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A. B. Watts
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The Development of the Concept of Isostasy

> *The keynote of isostasy is a working toward equilibrium. Isostasy is not a process which upsets equilibrium, but one which restores equilibrium.*
> *(Chamberlin, 1931, p. 5)*

1.1 Introduction

Isostasy is derived from the Greek words ‘iso’ and ‘stasis’ meaning ‘equal standing’. The term is used to describe a condition Earth’s crust and mantle tend to, in the absence of disturbing forces. In its simplest form, isostasy is the view that the lighter crust floats on the denser underlying mantle. It is an idealised state: a condition of rest and quiet. The transport of material over Earth’s surface during, for example, the waxing and waning of ice sheets, the growth and decay of volcanoes and the deposition and erosion of sediments, disturbs isostasy and, in some cases, prevents equilibrium from being achieved. Seismic and gravity anomaly data suggest Earth’s outermost layers generally adjust to these disturbances. One of the principal objectives of isostatic studies during the last two centuries has been to determine the temporal and spatial scales over which these adjustments occur. This information provides constraints on the physical nature of Earth’s outermost layers, thereby improving our understanding of what drives more complex geodynamical processes such as mountain building, rifting and sedimentary basin formation.

The term isostasy was first coined in 1882, but there is evidence that questions concerning the equilibrium of the Earth’s crust were being posed as far back as the Renaissance. Isostasy played a central role in the development of geological thought and featured prominently in some of the great controversies of the late nineteenth and early twentieth centuries such as the contraction theory, continental drift, and the permanence of the oceans and continents.

The discovery that the Earth’s crust might tend to or be in a state of isostatic equilibrium is one of the most fascinating stories in the history of science. There were periods, for example, when it was accepted by one group of workers but rejected by another. There has also been considerable debate on which isostatic models best apply at a particular geological feature. These debates have led to some vigorous exchanges on isostasy in the literature and,

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on occasion, to the development of 'schools of thought', which divided geophysicists and geologists and North Americans and Europeans.

Today, isostasy still holds a central place in Earth Science. This is true despite a considerable body of work that shows Earth to be a dynamic planet that responds to loads over a wide range of spatial and temporal scales. Since isostasy is usually only concerned with how the crust and mantle adjust to shifting loads of limited spatial and temporal dimensions, it is only a 'snapshot' of these dynamical processes. Nevertheless, it is an important snapshot. By comparing the observed adjustments to models based on flotation, differential heating and cooling and bending of plates, we have learnt a considerable amount about Earth, its rheology, its composition and its structure.

In this introductory chapter, we will outline some of the key developments in the concept of isostasy. Special emphasis is given to the Airy and Pratt models of local isostasy. These models proved useful to the geodesists since they helped them in practical problems related to surveying. They were of less interest to geologists who struggled to incorporate the models into geological thought. The tussle between the geodesist and the geologist was an intriguing one that helps set the scene for later chapters.

1.2 First Isostatic Ideas

Some of the first ideas about the equilibrium of the Earth's outer layers originate with the engineer, artist and humanitarian Leonardo da Vinci (1452–1519). Translations of da Vinci's notebooks by Edward MacCurdy (MacCurdy, 1928; 1956) show that da Vinci gave considerable thought to how Earth might respond to shifts in loads over its surface. For example, the following quote (Delaney, 1940) illustrates how da Vinci thought the removal of sediment from a mountain might cause it to rise:

> That part of the surface of any heavy body will become more distant from the centre of its gravity which becomes of greater lightness. The earth therefore, the element by which the rivers carry away the slopes of mountains and bear them to the sea, is the place from which such gravity is removed; it will make itself lighter . . .. The summits of the mountains in course of time rise continually.

It was not, however, until 100 years later, when the first attempts were made to determine the Earth's shape, that it became possible to assess the equilibrium state of the continents and the oceans.

