Warming and Climate Change. – Editor

*nairvca39gmail.com. #University Grants Commission

IX. EPILOGUE

9.1 Some Revelations of Interest shown by Author in the subject of Geophysics: 9.1.1 The Volcanoes of Northern California, US:

Readers will be surprised to know that the author has so much affection to the subject that what more can be expected of him of celebrating his 75^{th} birthday (15 August 2014) on the foothills of a volcano in the United States. Not one volcano but two of them so near that I thought of climbing over each of their lava dome. I am producing here with two photos of this geological wonder (Fig.below) with my photo in each of them. I started from my US residence at Foster City, central California-94404 on the morning of Friday the 15^{th} August 2014 and reached Siskiyou county in northern California a distance of nearly 300 miles (480 km) and reached Mount Shastha a stratovolcano of geological fame before noon driving nearly 5 hours. The brief details of the volcano is as under: The elevation is 14,179 Feet (4.322 km) above sea level and 9822 Feet (2.994 km) above the surrounding terrain; Volume: 350 $(km)^3$. Second highest peak and most voluminous strato volcano; Last eruption: Year 1786 (Date not known)

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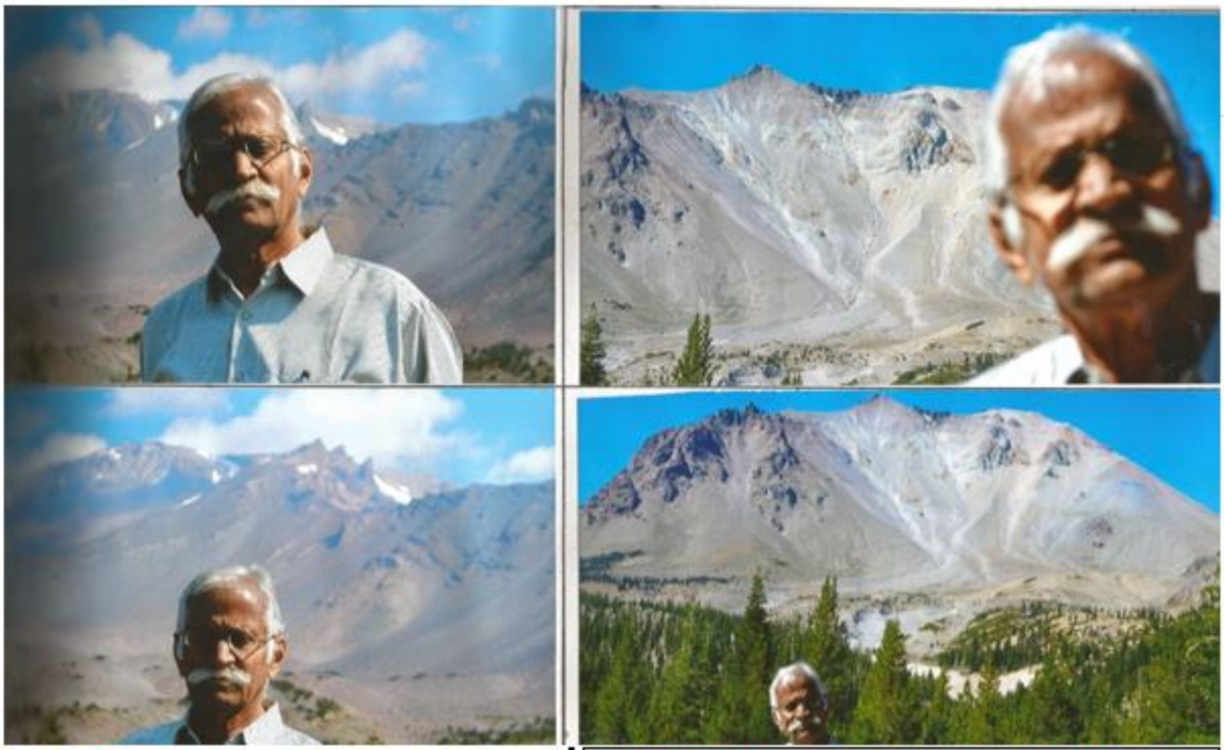

Mount Shastha (Strato Volcano also known as Composite Volcano) at Siskiyou county, Northern California, USA 96067 had a close look on my 75th Birthday, Friday the 15th August 2014. Second highest peak and most voluminous Strato Volcano
Last eruption: year 1786
Top: One side. Bottom: The other side

Mount Lassen (Strato Volcano also known as Composite Volcano) at Mineral, Northern California, USA 96063 had a close look on Saturday the 16th August 2014. One of the largest lava domes on Earth. Last eruption: 22 May 1915
Top: One side. Bottom: The other side

Fig.28 Author at the foothills of two Volcanoes in Northern California, US
15 & 16 August 2014)

9.1.2 Geothermal Power Station at Northern California, US:

In the Mayacamas Mountains, located north of San Francisco, naturally occurring steam field reservoirs below the earth's surface are being harnessed by Calpine to make clean, green, renewable energy for homes and businesses across Northern California.

