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Anton Linder Hales 1911–2006

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Anton Linder Hales died in Canberra on 11 December 2006. He was a distinguished geophysicist of international renown who made major contributions to understanding the structure and evolution of the deep Earth through the combination of theoretical developments, field experimentation and laboratory measurements, including in whole-mantle convection, palaeomagnetism, geochronology and seismology. He was also a creative and highly successful builder of research institutions on three continents, in South Africa, the USA and Australia. The last of these was as Foundation Director of the Research School of Earth Sciences at the Australian National University, leaving behind one of the leading geoscience research institutions in the world. His career spanned a period in which earth science was undergoing rapid evolution—from a 'fixist' view of the planet to the 'highly dynamic' view that we have today, an evolution to which he made important contributions both through his own research and his scientific leadership at institutional and international level.

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Introduction

Anton L. Hales was a geophysicist whose career spanned three continents, Africa, North America, and Australia (Fig. 1). When elected to the Australian Academy of Science in 1976, his citation included the following three phrases: 'for his exceptional contribution to earth science over a wide variety of disciplines; being one of the most versatile and original geophysicists in the world; international recognition for his natural leadership, wisdom and ingenuity.' These summarize exceedingly well Anton's scientific achievements over some five decades. His career spanned much of the twentieth century that saw so many remarkable advances in all branches of science, including the earth sciences. Not only did he witness at close quarters the revolution in the earth sciences from a 'fixist' to the 'highly dynamic' view of the planet that we have today, he also made important contributions to this revolution through his research and scientific leadership. His connections with Australia went back to the early 1950s but the most important period occurred from 1973 to 1978 when he was the first Director of the Research School of Earth Sciences (RSES) at the Australian National University (ANU). He came to RSES as an internationally respected scientist with wide experience in the administration of research laboratories and universities, having previously steered similar institutions in South Africa and the USA to national and international prominence. This institution-building experience, together with his world-wide network of contacts and his deep knowledge of the earth sciences across their entire spectrum, made him the ideal founding director to lead RSES from a department in the Research School of Physical Sciences at ANU to an independent school that within a relatively short period became one of the leading geoscience research institutions in the world.

Formative days 1911–40[1]

From Mossel Bay to Cambridge 1911–33

Anton Linder Hales was born on 1 March 1911 in Mossel Bay, Cape Province, South Africa, of Scottish descent. His father, James Hales, had arrived in South Africa from Dundee, after the end of the Boer War when emigration from England and Scotland was encouraged. His mother, Sarah Elizabeth Rudd, also from Dundee, arrived a few years later, a result of a return visit by James to Scotland, and they were married in 1909. Anton's father was manager of a hardware department in Mossel Bay, a position he maintained in different towns with different companies throughout his working days.[2]

Anton's early schooling was in Port Elizabeth. By his own account he was not much good at singing and the music teacher encouraged him to do arithmetic during singing classes. At the end of his primary education his family moved to Pretoria and shortly thereafter to Cape Town where he attended the small and then-declining Sea Point Boys High School. Copies of the school magazine 1925–8 reveal that he won a prize for English literature. Several published essays attest to his early writing ability remain: 'On catching flies', 'The pleasures or otherwise of reading poetry' and 'On a stone'—the last showing no signs of geological thinking. His younger brother Kenneth's contribution was a poem 'Who'll kill the examiner?' Anton's name does not feature in the lists of sporting heroes. At some stage he dropped history, despite it being his best subject and against the advice of the school principal who had urged him to drop mathematics instead!

Outside school, his social life was very much within the English community and Methodist influenced, centered around the church and Sunday school, tennis and scouts. In his own words to his

[1] See referencing of Hales' notes below, following *Acknowledgements*, for comments on sources used when referring to or quoting from the notes Professor Hales wrote in the latter years of his life.

[2] A detailed account of his parentage and his early life in Mossel Bay is given in a letter by Hales to his son Peter, 15 October 1990 (A. L. H. notes a.1).

Figure 1. Anton Hales, in 1978, with Nicodemus, his favourite dog.

grandson Peter Robert: 'Those were the days kids made things, not bought them. We made canoes out of corrugated iron'—his approach to experimental science throughout his later life. Apparently he was not adventurous with canoes once constructed: that was left to his brother. Anton did become much more adventurous with small boats much later in life during his seismic experiments in the Arafura Sea.

Under the influence of a good teacher, Anton acquitted himself well enough in the final exam to win a 'small scholarship' to the University of Cape Town (UCT), starting in 1927. There he studied pure and applied mathematics and physics, along with history and Latin to meet the humanities and language requirements of the degree. He had wanted to do German rather than Latin but the course timetable interfered with his Wednesday afternoon tennis and he took what was for him the more difficult Latin option.

Upon graduating (with distinction) in 1929 he accepted a demonstratorship to support him through his MSc degree. This had the fortunate consequence that he met the professor of applied mathematics at the University of Witwatersrand in Johannesburg who offered Anton a junior lectureship even before he completed his MSc in 1930, again with distinction. He took up this position in March 1931, teaching applied mathematics for engineers, only to resign towards the end of that year to take up a Jameson scholarship offered by the UCT for three years of study in Britain at £150 a year.[3] The path for South African students aiming for research and academic careers in physics and mathematics at that time was via Cambridge. By commuting his scholarship into two years at £220 a year, so that he could afford to live there, he applied to read applied mathematics at St John's College. The choice of college was on the basis that 'there were many more mathematicians there than at other Cambridge Colleges.' The choice of subject was based on advice he received from his advisor at Cape Town: 'that a few years earlier Riet Woolley' (who later became Director of Mt Stromlo Observatory and Foundation Fellow of the Australian Academy of Science) 'had been awarded a similar scholarship and received a first in applied maths and that pure maths students only received seconds.' His advisor also challenged him to match Woolley's Cambridge record. Both received firsts in Part II of the Mathematical Tripos; Woolley a *b* in Schedule B and Hales a *b**![4]

Before going to Cambridge in 1931, he had met his physics lecturer at UCT, B. F. J. Schonland, who, on hearing that Anton had set his goal on studying quantum mechanics, advised him that 'advances in that field were … published at least six months or more before they became known in South Africa and that if he intended to return to South Africa … it was better to choose a field like geophysics in which you made your own observations and could do research which would not be anticipated elsewhere.'[5] On arriving in Cambridge, Anton audited the first-year course in geology given by Edna Jannich,[6] and read Jeffreys' *The Earth* but when it came to deciding on his first-year program he still was intent on quantum mechanics. However, when he arrived at Gonville and Caius College to register for the course '… the staircase … was blocked with people and, remembering Schonland's remarks, I turned around and went straight back to St John's and arranged a series of lectures in geophysics.' Those who knew him later will recognize his impatience with time-wasting activities and he obviously developed this trait at an early age. He attended a number of courses of lectures by Harold Jeffreys, on hydrodynamics, elasticity, and figure of the Earth, with applications to the problems of geophysics and physical geology. Of his student, Jeffreys wrote: 'He impressed me very much with his keenness and quickness of understanding and his interest goes far beyond the mere requirement of an examination and he has studied during his tripos course a great deal for his own satisfaction that has nothing to do with the examination.'[7] Hales wrote, 'I found (these lectures) most stimulating and indeed most of my activities since then have their origin in those lectures, with the significant exception of palaeomagnetism.'[8]

[3] Letter from registrar UCT, 10 December 1930.
[4] The mark *b** is for 'those candidates who … deserve special credit in the subjects of Schedule B.'
[5] Letter Hales to B. A. Austin, 27 September 1998.
[6] Later Edna Plumstead, who became Anton's colleague at the University of Witwatersrand.
[7] Letter of recommendation from H. Jeffreys, 10 July 1933.
[8] Hales (1986).

Through the Methodist connection he had met Marjorie Jacoba de Villiers Carter, 'on the steps of the parsonage on a Saturday evening in January 1931'.[9] Of Afrikaans-speaking background, but with mainly English education, she was studying at the Cape Town Teacher's College. They corresponded sporadically while he was in Cambridge and met again when he returned to South Africa for the 1932 summer vacation because, he said, 'I lived at home which cost a great deal less than living in England and the fare was only £30 return'. When Anton returned and moved to Johannesburg in 1933, he and Marjorie managed to meet infrequently—involving epic car journeys over several days in his recently acquired new Willys 77. They were married in January 1936.

Witwatersrand and BPI 1933–40

Anton was appointed to the University of Witswatersrand (Wits) as junior lecturer in pure mathematics. He completed his PhD in 1936 (from UCT),[10] based on the work he had started in Cambridge. Graduation involved another epic journey with rain-swollen rivers and a cracked differential casing and parts for his now not-so-new Willys that had to be sent by train from Cape Town. Anton wrote that academic gowns were expensive for a junior lecturer on £300 a year so he made one himself, against the advice of his mother and his wife! If his workmanship was anything like the way he periodically fixed his spectacles in later life, with safety pins and elastic bands, it must have been a quite remarkable garment.[11] At Wits he progressed rapidly to senior lecturer, moving to the Department of Applied Mathematics in 1938 in the process.

At Wits he wrote three papers on geophysical convection that also made up the core of his thesis: in the atmosphere, in geysers, and in the solid Earth.[12] These demonstrated his versatility and ability to use his mathematical talents to quantitatively examine physical processes in different Earth environments. At this time the subject of mantle convection was discussed extensively by the leading geophysicists and geologists,[13] in the search for a driving mechanism of continental drift that had been hypothesized some years earlier by Alfred Wegener on the basis of geological and palaeobotanical observations. But it appears that the only thing upon which the two sides could agree was the desirability of making a quantitative study of it. This Hales did, specifically addressing the suggestion by his Cambridge mentor Jeffreys: that it was necessary to investigate whether the theory of convection currents in the outer shell [mantle[14]] is consistent with the fact that the gravity anomalies show that there are deep-seated stress differences of the order of 5×10^7 dynes cm^{-2}'.[15] This paper was published shortly after a similar paper by Chaim Pekeris,[16] wholly independent other than that it had also been communicated to the journal by Jeffreys. Both used modern fluid dynamic theory to estimate the conditions for convection, and both concluded that convection was possible in a viscous layer with an upward temperature gradient.[17] Their papers were to be the precursors to the analysis of how convection is reflected in gravity, geoid and topography, a discussion that is again important today. Interestingly, Hales concluded that 'convective currents could exert a drag on the base of the crust and cause drift', but he never argued explicitly that convection actually occurred[18]—in deference, one suspects, to Jeffreys. Jeffreys did acknowledge these results,[19] but remained a 'fixist' as did Hales for the next two decades in the face of the body of important geological arguments developed by the South African 'mobilists' Alex du Toit and Lester King and, later, of the palaeobotanical arguments from his now colleague at Wits, Edna Plumstead. She later wrote: 'Hales was my chief opponent at this time. We had many friendly arguments, but as a physicist, he needed proof of movement acceptable to his profession.'[20] In this, he clearly continued to follow Jeffreys who, at about the same time, had written: 'Considering that the theory has been advocated for 35 years, it is remarkable that nobody has suggested one of the right amount or even in the right direction … I seriously suggest that no more time should be spent on discussion of this theory until a mechanism for it is produced.'[21] Clearly, neither Jeffreys nor Hales himself was prepared to extrapolate from the latter's theoretical work to the real Earth. I return to his conversion to mobilism below.

