Indian Journal of History of Science, **29**(1), 1994

JOHN HENRY PRATT, ARCHDEACON OF CALCUTTA AND HIS THEORY OF ISOSTATIC COMPENSATION

MANIDIPA KAHALI
Research Scholar, Asiatic Society of Bengal, Calcutta

The East India Company encouraged an extensive survey operation, and the works of Major Rennell, Lambton and Col. Everest are well known in this connection. John Henry Pratt, Archdeacon of Calcutta was likewise asked by the then Surveyor-General to give a report on isostatic compensation caused by any superficial masses, such as mountains, oceanic depressions or any other defects. Pratt calculated the actual amount of the attraction of the Himalayan mass and formulated his famous Theory of Isostasy, an account of which is presented in the paper.

The name of John Henry Pratt is related inseparably with the history of the Theory of Isostasy. The principle of Isostatic Compensation was first developed in a scientific sense in Calcutta by Pratt in 1854. At that time, Pratt was the Archdeacon of Calcutta. He studied at Gonville and Caius College and at Christ's and Sidney Sussex Colleges, Cambridge and received his B.A. degree in 1833 and M.A. in 1836. He opted for a missionary career. In 1838, he obtained a chaplaincy under the East India Company and in 1844 became chaplain to the Bishop of Calcutta. He was appointed Archdeacon of Calcutta in 1850, a post he held till his death[1].

According to Pratt's concept, the crust with different densities in different segments of blocks is floating on an effectively liquid substratum; the base of the crust is at a uniform depth and is supporting a uniform weight per unit area. The level to which the crustal blocks sink is the level of compensation.

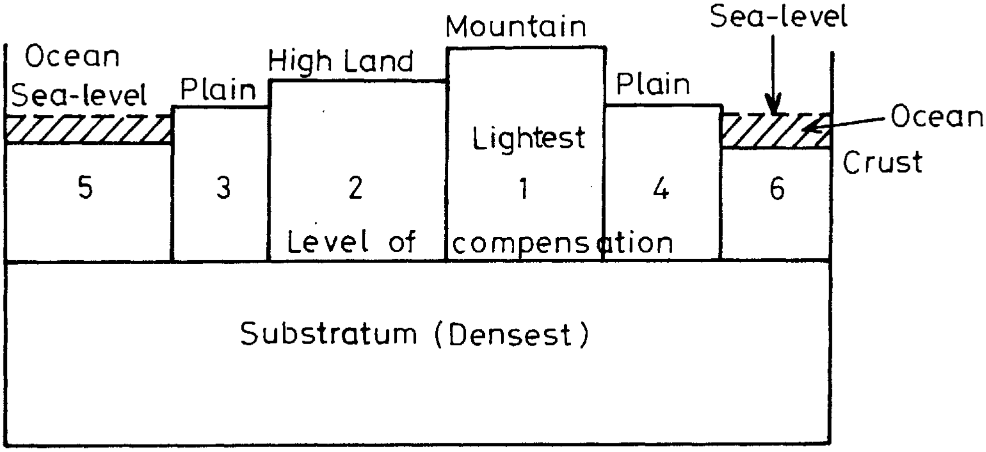


Fig. 1 Concept of Isostasy after Pratt (modified from A. Holmes) Columns 1-6 are made up of successively denser materials

In broad terms, the Earth is in isostatic equilibrium beginning from a certain depth in the earth's interior. The surface units are under the same pressure whether they are beneath the mountain, lowland or oceans.

Throughout the 18th century, a number of expeditions and experimental investigations were organized at a few selected places to determine the actual figure of the earth; special mention may be made of the expeditions led by Clairaut, Bouguer, De La Condamine and Godin[2]. One important result of these investigations was that mountain pulls the plumb-line and the mass deficiency of the ocean pushes it towards the mountain; thus, if a pendulum swings in the neighbourhood of a mountain, the plumb-line of the pendulum will be deflected towards the mountain (Fig. 2).

