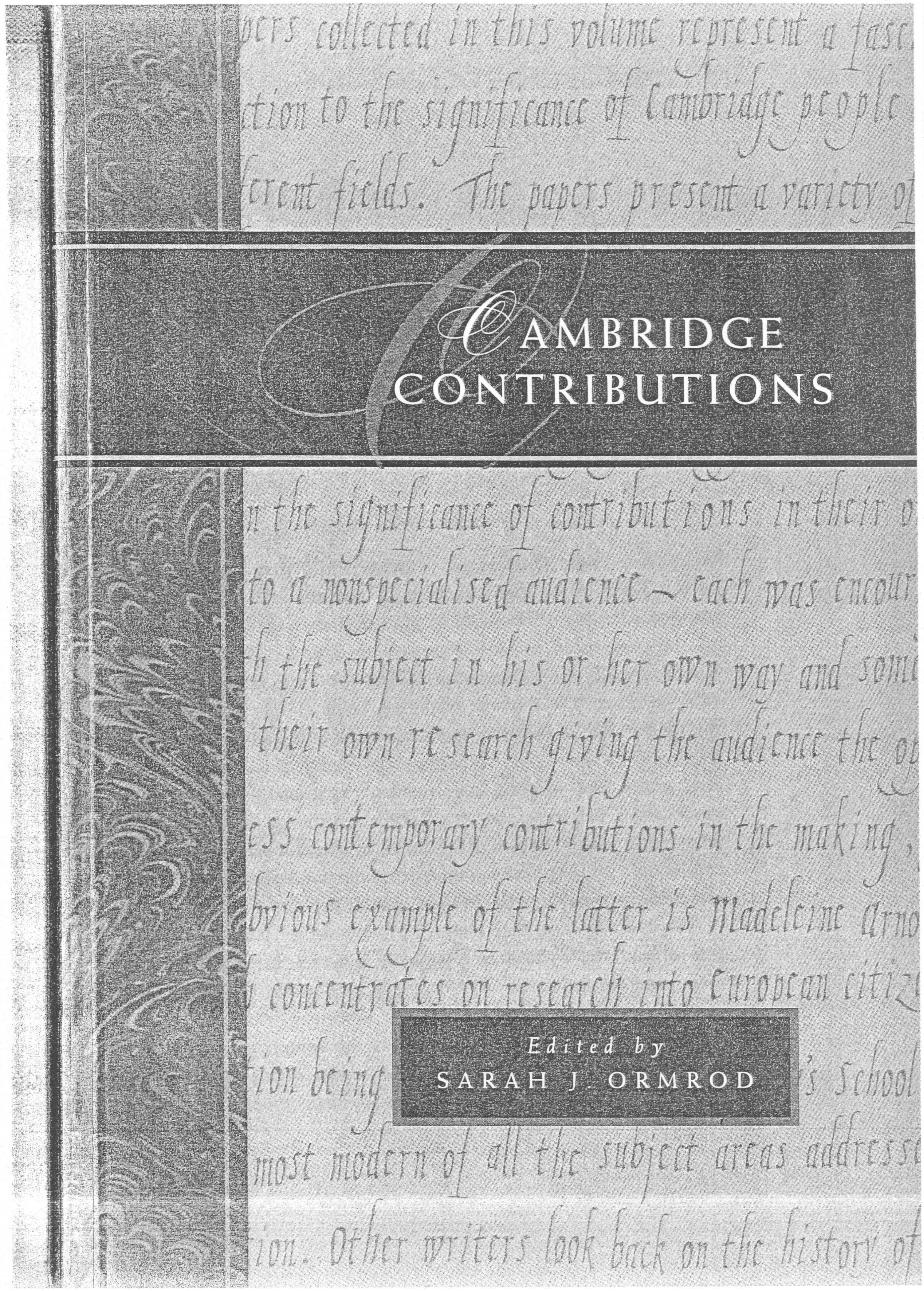

CAMBRIDGE CONTRIBUTIONS

Edited by
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CHAPTER 10

Geophysics in Cambridge: extinct and active volcanoes

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THE BEGINNINGS

Geophysics is the study of the structure and dynamical evolution of the Earth using the concepts of physics in a quantitative manner. Like many branches of physics, the study of geophysics can be considered to have commenced with Sir Isaac Newton, who occupied the Lucasian Professorship in Cambridge from 1669 to 1701 (the current occupant being Stephen Hawking). Before the time of Newton, our knowledge of the structure of the Earth was rather vague. Aside from knowledge of the transparent atmosphere and neighbouring oceans, extrusion of hot, smelly liquid from volcanoes on the Earth's surface gave rise to the notion of a predominantly solid Earth in which there were interconnected vast subterranean caverns of hot sulphurous material – somewhat consistent with the then current views of Hell.