In the early eighteenth century, there were two main schools of thought concerning the shape of the Earth: an English and a French one. The English school, led by Isaac Newton (1642–1727), considered the Earth to be flattened at the poles, while the French school under Jacques Cassini (1677–1756) thought the Earth to be flattened at the equator. The Académie Royale des Sciences, under the direction of Louis XV, sponsored a team of scientists to go to different parts of the Earth to measure the length of a meridian degree to resolve the controversy. The first team, led by Charles Marie de La Condamine (1698–1758), made measurements in the region of the equator near Quito, Ecuador, while the second team, led by Pierre-Louis Moreau de Maupertuis (1698–1759), made measurements in the region of the Arctic Circle near Tornio, Finland.

The techniques used by Condamine and Maupertuis involved the measurement of the distance between two points of known position. The positions were determined astronomically by measuring the angle of elevation, Φ, between the pole star (Polaris) and the horizon, as indicated by level bubbles on an astrolabe. Level bubbles follow a surface, known as an 'equipotential surface', along which no component of gravity exists. The equipotential surface, which coincides with Earth's mean sea level, is known as the 'geoid', and so Φ is the angle between the pole star and the geoid. Because the direction of the pole star is normal to the equatorial plane, then it follows (Fig. 1.1) that Φ is also the angle between the normal to the geoid (i.e., the plumb-line direction) and the equatorial plane and, hence, the astronomical latitude at a point.

The distance between astronomical positions was determined by triangulation. In this technique, a network of triangles with vertices permanently marked on the Earth's surface are set up so that they connect the astronomical positions. One of the astronomical positions is then chosen as one vertex on the first triangle. If the length of one side of the triangle and its included angles are accurately measured, then it is possible to determine the distance between each vertex of the triangle. By extending the network of triangles to include the second astronomical position (Fig. 1.2), it is possible to estimate the total distance between astronomical positions from an accurate measurement of a length in the first triangle (which may be quite short) and the angles between vertices of all the other triangles.

The length of the meridian degree measured by Condamine was, as it turned out, much smaller than that measured by Maupertuis (Table 1.1). Furthermore, the length of the meridian degree on the Arctic Circle was greater, by about 900 m, than the length

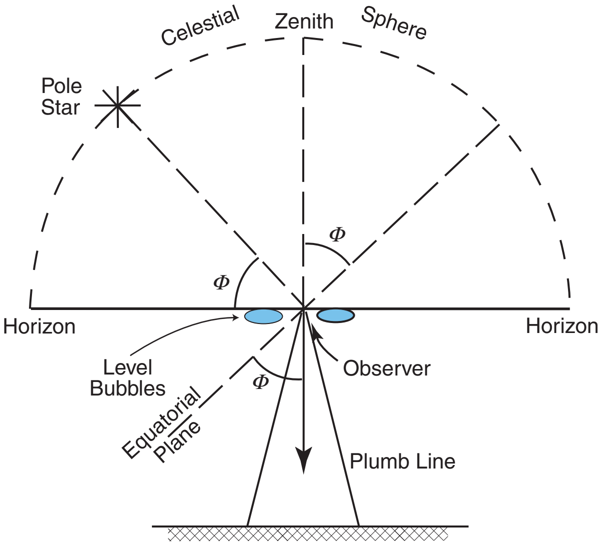

Figure 1.1 The determination of astronomical latitude, Φ, from observations of the pole star.

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Table 1.1 *Summary of measurements of the length of a degree meridian according to the surveys led by Condamine and Maupertuis*

Nearest Town/City	Approximate Latitude	Length of a Meridian Degree (Toise*)	Difference from Paris (Toise*)
Tornio, Finland	66° (Arctic Circle)	57,525	+342
Paris (L'observatoire de Paris)	48° 50'	57,183	0
Quito, Ecuador	0° (Equator)	56,753	−430

* 1 Toise = 1.949 m.

