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BY R.W. OGDEN, F.R.S.

School of Mathematics and Statistics, University of Glasgow, University Place, Glasgow G12 8SQ

Peter Chadwick studied mathematics as an undergraduate at the University of Manchester, graduating with first-class honours in 1952, from where he moved to Cambridge and completed a PhD in the Department of Geodesy and Geophysics under the supervision of Dr Robert Stoneley on the thermal history of the Earth. His research then developed to focus primarily on the propagation of waves, and he made a major contribution to the mathematical theory of elastic wave propagation and became a world-leading authority in this area. He also made fundamental advances in the modelling of the thermoelastic properties of rubberlike materials. At the University of East Anglia, where he was a professor for 26 years, he was the driving force behind the development of a research group in theoretical mechanics in the School of Mathematics and Physics, leading by example and supporting and encouraging fellow faculty members, especially the younger staff, academic visitors and students. He gave considerable service to the University of East Anglia in a number of capacities, including a period as Dean of the School, and to the scientific community, through substantial journal editorial activities and as a member of several national and international committees.

EARLY YEARS

Peter Chadwick was born on 23 March 1931 in Huddersfield, Yorkshire, the only child of Jack Chadwick (1905–1991) and Marjorie Chadwick, née Castle (1910–1982). His parents both worked in the textile industry, his father as a loom tuner in the woollen mills and his mother, first in her parents' tailoring business and later as a power loom weaver in the woollen industry. Peter described his childhood as happy and secure with a comfortable home and he was lovingly cared for and encouraged by his parents and other close relatives. Peter's mother, who herself had a grammar school education before leaving school early to work for her parents, realised the importance of education and encouraged him in his studies throughout her life. Peter attended the local primary council school in Moldgreen (a district of Huddersfield) from 1936 to 1942, and then, from 1942 to 1949, was educated at Huddersfield College, which was at that time the premier boys' grammar school in Huddersfield. Peter described both schools as being excellent.

At Huddersfield College he made good progress and his preferences for mathematics and physics were evident at an early stage. There he had the good fortune to be taught by an outstanding mathematics teacher, a Cambridge Wrangler, Mr. Leslie Horsfall, two of whose other pupils went on to become Fellows of the Royal Society. Mr. Horsfall was an inspiration for Peter and had considerable influence on his academic development. He encouraged Peter to aim for a place at a good university and his parents were supportive of this ambition. He was awarded a Major Scholarship by the County Borough of Huddersfield for his sixth form years and the Ward Prize for service to the school. In later years, Peter felt very strongly that the State education system that benefited him so much had been replaced by one that fails children from working class backgrounds such as himself.

Outside his academic studies Peter was involved in a variety of activities, including scouting with a strong outdoor orientation, and, at school, the music and science societies, and he was secretary of the latter for a period.

UNDERGRADUATE STUDIES AT MANCHESTER, 1949–1952

In 1949 Peter was awarded a State Scholarship on the basis of his Higher School Certificate results and had earlier taken the Open Scholarship examination at the University of Manchester, as a result of which he was awarded a scholarship tenable at Hulme Hall, a hall of residence of the university, and a place in the Department of Mathematics. Peter studied pure and applied mathematics and subsidiary physics, both theoretical and practical, and subsidiary statistics in his first two years, and then specialized in applied mathematics in his final year, graduating in 1952 with a first-class degree in mathematics.

Peter recalled that his undergraduate years in Manchester were highly enjoyable and stimulating. In those post-war years the Department of Mathematics at Manchester was probably as strong as any in the UK and most of the staff already had or went on to have distinguished careers, including several who were either Fellows of the Royal Society or subsequently elected as such.

PHD RESEARCH AT CAMBRIDGE, 1952–1955

During his final year in Manchester Peter became increasingly attracted to the idea of postgraduate work and he applied for a studentship in the Department of Geodesy and Geophysics at the University of Cambridge. Although he didn't gain the studentship, he was nevertheless admitted as a PhD candidate, working under the supervision of Dr R. Stoneley (F.R.S. 1935), Reader in Theoretical Geophysics, and was also given a place in Stoneley's college, Pembroke. Peter was supported by his State Scholarship, which was extended for three years, and he was able to supplement it by giving supervisions in mathematics.