The quantification of Newton's inverse square law of gravitation allowed the Earth to be 'weighed' . This was done in 1775 by measuring the deflection of a 'vertical' plumb bob by the mountain Schiehallion in Scotland at various distances from it. These measurements allowed the total mass of the attracting Earth to be estimated at 5×10^{24} kg. With the known mean radius of the Earth of around 6,400 km the result suggested a mean density of 4,500kg

m^{-3} (modern measurements give 5,520 kg m^{-3}) in sharp contrast to the measured mean density of 2,500 kg m^{-3} of almost all near surface rocks, including those that make up Schiehallion. The inescapable conclusion is that density within the Earth must vary, with at least some portions over twice the density of that at the surface. The only abundant element of high density is iron; and thus the prevalence of an iron-rich interior is suggested.

Earthquakes, which are often, but not always, associated with volcanoes, are viewed as destructive and to be feared by many; but they are also viewed by geophysicists as an important way of understanding the Earth. In 1761 a long paper appeared in the world's oldest scientific journal, the *Philosophical Transactions of the Royal Society* (of which I am on the current Editorial Board) by John Michel, then Woodwardian Professor of Geology at Cambridge, (Professorial) Fellow of Queens' College and rector of St Botolph's church (all of which he gave up three years later, preferring to get married. Only the Master of a College was allowed to be married until there was a change of statutes in the late 1800s). Michel's suggestion for seismic disturbances was that they resulted from the vaporisation of water when it came into contact with volcanic fire. His opinion was that the formation of small quantities of vapour would lead to a small vibrating cavity, while large quantities would lead to the vapour bursting out of the cavity and travelling through the space (or interface) between different layers.

Modern seismology began at the end of the last century, at about the same time as the phenomenon of X-rays which can see through human bodies were developed in medicine. When a disturbance occurs within or on the Earth, due either to natural or man-made processes, waves, known as seismic waves, propagate away from the source, in a similar way to the acoustic waves which propagate from a speaker's mouth to everywhere in a room to be picked up by each one of the audience. An important difference is that in an elastic medium there are two sorts of waves possible, which travel at different wave speeds, and are called

P (primary) and S (secondary) waves. P waves are quite similar to the compressional acoustic waves in air, while S waves cannot propagate in a fluid. On 18 April 1889 the effects of an earthquake in Tokyo, Japan, were observed one hour and three minutes later in Potsdam and Wilhelmshaven, Germany, half way across the world, as a result of waves which had travelled on the surface of the Earth. We now know that there are a myriad of waves, made up of the P and S waves, which travel a more direct route, through the interior of the Earth, and would have arrived earlier, but were apparently not then detected.

At the turn of the century, a British geologist, Richard Oldham, looked carefully at the travel times of earthquake waves travelling through the interior of the Earth as a function of distance (along the Earth's surface) from the source, which could be expressed as an angle (between 0 and 180°). He believed he could account for the observations if the Earth had a homogeneous (heavy) core whose radius was about 0.4 times the Earth's radius, that is, about 2,550 km. In this core, he suggested, the seismic wave velocity was considerably less (by almost a factor of two) than in the surrounding material. He argued that seismic waves which entered the core at an oblique angle change their direction of propagation, in the same way that a light beam is refracted as it passes into a medium, such as glass or water, in which its speed is less than in air. A spherical core – why should it be anything but spherical? – would bend the seismic waves entering at different angles, and they would be bent again on leaving. He suggested further, by considering S waves, which do not propagate in a fluid, that the core was fluid. What the Earth is made of, or for that matter the determination of the constituents of any part of it, requires more, and different, information. The argument that at least part of the core was fluid was put forward by the remarkably talented Cambridge geophysicist Sir Harold Jeffreys, of whom more will be said below. Jeffreys based his arguments on the rigidity of the core, which could be determined both from seismic wave velocities and from tidal motions of the solid Earth.

The final, and courageous step was taken by Inge Lehmann, sadly the only female geophysicist to enter our story. Born in 1888, Lehmann died at the age of 104, the holder of a coveted Foreign Membership of the Royal Society (of London) and admired by all who knew her. With careful theoretical calculations, guided by detailed seismological evidence, she wrote in 1936: 'A hypothesis will here be suggested which seems to hold some probability, although it cannot be *proved* [my italics] from the data at hand . . . that inside the core there is an inner core in which the velocity is larger than in the outer one', and that inner core is solid. Not all geophysicists agreed with Lehmann at the time and it was said that her results were based on 'exacting scrutiny of seismic records by a master of a black art'. Her hypothesis was not generally accepted until the 1960s when extra, and supportive, evidence came from analyses of the Earth's free oscillations generated as a result of the massive earthquakes in Chile in May 1960 and in Alaska in March 1964.

Our present view of the structure of the Earth is a solid inner core of 1,221 km surrounded by a vigorously convecting, liquid outer core to a radius of 3,486 km and a predominantly solid, silicate mantle to a mean radius of 6,371 km.