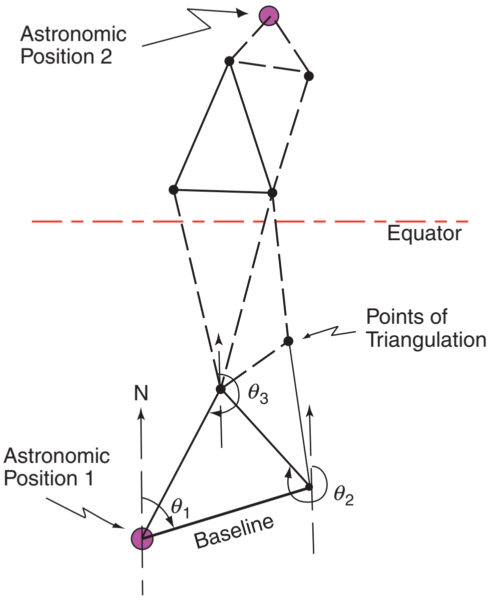

Figure 1.2 The measurement of the distance between two points by triangulation where astronomical latitude and longitude have been determined.

determined previously near Paris; and the length near the equator was smaller, by a slightly larger amount. These results convinced Condamine and Maupertuis that the Earth was indeed flattened at the poles, as suggested by Newton. The flattening, f_e, was estimated to be about 1/216.8 (Fig. 1.3). The measurements of Condamine and Maupertuis therefore solved the controversy of the overall shape of the Earth, although perhaps not quite in the way their sponsor, the Royal Court in Paris, had anticipated!

One member of Condamine's party though, Pierre Bouguer (1698–1758; Fig. 1.4), was not content, however, to let the matter rest there. Bouguer was puzzled by the consistency of the results because the measurements near the equator were obtained in the presence of much greater

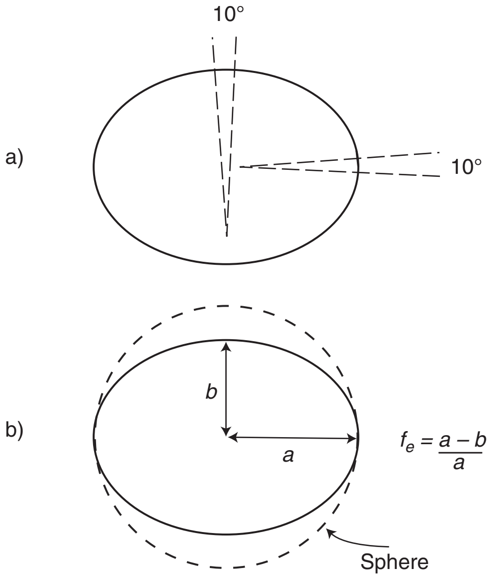

Figure 1.3 The flattening of the Earth, f_e, can be approximated by an ellipse with semi-major axis, a, and semi-minor axis, b.

Figure 1.4 Pierre Bouguer, the French mathematician and astronomer who accompanied Charles-Marie de La Condamine during the expedition of 1735 to Quito, Ecuador to measure the length of a degree meridian at the equator. (Pastel de Perroneau, eighteenth century; Musée du Louvre; Photo: Giraudon.)

topographic relief than those near the Arctic Circle. He surmised (Bouguer, 1749) that the mass of the mountains in the vicinity of Quito was sufficiently large that it should have caused the local plumb line to be deflected by as much as 1′ 43″ from the vertical.[1] Such a deflection would introduce errors into the astronomical positions because the elevation of a distant star is measured on a table with level bubbles so that the measurement is made with respect to the local plumb-line direction (Fig. 1.1). The astronomical positions were apparently not in error, however, leading Bouguer to conclude that the attraction of the mountains in the vicinity of Quito 'is much smaller than expected from the mass of matter represented in such mountains'.

A few years later, an Italian astronomer and mathematician with strong links to Croatia, Ruggero Giuseppe Boscovich (1711–87), provided an explanation of the problem that puzzled Bouguer. He said (Boscovich, 1755): 'The mountains, I think, are to be explained chiefly as due to the thermal expansion of material in depth, whereby the rock layers near the surface are lifted up. This uplifting does not mean the inflow or addition of material at depth, the void within the mountain compensates for the overlying mass.'

This passage is the first to use the term 'compensates'. Boscovich speculates that the mass excess of the mountain is compensated in some way by a mass deficiency at depth. Thus, the deflection of a plumb line near a mountain range may well be small, as Bouguer had suspected.