Another person who was important in Hales' early career was B. F. J. Schonland (later Sir Basil Schonland, FRS), first at the UCT and later at the Bernard Price Institute of Geophysical Research (BPI) of which Schonland became the founding director.[22] BPI was established 1936–7 at Wits by Bernard Price, head of the Victoria

[9] Letter to Peter Hales, 'How I met Peter's grandmother, October 1990', (A. L. H notes a.1 p.14).
[10] Letter from Registrar at UCT dated 7 December 1936.
[11] The gown has not survived. It was stolen during a house break-in and his wife had commented that this was no doubt because it was used to wrap-up other stolen items.
[12] Hales (1935). Hales (1936). Hales (1937).
[13] See Frankel (2012*a*).
[14] My insertion.
[15] Jeffreys (1929) p. 201. Jeffreys had rejected, and continued to reject, all arguments for the existence of mantle convection on the grounds that there were no quantitative evaluations that demonstrated that such a process could exist on time scales less than the age of the Earth.
[16] Pekeris (1935).
[17] See Bercovici (2009) for a more detailed discussion of these papers.
[18] Frankel (2012*a*) p. 234.
[19] Jeffreys (1976) pp. 457–458. While not disagreeing with the Hales results he argued that the time-scale of the process was significantly longer than the age of the planet.
[20] Quoted in Frankel (2012*a*) section 6.12, from a memoir by Plumstead 1982.
[21] Jeffreys (1951). His remarks at the meeting of the British Association for the Advancement of Science in Birmingham in 1950 were quoted by Shea (1985) p. 265.
[22] Schonland's name was to reappear in an Australian context in 1953. With strong support from Professors Mark Oliphant and John Cockcroft, Lord Bruce and initially Dr H. C. Coombs, he was a leading candidate for the Vice-Chancellorship at ANU to follow Sir Douglas Copland. The other candidate was L. Melville, Executive Director of the International Monetary Fund but at the insistence of Prime Minister Robert Menzies with 'no Melville, no money', Schonland's appointment did not proceed. (Austin (2001) p. 436). Forster and Varghese (1996) pp. 116–118.

Falls and Transvaal Power Company (that supplied much of the electrical power to the Johannesburg gold mines) and with a substantial grant from the Carnegie Institution in Washington.[23] A specific requirement by Price was that Schonland be appointed to head it as professor at Wits. Schonland's research at the time was directed at lightning including the associated electrical disturbances in the atmosphere and their effect on radiowave propagation, work that became of great importance a few years later in the development of wireless direction finding.[24] Price's motives in establishing BPI were partly altruistic but also, 'that his company would certainly benefit from whatever lightning protection measures might spring from the institute's work.'[25] The intent was that BPI would become self-supporting within a ten-year period and that this would require support from South Africa's mining industry. This would have been an important consideration in the appointment of Hales to BPI in 1937—as an honorary senior research associate while keeping his appointment as senior lecturer in the Department of Applied Mathematics at Wits—to work on the causes of small earth tremors that occurred frequently in central Johannesburg and to establish whether they were 'natural' or triggered by mining activity. This was part of Schonland's strategy; that South Africa's largest industry might one day come to appreciate more the value of science.[26]

This marked the start of Anton's work in seismology, a field to which he would contribute greatly in his later years at Dallas, Texas, and at ANU. It also marked his first departures from purely theoretical work. With P. Gane, deputy director at BPI and a geophysicist but also skilled in electronics, and J. A. Keiller, a talented instrument maker, they built a network of six recorders, their own seismometers (inverted pendulums of the Weichert type), recording (on smoked paper) and timing (daily recording of time signals transmitted by local radio) systems. They also had to develop their own analysis methods (using a graphical location board) to locate the positions of the tremors that took into consideration that the location and timing of the sources, as well as the velocities of the compressional and shear waves, were unknown. The first records were obtained and analysed by Gane and Hales and the network was declared operational by the time war was declared in 1939, locating 'the events with considerably greater accuracy than any other network of the time, other than those studies using timed explosions at known locations'.[27] The first scientific papers did not appear until 1946.[28] These demonstrated convincingly that the sources of the tremors occurred close to the areas of mining and 'that it was legitimate to assume that the tremors resulted from the weakening of the structure resulting from mining operations.'[29] But more important perhaps was that they led to the development of methodologies for determining the local and regional seismic structure that led to the detection of an 'intermediate layer' in the crust.[30]

The war years

South Africa entered the war a few days after Britain declared war on Germany, and the resources of BPI were directed to the war effort, 'for research work of a special nature',[31] with no further elaboration but which was later declared to be designing and building radar for the protection of South Africa's coastline.[32] Because of the now-classified nature of the institutions work, seismology was to continue until complete outside of BPI at Wits and without Ganes and Keiller. Hales was asked to take responsibility for the project and complete the report to the Chamber of Mines. For this he still had to have access to the BPI dark room, which required him to sign the Official Secrets Act in the event that he saw the highly prized glass slides containing the British secrets of radar, obtained by Schonland from the New Zealander Ernest Marsden.[33]

When the report had been submitted, Hales volunteered to join the 42nd (Geological Survey) Section of the South African Engineering Corps that he joined in East Africa in early 1941 as 2nd lieutenant (physicist).[34] The specific objective of this unit was prospecting for groundwater in East Africa, Somalia and Ethiopia using geophysical means, primarily resistivity but also magnetometer surveys, in support of the northward advance of the South African army against Italian forces.[35] But the advances were generally too rapid to make effective use of the experiments that he conducted, experiments that were plagued by instrumental failures resulting from the rough transport conditions. This was to be Anton's introduction to geophysical field work in remote and harsh conditions, work that he was to continue years later in the western USA, Central and South America and later still in Australia. He learned to improvise, for example, so that the galvanometers used in his resistivity experiments could be repaired using the balance springs from watches. He returned to South Africa briefly in July 1942 to obtain spares for his instruments but by the time these arrived in Cairo the packages had been pilfered. In Egypt, his unit

[23] Allibone (1973).
[24] Austin (2001).
[25] Austin (2001) p. 140.
[26] Austin (2001) p. 159.
[27] Hales notes e.1, 'The Bernard Price Institute of Geophysical Research Years 1937–1962', undated other than post 1988 and possibly an early draft of a shorter paper published that year, 1988 (Hales 1988).
[28] Gane and others (1946).
[29] The quote is from a later paper of Hales (1960).
[30] Willmore and others (1952).
[31] Austin (2001) p. 170. The secret work turned out to be the design and construction of radar.
[32] Allibone (1973). Schonland spent much of the war years in the UK as Superintendent of the Army Operational Research Group in the War Office and later as scientific adviser to General Montgomery as Brigadier in the Army of Liberation.
[33] Distinguished New Zealand Physicist who had worked in the Rutherford Laboratory in Cambridge where he made important contributions to the discovery of the nucleus of the atom (and who, by 1939 was working on radar and had possession of British radar documents when he and Schonland first met on a ship travelling between Cape Town and Durban. Austin (2001) p. 177. Hales Notes B p. 4.
[34] Rose and Clatworthy (2008). By 1942 the unit consisted of five officers, two geologists, two geophysicists and the physicist Hales.
[35] Mather (2004).

spent most of its time between the Nile and the Red Sea, exploring and drilling for water in support of a port construction on the Red Sea and a road and rail link to Qena in upper Egypt but by the time of the second battle of El Alamein most of his unit had already been moved to Syria, with the exception of Hales and two others who remained in Cairo 'to destroy equipment and reports if that became necessary', only to discover, after the main unit had left, that the store had been depleted of gasoline. The location of potable water sources was also a major activity for the British Army in North Africa who had relied almost exclusively on existing geological maps to identify likely aquifers. The significance of the geophysical methods developed by the South Africans, thoroughly tested by now in the Abyssinian and Somaliland campaigns, became much appreciated and widely used across the Middle East and Mediterranean in the later years of the war.[36]

With the immediate threat of German expansion into Africa averted, the unit was moved to the Middle East but Hales was honorably discharged in August 1943 (with £5 cash allowance paid),[37] from full-time military service and transferred on 'Indefinite Release' to the Director of War Supplies where he worked in the Instruments and Wireless Section.[38] There he initially helped in the ray tracing for the design of the lenses for an artillery instrument. I have not been able to find details of his work in this period, but a letter of appreciation from the Office of the Director-General of Supplies includes the paragraph:

> Your task was an exceedingly difficult one, both from a technical and personal point of view, and the sound way in which you carried out your duties and the tactful manner in which you handled difficult situations resulted in what I consider a splendid production of instruments.[39]

Post war in South Africa, 1945–62

BPI and Witswatersrand University 1945–9

Anton returned to Wits as Senior Lecturer in September 1945 to give courses in applied mathematics. But this did not provide research opportunities and in the following year he accepted an appointment as Senior Research Officer at BPI while continuing his university function. His initial work at BPI was to revisit the work on the Johannesburg earth tremors. Arguably, his most important contribution from this period was the recognition that the tremors were sufficiently large to be recorded over distances of several hundred kilometres from the source so that it would be possible to probe the deeper crust if the seismometer network was expanded well beyond the mine region and using the local network to determine the timing and location of the events.[40] This pioneering work, combined with further instrumental developments, led in 1948 to the first Moho reflections and measurements of deep crustal velocities and crustal thickness in South Africa.[41]

At this time Anton also demonstrated his flexibility in his scientific pursuits with a paper on ionospheric structure.[42] This resulted from his observation that some of Schonlands's records of electrical disturbances looked remarkably like seismic waves he had studied for some of the larger rockbursts: in one set they resembled multiple reflections, in the other a surface wave train. Schonland had challenged him to 'see what I could do about it' and the outcome was that the ionospheric *D* layer had to reach down closer to Earth's surface than predicted by the then current models, an observation that stood the test of time.[43] The third main research activity at this time, assisted by a recent MSc graduate D. I. Gough, was into absolute gravity measurements using borrowed Cambridge pendulum instruments. It was a real challenge to maintain these precision instruments while transporting them long distances over dusty rough roads yet, thanks to a variety of improvised repairs, they succeeded in establishing a network of base stations that formed the foundations for the future gravity survey of South Africa,[44] work in which Hales and Gough continued to play a major role, including in the geophysical interpretation of the results.

The immediate post-war period had seen a revival of interest in the origin of Earth's magnetism, largely under the influence of P. M. S. Blackett, FRS, in Britain who advocated that this field was a result of planetary rotation, and of W. M. Elsasser in the USA who had earlier argued for a self-exciting dynamo in Earth's fluid metal core.[45] E. C. Bullard in 1947 had made the suggestion that it should be possible to distinguish between the two theories if the magnetic field could be measured at depth inside the planet.[46] For the dynamo model, both the horizontal and vertical components of the field should increase with depth whereas in the rotation model the vertical component should decrease with depth. One of the first (and possibly the first) such tests was attempted by Hales and Gough in the Witwatersrand mines and seemed to support the rotation hypothesis but with reservations expressed because of the short period of observation and because it had not been possible to map the regional variations in the surface field with sufficient accuracy.[47] According to Hales, follow up experiments were conducted in 1949 by A. M. van Wijk with a more extensive surface survey and

[36] Rose and Rosenbaum (1993).
[37] Hales. Voluntary Identity Book for use on discharge.
[38] 7 July 1943; Indefinite Release: 131770 Lt. A. L. Hales.
[39] Letter from Director-General of Supplies to Hales, 10 April 1946.
[40] The instrumentation for this is described in Gane and others (1949).
[41] Willmore and others (1952).
[42] Hales (1948).
[43] Budden (1951). Wait (1960).
[44] D. I. Gough was appointed to assist with this work that laid the foundations for the gravity survey of South Africa. Hales and Gough (1950).
[45] The history of this is well described in Frankel (2012*b*) chapter 1.
[46] Bullard had first visited BPI in 1938, the first overseas visitor to do so (Austin (2001) p. 162) to work on the thermal conductivity of the Rand quartzites in order to understand the temperature gradients in the upper crust, a subject of considerable importance to the mineral exploration industry. This led to significant further collaborations in the areas of seismology, geomagnetism and gravity all areas within Hales' activities. Bullard had drawn Schonland's attention that the Rand mines were ideal for his proposed test, leading to the Hales-Gough measurements. Austin (2001) pp. 359–361.
[47] Hales and Gough (1947).