A SCHOOL IN CAMBRIDGE

However, I am allowing the scientific description to outrun the chronology and especially Cambridge chronology. Let me go back to 1891 when Hugh Newall, the Professor of Astronomy, had built the fine Victorian House, Madingley Rise, off the Madingley Road, just over half a mile north-west of the centre of Cambridge. In 1898 there was a total eclipse of the sun visible from northern India, and Newell, with his wife, journeyed to one of the two officially designated observation sites at Pulagaon. He met there, and became good friends with, Gerald Lenox-Conyngham, who had been to the Royal Military Academy at Woolwich and who was then Assistant Surveyor-General of the

Indian sub-continent (and whose wife was in charge of the domestic arrangements at Pulagaon). Lenox-Conyngham was engaged primarily with astronomical measurements and determining the local value of gravity by measuring the period of an oscillating pendulum. A knowledge of the local value of gravity and using Newton's law of gravity allowed Lenox-Conyngham (and others) to determine the local density of the rocks beneath the surface. For this work Lenox-Conyngham was elected a Fellow of the Royal Society in 1918 and knighted in 1919. He retired from the Indian Survey in 1920 and left India in May 1920 at the age of fifty-five, considering a peaceful retirement in Oxford.

For the first twenty years of this century there had been various suggestions that practical geodesy needed strengthening in Great Britain and that a Geodetic Institute should be set up. The scientific necessity was recognised, but, as often, there were financial difficulties. In 1920 the Vice-Chancellor of the University of Cambridge proposed that, if finances could be secured, a Geodetic and Geophysical Institution be established within the University, and a small committee which included Professor Newell was set up to investigate the possibility. Newell was also a Fellow of Trinity, the Bursar of which wrote to the Vice-Chancellor early in 1921 saying that: 'if the University made satisfactory arrangements for . . . research in geodesy, the College would be prepared to assist [with the finances]'. Newell then turned to his friend Lenox-Conyngham, who was elected to a Fellowship of Trinity and a Readership of the University on setting up the School of Geodesy on 7 October 1921. Thirty-four years later, the Department of Geodesy and Geophysics, as it was then to be known, most appropriately moved into Newell's old home, Madingley Rise, which still houses some of the most active volcanoes of British geophysics.

Lenox-Conyngham continued his work on determining the local value of gravity by using swinging pendulums, taught undergraduates and expanded his School by hiring (amongst others) two of the great British geophysicists: Harold Jeffreys and Teddy Bullard. In later life, Lenox-Conyngham was once asked how was it that without having attended a university (as an undergraduate) he could become: a Fellow of the Royal Society; a Fellow of Trinity; and a Professor (Reader actually) in Geophysics. 'Easy . . . I started the subject' was his reply.[1]

SIR HAROLD JEFFREYS AND THE EARTH

Harold Jeffreys was a lecturer in mathematics at Cambridge of considerable standing, when in 1931 he was elected to a Readership in Geophysics and became part of Lenox-Conyngham's 'team'. He was a highly skilled mathematician who applied the concepts and methods of classical mechanics to unlock the secrets of the interior of the Earth. He once said: 'If it takes complicated mathematics to understand the Earth, blame the Earth; and not me.' After showing that the core was fluid, as described above, Jeffreys turned his attention to the propagation of seismic waves through the interior of the Earth. If the velocity of waves (either P or S) is known as a function of radius within the Earth, then the travel time of the various rays between an earthquake and an observation point can be calculated. There can be many such rays. With such knowledge any earthquake can be located in both space and time by recording arrival times of waves at a number of stations on the surface of the Earth. Jeffreys, in collaboration with his young research student from New Zealand, Keith Bullen, who was to become Head of the Department at the University of Sydney from which I obtained my undergraduate degree, analysed enormous amounts of data from a large number of earthquakes collected on a routine basis to determine travel timetables, which came to be known as the Jeffreys–Bullen or J–B tables. The first J–B tables were published in 1935 and were then upgraded in 1940. They continue to be used up to present time, with very little modification, to locate earthquake epicentres world-wide. Dealing with the large amount of data, and the inherent errors, led Jeffreys to initiate important aspects of probability theory; but this is another story.

Jeffreys's main influence, on countless geophysicists, was his celebrated book *The Earth*, the first edition of which appeared in 1924 and the seventh and final edition in 1976. In it he described the interior structure and history of the Earth as he saw it. The third edition was reviewed as 'probably the most frequently quoted book on the interior of the Earth'. Already in the introduction to the first edition Jeffreys stated one of the most important and challenging aspects of geophysics: 'the problem . . . is to make physical [and chemical, actually] inferences over a range of depths of over 6,000 km from data determined only for a range of 2 km at the outside'. Somewhat surprisingly, given their importance, *The Earth* says very little about volcanoes, although Jeffreys recognised (in an ungrammatical sentence) that 'the formation of volcanoes . . . in a liquid or partially liquid state, to [*sic*] the surface or near it requires explanation'. The discussion which follows has now been largely superseded; and more modern ideas on this matter will be presented near the end of the chapter.