The Geysers, comprising 45 square miles along the Sonoma and Lake County border, is the largest complex of geothermal power plants in the world. Calpine, the largest geothermal power producer in the U.S., owns and operates 13 power plants at The Geysers with a net generating capacity of about 725 megawatts of electricity - enough to power 725,000 homes, or a city the size of San Francisco.
Date of Visit: 12 August 2017

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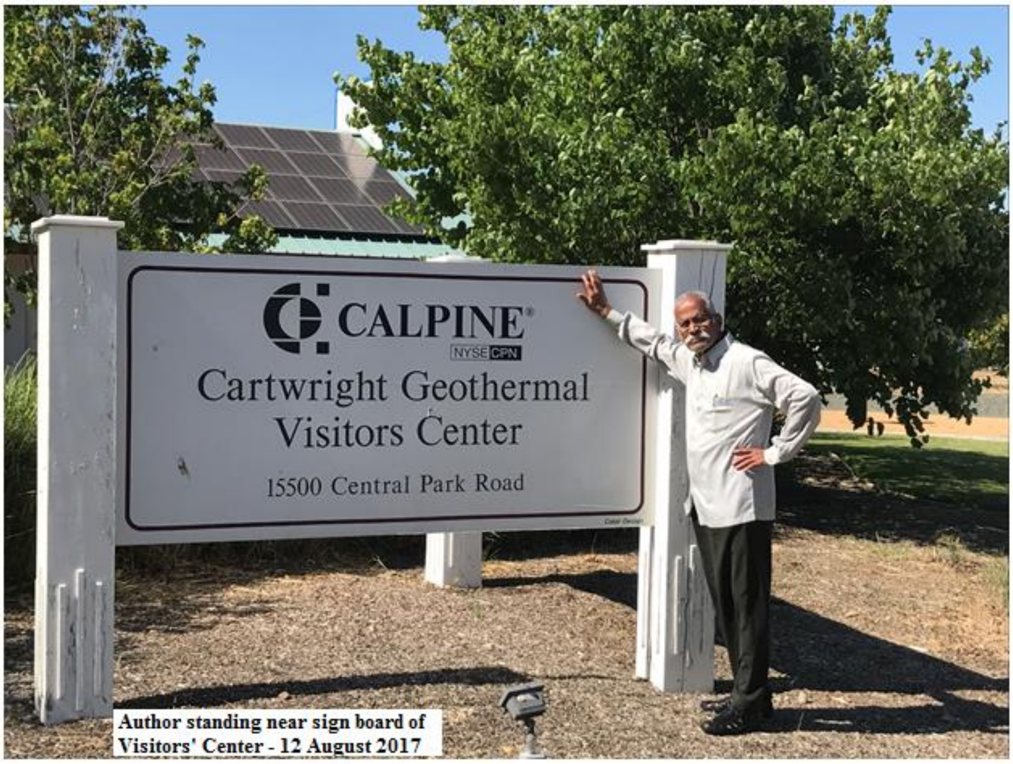

Fig. 29 At the entry to Geothermal Power Station in Northern California
(12 August 2017)

Fig.30 Author studying a Flow Chart of the Geothermal Power Plant at the Power Station
(12 August 2017)