improved underground measurements and found that the horizontal component increased with depth, consistent with the core origin.[48]

University of Cape Town, 1949–54

In 1949, Hales was appointed to the chair of applied mathematics at UCT. The appointment did not provide many opportunities for his new-found interests in experimental geophysics and so he retained his link with the BPI by spending the summer months in Johannesburg on the projects started in earlier years. He did become involved in university politics, something he had avoided at Wits, but otherwise was mainly involved with teaching first year students in both pure and applied mathematics. The problem he faced was that the majority of the students in pure mathematics saw it as a tool and not an end in itself and he devoted his inaugural lecture in 1950 to 'Mathematics: end or tool?' An important indirect aspect of the appointment was that UCT received more international visitors than did Wits, and of these his meeting, on the evening of his inaugural lecture, with Harry Hess (professor of geology at Princeton) and Tuzo Wilson (professor of geophysics at Toronto) was important. Hess and Wilson were to make fundamental observations upon which the plate tectonics hypothesis was built some fifteen years later but Anton recalls that on that evening 'Not one of us believed in continental drift'. Another important visitor during this time at UCT was J. C. Jaeger, the Foundation Professor of Geophysics at ANU, and I return to this below. In 1952, Hales took sabbatical leave for a term, spending the greater part of the time in Cambridge with Marjorie and their first (newly born) son, James. There he worked mainly on the theory of thermal contraction of the Earth.[49] More important was that this visit introduced him to S. K. Runcorn and his students[50] working on palaeomagnetism, work that led to the detection of the drift of the magnetic pole across Earth's surface through geological time and ultimately to the recognition that the continents themselves had changed their relative positions through time.[51] Anton was, however, still not ready to shift from his earlier position, it being 'impossible' (for physicists) 'to think of the stiff ocean floor permitting movement of the continents'.

Director of BPI 1954–62[52]

In 1954, Schonland had joined the Atomic Energy Research Establishment at Harwell as Deputy Director and Hales had been sounded out about whether he would accept the post of Director of the BPI if it were offered to him.[53] The immediate post-war years had seen the start of the transition of a mathematician comfortable in both the applied and pure areas, into an experimental geophysicist with a willingness and ability to branch out into emerging new fields, identifying and executing problems that addressed fundamental questions about the physics of Earth. During his 1952 sabbatical he would have witnessed a renewed recognition that support for scientific research was essential for the development of a country and that it was the start of an interesting period for geophysics in which it would become possible to test many of the theories that had their embryonic roots in the pre-war period, thanks to the technological advances from the war period. BPI, with a growing international reputation was a good place to pursue these activities and to expand the research programs initiated by Schonland and this Hales set out to do. He 'gave it some thought' and later wrote 'Marjorie and I talked about the letter that evening. Marjorie said that she would be quite happy to stay in Cape Town, adding that she thought I was easier to live with when I was teaching rather than doing research, but that she knew I would not be happy if I turned down Schonland's suggestion and so would leave me to make the decision. I wrote and said yes the next day'.[54] He resigned from UCT before an actual job offer had eventuated from Witwatersrand University.[55] Other than the ability to make very rapid career decisions, another pattern established at this time, was Anton as house builder. When he and Marjorie first moved to Cape Town they built a house outside of the city, but the soil was unsuitable for establishing a garden and because he was at BPI for the summers they decided to move nearer the university. Schonland's letter arrived on the day of the first concrete pour of the footings of their new house![56] The Hales family (now including a second son, Peter, born in 1953) drove from Cape Town to Johannesburg and in September 1954 he took up the BPI position along with that of Carnegie-Price Professor of Geophysics at Witwatersrand University. 'It is a journey I remember for one night Marjorie told me that she had felt a lump in her breast' leading to surgery 'within a few weeks'.[57]

When he took over the Directorship the BPI, programs were lightning (by D. J. Malan[58] who following on with this research after Schonland's departure), seismology (under Gane), geochronology (under G. D. L. Schreiner and R. T. Jamieson)[59] and hammer seismology, heat flow and paleomagnetism under Gough. Seismology caused him the one major concern about accepting the BPI

[48] From the South African Magnetic Observatory at Hermanus. I have not been able to find any publications reporting on the outcomes.
[49] Hales (1953).
[50] Including E. Irving whose work two years later was to be the critical element to Anton's conversion from 'fixist' to 'mobilist'.
[51] Frankel (2012*b*).
[52] In reviewing Hales' contribution to BPI, I have restricted my discussion primarily to those areas relevant to the development of the research programs at ANU.
[53] Letter from Schonland to Hales dated 6 June 1954.
[54] Admittedly Schonland, in his letter, gave him little choice, wanting an answer by wire so that the recommendation for appointment could go to the University senate for decision.
[55] Letter from the Principal of Witswatersrand, dated 8 July 1954.
[56] His last building project started in 1983 outside of Canberra, on equally unsuitable land for gardening.
[57] Hales notes a.2.
[58] Not to be confused with D. F. Malan, the Nationalist Prime Minister after Smuts, to whom Schonland, as president of CSIR reported on all matters of science and technology until the Nationalist Government insisted that CSIR, like all other institutions, should reflect the 'Suid Afrikaanse Kleur'. The resulting tensions arising rise from this policy and the growing influence of H.F. Verwoerd's race policies ultimately played a major role in Schonland's decision to leave South Africa. Austin (2001).
[59] Jamieson and Schreiner (1957).

position in that its deputy director was the seismologist Phillip Gane and so Anton decided that he would leave this field to him.[60] The program Hales developed focused on some of the then fundamental questions being asked about the structure and evolution of Earth but framed in terms of more immediate objectives but 'always we hope that by solving the immediate problem we shall contribute a new piece of information bearing on the major problems of earth history'.[61]

Palaeomagnetism

Paleomagnetism at BPI had begun in the early fifties, before Hales was appointed Director, by an initiative of Gane who, on sabbatical in the USA had been impressed by J. W. Graham's airspinner magnetometer,[62] had suggested in a letter to Hales that they might try to build one from the rough sketch in the letter's margin.[63] This was successfully done and the question became one of what measurement to make. Anton suggested sampling the Pilanesberg dykes that cropped out north of Johannesburg where earlier experiments had indicated that the vertical component of the magnetic field was in the opposite sense to the present field. These first experiments were inconclusive because the poles scattered randomly, and consequently paleomagnetism at the BPI nearly came to an end as a subject of investigation. But Anton persevered by suggesting that the dykes might be accessible underground where palaeomagnetic records may be better preserved. This turned out to be the case and by 1952 Gough had made measurements in one tunnel that showed consistently that the magnetic pole at the time of the magnetization of the dykes—at the time of their formation—was in Ethiopia, north of the Equator.[64]

In 1954, Anton attended the general assembly of the International Union of Geodesy and Geophysics in Rome and there he met E. Irving who had been one of Runcorn's students when Hales was on his previous sabbatical and who was now on his way to ANU where Jaeger had appointed him as a research fellow to develop paleomagnetism. Irving described their Cambridge results that S. K. Runcorn argued showed that the magnetic poles established for eastern North America and western Europe were consistent with those continents being in their present positions since the time of magnetization (of Palaeozoic to Mesozoic age) and that the results were evidence for a wandering of the pole path through time.[65] But Irving, whose contribution to this study had been critical, disagreed on the grounds that the 95% confidence areas for the poles from the two areas did not overlap and that this could only be explained if the continents had moved relative to each other. Anton's fixist views did not waver at this point but upon his return to BPI he decided that the results were sufficiently interesting to warrant further research. He was able to recruit a student, K. W. T. Graham, and told him that if they made enough measurements they would find that the African continent had not moved.[66] The first results of their new Karroo dolerite dyke measurements were promising, indicating that the South African pole positions are not consistent with those of Europe, North America and Australia and that 'the simplest way of reconciling the divergent pole positions … is to postulate relative displacements of the continents, i.e., Continental Drift.'[67] Yet in another paragraph they noted reservations about the underlying 'assumption of a slowly varying direction of magnetization is an over-simplification' and that the results were also 'indicative of a fairly rapid movement of the pole or of the continent'.[68] In his retrospective of 1986 Hales wrote: 'From that time on I called myself a reluctant drifter.'[69]

Several other important results came from the palaeomagnetic research at BPI under Hales' guidance, including the explanation that the dispersion of the earlier surface measurements by Gough were a consequence of remagnetisation caused by lightning and a first and very detailed study of the behaviour of the magnetic field during a polarity reversal.[70] But in the meantime Anton had moved on to other questions.

Geochronology

An important issue hampering the deciphering of the palaeomagnetic records was the imprecise dating of the rock samples. Radiometric dating of rocks had been possible since the discovery of the uranium decay chain but did not become readily accessible until the late 1950s. Developments had started a few years earlier at South Africa's National Physical Research Laboratories (NPRL),[71] with a focus on uranium minerals. This was taken up at BPI with parts provided by the Carnegie Institute and new electrical circuitry by Jamieson, Schreiner obtained the first ^{87}Rb–^{87}Sr whole rock ages

[60] Schonland had written to Hales (15 June 1954) to explain why Gane, as Deputy Director, was not considered for the position because of a speech defect that seriously affected his ability to communicate with those who secured the funding for the BPI. Gane left BPI in 1955 for an appointment in Industry and seismology again became a key research interest of Hales. Interestingly, Jaeger, who had told Hales in 1953 that he did not intend to develop seismology at ANU, wrote to Hales about possibly recruiting Gane.

[61] Hales (1960). This paper also provides a comprehensive review of then research at BPI.

[62] At Carnegie Institute for Terrestrial Magnetism in Washington. Graham's later visit to BPI led to critical parts of the instrument being transferred from Carnegie to BPI.

[63] Gough (1988).

[64] These results were not published until 1956 until Gough had made additional measurements in other mine exposures that confirmed this first result. Gough (1956).

[65] The work that Runcorn reported was probably that of K. M. Creer another student at Cambridge at that time. See Frankel (2012*b*) for a detailed account of this early period in the development of palaeomagnetism.

[66] Hales (1986).

[67] Graham and Hales (1957).

[68] Frankel ((2012*b*) p. 209) noted this divergence and suggested that the first paragraph was the geologist Graham and the second was the physicist Hales.

[69] Hales (1986).

[70] Graham (1961). Van Zijl and others (1962).

[71] The National Physical Research Laboratories of the South African Council for Scientific and Industrial Research (CSIR). The early work at BPI was carried out in collaboration with the former. The Director of NPRL specifically asked Hales that during his 1960 travel to 'drop a line whenever you come across developments I should know of'. Letter E. J. Marais to Hales dated 14 January 1960.

for the Pilanesberg dyke that had previously been examined for its palaeomagnetism.[72] Jamieson left BPI in 1955 and Hales had to stand in for the electronics work until a replacement could be found. This experience gained in mass spectrometry stood him in good stead later, in both Dallas and Canberra (see below).