Jeffreys also made important contributions to our understanding of the dynamics of both the atmosphere and the oceans, central areas of geophysics, descriptions of which are lamentably absent from this presentation. But the Earth is a big place and one can't describe all of its workings in one chapter. The absence of any discussion of meteorology and oceanography also precludes any mention of the highly creative theoretical and experimental research of one of the central founders of fluid mechanics, Sir Geoffrey Taylor, who spent the seventy years between 1905 and 1975 working almost exclusively in Cambridge.

SIR EDWARD BULLARD AND CONTINENTAL DRIFT

Sir Edward Bullard, or Teddy as he was known by almost all, was one of Lenox-Conyngham's early recruitments. It has been written that Teddy 'will be remembered as one of the major figures in the development of the Earth Sciences during the twentieth century' and definitely one of the most colourful characters. A one-hour lecture could easily be given consisting just of anecdotes about his doings, sayings and buccaneering style. One, motivated by a famous photograph, will suffice here. I was a graduate student in the mid-1960s in the Institute of Geophysics and Planetary Physics (IGPP) which was housed in a beautiful, purpose-built, redwood building overlooking the cliffs of La Jolla, California. One of the many imaginative aspects of the building, which was partially designed by Judy, the wife of the then Director Walter Munk, who himself is a very creative geophysicist and a colourful character in his own style, was that offices had no numbers attached to them. To differentiate office from office, a large photograph of a distinguished geophysicist, generally in informal dress, was hung on each door. My office was adorned by a life-size photograph of Teddy taken while he was measuring gravity in the East African Rift Valley. Teddy was a much welcomed visitor to IGPP. I often heard him approach with visitors, some quite distinguished, and he would always say something like: 'Aren't I well dressed – I choose the hat to match perfectly the rest of my clothing!' (He was dressed *only* in a hat.)

Lenox-Conyngham was at first uneasy about hiring this tall, larger-than-life character who, much later, was to say: 'I always had the feeling that I was really the Wizard of Oz, the best wizard there was around. . ., but behind it all a bit of a fraud.' At some time during Bullard's early days, Lenox-Conyngham was sharing his doubts about Teddy with Lord Rutherford over port at Trinity, where they were both Fellows. Rutherford's view was: 'I'll tell you what, Conyngham, he's a damn sight cleverer than you are.'

Teddy was trained as an experimental physicist working in the Cavendish under the direction of two Nobel Laureates and Peers of the Realm: Lords Blackett and Rutherford. He used his extensive experimental abilities to investigate (and often initiate) a number of fundamental areas of geophysics. Very early in his scientific career he realised that although approximately 75 per cent of the Earth's surface was covered by oceans, virtually nothing was known about marine geology, in contrast to continental geology, although admittedly the latter was much easier (and far less expensive) to study. After the Second World War, due to extensive work at sea by Teddy and companions in Cambridge and other groups in America, it gradually became clear that the geology of the ocean floor differed considerably from that of the continents. At sea, all the hard rocks are basalts, indicating a volcanic origin; all the hills are volcanoes, in contrast to, for example, the massive, non-volcanic Himalayan range consisting almost entirely of granite; the covering sediments are considerably thinner than those found on the continents or the surrounding continental shelves; and, most important, all rocks, no matter where or how the ocean floor was dredged, were younger than 100 million years, in contrast to continental rocks which are up to 4,000 million years old. The inescapable conclusion was that the ocean floor was much younger than, and formed in a different way from, the continents. Further, gravity measurements indicated that rocks well below the ocean floor were not just sunken continents covered by lavas from volcanic eruptions in the ocean (or elsewhere) and recent sediments. In addition there is the curious fact, that there are relative highs, or long, quite thin ridges, positioned rather accurately half-way between the two continental edges.

Almost every schoolchild who has sat (bored) through geography lessons has wondered about the apparent fit between the west coast of Africa and the eastern coast of South America. The 'fit' has been commented upon since at least the time of the great English essayist Francis Bacon in 1620 and advocated strongly (using some incorrect arguments) by Alfred Wegener in 1912. Teddy, stimulated in part by contemporary themes we shall discuss in a moment, decided to investigate the fit quantitatively. He introduced two essential constraints. First, he matched the continents *at the edge of the continental margins*, rather than at the shoreline, explicitly taking into account a difference in position which varies quite considerably along the coastline. He did this because geological investigation had indicated that the continental shelves, often covered by relatively thick sediment, where oil and gas has so successfully been found, are part of the adjoining continent, rather than part of the oceanic floor. Second, he applied a powerful result of spherical geometry, known as Euler's Theorem and occasionally used by mathematicians since 1776, that states that the *rigid* motion of a (partial) covering of a sphere to another location is equivalent to a rotation of a particular angle about a specific pole of rotation. This study, with his Madingley Rise colleagues, Everett and Smith, led to the wonderful fit which is reproduced in many textbooks on the Earth. This result, and Teddy's dramatic and showmanship manner of presenting it, had considerable influence and suggested that the relatively older continents once made up one much larger land mass before the continents drifted apart to form the relatively younger oceans between. This was the quantification of an important area of geophysics called *continental drift*.