9.1.3 The Henry Hinds Laboratory for the Geophysical Sciences of the University of Chicago:

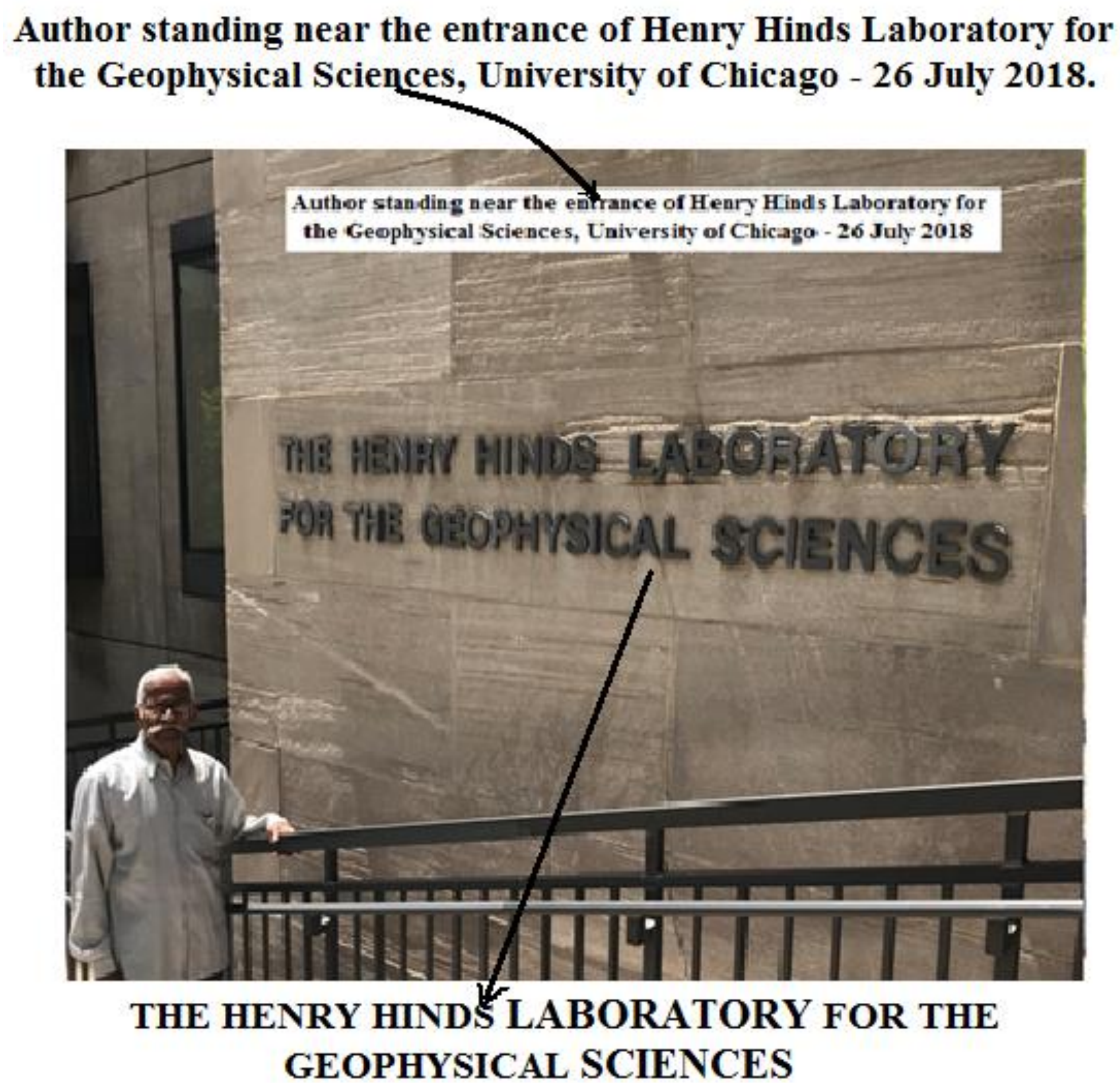

Fig.31 Author just at the entrance of the Henry Hinds Laboratory, University of Chicago (26 July 2018)