Seismology

When Gane left BPI in 1955, responsibility for the seismology program returned to Hales. He was able to recruit 'a very bright electrical engineer', S. I. Sacks, who convinced him of the potential of very slow-running analogue magnetic tapes for recording seismic signals at considerable distance from their source and this would permit of an expansion of the local seismic monitoring well beyond the mine area and enable the deeper crustal structure to be probed.[73] These instruments would become the forerunners of those successfully used years later in the USA and Australia. Sacks and Hales also introduced other instrumentation improvements to solve timing, clock stability and power consumption issues producing equipment with which they were able to record the Johannesburg mine explosions across the Eastern Transvaal to the coast along a 500 km long profile. These results led to the first estimates of the depth of the crust-mantle boundary, the Moho, in Africa, confirmed the existence of an intermediate crustal layer identified earlier from the local network analysis, as well as a confirmation of the Airy-Heiskanen isostatic hypothesis.[74]

1960: a critical year

In 1960, Anton travelled extensively in the USA, visiting the Carnegie Institution in Washington and the California Institute of Technology, and institutions in Europe. He kept extensive records for much of this period in the form of 'pen carbon books' (with the originals sent back to BPI with appropriate instructions for follow-up actions). These are a treasure trove of technical information: notes on building seismic recorders and mass-spectrometer design for future use; correspondence, notes on papers he read; meetings he attended and people he met; visits to academic and industrial research laboratories; outlines of lectures; and correspondence with BPI on directorial matters. Together they display the wide range of interests that he developed in this period as well as the growing network of contacts with whom he would work in later years. The two principal disciplines dealt with were seismology (across the entire wavelength spectrum) and geochronology (with a focus on whole rock radiometric dating methods but also learning about Potassium/Argon dating). In between, his notes cover questions of gravimetry and crustal structure, palaeomagnetism and continental drift, heat flow and anything else in geophysics that he saw as relevant to the future BPI program in particular and to South African geophysics in general. They record bits of information that one can see surfacing time and again in his subsequent career in the USA and at ANU. There is, for example, useful information on producing explosives from ammonium nitrates and diesel oil in an environment where 'regulations on moving this material are not strict'[75] that was to be useful for his subsequent explosion seismology experiments in the USA. There are comments on both detecting and masking seismic signals generated by nuclear explosions. At the Atomic Energy Research Establishment (AERE) Harwell he was told 'that a chemist with little knowledge of mass spectrometry could get as good a result from a large radius instrument as a physicist could get from one half the size',[76] and we see this message reflected in his later very strong support for the mass spectrometry development at ANU led by the physicist William Compston. There are derivations with detailed error analysis for the calculations of whole rock ages from radiometric isotope measurements in support of the emerging geochronology program at BPI, complemented with constant correspondence to Schreiner keeping him up to date on similar developments in the USA, providing advice and urging him to publish his results on the ages of the Bushveldt granites.[77] They show that already in 1959 he was convinced that the methods of whole-rock dating on multiple samples, being successfully developed and applied in South Africa, were preferable to methods that relied on dating the constituent minerals. Hales was able to talk about the BPI work on several occasions, one in March 1960, at a New York Academy of Sciences symposium on geochronology,[78] after which he reported back to BPI 'I came away with the feeling that we at NPRL and BPI had done quite well considering our resources relative to those available in the United States'.[79] The experience gained and contacts made largely shaped his subsequent career. He was increasingly recognised as an outstanding earth scientist who could debate the science with the best in the field and as someone who was not going to waste time unnecessarily.

Family matters up to 1962

Marjorie died of cancer in February 1957.[80] Her death left Anton with two small boys, James and Peter, at a time when he was entering into a new phase of his career that took him across South Africa and that also saw a growing involvement in international science programs. Anton had to find a solution, as travelling with a governess/housekeeper across the USA and Europe was not wholly

[72] Schreiner (1958*a*). Jamieson and Schreiner (1957). Schreiner (1958*b*).
[73] Hales and Sacks (1959).
[74] Hales and Sacks (1959). Hales (1960).
[75] Pen Carbon Notebook 1A, p. 33, 16–17 February 1960.
[76] Schonland was at Harwell at this time, leaving in January 1961. He was not told what sized instrument a geologist would require!
[77] The method was to be developed further by Compston and Jeffery (1959) with whom Hales had discussed the South African work during a visit to UWA in March that year (March) (Anton's notes. Book 1A p. 45).
[78] Hales (1961).
[79] Pen Carbon Notebook 1A. p 53, 6 March 1960.
[80] Letter written some fifty years later, Anton refers to a book he borrowed from the Queanbeyan Library: 'it describes a boy of 14 or 15 whose mother had died when he was four. He was concerned that his father had never been willing to talk about his mother. I wondered whether I had been guilty of a similar fault and could not settle whether I had or not.' He then proceeds to tell them about his mother, explaining the difficulties Marjorie had had in conceiving and the procedures she endured in successfully overcoming this as well as the details of her cancer, concluding: 'Marjorie enjoyed having you around and was proud of you.' Letter to James and Peter, undated but probably after 2000 (See Hales notes a.2).

successful, particularly when the latter returned to South Africa before the end of the travels. Nor was leaving his two sons in the care of a London Hotel for a few days while he travelled to an IUGG meeting in Helsinki—with instructions to the nine-year old that they could explore London provided that they did not cross the road.[81] Something else had to be tried.

Anton and Marjorie had developed a friendship with Lilian and Edwin Adcock in 1952 across the bridge table in Cape Town. This couple had a daughter, Denise, who would baby-sit James, now aged two, as well as her own brother of similar age, in exchange for Anton providing help in preparing her for the university entrance exams in mathematics.[82] Later, again by chance, the Adcock family also moved to Johannesburg in 1956, finding themselves in adjacent suburbs. Until 1959, Denise's parents helped in looking after James and Peter but then moved back to Cape Town while Denise stayed in Johannesburg at the teacher training college, acting as a conduit for her mother to provide long-distance care for James and Peter, charging the purchases of school uniforms and the like to Anton's account, apparently without the latter's awareness. But there was still a problem. He had committed to gravity and seismic measurements at sea south of South Africa and to other overseas travel and he needed someone to live in his house to look after the boys. So in February 1962 Anton approached Denise's mother to ask whether it would be all right to ask Denise to move into his house to keep an 'eye on the boys' as he had a number of overseas trips planned. In Denise's own words, 'she would fetch them from school—unlike "Prof Hales" who would often forget them—take them to the movies and do all the things that mothers do but Anton didn't.'[83] Within a month this led to Anton proposing marriage; an engagement party the next day with John and Patty Jaeger in attendance; and a wedding a week later, on 3 March 1962—a remarkable achievement since the marriage took place in the local Anglican Church, 'thanks to an understanding priest'—and a two-day honeymoon. There was reason for this urgency that Denise may not have been immediately aware off. He was booked to spend a couple of weeks in France starting in the first week of March followed by a quick trip to Dallas at an invitation of L. V. Berkner to discuss the directorship of a newly created research center,[84] and he had recognised that if he accepted the position—which he already had accepted in his own mind—that this would require a quick marriage to avoid USA visa problems for Denise!

Southwest Center for Advanced Studies and University of Texas, Dallas[85]

In February 1961, Hales had been approached by H. H. Hess[86]—whom he had met in Cape Town some twelve years earlier—to accept appointment at Princeton University, noting that the 'Geophysics there needs upgrading.' Hess' letter contains the first reference in Anton's correspondence and notes to the politics and social issues facing South Africa, in which Hess noted, 'I guess what you have to gauge is how long it is before the storm breaks … when it does …don't be too sure the Afrikaners won't win but it will be chaos for a long time as in Algeria today.' Anton's part of the correspondence does not appear to have been preserved and the only other insight into his views on these matters is provided in an undated but post-1959 letter to the *Johannesburg Star* newspaper in which he attempts to provide an alternative to the view presented by the South African writer Alan Paton—that the only solution to the South African problem is that the Afrikaner should 'consent to his own death'—with, for its time, a cogently argued case for an, as near-equal as possible, partitioning of South Africa into two coexisting separate nations that 'would call for sacrifices by all.'[87]

Having declined the Princeton offer, Anton Hales left South Africa in September 1962 to take up a position as the foundation head of a new geoscience program at the Southwest Center for Advanced Studies (SCAS) in Dallas that had been established only the previous year as an independent non-profit research centre by Texas Instruments.[88] During his three-day visit in March 1962, Anton must have felt attracted to this young institution from the outset and he was to develop close links with both Berkner and C. H. Green, one of the TI founders. The manner of the appointment has echoes of his later move to ANU: 'I sat down with Berkner at 8.30 on Monday morning. We talked for half an hour. He called in his secretary and dictated a letter of offer. I then dictated a letter of acceptance. The letters were signed before 10.30. I left for Johannesburg later that day.'[89] The family arrived in Dallas six months later, in September 1962, with all assets frozen by the South African Government.[90]

[81] James recalls: 'We were left at a rather grim bed and breakfast whose proprietors undertook to feed us. However, it was Christmas time and we did venture out to a nearby department store'.

[82] Denise Hales notes.

[83] Hales notes A, Family History. At this time Anton's father, lived with him. Denise called Anton "Prof. Hales" until they became engaged.

[84] Berkner installed one of the first automated ionospheric sounders in Australia in 1938 at the Carnegie Magnetic Observatory Watheroo (WA). Needell (2000).

[85] This period has been well documented in reports from UTD, including: Ward and Mitterer (1983). Anonymous (1989). Here I will focus mainly on those aspects of Anton's career that are relevant to his subsequent move to ANU.

[86] Letter, H. Hess to A. L. Hales, 28 February 1961.

[87] The problem facing South Africa, typed letter, undated but post 1959.

[88] The Center was set up 'to provide an intellectual atmosphere that would train and attract scientists and engineers for the new industries dependent on highly trained and creative minds that were growing up in the area.' It was originally named the Graduate Research Center of the Southwest, headquartered on the Southern Methodist University campus. The name change to Southwest Center for Advanced Studies (SCAS) occurred in 1966 followed in 1969 to The University of Texas at Dallas of which he became Acting Vice President of Academic Affairs. I have used the name SCAS throughout. The circumstances of the creation of SCAS bear considerable similarity with the creation of the Bernard Price Institute nearly thirty years earlier.

[89] Anonymous (1989) p. 3.

[90] As on an earlier occasion, he resigned from BPI and Wits before the Dallas appointment was finalised and before visas had been issued. On his initial inquiry with the consulate in Johannesburg he had been informed that this would take a year or so but Berkner had assured him that something would be sorted out. It was, but only two days before departure date when they received a letter signed by the science advisor to the US President saying that Hales was necessary for the security of the USA. After a traumatic interval, upon arrival at immigration control in New York with 'look what this fellow is offering in lieu of a visa' and a number of phone calls they were allowed entry, on September 3, at 3 am, 1962. (See Hales notes a6.)

What led to Hales' decision to leave South Africa at this time, having earlier rejected the Princeton offer? He did note later that' 'it was an appropriate time to hand over the BPI to new leadership.'[91] I can only speculate that he saw opportunities within a like-minded group at Dallas to build his own programs, rather than the more sheltered life offered by a well-established traditional university such as Princeton. Undoubtedly, the resources available at Dallas and the vitality of the research environment that he had witnessed when he travelled across the USA in 1960 helped. Yet another must have been the darkening political situation in South Africa that affected both him and Denise: He had been called up, at the age of fifty, for reserve officer duties, and the recognition that Denise's support for the work started by Trevor Hudleston in the black community of the slums of Johannesburg was likely to bring her into serious conflict with government forces,[92] may have played a part.[93]

In Dallas, the core of SCAS quickly developed with Hales responsible for the Division of Geosciences and F. S. Johnson for the Division of Atmospheric and Space Sciences in September 1962 and with the Division of Mathematics and Mathematical Physics, headed by Professor Ivor Robinson, added in March 1963.[94] The geoscience program was similar to that at BPI—seismology, palaeomagnetism, geochemistry and geochronology—and quickly attracted a large group of research scientists, faculty and visitors. Early members of SCAS included: Mark Landisman and Adam Dziewonski who made important contributions to the understanding of Earth's interior from seismic wave propagation studies; J. W. Graham, who had been instrumental in the early success of the palaeomagnetic work at BPI; and C. E. Helsley. Also, with a rapidly deteriorating political situation in South Africa and with the available new resources, it is not surprising that some of his South African colleagues, notably D. I. Gough, K. W. T. Graham, J. Keiller and R. W. E. Green also joined SCAS in different capacities.[95] Other staff members to SCAS included two Australians, Ken McCracken (experimental investigations of the cosmic radiation) and G. H. Riley (geochronology and isotope geochemistry), both of whom later joined CSIRO. McCracken captured well the Hales approach to doing science:

> Arriving at Dallas in 1962 .... I was taken to the room set aside as my laboratory. It was completely bare, and only about 4 metres long and 2.5 metres wide. As I looked at it in horror, I was told – "you will be sharing this laboratory with Professor Hales". Anton and I soon came to an arrangement- we put three tables down each side of the room, with a narrow walking space in between. He had the right hand set of tables, I the left. With great dexterity he avoided being electrocuted by the high voltage power supplies I was building.[96]

Through the Jaeger connection, two ANU seismologists J. R. Cleary and A. H. Doyle also spent extended periods at SCAS as research associates.