At about the same time, Fred Vine and Drum Matthews, a PhD student and his supervisor at Madingley Rise, presented a new and powerful interpretation of measurements of the magnetic field in rocks on the ocean floor. Such measurements had begun to be collected near the end of the Second World War by Blackett, Teddy's own PhD supervisor. Vine and Matthews employed the well-known result that all magnetic substances have a particular temperature known as the 'Curie point'. On being heated above their Curie point, substances take on any prevailing magnetic field; as they cool below the Curie point the direction of the magnetic field is frozen into the substance forever (unless it is either once again raised above its Curie point or significantly altered, such as by repeatedly subjecting it to severe blows). Vine and Matthews, analysing magnetic surveys they had undertaken in the Indian Ocean (following extensive, earlier surveys by others in the sea floor off California) showed that the map of frozen-in magnetic fields consisted of parallel lineations bearing no relationship to the topography of the local sea floor but aligned with the axes of the giant ridges. Vine and Matthews proposed that new, hot lava was being continuously (on a geological time scale) extruded from undersea eruptions along the length of the mid-oceanic ridges and then spread sideways at between 1 and 10 cm/yr – about as fast as one's fingernails grow. With each reversal of the magnetic field of the Earth a separate 'track' of magnetisation was laid down. This turned attention from *continental drift* to *seafloor spreading*.

It is (at least to me) an interesting, but a not unusual twist of science that when these suggestions became known to a quite senior marine geophysicist in California he said: 'What rubbish. I am the world's expert, and holder of the greatest amount of data, on magnetic field observations on the ocean floor. If the Vine–Matthews hypothesis had any validity it should be clear in my own data.' He then looked; and it was obvious.

DAN MCKENZIE: PLATE TECTONICS AND COMPACTION

The fundamental concepts were then finally completed by one of Teddy's very brightest, and definitely most successful, graduate students, Dan McKenzie, who is very much one of today's active volcanoes. Using a sophisticated computer programme devised by his friend, Bob Parker, who had also just graduated with a PhD under Teddy's direction, McKenzie and Parker showed from the motions of earthquakes that large portions of the surface of the Earth do actually move as rigid, spherical caps or plates, with an average depth of order 75 km, with little seismic activity within the plates. So arose the final terminology of *plate tectonics*, whose introduction in the mid 1960s represented the largest revolution ever in the concepts and consequences involved in the Earth Sciences. Somewhat surprisingly, the transition was very rapid by scientific standards – especially given the time scale of geology. It has been said that in the early 1960s no one who even suggested that there may be something in the idea of continental drift could hope to be hired in a reputable North American university, but by the late 1960s no such position was available to anyone who didn't believe totally in its concepts.

There were, of course, many further details of plate tectonics to be worked out; and this was done over the next thirty-five years, in part by McKenzie himself. We are now in the amusing situation where, in contrast to when Teddy started thinking about marine geophysics, we have a better understanding of oceanic plate motions than continental geology.

What drives the plates? The simple and superficial answer is convection in the mantle below, driven by two processes. First, the loss of heat initially contained in the Earth. Very roughly, there are indications that the temperature of the interior of the Earth has decreased 400° C in its 4,500-million-year history. Second, heat is generated by the decay of radioactive elements within the Earth. The convective motions are loosely akin to those when porridge with a thin crust is heated from below. But there are still many unanswered questions, including the following. To what depth does the convection (in the solid rock) extend? Some say from just below the crust down to 670 km; others say down to the base of the core, 2,885 km below the Earth's surface. How temporarily and spatially varied is the motion? Why are the plates the size and shape we observe? All these questions, and other related ones, are being actively researched at the moment, frequently involving the most powerful computers in the world. Even though we don't fully understand all about the driving mechanisms of plate tectonics, the concepts have a firm foundation. As the powerful mathematician of the last century, Oliver Heaviside, said in reply to critics of his new calculus which produced the correct answers, even though he, and more importantly, his critics did not understand why: 'Should I desist from eating, just because no-one understands the workings of my digestive tract.'

McKenzie has gone from strength to strength; and has won major international awards for his scientific contributions almost every year in the last fifteen. One of his contributions came from asking, as Jeffreys had previously, how does liquid, formed in small gaps in the solid Earth, escape to produce the enormous amount of volcanism at the Earth's surface? In a study which has been highlighted on a special Horizon TV programme, McKenzie showed that liquid in the space between the exceedingly small crystals or grains that make up most of the rocks of the Earth is interconnected and can flow along the boundaries between the grains. The liquid forms because as the solid rock slowly moves it comes to areas where the local temperature (at that local pressure) exceeds the melting temperature of some of the constituents of the rock and these components therefore begin to melt. The melt can then be squeezed out of the solid matrix by the overlying pressure by a process known as *compaction*. The small trickles of magma or molten rock, at around 1,000° C, can be separated from the solid matrix and wind their way upwards in channels of increasing width, until, by processes that are not yet fully understood, they erupt at the surface in volumes as large as 10 km^3 and instantaneous rates of up to 1 km^3 / day – fast enough to fill a fair-sized lecture hall in about a second.