Boscovich, with broad interests beyond astronomy and mathematics, may, we speculate, have been influenced by a fellow Italian, the eminent scientist Luigi Ferdinando Marsigli (1658–1730). In 1728, 27 years prior to the appearance of Boscovich's paper, Marsigli illustrated in a beautiful set of drawings the difference in elevation and thickness of 'marine' (oceanic) and 'mountainous' (continental) crust. His beautiful, hemispherical, water-coloured and pen-drawn cross sections show a juxtaposed mountain-peak height and seafloor depth that appear to be in some sort of isostatic balance with a thicker crust beneath the mountains than beneath the oceans (Vai, 2006).

Little more appears to have been said on the matter for another 100 years. The statements made by Boscovich and the drawings of Marsigli on the compensation of mountains, as significant as they were, evidently had little impact on leading geologists of the time.

In the early 1800s geological thought in Europe was dominated by the contraction theory. According to this theory, the Earth's surface features were thought to have been the consequence of a gradual cooling of the Earth following its formation. Mountains were considered to be regions that had not cooled as much as ocean regions. The theory had its origins in the work of Gottfried Wilhelm Baron von Leibnitz (1646–1716) and René Descartes (1596–1650). Baron Jean Baptiste Joseph Fourier (1768–1830) subsequently measured the temperature gradient at shallow depths in the Earth, concluding that it was in accord with the predictions of the contraction theory. Therefore, Boscovich's statements on the thermal expansion of mountains may not have seemed all that inconsistent with the theory.

The eminent British geologist, Charles Lyell (1797–1875), was sceptical about the contraction theory. By 1833 he had completed his widely acclaimed book, *Principles of Geology* (Lyell, 1832–3), in which he proposed that the Earth's surface is continually

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[1] Smallwood (2010) has pointed out that Bouguer grossly overestimated the predicted deflection of the vertical due to the mass of the mountains. Using a Digital Elevation Model (DEM) and local rather than whole Earth densities, he showed that the predicted deflection should be ~14±4″, more than a factor of ~6 smaller than that estimated by Bouguer.

subject to periods of rest and change. He disagreed strongly with theories of catastrophes to explain geological events and with ideas forwarded by Leonce Elie de Beaumont (1798–1874) in France and Henry Thomas de la Beche (1796–1855) in England that geological processes, such as mountain building, were global events that occurred at similar times over widely separated regions. Lyell wrote: ‘It is preposterous to imagine that just because they had similar trends the Allegheny and Pyrhenees mountain ranges could have been formed by the same catastrophic event.’ Among Lyell’s many influential friends was John Herschel (1792–1871, Fig. 1.5). In a letter addressed to Lyell, Herschel (1836) pointed out that he disagreed with the contraction theory. In his opinion, the outermost layer or ‘crust’ of the Earth was in some form of dynamic equilibrium with its underlying substratum or ‘sea of lava’. He wrote ‘the whole (crust) [floated] on a sea of lava’. According to Herschel, if the crust was loaded, say by sediments, it would sink, thereby causing the underlying lava to flow out from beneath the load and into flanking regions (Fig. 1.6).

Herschel’s ideas on the equilibrium of the Earth’s crust might never have been published had it not been for Charles Babbage (1790–1871), the mathematician and inventor of the computer, who had also befriended Lyell. Babbage decided to include the letter that Lyell had received from Herschel in a treatise he was writing. The treatise was prepared by Babbage, on his own initiative, as a sequel to the eight volumes of the ‘Bridgewater Treatise’, which had just been

Figure 1.5 John Frederick William Herschel, the son of the astronomer William Herschel who discovered the planet Uranus. Reproduced from the portrait on p. 161 of Robinson (1980) with permission of the Royal Society.