When Hales started his seismological work at SCAS, the goal of mantle seismology had been to establish global radial profiles of seismic velocities from which, with certain physical assumptions and other geophysical constraints, it was possible to infer the density and elastic moduli profiles and hence the chemical and mineralogical properties of the planet's deep interior. The dominant models of this epoch were based on the tabulated Jeffreys-Bullen travel times of P and S waves but seismic investigations in various parts of the world were beginning to reveal a need to modify these tables, at least regionally.[97] There had been few systematic attempts to map this variability although other geophysical disciplines were pointing to clear evidence for three-dimensional structure. Hales saw the opportunity to do this both through existing seismic records and designing new field programs with mobile arrays and most of his seismological work during the SCAS years were devoted to this, with focus mainly on the structure of the crust and upper mantle. Soon after his arrival he became aware of the seismic database from the Long Range Seismographic Monitoring (LRSM) program established a few years earlier for analysing seismic signals generated by the USA underground nuclear tests and recognised their potential for studying the regional variations in earthquake-generated seismic travel times. This was achieved with Cleary and Doyle, working respectively on the variation in P and S wave travel time anomalies, work that led to important new insights into the deep structure beneath the North American continent.[98] With C. E. Helsley, Hales participated in multi-institutional experiments at sea including the East Coast onshore/offshore project that involved firing one and five-ton shots offshore the USA Atlantic coast and recorded both on land and at sea that led to improved understanding

[91] Hales (1986).

[92] Hudleston, a co-founder of the Anti-Apartheid Movement, had been recalled to England for fear of his safety but the social welfare movement continued on. A fellow activist during Denise's involvement was Desmond Tutu, a theology student and ordained priest at that time.

[93] L. O. Nicolaysen was appointed as Hales' successor after lengthy considerations including consultations with Jaeger, who was in Johannesburg at the time and who was invited to consider appointment to the position. (Report of selection committee, File Misc.C/209/63, University of Witwatersrand). Nicolaysen directed BPI for the next 30 years successfully building on the foundations laid by Hales.

[94] Ward and Mitterer (1983).

[95] R. W. E. Green had been a PhD student in seismology at Witwatersrand University. J. A. Keiller was the instrument maker at BPI who, amongst his many other contributions, went on to build the mass spectrometer designed by G. H. Riley for Rb/Sr age determination. According to James Hales, Anton greatly admired Keiller for 'his ability to turn conceptions into working scientific instruments'.

[96] Ken McCracken FAA recalls (Letter to Denise on the occasion of Anton's death: 'South Africans and Australians have many things in common. Having been required to do our research on the smell of an oily rag, both were great "scroungers". On one occasion Anton talked me into sharing with him the purchase of a stack of equipment from a decommissioned inter-continental ballistic weapon launching facility in Montana. He had a large room stacked to the ceiling with stuff collected from many such sources, and whenever in need of some unusual widget he would let us hunt through this treasure trove. It seldom failed to yield something that would do the trick.' McCracken also recalled two other characteristics that have later echoes at ANU: 'To fill a wide gap in my education, he provided a list of the appropriate hard liquor for social occasions in Texas' and 'My cosmic ray group and I would frequently be in our laboratory until the wee hours of the morning, and Anton would frequently sidle in about midnight to see what we were doing. He clearly liked talking, in a relaxed manner, with others like me who were mad enough to spend their evenings coaxing their equipment, or calculations, to behave.'

[97] Hales (1979). K. E. Bullen (1906–1976) was a Foundation Fellow of the Australian Academy of Science and early student of Jeffreys.

[98] Cleary and Hales (1966). Doyle and Hales (1967). Some ten years later these papers provided me with valuable information for an early attempt at formally inverting seismic and gravity data for upper mantle structure beneath the continent, work that led to the much more successful solutions by my then student B. A. Romanowicz.

of the crustal structure across the zone of transition from oceanic to continental crust.[99] Another major involvement was his participation in the Early Rise project that involved thirty-eight five-ton chemical explosions fired in Lake Superior (in July 1966) and the recording of the reverberations along profiles radiating out across North America. This led to the discovery of what became known as the 'Hales discontinuity', a rapid increase in P-wave velocity at a depth of 60–100 km, which they interpreted as the mineralogical phase transition from spinel to garnet that had been observed in laboratory experiments in rocks of pyrolite composition at upper mantle temperatures and pressures.[100] Subsequent programs in the western USA and in South America, using explosives as controlled energy sources, prepared the ground for Hales' subsequent work in Australia and possibly also to his first public notice in Canberra.[101] The result was a substantial body of research output on the propagation of seismic waves from crust to inner core in which he identified many of the radial and lateral variations in wave velocities and attenuation that were to find their way into the later global three-dimensional models.

Denise describes the Dallas years as 'an exciting time'. Anton apparently did not believe in holidays and Denise can only account for three short breaks in some forty-five years of marriage that were not work related. But she did participate in many of the field trips around the USA and conferences,[102] accompanied by the four boys. She was there for the Early Rise field work where he celebrated her birthday with a gift of clean nappies for six-week-old Mark but then flooded the cottage basement because he forgot to turn off the tap while talking to his colleagues. Other years the gifts would consist of useful things for the garden, like bags of manure or cement for a pathway. Apparently there was little formal social life around the new centre in Dallas and in consequence most entertainment focused on the Hales residence and their visitor book, recording those who stayed a night or more, families included, is a virtual who's who of geoscience at that time.[103] Visitors included K. E. Bullen, J. C. Jaeger, H. Jeffreys, E. Teller,[104] and a host of visitors, staff and students to SCAS in need of short—and not always so short—term accommodation. James noted that his father saw 'his fellow scientists as extended family.' At this time Anton's own father, in his late eighties and with dementia, had also joined them in Dallas adding to the household confusion. Helsley's description is apt:

> we often met at Anton's home and poured ourselves a scotch and retired to the den for a lively and intense discussion of the latest problem—much to Denise's chagrin. Eventually, she would win and we would emerge and join our wives for dinner and socializing. Even then, most discussions were about work![105]

Early connection with ANU and Australia[106]

In 1952, Professor J. C. (John) Jaeger had been appointed Professor of Geophysics in the Research School of Physical Sciences (RSPhysS) at ANU.[107] Jaeger was, like Hales, an applied mathematician with a special interest in application to earth physics problems and, again like Hales, recognized the opportunities offered by the technological advances wrought by the war, and had set about developing a department that addressed key questions in the earth sciences. This growing department would be quickly recognized as a world player. In October 1953, Jaeger as Professor of Geophysics made the first of his many trips around the world to visit geophysics laboratories and his first stop was South Africa during which he visited Hales in Cape Town. Hales recalled: 'Jaeger and I talked over dinner. We discussed the BPI program, Jaeger remarking that he would not put as much effort into seismology as was the case at the BPI.' From this time onward a long-term correspondence and friendship developed that served both institutions well. Jaeger was to change his mind on the question of seismology at ANU and in 1954 had written to Hales about the possibility of recruiting Phillip Gane, then at BPI, to develop a seismology program at ANU.[108] In 1956, Jaeger was able to borrow seismometers and recording equipment from BPI to record seismic signals generated across the Nullarbor by the Maralinga explosions. A few years later Jaeger again visited South Africa and became aware of the experiment initiated by Hales to monitor earthquakes generated during and after the filling of the Kariba dam in Rhodesia. In this case Jaeger was able to return the earlier favour through a loan of ANU seismometers to BPI, thereby turning an inadequately funded project into a successful one. In 1955, Jaeger had sought support to solve a problem that had arisen at ANU when Cambridge University

[99] Hales and others (1968). Helsley captured Anton well in his letter to Denise in December 2006: 'a chain-smoking individual dressed in a dark suit and wearing a tie, even when he was digging a hole for a seismometer.'

[100] Green and Hales (1968). Green and Ringwood (1967–1968).

[101] When he left Texas his students presented him with a photographic record of his field experiments, including made-up newspaper headlines about running explosives across the US-Mexico border. Later in Canberra this record was left on his car roof and was only returned after it had been handed in to the *Canberra Times* and made its own headlines! Whether this was via the Federal Police was not established.

[102] On one occasion in California, Denise had been introduced to Harold Jeffreys who was not known for his small talk. In desperation she asked him what he did to which he replied 'I taught your husband everything he knows' to which Lady Jeffreys corrected him with 'Rather, Anton was exposed to everything my husband knows'. After that, Denise never attended a social event without Anton first telling her who everybody was.

[103] Visitor Book kept by Denise Hales.

[104] Edward Teller, controversial physicist involved in development of the atomic and hydrogen bombs, ostracized by the scientific community for betraying his colleague J. Robert Oppenheimer, perhaps better known today for his 'freedom through defense' views. Because of furore surrounding his visit to the UTD campus in 1965 he stayed with the Hales' rather than in a hotel (Denise Hales notes). Of interest is that he was one of the early voices warning against the dangers of burning fossil fuel when in 1959, as president of the Sun Oil Company and as a director of the American Petroleum Institute he spelled out to the US oil industry the impact of uncontrolled growth of carbon dioxide emission (Guardian Weekly, 1 January 2018).

[105] Email from C. E. Helsley to Denise Hales, 16 December 2006.

[106] The quotes in this section are mostly from the Hales Notes E.1, *Interaction with John Jaeger*, undated but post 1982.

[107] Paterson (1982).

[108] In a 1971 'History of Seismology in the Department of Geophysics, Jaeger wrote: 'Seismology was begun because someone in Government asked Oliphant to provide a job for (G. de Q.) Robin.'

rejected E. Irving's PhD thesis (Irving had already been accepted for an appointment at ANU). Jaeger was convinced that the appointment should go ahead and asked, should Anton agree, if he could write to ANU. This Anton did, without reservation, as he had been impressed by Irving when he first met him in 1952, reinforced by the 1954 Rome meeting, and by his now full recognition of the importance of Irving's thesis work.

Hales visited Canberra in 1959 where he and Jaeger discussed, amongst many other matters, the geochronology programs that both were attempting to establish at their respective institutions. Jaeger was looking at making several appointments around a small geochronology program within the Radiochemistry Department of RSPhysS. 'He asked', Hales recalled of Jaeger, 'whether, if the director of RSPhysS (M. L. Oliphant, FAA) invited me, could I talk to those concerned and report to Oliphant.' Hales agreed and after the discussions reported the program would be more productive if it were more closely linked to earth sciences. This occurred and the facility moved across to geophysics where it quickly became a world-leading K–Ar dating facility under Ian McDougall. On his return to South Africa, Hales stopped over at Perth where the University of Western Australia had embarked on a geochronology program under the direction of P. Jeffery.[109] One consequence of the visit was that the BPI work in rubidium/strontium age determination became better known and successfully used by the UWA group. Perhaps a more significant consequence was that he was sufficiently impressed with W. Compston to suggest to Jaeger that if he (Jaeger) were serious about developing geochronology research at ANU then he should consider appointing Compston. This happened in 1961, leading to one of the major success stories of scientific research at ANU.