GEOLOGICAL FLUID MECHANICS

One morning, in September 1979, the telephone rang in my office in the Department of Applied Mathematics and Theoretical Physics and the voice at the other end introduced himself as Steve Sparks, a volcanologist in the Department of Earth Sciences, saying: 'Dan McKenzie told me that you knew some fluid mechanics; is that true?' We arranged to meet; we talked about his research in volcanology and mine in fluid mechanics (mainly applied to oceanography and meteorology); and roughly, neither of us understood a word the other was saying. But I quickly realised that Steve was an outstanding scientist and a very nice individual, who was working in a potentially exciting area; and he realised the power that a quantitative understanding of fluid mechanics could bring to his research. Put briefly we (and our families) became good friends and together we initiated the new field of *geological fluid mechanics*, some of whose results I will quickly discuss here.

First, however, I would like to digress for a moment, motivated by my statement that Steve is a very nice individual. The Australian, Nobel-laureate developer of penicillin, Lord Florey, once said: 'I'd work with the devil, if he had something to teach me.' Florey's Nobel-prize-winning student, Sir Peter Medawar, once wrote, I am sure with his teacher's comment in mind: 'I don't like to work in the lab. with someone whom I am not equally pleased to socialise with on Sundays.' Here is not the place to debate these two extreme but interesting views. Let it suffice to say I still enjoy seeing Steve and his family on Sundays. But back to science and in particular the work on the volcanic aspects of geological fluid mechanics which have been developed in Cambridge over the last twenty years or so.[2] Readers interested in a more detailed discussion might consult the references listed in notes 2–7 below.

Magma chambers

As discussed previously, liquid rock, or magma, rises to the Earth's surface by the process of compaction. It is believed that it may do this by trickling through a series of thin contorted channels or by migrating in batches as much as 1 km^3 in volume. Just a few kilometres beneath the surface the melt often accumulates in storage reservoirs, known as magma chambers, which exist beneath all volcanoes, both on land and (the much more numerous ones) at the bottom of the ocean. These magma chambers, full of hot turbulently moving melt with suspended crystals, act as the 'powerhouse' for all volcanic processes. The chambers range in size from a fraction of a cubic kilometre to a few thousand cubic kilometres (a few tens of kilometres in horizontal extent and a few kilometres in the vertical). Magma may repose in one or more such chambers during its ascent towards the Earth's surface. The repose time for a particular fluid element can range from as little as a few hours through to effectively forever, the latter limit occurring if the magma cools sufficiently while in the chamber to solidify there. In general, however, the repose time stretches from years to thousands of years or much more, during which time the magma cools, partially solidifies and evolves chemically and physically. Fluid-mechanical thinking is making a large contribution to understanding the various processes that occur in magma chambers. In addition, many of the new processes considered, motivated by a desire to understand the natural workings of volcanoes, have direct industrial application. Thus, for example, the solidifying of a multi-component magma and the resulting motion of the remaining fluid, in the form of convection, has parallels with the industrial processing used in the manufacture of steel ingots.

Dry fissure eruptions

As is well known, volcanic eruptions display a range of fascinating and at times awe-inspiring features. This subsection will concentrate on the eruption of magmas of relatively low viscosity (or stickiness) and low volatile content, which is the case when the magma comes from great depths within the Earth, as occurs, for example, beneath Kilauea in Hawaii and Mount Etna in Italy. The magma then tends to be extruded in a non-explosive continuous fashion, often from a long fissure which produces a flow of lava known as a 'curtain of fire'. The subsequent development varies from eruption to eruption. In some cases the height of the curtain of fire and the flow rate decrease and the eruption ceases, generally within a fraction of a day. In other eruptions, after a few hours, a second phase is gradually initiated in which there is a decrease in the length of active fissures accompanied by a concentration of the height of fountaining at certain points along the fissure. If the eruption continues, the flow of lava can become localised to only a few surface vents, around which volcanic cones are gradually built up.

Aside from the initial geometry, the change in temperature of the rising magma and the surrounding solid rock plays an important role throughout the eruption. When magma first fills the fracture, known as a dyke, it initially solidifies against the cold channel walls. Continued solidification may eventually block the channel, which tends to end the eruption at that site even though the driving pressure in the magma chamber may remain substantial. However, the continual supply of heat to the walls of the magma flowing from the chamber may eventually exceed the possible conductive transfer into the surrounding rock. Initial solidification will then be halted and the walls subsequently melted. The width of the fissure then continues to increase until the magma supply diminishes. Which style occurs depends on the initial width and length of the dyke, the driving pressures and the initial temperature difference between the magma and the surrounding rock. All of these effects have been quantitatively examined[3] and the results have increased our understanding of the field data.