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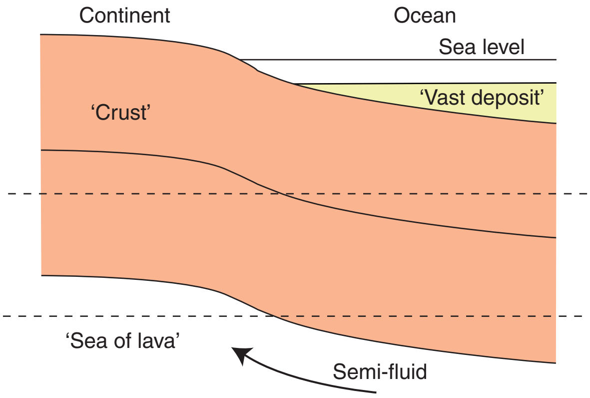

Figure 1.6 The adjustment of the crust to a 'vast deposit' by flow in the underlying 'sea of lava'. Reproduced from a figure in Herschel (1836) with permission of the Royal Society.

published using proceeds from Lord Bridgewater's estate. Babbage felt compelled to publish a ninth treatise because, in his opinion, a prejudice was emerging that the pursuit of science was unfavourable to religion. In a letter to Lyell, he pointed out that the ninth treatise would provide 'an opportunity to illustrate some of the magnificent examples of creation'.

In the ninth treatise Babbage included some observations (Babbage, 1847) he had made at the Temple of Serapis in Pozzuoli, Italy. Built towards the end of 200 AD, the temple had served as a spa (Fig. 1.7) for wealthy Romans. When Babbage visited the site in 1828, the temple's three remaining columns showed a dark encrustation about 4 m above their base. Above the dark encrustation, 2.5 m of the column had been perforated in all directions by a marine boring animal (*Modiola lithophaga*). This observation[2] suggested to Babbage that the temple had undergone a period of subsidence, followed by one of uplift. He attributed these movements of the crust to the action of heat, because of the location of the temple near the historically active volcano of Vesuvius. Babbage considered that the heating caused the crust to expand and contract locally and that these movements were in some way accommodated by movement in the underlying fluid lava. Thus, Herschel and Babbage agreed that the crust accommodated loads by lateral flow in a weak underlying substratum. While Lyell supported this view, it was strongly opposed by the supporters of the contraction theory, who believed that the subsidence and uplift was the consequence of thermal contraction and expansion on a global scale.

The ninth Bridgewater treatise was published in 1837, the same year that Charles Darwin (1809–1882) made a brief statement, to the Geological Society of London,[3] on some observations on the subsidence of ocean islands he had made during his circumnavigation of the world onboard HMS *Beagle*. Darwin, who was given a copy of Lyell's book by Captain FitzRoy at the start of the voyage, recognised three types of ocean islands: volcanic, coral and combinations of the two. It was his view (Darwin, 1842, p. 98, woodcut 4; p. 100, woodcut 5) that a submarine

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[2] Sir Harold Jeffreys, a British geophysicist, was later so intrigued by this observation that he suggested (Crittenden, 1967, p. 279) a picture of the Temple of Serapis should hang in every Department of Geophysics as a reminder that movements of Earth's crust are not simple and may involve both subsidence and uplift at the same locality.

[3] Charles Darwin was elected to fellowship of the Geological Society in 1836 and early in 1838 became one of its 'secretaries'.

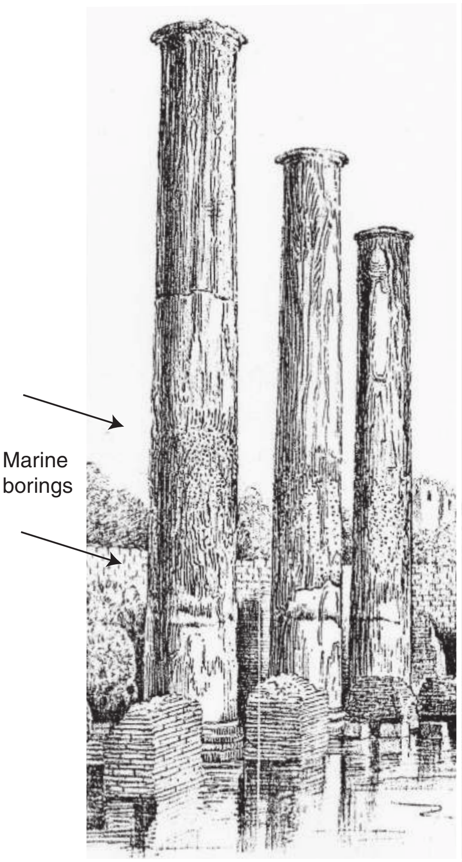

Figure 1.7 The Temple of Serapis in Pozzuoli, Italy. The borings in the Roman-built columns were used by Babbage to infer that the crust had undergone subsidence followed by uplift. Reproduced from Babbage (1847) with permission of the Geological Society of London.