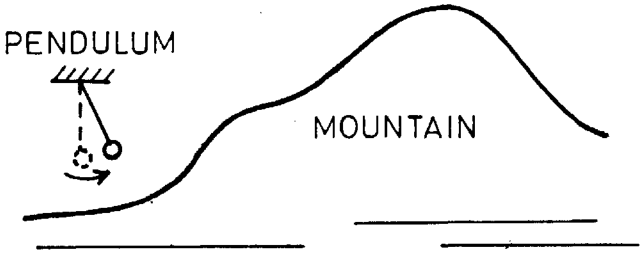


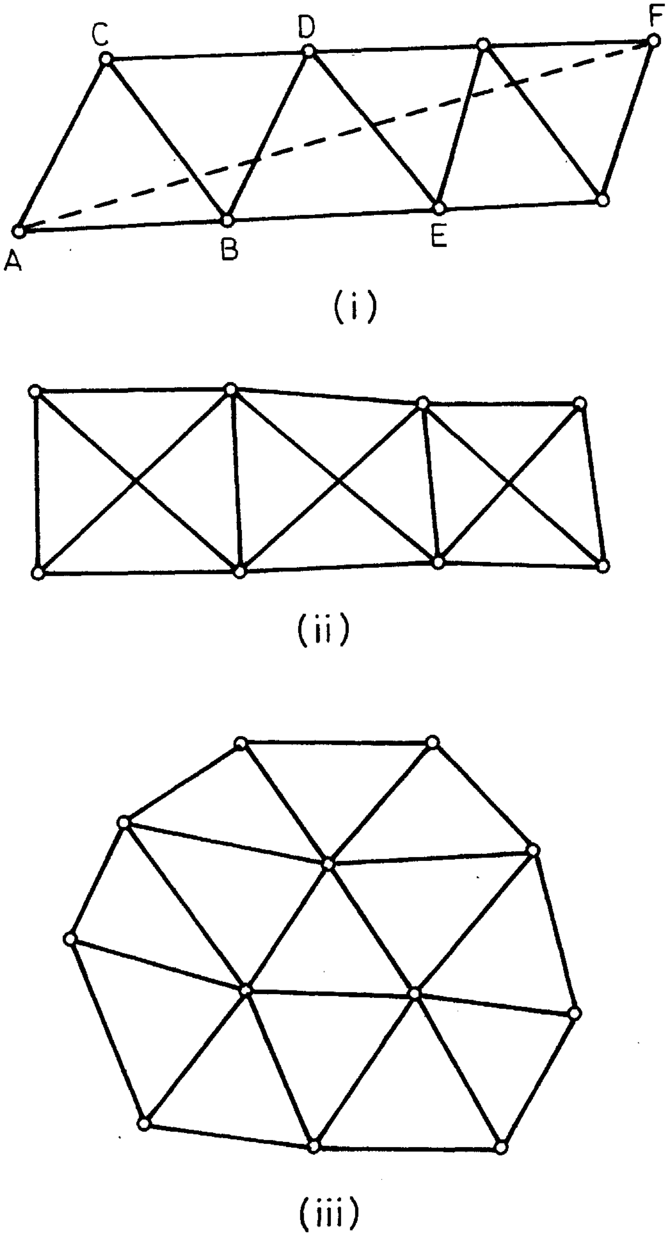
Fig. 2

Newton, in his Principia, while discussing the gravitational attraction, which is mutual attraction between the masses of matter, had the idea that the every hill must by its attraction, alter the plumb-line of the heavy bodies in its neighbourhood[3].