One notable instance in which Hales' advice was not accepted occurred in 1962 when his recommendation 'to the Vice Chancellor making the case for a Research School of Earth Sciences', was denied. ANU established research schools of chemistry and biological sciences, but earth sciences had to wait another decade for its independence from RSPhysS.

Jaeger continued to visit South Africa on most of his round-the-world annual trips, because of his interest in South African deep mines as laboratories for the study of rock mechanics,[110] and because he had distant cousins in South Africa. The strong bond that had developed between Jaeger and Hales must also have been an important element for these visits because, when Hales left South Africa for Dallas, Jaeger visited him there a number of times before abandoning his globetrotting. Both were essentially private people. Both started as applied mathematicians but became involved in experimental geophysics strongly underpinned by mathematical and physical principles. Both liked building things and both enjoyed whisky.[111] Anton wrote that:

> Jaeger's strategy …. was to consult widely on his round the world trips about the fields in which there was a prospect of exciting new developments. Once decided that it was worthwhile to enter some field he consulted equally widely about people to recruit. He talked with those suggested to him and I think had decided whom he would appoint before advertising the post.

He could have been talking about his own strategy. Both were versatile and willing to tackle difficult problems that were not mainstream science at the time. Hales also noted that 'Jaeger said he did not like telling people what to do. Nevertheless he seemed always to get people to do what he wanted.' The same could have been said of Hales.

I have dwelt on the relationship between these two men because it demonstrates the early influence Anton had on the development of geophysics at ANU and that this provided him with both a very deep understanding of the geophysics program at ANU and of the talents of the principal staff such that when he became director of the newly established RSES in1973 it ensured a smooth transition that was at the same time transformative and leading to an institution of growing national and international distinction: something that no other director appointed from outside has been able to achieve since.

Research School of Earth Sciences 1973–8

Appointment as Director RSES[112]

By 1971, Jaeger was in poor health and indicated that he would soon retire. Hales was approached by Ernest Titterton, then Director of RSPhysS, in a letter of 22 October 1971, about whether he would have an interest in the position of head of what had now grown into the Department of Geophysics and Geochemistry within RSPhysS.[113] Anton did not pursue this but it is of interest is that Titterton made no mention of the plans, strongly opposed by him, but that were being widely discussed throughout 1970–1 within the school and at the board level of the Institute of Advanced Studies (IAS), to establish a Research School of Earth Sciences.[114] Despite, and according to some, because of, Titterton's opposition, the creation of the school did proceed this time.[115] After lengthy debate at both BIAS and the ANU Council establishment of RSES was approved, with the proviso for 'the VC to keep the Australian Universities Commission (AUC) informed and to make such

[109] De Laeter (2008).

[110] Together they went down one of the Kimberly mines, once the problem of not finding overalls large enough for Jaeger had been overcome.

[111] Dean Presnall who succeeded Hales at UTD wrote (letter dated 21 November 2006) 'After he left Dallas, I requested his desk, which I have used ever since in my office, …. it is a very ordinary metal desk, the kind of thing Anton would use in order to save every penny of departmental funds for more important things like scientific equipment.' I was more fortunate. I inherited a rather fine Tasmanian Blackwood desk that had passed from Jaeger to Hales and, a few years later my son idly opened one of the small cupboards built into the back of it and found a half-full bottle of Johnny Walker!

[112] A. L. H. notes F (g.1 and g.2), '*The Canberra Years*' and Hales (1986). I received copies of the correspondence referred to in this section from A. L. Hales upon his retirement and from a source who expressed concern that there was a risked they would be shredded. These documents will be included in the Hales papers when properly archived.

[113] Letter from Titterton to Hales October 1971.

[114] Proposal for a Research School of Earth Sciences, March 1970. RSPhysS Paper 2885/1971, The case against the proposal for a Research School of Earth Sciences.

[115] See the informal report of an early Council debate by O. H. K. Spate, Director of the Research School of Pacific Studies at that time. 'Sensible people do not vote for a bad case because its opponent annoys them: but when a reasonable case is opposed as RSES has been by RSPhysS, then in the view of sensible people its cause is strengthened.' (12 November 1971)

submissions as he deems necessary.'[116] There were higher-level hurdles to overcome and the final approval for the establishment of the school was given by the Commonwealth minister in late 1972.[117]

The search for a foundation director began and advice was again sought by the university from Hales on both the development of the proposed research school and the directorship. Hales had made it clear that he himself was not a candidate and argued strongly that A. E. Ringwood, who had largely developed and led the proposal for independence,[118] should become director; despite the former's insistence that he was not a candidate.[119] However, the minutes of the meeting of the appointments committee shows that this committee had not given up hope of recruiting Hales: in a letter, dated 18 September 1972, the vice-chancellor thanked Hales for 'his most helpful' letter and asked 'if there is any possibility of you allowing your name to be considered'. This was followed up by a letter from Jaeger four days later in which he asked this same question and asking whether Ringwood could visit him to discuss the matter. Jaeger noted that, 'Now here we are embarrassed and handicapped by not knowing your age, my guess is that you are about five years younger than me which would put you at around sixty. The normal retiring age here is sixty-five but it can be stretched to sixty-seven'.[120] This meeting in Dallas turned out to be critical. Anton continued to argue that the most suitable candidate was Ringwood himself who responded, 'Look, Anton, I am not becoming Director so that people could say that he fought for the School to become a Director'. Ted Ringwood then began to talk to Denise and to compare life in Dallas with that in Canberra, particularly stressing its nearness to the coast compared to Dallas.[121] 'Denise was hooked and clearly I had to give Canberra serious consideration.'[122] He visited ANU for a week in early January 1973 and during this brief visit he was invigorated by the strength of the existing faculty; able to formulate plans—in discussion with Ken Muirhead—for his own research in seismology; hold a discussion about the potential of ion probe isotope developments, possibly jointly with CSIRO through the intermediary of Glen Riley, who was previously at SCAS and a former student of Compston at UWA; and discuss building and funding requirements with the administration. He was already in command except that, according to Denise, he forgot to discuss his own terms for appointment!

Appointment committees at ANU were efficient in those days and before the week was over Hales had been offered and agreed to take up the appointment to start in June 1973. The formal letter of appointment took a little longer and was accompanied by an embarrassed note from the registrar asking Anton if he could please send a biographical statement since the committee and the university had never seen one. In discussions with the administration and in a letter on 12 February, the vice-chancellor had stressed the constraints placed on expansion of the school by the Federal Government: that the university 'does not intend to seek supplementary capital or recurrent funds in connection with the creation of RSES during the present triennium' and that 'the Government would not wish to see any developments which would pre-empt decisions about the nature and level of Government support of research in these fields,' referring specifically to fluid dynamics, environmental geochemistry, marine geophysics and geology, although 'the Minister fully understands that you would be free, within the funds available in 1973–1975, to make appointments in new fields of the kind we discussed'.[123] With these rather bleak prospects, a man close to retiring age who had already developed two institutions on two different continents could be excused for not accepting the offer, particularly as he was placed under strong pressure by C. H. Green, one of the founders of Texas Instruments and great benefactor to UTD, not to accept the Australian offer.[124]

Again the question: why did he accept? Possibly there is an element of some disenchantment with the University of Texas when he was Acting Vice President for Academic Affairs ('pitchforked into the job') over the appointment of its first President of the University of Texas, Dallas.[125] Possibly after eleven years building a new department and contributing to the founding of a new university in Texas he felt that he had given to the institution what he could. Whatever the reason, Hales, at the age when most people are contemplating retirement, was convinced that ANU represented a new challenge for him. Despite the fact that the 'Director's salary was about half of my US salary' and Crawford's gloomy budget prospects, he accepted the position, arguing to himself 'I did not think that the ANU Council would have accepted the Council Committee proposal for a RSES …. clearly hoping for the appointment of senior people (to lead the new groups) … without expecting

116 Report by Sir Frederick White, Chairman of the Advisory Committee to advice ANU Council on the broad fields of study for the new School.

117 On 31 May 1972 the ANU Vice-Chancellor, Professor John Crawford, had written to the then Minister for Education, Malcolm Fraser, about establishing RSES. In his reply, the Minister endorsed the view of the Australian Universities Commission 'that it does not favour the concentration of the development of national research schools in the one institution' and concluded 'I suggest that the University refrain from entering into any commitments in respect of the new School'. (Letter J. M. Fraser to J. Crawford, 23 August, 1972). The change in Government later in 1972 led to more encouraging news, with the new minister, Kim Beazley writing that the 'Government has noted with approval the University's decision to establish the RSES' and that 'The University should not regard itself as constrained by the terms of Mr Malcolm Fraser's letter' although it did come with the proviso that 'at this stage this decision is one of internal reorganisation' within the ANU's Institute of Advanced Studies, a clause that was to stymie early growth of the School (Letter K. E. Beazley to J. Crawford, 8 Feb. 1973).

118 Letter to the Vice-Chancellor J. Crawford, received 31 October 1972.

119 Letter from A. E. Ringwood to Vice-Chancellor, 12 July 1972. Director of RSES Electoral committee meeting, 8 January 1972.

120 Letter from Jaeger, 22 September 1972. Hales would be 62 when he took up the appointment

121 Ted Ringwood was later to use this approach at least twice, but now as a joint force with Anton, in attracting senior staff to the new School.

122 Hales Notes g.1.

123 Letter from Vice-Chancellor Sir John Crawford to Hales, 12 February 1973.

124 Letter from C. H. Green to Hales, 7 February 1973. He wrote 'I am, of course, most anxious to advise that I am very unhappy to even contemplate the possible idea of your leaving UTD … and please understand that I would not be a good friend if I did not at least voice my opinion in the matter.' On 6 June 1977 he wrote 'I am certainly glad to have your assurance, by your good letter of 23 May, that …(you are) …. beginning to look forward to the trek back here to the U.S.'.