Explosive eruptions

In other parts of the world the chemical composition of the magma is such that it is quite viscous (sticky) and it includes a small amount of dissolved water – generally less than a few per cent (by weight), but this is sufficient to have considerable impact and lead to explosive eruptions,[4] as occurred at Krakatoa in 1883 and Pinatubo in 1991. Generally, as the magma cools and crystallises it forms anhydrous crystals (i.e. none of the water is taken up by the crystals). Thus the relative amount of dissolved water remaining in the magma increases, until it reaches saturation. (This happens quite easily; magma is not able to dissolve much water.) Thereafter the water exsolves and forms small bubbles of relatively low density. If this happens while the magma is still in the chamber the pressure can increase dramatically; and trigger an eruption. Alternatively, the magma may have already begun to rise to the surface. Now the continuing decrease in pressure causes the bubbles to exsolve – just like when removing the cork from a champagne bottle. The small, light bubbles rise and, because the magma is so viscous, they take much of the magma with them. As the magma and bubbles rise in unison, the pressure decreases further. The amount of vapour bubbles increases until at a volume fraction of around 75 per cent the mixture behaves like a foam (rather than a fluid). A short distance beyond that the gas content is so large that the behaviour is akin to a high-speed gas flow taking along many small ash particles (all that remains after disruption of the once continuum magma). This flow can become supersonic – move faster than the *local* speed of sound – and then vent into the atmosphere at speeds of between 300 and 700 feet per second as a hot, turbulent, gas-enriched, particle-laden plume which penetrates many tens of kilometres into the atmosphere. The physics of such eruption columns is described in the next subsection.

Volcanic plumes

The greatest height a plume has penetrated the atmosphere this century is 45 km (Bezymianny, in Russia in 1956). While the gas jet at the base of the plume has considerable vertical velocity (and momentum) this is nowhere near sufficient to allow it to rise 45 km. The potential energy is *not* gained from the kinetic energy at the source, but indirectly from the thermal energy in the erupted plume, as follows. The hot, (ash) particle-enriched gas plume erupts turbulently into the base of the atmosphere in the form of a jet, whose large-scale turbulent eddies engulf surrounding air and mix it in with the plume. The small, hot particles readily transfer their heat to the engulfed, relatively cold air which can thus become less dense than the surrounding air (even *after* taking into account the excess contribution to the bulk density made by the relatively (very) heavy particles, whose density is roughly three orders of magnitude larger than that of air). Because of this decreased bulk density, the jet has an increased upward force acting upon it. In this way the plume can penetrate to great heights into the atmosphere by the gradual transfer of the thermal energy in the ash particles.

The currently best quantitative model of such an eruption was developed in the mid-1980s by a then student of mine, Andrew Woods, now Professor of Mathematics in Bristol, whom I set the task of reviewing models of eruption columns and who evaluated for himself a comprehensive sophisticated model.[5] This style of eruption is called a Plinean eruption, as described by Pliny the Younger after the eruption of Vesuvius in AD 79. The plume width increases with height as surrounding air is engulfed, while the velocity of penetration and temperature difference decrease, all in a way which we can now quantitatively evaluate. Because the density of the atmosphere decreases with height, eventually the plume must reach a height where its (bulk) density is no longer less than that of the surrounding air, and so it can go no higher. (Strictly speaking, the plume penetrates slightly higher, driven by the momentum in the plume, but it then falls back to almost this same level due to its relatively larger density at higher levels.) The plume, along with its particles then penetrates sideways into the atmosphere to produce a large 'umbrella cloud' from which the small ash particles slowly settle. These clouds can cause enormous problems for aircraft, as evidenced by the chilling story of the British Airways pilot who controlled a 20,000-ft free descent before being able to restart his engines which had been choked with ash after flying through the volcanic debris of Mount Galungung in south-east Asia in 1982.

The distributed ash in the atmosphere can also greatly influence the weather on a global scale. The whole Southern Hemisphere experienced beautiful daily sunsets for almost a year after the eruption of Pinatubo in 1991. On a larger scale, North America suffered a severe crop failure after the eruption of Tambora, Indonesia, in 1815, leading to a famous book by Dr and Mrs Stommel entitled *Volcano Weather: The Story of 1816, the Year without a Summer.* In a less-well-documented but fascinating account, a religious Cambridge geophysicist (working at Madingley Rise) teamed up with a Cambridge metallurgist to argue that the violent eruption of Santorini in the Mediterranean was exactly at the time of the famous seven years of famine in Egypt.[6] Usually, they argue, in those times the Nile annually overflowed its banks to supply the water needed for crops and cattle. Due to the enormous amount of ash deposited in the atmosphere by the Santorini eruption, the weather would have been completely altered (for seven years) and there could have been an acute shortage of water. On the cause and interpretation of Pharaoh's dreams they are strangely silent!