In the next phase, steps were taken to measure the amount of the deflection of the plumb-line. In 1735, Bouguer, De La Condamine and Godin, with the support of the French Government, studied the deflection of the plumb-line near Mt Chimborazo in the neighbourhood of Quito in Peru. In 1738, Bouguer repeated these experiments for two places in England, one in Yorkshire and the other in Lancashire. In 1749, he once more visited Chimborazo to measure the horizontal pull. In 1774, Navil Maskelyne performed similar experiments near Mt Schiehallion. About the same time, the Russians, conducting similar experiments near Moscow, had observed such an anomalous behaviour of the pendulum even when there was no mountain nearby and ascribed it to local attraction. Strangely enough, all these measurements gave conflicting results from which no definite conclusion could be derived.

In India, the problem received attention in connection with the survey work initiated by James Rennell under the East India Company in the later half of the 18th century. Rennell and his surveyors had carried out an extensive determination of the latitude and longitude of a large number of places for preparing reliable maps. His successor, Major Lambton, not only depended on the astronomically determined latitudes and longitudes but also introduced a new method, namely, survey by the triangulation method from which latitudes and longitudes of places could also be determined independently. In this work, Lambton noticed measurable discrepancies in a few places and realized that such discrepancies arose due to local attraction, which were moreover related to what his predecessors Bouguer and others had already found.

Here, a few words may be said about the method of triangulation. The idea of triangulation was first conceived by Tycho Brahe in the 16th century and used by him to establish a geodetic connection between Ven Island and the main islands of Denmark. Triangulation was developed as a science by Snell[4]. The idea of triangulation is to measure only the angles of consecutive triangles. In Fig. 3, (1) represents the single triangulation chain, (ii), the envelope chain, and (iii), triangulation net. If one side and one angle are known, then all sides of the triangle can be computed by using the sine theorem. The triangulation points are chosen on hill tops and mountains, so that the neighbouring points A,C,D,E can be from the point B and thus the angles between then can be measured. When the lengths of sides are known, the distance between A and F can be computed along the reference ellipsoid[5] and thus all points of the triangulation can be referred to the same



(i)

(ii)

(iii)

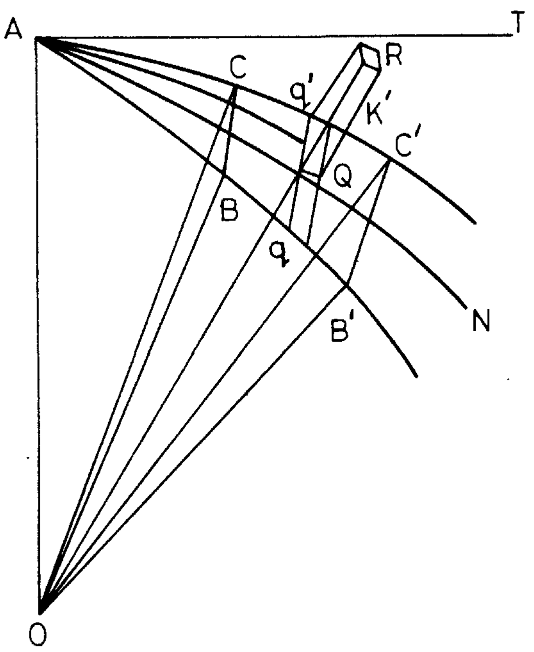
Fig. 3

geodetic system. The length was measured by chain and the angles by a theodolite.

Lambton had started from southern peninsula and proceeded towards the north. He simultaneously took astronomical observations with geodetic calculations, i.e. the determination of latitudes and longitudes by triangulation method[6]. He noticed that there were discrepancies due to local attraction between astronomical and geodetical results in some stations but not in all. He brought this problem to the notice of the high authority and submitted a proposal for undertaking pendulum operations simultaneously with the survey work, but he did not receive any encouragement. In the circumstances, he rejected those stations which gave anomalous results and proceeded to select new stations.