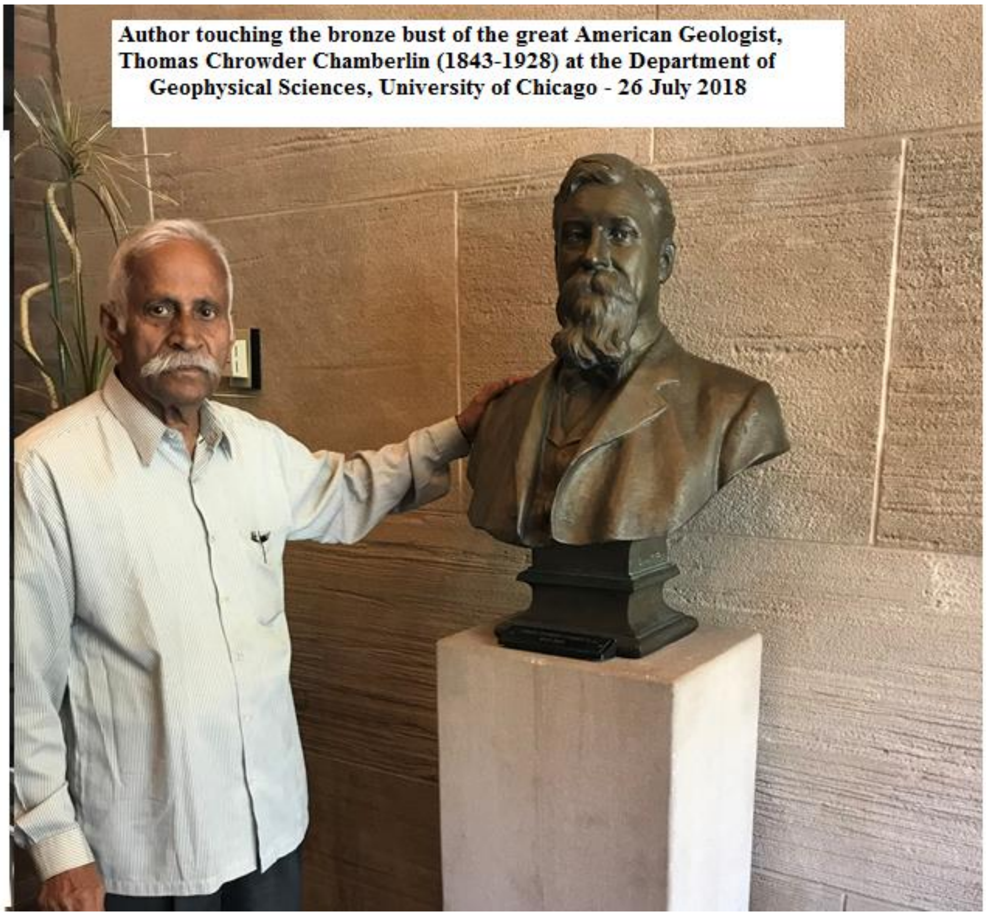

Fig.32 Author lucky enough to put his hand on the shoulder of the bust of the great American Geologist, Thomas Chrowder Chamberlin at the Department of Geophysical Sciences, University of Chicago (26 July 2018)

This Research Paper is prepared amidst the outbreak of Corona Virus disease all over the world. As a physicist, I felt like preparing some write-up like a Poem and circulate the same among my friends. The same has been sent by E-mail to a large number of people. I take this opportunity to publish the same at the end of this paper and it follows. Readers may please note that I have not used Shakespearean English nor is it with rhymes and rhythm. It is a set of meaningful statements. Have a look at it.

Coronavirus, the terrible unwanted incarnation on Earth
The following is a Poem on Coronavirus written by a Physicist

- **I am Coronavirus**
- **I shall not come to you if you don't get afraid of me**
- **But, if you get afraid of me, I shall search for you**
- **This is what the people do**
- **People get afraid of me at alarming levels**
- **That is why I am after them**
- **Do not allow me to search for you**
- **Allow me to stay where I am supposed to**
- **Try to be a Physicist following Newton's Laws**

- **Your Reaction was not equal and opposite**
- **It surpassed my Action with some of your Reaction lingering around**
- **This lingering Reaction created by you affects your health and normal life**
- **To contain me, you have to find a Black Body and follow Quantum Theory**
- **Call either Planck, Heisenberg or Schrodinger or all of them to contain me in the Black Body**
- **Well ! If you succeed, I shall remain a part of radiation from the Black Body with Einstein looking at his famous equation, $E = mc^2$**
- **Your excess Reaction still lingers near me and created all the problem**
- **I still have not entered the Black Body because you are wrong at the very base of Newton's Laws exceeding your Reaction more than my Action**
- **I travel faster with the rotation of Earth which is some1000 miles per hour**
- **I shall give a solution to your problem**
- **Maintain "Status quo" and try to reduce your Reaction and bring the same at level with my Action**
- **I shall then enter the Black Body and be a part of Radiation as before**

Prepared by
***Dr.(Prof.) V.C.A. NAIR, Ph.D**
A Research Guide in Physics from Mumbai, Age: 80+ and a native of Palakad, Kerala.
***nairvca39@gmail.com**

Date: 22 March 2020 coinciding with the Birth date, 22 March 1868 of Prof. R.A. Millikan, the great American Physicist and 1923 Nobel Laureate in Physics

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