But back to present-day descriptions. The observant reader will have wondered (correctly) why in the above description of plume motion the bulk density of heavy particles plus hot air must exceed that of the atmosphere at the base of the plume. The answer is that it need not always be so; a different, and important, style of eruption then ensues. Above a critical mass of ash particles, although the exiting jet has an upward momentum, it cannot engulf (and heat) sufficient air to continue propagating upwards. The 'plume' falls back to the ground and travels along it, in what is called by geologists a 'pyroclastic flow'. Both styles of eruption can occur from the same volcano – after some twenty-four hours the Vesuvian eruption produced a pyroclastic flow, which is what killed most of the population of Pompeii and nearby Herculaneum (and Pliny's uncle).

Ash-laden pyroclastic flows can travel enormous distances (in excess of 100 km) at considerable speeds (in excess of 100 metres per second). Given the conditions at the source of the eruption – the mass and momentum of the gas at exit and the particle concentration – it is now possible to calculate the characteristics of the resulting flow: propagation velocity along the ground, final extent of the flow and the variation of the thickness of ash deposited from the turbulently moving flow. This form of calculation is called a forward calculation by earth scientists: given the input (initial) conditions, calculate what happens next. Often, the real problem of interest, however, is an inverse problem: given only (aspects of) the final result, calculate the conditions which gave rise to this result. In this particular case: given the observable deposit from an (ancient) pyroclastic flow, calculate the size and parameters of the eruption. The mathematics to answer this particular situation has only recently been developed[7] and was applied to analyse one of the largest pyroclastic flow eruptions in the last 10,000 years: the eruption of Taupo, New Zealand in AD 186. Our calculations indicate that the total flow rate of gas and solids was around 40 cubic kilometres per second for around fifteen minutes. The near-vent solids concentration was only about 0.3 per cent by volume and led to a pyroclastic flow of about 1 km thick which travelled outward from the vent with a typical speed of 200 metres per second. The low particle concentration was a new (and somewhat controversial) finding, which the science writer for the *Cambridge Evening News* headlined as: 'Cambridge Professor proves ancient eruption nothing but hot air.'

Since pyroclastic flows, world-wide, represent one of the largest natural disasters and have contributed to thousands of millions of dollars' worth of damage to property this century, they warrant further serious quantitative analysis and evaluation.

THE INSTITUTE OF THEORETICAL GEOPHYSICS

In the late 1980s it was thought that theoretical geophysics, particularly seismology, needed strengthening in Great Britain. It was decided by a committee set up by the then University Funding Council to start an Institute of Theoretical Geophysics in the University of Cambridge. The Institute was to be housed in both the Department of Earth Sciences (which by now had taken over, or in, the Department of Geodesy and Geophysics) and the Department of Applied Mathematics and Theoretical Physics. Although quite common in North American universities, such a formal partnership between two separate Cambridge departments had not happened before. There was initially some apprehension shown by the Heads of the two departments, but they both wanted to see the new Institute thrive and worked well together towards this aim.

I was appointed to the Directorship of the Institute in June 1989 and the Institute opened its doors on 1 October 1989, a day which is celebrated annually with a birthday luncheon by its staff. As with the School of Geodesy, Trinity College has helped financially, through its Foundation the Isaac Newton Trust, though not with a Fellowship for the Director – I am a Fellow of King's. The most recent assistance has been with the purchase for £1.2m of an extremely powerful computer for the Institute. It will be devoted entirely to calculations in geophysics. Its speed is such that it can evaluate in considerably less than a second *all* the calculations a scientist, such as Oldham or Jeffreys, could carry out in a lifetime (if they did nothing else). Fortunately, or unfortunately, depending upon your outlook, the thinking power and creative ability of humans is not mirrored in these powerful machines. Combining these two attributes, however – creative imagination and computational power – we are in a wonderful position to learn more about the world around us, to the benefit of us all.

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NOTES

1 Peter Bottomley MP, his grand-nephew, private communication.

2 H. E. Huppert, 'The intrusion of fluid mechanics into geology', *Journal of Fluid Mechanics.* 173 (1986), 557–94.

3 P. M. Bruce and H. E. Huppert, 'Thermal control of basaltic fissure eruptions', *Nature* 342 (1989), 665–7 with front cover photograph.

4 A. W. Woods, 'The fluid dynamics and thermodynamics of eruption columns', *Bulletin of Volcanology.* 48 (1986), 245–64.

5 A. W. Woods, 'The dynamics of explosive volcanic eruptions', *Reviews of Geophysics.* 33 (1995), 495–530.

6 R. S. White and C. J. Humphreys, 'Famines and catyclismic volcanism', *Geology Today*, 10 (1994), 181–5.

7 W. B. Dade and H. E. Huppert, 'Emplacement of the Taupo ignimbrite by a dilute turbulent flow', *Nature*, 381 (1996), 509–12.