Lambton's successor, George Everest, extended the triangulation operation to the nearest point in the Himalayan ranges. In 1822, he also found such discrepancy at the station Takal K'hera, where the plumb-line is attracted 5" northwards by the table-land of the Mahadeo Hills. It occurred to him that the existence of a massive denser formation might cause a deflection of the plumb-line of such magnitude[7]. The Himalayan Mountain ranges have always been regarded as a very disturbing element in Indian geodesy. Between 1830 and 1840, the Trigonometrical Survey was first extending its operation across the plains of Northern India. From Everest's calculations it was found that the deflection of the plumb-line was large at the station Kaliana at the northern extremity of the Great Arc. That deflection was due to Himalayan attraction[8]. Between Kaliana and Kalianpur, the astronomical amplitude was 5".236 less than the geodetic amplitude; again between Kalianpur and Damargida, the astronomical amplitude was 3".791 greater than the geodetic amplitude[9].

At that time it was generally held that local disturbance was the cause of the deflection, but there was no scientific explanation. In 1852, Andrew Waugh, the then Surveyor-General, requested Archdeacon Pratt to consider the problem from a scientific and mathematical point of view[10]. During the next nine years, Pratt devoted himself seriously to the solution of the problem. In his initial attempt to calculate the amount of attraction of the Himalayan mass by some direct method, he obtained a formula for the deflection of the plumbline in terms of the average height of the mass concerned and an angle subtended by the mass element. In Fig. 4, A is the observation station.[11] The superficial mass element is cut into number of lines by two great circles ABB' and ACC' passing through the attracted station A, Pratt divided the surface through A, parallel to the sea-level, into a number of crescent moon shaped regions which all meet again in a point on opposite side of A. The whole surface was divided into a number of four-sided compartments. O is the centre of the earth; and AT, the tangent at the point A. Let BCC'B' be one four-sided compartment and $\angle BAC = b$, $\angle AOB = a$ and $\angle BOB' = \varnothing$. Let Q be an element of the compartment, q Q q' being parallel to BC, $\angle QAN = y$, AN being a great circle bisecting the angle b and $\angle AOQ = q$, K' be the height of R, the earth's surface, above Q. So, there is a mass of prism QR. Pratt calculated the attraction of prism QR on A along AT. After integrating, he got the attraction of mass standing on the compartment BC B'C' = 4/21 p x Sin ½ boh, where



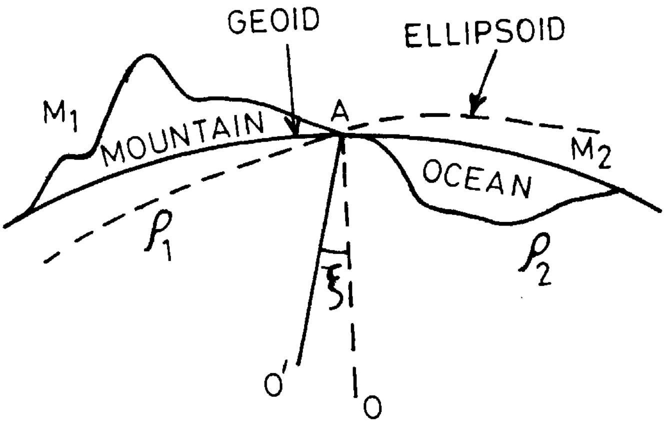
P is the mean density of the superficial matter. The average height of the surface of the mass element inside the compartment BCC'B' above the surface through A is "h". Let ξ be the angle of deflection of the plumb-line at the station by the mass element standing on the compartment BCC'B'. After complicated mathematical procedure into which we need not enter, Pratt gave the deflection of the plumb-line.

$\xi = 1''.1392 \text{ h Sin} \frac{1}{2} \text{ b}$ (1)

Taking this formula (1) and after doing elaborate mathematical calculations, he obtained the deflections and amplitudes of the arcs, which were very much larger than the results given in Everest's work. Full calculations were published in the *Philosophical Transactions of the Royal Society of London* in 1854.