125 Letter from Hales to Chancellor of UTD, 22 January 1971, and his file notes of 24 January 1971.

to provide funds for the development.' He arrived in June 1973, having left Denise behind in Dallas—with two small boys, Mark, born in March 1963 and Colin in November 1964; the two older boys, James and Peter from the earlier marriage, having decided to stay in the USA—to pack and sell the house. She arrived in Canberra in late October of that year.[126]

Directorship RSES 1973–8

So, in 1973, Anton began his third adventure. He recognized the challenges of making new appointments, of the necessary future building program to go with this expansion,[127] and of the importance of continuing the strong experimental programs upon which the emerging school's reputation rested. He remained optimistic throughout, constantly reminding all in chancellery and on council of the unwritten promise that RSES would be allowed to grow to the scale of the Research Schools of Chemistry and Biological Sciences. Of importance was that from his long interactions with Jaeger he had an intimate knowledge of, and confidence in, the research carried out by the senior staff so that he could provide wisdom and direct resources when and where required without causing major ructions within the school. Once in Canberra Anton set about to fill the chairs identified in the RSES plan. In so doing he told the faculty board that 'we would not be able to find candidates for the new programs with greater international reputation than some of the faculty and (that RSES) would have to offer higher academic ranking than some of them had.' This was accepted with one exception: the first appointment was to be in environmental geochemistry for which there was an outstanding young candidate but faculty board recommended that the appointment should be as professorial fellow as he was too young at thirty-five to be appointed professor.[128] Instead, the chairs in economic geology (L. B. Gustafson) and geophysical fluid dynamics (J. S. (Stewart) Turner) were filled in 1975, and the geophysics chair (myself, in 1977) vacated by John Jaeger.[129] Hales' great disappointment was that he could not attract a good seismologist to the school for this position and I looked after seismology when he retired. He was delighted when B. L .N. Kennett was appointed seven years later as a professorial fellow. In making these appointments Hales was a strong supporter of a non-departmental structure for the school such that the science would not be contained within the traditional boundaries and was looking for people with like minds. This led, for example, to the innovative collaboration between Turner and Gustafson, with Anton's strong encouragement, on the role of double diffusive processes in mineralization.[130]

Following Jaeger, and his own experience at BPI, Hales encouraged in-house instrumental developments that would lead to front-line research in areas not accessible with off-the-shelf equipment. Most notably he made it possible for Compston to develop the ion microprobe 'SHRIMP'.[131] This particular development was illustrative of his style and of the period. He had recognised the potential of this high-risk project for both basic and applied research but recognised that the then IAS environment was one of the few places in the world where this could be attempted.[132] Despite some internal opposition and international un-asked for advice that the project was ill-advised, he directed the necessary resources from within RSES without requiring further detailed proposals and reviews.[133] Early results, showing that cores of zircons had ages greater than that of the granites from which this mineral was extracted, as well as the determination of the oldest terrestrial material, with zircon ages of 4.2 billion year old metamorphosed sandstones from Mt Narryer in Western Australia,[134] vindicated Hales in his conviction that this project would succeed. It is hard to see how this very major, and not without very considerable risk, instrument development would have fared once the Institute for Advanced Studies at ANU lost its block funding some fifteen years later.

Hales' research at ANU

Seismology

Despite Jaeger's initial reluctance to start a research program in seismology, this did occur as a result of several special circumstances: a request in the mid-1950s to monitor seismic activity in the Snowy Mountains during and after major dam constructions; an

[126] When the packing started and unbeknown to Anton, Ken McCracken arrived with a king-size bed and asked if that could be included in the container (along with a 'strange shaped object covered in brown paper that Denise thinks was the hatch of one of the American space capsules'). Hearing about this, Glen Riley thought it a good idea and a second such mattress arrived. This left quite an impression with the workshop staff who had offered to unpack the container upon arrival: they still talked about it four years later when I arrived.

[127] Expansion of the workshop facilities and plans for laboratory and office space that would be required for the anticipated expansion of the School but that did not materialize, and then in disjointed stages, until decades later.

[128] Fortunately, no one seemed to have remembered this when it came to the appointment of the Professor of Geophysics a few years later.

[129] The process used is illustrated by my own appointment. Hales, whom I had only seen from the distance some five or six years earlier, passed through Paris on his way to the 1975 IUGG meeting in Grenoble and sought me out. Ted Ringwood had apparently learned earlier from Caltech about this Australian in Paris who was in discussions with the Harvard-Smithsonian Observatories about an appointment there and he had suggested to Anton that he make a stop-over in Paris. We discussed what I had been working on—satellite orbit analysis, atmospheric excitation of the Earth's rotation, tides, and tidal evolution of the earth-moon system—and left it at that. A month or so later, Ted Ringwood, who, likewise, I had only seen from a distance, also came through Paris, and we had some general discussions about my research that ended with an invitation to spend some time at ANU the following year, with the argument that as I was going to Harvard I should probably return to Australia for a couple of months. This I did in 1976 but before I left Canberra to return to Paris I had been interviewed and proposed for the Chair of Geophysics.

[130] Turner and Gustafson (1978).

[131] Sensitive high-resolution ion microprobe. A history of isotope geology at the ANU has been written by McDougall (2008) and of the SHRIMP by Ireland and others (2008).

[132] This was not based merely on faith, but on Compston's track record of previously directing the design and construction of one the most sensitive mass spectrometers then in existence, that was used among other applications for dating Moon rocks.

[133] Hales had recognized that pushing for a joint project with CSIRO would not be well received within the School and did not pursue this avenue further. Once the project was well advanced and had passed some of the critical stages, the Bureau of Mineral Resources (now Geoscience Australia) under the direction of R. Rutland did provide support for software development.

[134] RSES Annual Report, 1982.

opportunity offered by the first Maralinga nuclear explosion in 1956 for a large-scale controlled source seismology study of the deep crust of Australia; and a request from the UK in 1965 to establish a seismic facility for monitoring underground explosions.[135] The last, the Warramunga seismic array (WRA) outside of Tennant Creek—in addition to its monitoring function—had been seen as an attractive option for the scientific exploration of the mantle beneath the Australian continent using the earthquakes to the north and east of Australia as energy sources.

When Hales arrived in Canberra, the seismology group was small, consisting of J. R. Cleary and K. J. Muirhead with Australian-data sources collected from WRA and a number of field recording systems built by Muirhead with encouragement from Jaeger. Hales found an array that operated at less than half efficiency because of a combination of climate conditions, lightning and termites,[136] and with limited computer capability for data analysis. While there was another seismic array outside Alice Springs, operated by the USA Air Force, data from which was not generally available for scientific research, Anton thought that it be desirable that 'some country other than the US' should be involved. No doubt motivated by the recognition that the array could reveal finer details of the velocity distributions within the mantle, new arrangements with the UK were set up in late 1973, and updated in 1976.[137] RSES took a more proactive role in this upgrade to ensure reliable access to the records for scientific purposes, leading to improved transmission of the seismic signals from the individual instruments to the central recording system, installation of a computer for partial on-site data processing, changing from analog to digital recording, new power generators, and the inclusion of horizontal seismometers, all with a firm limit placed on the RSES contribution to costs. With these upgrades the first new results for the structure of the mantle beneath the Australian continent followed, including the detection of discontinuities in seismic velocities below 650 km and that the discontinuities above this depth were relatively sharp.[138]

These seismic studies also revealed the limitations of fixed array data when the source locations are pre-determined by the earthquake distributions, such that for sampling the entire mantle beneath the continent the field program would have to be complemented with mobile arrays. This had been anticipated by Hales who had arrived with a number of the recorders developed in Dallas, and it had been discussed with Muirhead during the January 1973 visit. The practical requirements of these recorders, analog and recording on slow-running magnetic tape, was that they could operate remotely for long periods of time (up to several months) without mains power. Muirhead recognized quickly that the bulky and power-hungry Dallas instruments—requiring wet-cell batteries that could not be transported by air—were not a solution for field work in remote areas and re-engineered the electronics for subsequent mobile array studies. The first profile was in the Northern Territory and closer to the earthquakes originating below the Banda Sea with subsequent profiles covering many parts of the country, including the southern part of the Northern Territory, northern Western Australia, Queensland, and New South Wales, all at different distances from the source regions. All results showed significant velocity departures from the Jeffreys-Bullen travel times over all distances.[139] Through a conjunction of otherwise separate events and Hales' good connections with USA institutions—a joint Woods Hole, Scripps and Indonesian Geological Survey and supply support provided by the area by Australia's Departments of National Mapping and Transport—the first experiments were conducted in the Arafura Sea, with in-house-constructed shallow-water ocean-bottom recorders close to the earthquake source area to provide improved control on both the source locations and seismic structure in the source region.[140] The computing problem at RSES was resolved with a Datacraft /4, the purchase of which caused some concerns with an ANU administration that did not favour computers outside of its central facility and that looked askance at a machine that would be the only one of its kind in Australia. But Hales prevailed and 'with a full set of maintenance documentation and several sets of every type of integrated circuit' it was kept going throughout his time at RSES. Muirhead noted that 'just by listening to people I am sure Anton knew more about computers than I, even though he had never been near one and I had been using them ever since graduating',[141] a reflection equally true of much of Anton's other work.

The array results with the identification of an increasing number of discontinuities in seismic velocities at depth, together with his earlier experience in the USA, convinced Hales that the standard Jeffreys-Bullen model was not adequate for representing the upper mantle for both ocean and continental regions and that there was a need to develop new reference models separately for the two type-regions.[142] Early models were developed in collaboration with

[135] The UK Atomic Weapons Establishment. It had set up a group 'outside the fence' with the task of developing methods of detecting and identifying underground nuclear explosions.

[136] Hales, A. L. History of the Warramunga Seismic Array Station, report dated 8 July 1976. The cable used at WRA had been tested for termite resistance by burying a drum of cable in a termite nest and no damage was found after one year. Thinking that the damage must be cause by lightning strikes Muirhead took a section of damaged cable to the Telecom engineering office and told them about the Blacknest experiment. 'They just laughed and said that it was termite damage and that there were at least one hundred different varieties in the Northern Territory' (K. J. Muirhead notes, 5 March 2018).

[137] Letter from NERC (UK) to Director, RSES, 8 November 1976.

[138] Datt and Muirhead (1976). Muirhead and Hales (1980).

[139] Hales and others (1975). Muirhead and Hales (1980). Hales and others (1980). A feature of these field programs was that the next one started before the previous one was fully analysed by students and research fellows with the result that the publications mostly occurred much later.

[140] Rynn and Reid (1983). It also led to one of the rare occasions where I witnessed Anton losing his temper. As his retirement date approached the young staff that he had recruited tended to discuss with me their future plans and one of them raised the question of developing improved ocean bottom seismic recorders. I raised this possibility with the workshop staff to get some idea of what may be involved in such a venture. Within an hour Anton stormed into my office with, 'You too think that I have one foot in the grave!' and gave me a dressing down that I was not to interfere with his program. I did not consider it wise to ask who the other person was who may have thought this, but I did go home for a swim to cool off whereas he continued on as if nothing had passed between us.

[141] K. J. Muirhead notes, 5 March 2018.

[142] Hales (1974*a*). Hales (1974*b*).

A. M. Dziewonski and E. R. Lapwood, both visitors at RSES, and published in 1975,[143] and were the forerunner of the more comprehensive and influential Preliminary Earth Reference Model published by Dziewonski and Anderson in 1981.[144] Another game-changing outcome of this collaboration at ANU was the use of travel time data for the first attempt at a full three-dimensional model for the global mantle:

> After dinner we sat down and talked about this until one or two am (at which point) I had agreed that it was worth trying. I called … [the deputy director of the International Seismological Centre] and said that Adam would send him a Harvard order for copies of the tapes… (who) agreed that the order would be accepted.[145]

The five years of mobile array studies produced a vast amount of data whose analysis took much longer and was never entirely completed, because Hales took all records from the modified Dallas recorders back to Dallas when he left RSES in 1978. Muirhead, instead, focused on building new generations of digital recording systems that formed the basis of a new and much-expanded field program under Kennett that made it possible for the first time to examine in detail the 3-D structure of the Australian mantle and that led to the realisation that some of the previously identified layering was a consequence of mapping three-dimensional structure into a one-dimensional framework.[146]

Infrasonics

Infrasonic research (the study of sound waves below the frequencies of audible sound) at RSES began in 1973 under circumstances that are typical of Hales' 'modus operandi'. During a return visit to Dallas, soon after taking up the RSES Directorship, he was invited to an unspecified lunch in Washington that turned out to be with an assistant secretary of the Air Force to discuss a politically embarrassing situation that had arisen over the Whitlam Government being under pressure to reduce the number of US installations in Australia. The Australian Government had been advised by its Department of Defence that these installations provided data that were of use to Australia and cited an infrasonic array in Queensland as an example,[147] and Whitlam had used that example in a reply to a question in Parliament. But simultaneously the USA had signalled that they were closing this installation and Hales was asked whether ANU would take it over. Hales replied that in theory as director, 'he could do anything he thought worthwhile but that in practice a wise director would want to be sure that there was an interesting bit of science that could be done with it.' While in Dallas he discussed possibilities with his colleagues, one of whom mentioned a recent observation at a similar infrasonic array in Colorado of unusual waves believed to have been generated by a thunderstorm. This was sufficient for Hales to agree to take over the system subject to agreement with chancellery at ANU. This was reached and with US Air Force support the array was moved to the site of the Warramunga array and a research assistant, D. R. Christie, was appointed to make it work. By 1976, it was operating and led almost immediately to the discovery of unusual large-amplitude long-period waves of which there was nothing similar in the literature. Christie came to the conclusion that they must be solitary waves, but that they were not generated by thunderstorm activity.[148] Rather, it became recognized that they were generated over the upper Cape York Peninsula some 1800 km from the array and associated with the spectacular 'Morning Glory' cloud formations over the Gulf of Carpentaria.[149] Also, it was quickly recognized that because of the combination of high wind shear, their often 'clear air' nature, and travelling for the most part close to the surface, they posed risks for aviation during landing and take-off.[150] As Hales remarked years later 'the Pentagon lunch in 1973 had its consequences.'