volcano would grow up on the seafloor to become a high island. Coral would grow in the shallow water fringing the volcano (e.g., as at Moorea in the Society Islands), and then as the volcano started to subside, the coral would attempt to keep pace and grow upwards, leaving a gap between a 'barrier reef' and the central volcanic island (e.g., as at Bora Bora in the Society Islands). Eventually, the island would sink below sea level and all that would remain is an atoll with a central lagoon (e.g., as at Aratika in the Tuamoto Islands). Darwin found direct evidence for subsidence at Santiago in the Cape Verde Islands where the volcano had 'disturbed' and 'bent' downwards a 'bright white' layer of limestone,[4] which Darwin supposed had been deposited horizontally and now underlay the volcano edifice (Darwin, 1844, p. 9, woodcut No. 2). He went on to propose that either the volcano had been uplifted and then subsided or that

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[4] We now know that the volcanic evolution for Santiago ranges in age from 4.6 to 0.7 Ma and that the white limestone observed by Darwin is entirely Pleistocene in age (Johnson et al., 2012).

it had never been uplifted, which implied that the volcano somehow maintained its elevation despite the subsidence. Interestingly, from the viewpoint of isostasy, Darwin favoured the latter hypothesis.

It is tempting to speculate that the observations of Herschel and Babbage and, especially, those of Darwin relating to subsidence and uplift had set the scene for the next major development in our understanding of the science of the equilibrium of Earth's crust. However, it was not the geologists, but the geodesists who were to make the key observations that eventually led to the theory of isostasy.

1.3 The Deflection of the Vertical in India

The first measurements of the length of a meridian degree in the India sub-continent were carried out in 1840–59 by George Everest (1790–1866), who as Surveyor-General was charged with mapping the country. Everest's measurement techniques differed from those of the earlier surveys of Condamine and Maupertuis, as he considered astronomical as well as geodetic positions. Geodetic positions were computed at the vertices of each triangle by assuming the position at one vertex of the first triangle was known and then using the equation for the Earth's best-fitting reference ellipsoid to compute the other positions (Fig. 1.8). (Thus, instead of regarding the flattening of the Earth as an unknown, as the Condamine and Maupertuis parties had, Everest assumed it was by now well enough known to compute geodetic positions at points in between the astronomical positions.)

At points where both astronomical and geodetic positions are determined, it is possible to compare them. As Fig. 1.9 shows, astronomic and geodetic latitudes are referenced to a common surface: the equatorial plane. The astronomic position is defined as an angle between the equatorial plane and the local plumb-line direction, whereas the geodetic position is defined as an angle between the equatorial plane and the local normal to the Earth's best-fitting ellipsoid. The plumb-line direction does not necessarily follow the local normal to the ellipsoid because of disturbing masses in the Earth. The amount that the plumb line is deflected from the local normal is known as the 'deflection of the vertical'.

As part of his survey in India, Everest computed the geodetic position at a number of localities where he had already measured the astronomic position. He found that for two

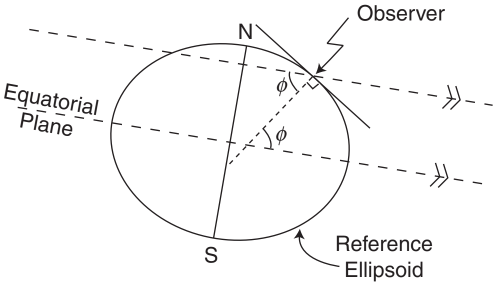

Figure 1.8 The determination of geodetic latitude, ϕ, from the theoretical formula for the Earth's best-fit reference ellipsoid.