In 1854, Pratt surmised that the mean density of the crust below the mountains must be lower than that in the lowlands in order to compensate for the attraction of the mass of the mountains. This idea of the compensation led to the Theory Isostasy in Geodesy. In 1889, American geologist, C.E. Dutton, coined the term "Isostasy", but as we have seen, the idea of this compensation of the earth's internal density was actually mooted by Pratt in 1854, i.e. about 35 years before Dutton. So, undoubtedly Pratt was the originator of the Theory of Isostasy. Pratt visualised that mountains rose from the subcrustal area after the manner of fermenting dough, the density of which would be lower as it rose higher[12]. His hypothesis generated at the time a great deal of interest and discussions among the scientists all over the world. In 1855, G.B. Airy, Astronomer Royal, explained the isostatic equilibrium in a somewhat different way. He suggested that the high mountains had sunk in the substratum and floated as timber or iceberg. It appeared to Airy that the state of the earth's crust lying upon the dense lava could be compared with the state of a raft of timber floating upon water.

Pratt also conceived the idea that the difference between the geodetic and astronomical amplitudes might arise not solely from the attraction influencing the plumb-line but in part from the curvature of the Indian arc being somewhat different from the curvature of the mean figure of the earth. The earth's surface has undergone changes of level. So, it cannot be an exact spheroid. In that case, the normals at the extremities of the actual arc would include an angle not equal to the amplitude of the mean or undisturbed arc. [14]. It can be explained by reference to Fig. 5. The mass surplus of the mountain pulls the plumb-line, the mass deficiency of the Ocean pushes it towards the mountain. The plumb-line (solid-line) and the normal of the ellipsoid (dotted-line) do not coincide but make an angle with one another, the deflection of the vertical, ξ. We know that the angle of tilt between the ellipsoid and the normal of geoid or plumb-line is called the deflection of the vertical or deflection of plumb-line. The surface of the reference ellipsoid is assumed to be a regular mathematical surface, where density is the same throughout. If there is no mountain or ocean, the surface of the geoid will co-exist with the surface of ellipsoid and there will be no deflection of plumb-line. But when irregularities of the geoid are present, as shown in Fig. 5, the deflection of plumb-line is present. Let us consider the point A which is the point of intersection of the geoid and the ellipsoid. Now M_1 is the mass density of the mountain and ρ_1 is the density just below the mountain and likewise M_2 is the mass density above the sea-bed, and p_2, the density just below the sea-bed. Then, the total mass-density on oneside of the point A is $(M_1 + \rho_1)$ and that on the other side $(M_2 + \rho_2)$, which are equal, i.e., $M_1 + \rho_1 = M_2 + \rho_2$. But M_1 is always greater than M_2, so that ρ_1 must be less than ρ_2, which indicates that the density of the crust just below the mountain is less than that of the crust below the ocean-bed.



Pratt said that this deflection was due to the internal constitution of the earth. In his own words: "This (deflection of the plumb-line) shows that the effect of variations of density in the crust must be very great in order to bring about this near compensation. In fact, the density of the crust beneath the mountains must be less than that below the plains and still less than below the ocean bed"[15].

Pratt's Theory of Isostasy received another important confirmation from the situation obtaining in the Tibetan Plateau, which is flanked on one side by the Himalayan Range and the other side by the Thian-Schan Range and the Kuen-Luen Range, which is the continuation of HindooKoosh. He himself discussed the point, and others like Prof.

T.J.J. See in connection with his work on the theory of earthquakes, later on reported satisfactory agreement with the hypothesis.[16] Crosthwait, in his book '*Theory of Isostasy in India*' wrote as follow : "The excess of material represented by that portion of the continent which is above sea-level will be compensated for by a defect of density in the underlying material. The continents will be floated, so to speak, because they are composed of relatively light material and similarly, the floor of the ocean will be depressed, because it is composed of unusually dense material. This particular condition of approximate equilibrium, has given the name isostasy"[17]. The above idea of Crosthwait accepted the theory of Pratt. These ideas were further developed by J.F. Hayford, William Bowie, Heiskanen and others. Heiskanen, for example, gave a hypothesis which is intermediate or is a compromise between the two models given by Pratt and Airy[18].