International

Already in South Africa Hales had recognized the importance of multi- and international programs as a way of reaching outcomes that, especially for economically small countries, could not otherwise be achieved. He learnt this lesson particularly through involvement in joint marine and Antarctic projects, and he continued to be actively involved in international programs throughout his subsequent scientific career. During his Canberra years he was a member of three significant international organizations: the Inter-Union Geodynamics Commission Bureau, the International Association for Seismology and Physics of the Earth, and the International Seismological Center. He played a leading role in their restructuring in all three cases, creating strong and effective bodies that influenced national and international programs in geophysics and geology. Of the three, his role in the Geodynamics Commission was arguably the most important. This was a ten-year program, from 1970–80, established under the International Council of Scientific Unions (ICSU) and directed at understanding both the kinematics of the major tectonic plate movements and the dynamics of the processes driving these plates. Hales became its second president (1975–80), for the latter half of its scheduled lifetime by which time the kinematics of the plate motions were well understood

[143] Dziewonski and others (1975). This involved large computer runs that were only possibly after 10.30 PM. That was all right with Dziewonski who would work through the night to emerge at lunch the next day but not for Anton who would be back in his office at 8.30 next morning.

[144] Dziewonski and Anderson (1981). This paper as well as that by Dziewonski and others (1977), cited in following footnote, acknowledge fully the influence of Hales in these studies.

[145] Hales notes g.2; Dziewonski and others (1977).

[146] Kennett and Bowman (1990).

[147] For monitoring atmospheric explosions.

[148] Christie and others (1978). Christie and others (1979).

[149] Later, with additional pressure sensors obtained from the abandoned US infrasonic program, Christie was able to substantiate this inference by tracking these waves, often devoid of the tell-tale cloud formations, from the gulf of Carpentaria to WRA halfway across the Australian continent.

[150] Christie and Muirhead (1983).

although this could not be said of the dynamics.[151] He realized that the only way to continue the successful international cooperation was to direct its focus more at the underlying processes as well as to change its name. With strong support from the American Geophysical Union (AGU) this was successfully established by ICSU in 1980 as the International Lithosphere Program. The legacy of the Geodynamics Commission and of Hales' contributions is the Geodynamics Series of volumes published by the AGU under his chairmanship of the editorial board.

'Retirement'

Anton Hales, having passed the then obligatory retirement age at an Australian university, stepped down from RSES and ANU in 1978, an event that was marked by the launch of the book, *The Earth, Its Origin, Structure and Evolution*, in honour of both the founding head of the Department of Geophysics, J. C. Jaeger, and the Foundation Director of the Research School of Earth Sciences, A. L. Hales.[152] Written entirely by ANU present and former staff it covered the spectrum of the solid earth sciences and reflected the depth of the research capacity built up by these two men within less than thirty years. Anton, however, clearly was not ready to retire and returned to the USA while maintaining his family home in Canberra: first as Fairchild Scholar at California Institute of Technology, followed by UTD as Professor of Geophysics until 1982. At this point he returned to ANU as visiting fellow. His retirement from UTD was marked by a symposium *Some Recent Advances in Geophysics* with a number of the papers published in a special volume of the *Journal of Geophysical Research*. The two 'retirement' volumes are a fitting memorial to the influence Hales had on the developments in earth sciences over the best part of half a century.[153]

Scientifically Hales remained active for another decade, participating fully in scientific discussions at a time when academic life became increasingly pre-occupied with bureaucratic matters and he became a valuable guide to many of the staff and students. In the years following his retirement from ANU he never interfered in the direction of the school but was always willing to discuss such matters when asked and during my directorate he was a source of experience, history and wisdom. His penultimate publications were in 1992 and 1997. The former was published in the *Journal of Geodynamics* of which he was the foundation editor in chief in 1984.[154] Hales was a strong supporter of journals such as this that complemented the higher-profile earth science journals as a vehicle for broader interdisciplinary research that may not be mainstream, and it was appropriate that this paper was published in this journal. It marks the transformation of a mathematician to a complete Earth scientist who is willing to speculate on the interpretations of geophysical and geochemical data to try to steer debate on important geological questions into different directions. As he noted in his acknowledgements, 'I hesitate to suggest that my colleagues share any, much less all, of the views expressed in this paper', but it is one paper that I believe all earth scientists can read with profit.[155] A full bibliography of Hales' publications is available as Supplementary Material to this biographical memoir.

The great energy that remained with him went into establishing a new family house and garden on a bush block in Wamboin outside of Canberra, built by himself with Colin and Mark (the latter during weekends), from foundations to roofing. He was very proud of this achievement, particularly when the building inspector praised the quality of his work. As could have been anticipated, this was not without its' own wealth of stories. My favourite is when Denise went onto the roof to clear the leaf litter in the gutters and he tidily put the ladder in the shed and went inside to watch TV, only to wonder some considerable time later why he had not received his afternoon tea! He loved roses and planted up to 300 different varieties, much to the delight of the local possums. He also loved dogs, something he had shared with both Marjorie and Denise. At Wamboin they had up to six dogs at one time and, according to Denise, there was always a dog on the end of his bed.

Summary

To summarize Professor Anton Hales' career in a few paragraphs is impossible. This biographical memoir is hardly more than a synopsis of a near-century in which major advances occurred in the earth sciences at each critical step of which one can see his influence through his personal and leadership contributions. He was, at least to the outside world, a private man almost totally dedicated to his work, perhaps with the one or two exceptions of gardens and animals. He would rarely discuss political or social issues and, whether on a late Friday afternoon, or helping him round-up his ducks at his Wamboin property, he would invariably turn any comments or questions on such issues back to science-related topics. He was concerned about protecting his reputation, but in the notes written in his retirement years he revealed a remarkably detailed, frank and sometimes self-critical account of his earlier days that suggest that his early prowess in history remained with him. He could on occasion lose his temper but this dissipated as quickly as it arose with perhaps the exception of when it was directed at bureaucrats whose dictates were not consistent with running an efficient and creative institution. He would be appalled at the changes that have occurred in institutional direction and management since his final retirement. As a scientist, his work demonstrated the power of the combination of mathematics and physics when this is combined with a natural curiosity about geological processes and the ability to absorb and understand knowledge from a range of fields. He recognized critical questions and found solutions commensurate with the tools and materials available at the time. His role as leader is evinced by his direction of three institutions, in quite different circumstances, building each up to high

[151] To suggest that this situation is not so different from that Hales found himself in the pre-war period—with increasingly compelling observational evidence but an absence of a compelling mechanism—is not wholly justified. The observational evidence is now quantified beyond doubt by the geodetic evidence, and the understanding of the mantle rheology, the convective processes in the mantle and its interaction with the lithosphere is now at a level where predictive modelling of the motions becomes possible.

[152] McElhinny (1979). The actual publication date was 1979 but a page-proof was used for the occasion.

[153] Ward and Mitterer (1983).

[154] Hales (1992).

[155] His last paper, 'The Anelasticity of the Earth; how much do we know about Q?' was published in 1997. Hales (1997).

international profiles, as well as by his international roles at critical junctions. The influence of his personal leadership in institution building as well as the impact of his direct and indirect input into the development of modern geophysics in areas beyond his immediate personal research interests, have not often been matched. As a mentor, he influenced his peers and shaped following generations, generous to the end in helping others in their scientific journeys. One of his strength was to get the best out of the technical staff. As James Hales has noted, 'My Dad loved to build physical things himself but I think he realized that there were others better at that sort of thing than himself'. As a husband, this assessment is best left to Denise, but I would sum it up by 'he was fortunate to have enjoyed two very loyal women in his life who did not abandon him when he abandoned them on his long field and overseas excursions or his long nights in the lab.' As a father, James notes 'he pretty well left us to our own devices without pressure of any sort… Notwithstanding a light-handed approach to parenting he came through when required with various projects: science fairs, cub-scout projects, costumes for fancy dress parties and the like. But for the most part he left things up to you'.

Anton Linder Hales died on 11 December 2006 in Queanbeyan. He is survived by Denise Lynne Hales (née Adcock); his sons, James Andrew, Peter John, and Colin Adcock; and his grandchildren Peter, Michael, Megan, Brendan, James, Oscar, and Hayley. His fourth son, Mark Anton Hales, died in May 2004.

Conflicts of interest

The author declares no conflicts of interest.

Referencing of Hales' notes

Professor Hales started writing these notes after he returned from Dallas in 1982 and primarily after about 1990. The majority are undated but an approximate chronology can be established from the declining hand writing. As a result, there is considerable overlap and repetition that I have not, at this stage, edited. These notes, together with copies of correspondence or other non-readily available material to which I have made reference, will be held in the Australian Academy of Science archives, as will be the five 'Pen Carbon' books (cross referenced to as IA, IB etc.) that cover the period December 1959 to January 1961, a near as possible complete bibliography of his published papers, and the notes I received from Denise Hales. The provisional referencing that I have used for his notes is the following:

A. *Early and Family History*

a.1 Answers to (grandson) Peter's questions (15 October 1990). (Includes notes on his undergraduate days at UCT and the war years)
a.2 Letter to James and Peter (sons). (Notes on their mother)
a.3 Family history (February 1999). Covers the period up to about 1921
a.4 More Family history (2) (undated but probably post a.3). (Covers similar ground to a.3 but extends to his undergraduate years at CTU, his Cambridge years, and early appointments at Witts and CTU up to the time of his BPI appointment.)
a.5 Family History (mainly up to 1923)
a.6 Family History 1954–1962 (but including notes on his move to Dallas and ANU appointment).

B. *University of the Witswatersrand 1933–40*
C. *The War Years 1940–5*
D. *The Cape Town years 1949–54*
E. *The BPI Years 1937–62*

e.1 The Bernard Price Institute of geophysical Research Years
e.2 Curriculum Vita (Background Materials 1927–62)
e.3 A glimpse into the fifties—Selwyn Sacks' PhD project
f.1 Interaction with John Jaeger
f.2 The campaign for a Research School of Earth Sciences

F. *Early Interaction with ANU*

f.1 Part I
f.2 Part II

G. *The Canberra years*

g.1 Part 1
g.2 Part II

H. *Miscellaneous*

h.1 Additional note on time at UTC 1929–30
h.2 Additional notes on time in England in 1931–3
h.3 Additional note on early link with Jaeger and ANU
h.4 File note of 24 January 1971: Events of January, 1971, dealing with the appointment of President of the to be formed UTD
h.5 Note on 'Crustal Growth and Granites' that provides insight into the 1992 paper about crustal evolution (see footnote 149)

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Anton and Denise for as long as I have, and H. McQueen have carefully read the manuscript and modified at least some of my grammatical constructs. I thank them all for their inputs. Finally, Denise and James have read the final manuscript and picked up, what I hope, are any final inaccuracies.

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