NOTES: COMPLETE CITATIONS WITH THE HELP OF BIBLIOGRAPHY

1. DSB, Vol. 11, 126
2. EB (c), 458
3. Maskeline, 701
4. EB (a), 133
5. Reference ellipsoid – The surface of the earth is called geoid which over the sea is the average sea-level and under the continents the imaginary continuation of sea-level. The visible and invisible mass anomalies of the earth cause essential irregularities to the geoid and bring about essential errors. Because of these facts geodesists use a reference surface, a regular mathematical surface that fits the geoid as closely as possible. This surface is an ellipsoid of revolution called a reference elliposid. Its surface is in some areas below, in other regions above the geoid. A Holmes, *Principles of Physical Geology*, (ELBS Ed.), London, 1978.
6. Phillimore, Vol. II, 261
7. Phillomore, Vol. III, 254
8. Walker, 800
9. Everest, CL XXVIII
10. Pratt (a), 3
11. Pratt (c), 60
12. EB (b), 139
13. Airy, 103
14. Pratt (a), 4
15. Pratt, (b) 134
16. Webb, 151
17. Crosthwait, 4
18. EB (c), 425

BIBLIOGRAPHY

Dictionary of Scientific Biography (DSB). Charles Coulston Gillispie, Princeton University, Editor in Chief. Vol. II Charles Scribner's Sons, New-York.

Phillimore, Col. R.H.C., C.I.E., D.S.O., "Historical Records of the Survey of India". Vol. I, II, III & IV. Published by Order of the Surveyor General or India. Printed at the office of the Survey of India. Dehra-Dun (U.P.), India, 1950.

Encyclopedia Britannica (EB)
(a) EB, Vol. XII, 1910

(b) EB, Vol. 10, 1965
(c) EB, Vol. V, 1974

Maskelyne, Rev. Nevil, "A proposal for measuring the Attraction of some Hill in this Kingdom by Astronomical Observations''. *Philosophical Transactions, Vol. 13, 1770-76, pp. 700-702.*

Walker, General J.T., "India's Contribution to Geodesy. *Philosophical Transactions, 4, Vol. 186, 1895, 715-816*

Pratt, John Henry.
(a) "A series of papers on Mountain and other Local Attraction in India and its effect on the calculations of the great Trigonometrical survey". Extract from the Transactions of the Royal Society, London for 1854, 1855, 1858 & 1861.
(b) "A Treatise on Attractions, Laplace's Functions and the Figure of the Earth" Cambridge: Macmillan & Co. And 23, Henrietta Street. Convent Garden London, 1861.
(c) "On the attraction of the Himalayan Mountains and of the elevated regions beyond them, upon the plumb-line in India".
Philosophical Transactions of the Royal Society of London, 146, Pt. 1 1854, 53-100

Airy, G.B., Astronomer Royal, "On the Computations of the Effect of the Attraction.... Latitude of Stations in Geodetic surveys'. *Philosophical Transaction of the Royal Society of London, B, 145-1855 101-104*

Crosthwait, Major H.L., R.E. "Investigation of the theory of Isostasy in India". Published by Order of the Government of India, Printed at the Office of the Trigonometrical survey of India, Dehra Dun, 1912.

Everest, George, "An Account of the Measurement of Two sections of the Meridional Arc of India Bounded by the Parallels of 18°3'15", 24°7'11" & 29°30'48", London, Printed by order of the Court of the Hon. East-India company" By J & H. Cox. 74-5, Great Queen Street. 1847.

Webb, W.L., "Brief Biography and Popular Account of the unparalleled Discoveries of T.J.J. See" Thos. P. Nichols & Sons. Co., Publishers, Lynn, Mass, U.S.A., Wm. Wesley & Son, London, England, 1913.