Stoneley's research field was theoretical seismology and he also made important contributions to elastic wave theory, subsequently one of Peter's major interests. Indeed, Peter's research has impinged on several aspects of Stoneley's classical work on elastic wave propagation. However, at that time Stoneley's choice of project for Peter was a study of the Earth's thermal history. Stoneley was unfailingly kind and supportive, but by and large Peter was left to find his own way. It may be argued that research students who are lightly supervised acquire confidence and independence, but the experiences can be difficult and demoralising, and this was so for Peter. In his final year, to his surprise, Peter was asked by the Head of Department to take charge of an experiment, a determination of the thermal flux in a borehole that had been drilled near the laboratories at Madingley Rise. The drilling had been beset by various problems that had a significant impact on the analysis of data, particularly the temperature readings. The result Peter obtained in his first publication (1)*, seemed somewhat conjectural at the time, but it was confirmed by a later measurement. His theoretical work was concerned mainly with the conduction of heat and the accompanying deformation in idealised models of the earth. It took him over a year after leaving Cambridge to put together a satisfactory thesis, the title of which was "Some studies on the thermal state of the earth" and was approved for the PhD in January 1957.

Before he left Cambridge it had become clear to Peter that he was not suited to a career in geophysical research. He felt that his postgraduate studies might have been more fruitful if he had followed up his undergraduate specialism in applied mathematics. In retrospect, however, he considered that this first research experience was extremely valuable. He gained expertise in the earth sciences and extended his knowledge of applied mathematics and theoretical physics by attending advanced lecture courses, as well as making useful contacts and gaining some teaching experience. His years in Cambridge certainly stood him in good stead for his later career. There were also many non-scientific benefits, by far the greatest of which was meeting his future wife, who was a teacher training student at Homerton College.

ALDERMASTON, 1955–1959

Early in 1955 at the Atomic Weapons Research Establishment at Aldermaston (AWRE) in Berkshire, Dr H.R. Hulme was seeking staff for the Physics Division. After a meeting between Hulme and Stoneley in Cambridge, Peter was interviewed and appointed as a Scientific Officer at AWRE. He started work there in the following summer and joined a group directed by E.P. Hicks that was studying the effects of explosions. The two years spent in this group saw a return to the level of scientific stimulus that he had enjoyed in Manchester, and it was then that his research career really began.

The main project on which he was engaged was an analysis of the ground motion produced by a confined conventional explosion. To gain familiarity with the mathematical theory of plasticity that was needed for this analysis he attended a graduate course at King's College, London, while In-house training was provided in the use of the Division's powerful (at that time) IBM computer. Peter also benefited greatly from a collaboration with a research group at the Armaments Research and Development Establishment at Fort Halstead. Much of this research was unclassified and later resulted in several publications.

In the course of his work at AWRE he met colleagues who were to become long-time friends, including I.N. Sneddon (F.R.S. 1982), who was a consultant to AWRE and recently appointed Professor of Mathematics at the University of Glasgow; contacts at Fort Halstead included L.W. Morland, who later became a colleague at the University of East Anglia (UEA). Peter and Sneddon collaborated on a study of harmonic wave propagation in an isotropic heat-conducting elastic material (2) which had points of mathematical similarity with work that he had carried out in Cambridge. Sneddon then invited Peter to write a review article on the dynamical theory of thermoelasticity, and he worked on this in his spare time; it was published in 1960 after he had left AWRE (3).

*Numbers in this form refer to the bibliography at the end of the text.

In 1957 he was promoted to Senior Scientific Officer and, to his regret, moved from Hicks's group to research on weapons design. This was top secret work at the time, but a detailed account is now available in the open literature in Lorna Arnold's book "Britain and the H-bomb" (Palgrave, Basingstoke, 2001). Peter remained at AWRE until September 1959, the final year being a particularly interesting period since, as described in Chapter 14 of Arnold's book, it saw the resumption of collaboration with the USA on matters concerning the design of nuclear weapons.

Peter's interests had evolved from geophysics to theoretical solid mechanics, and his former colleagues from AWRE and Fort Halstead had a decisive influence on his future career path, and they all went on later to occupy senior positions in British universities.

Peter came to believe that his contributions to the project at AWRE would never match the quality of his earlier work, and he considered that the researches in dynamical plasticity and thermoelasticity initiated during his first two years at AWRE had further potential. For these reasons, and because he had an interest in the presentation and teaching of mathematics, he decided to seek an academic post. In the summer of 1959 he was appointed to a Lectureship in Applied Mathematics at the University of Sheffield and took up his duties there in the following October.

SHEFFIELD, 1959–1965

In Sheffield there was little active research interest in theoretical solid mechanics. This did not unduly worry Peter because he interacted with former colleagues at AWRE and Fort Halstead who had also moved into university posts. He also came to know and profit from the advice of senior figures in the field, notably Professor A.E. Green (F.R.S. 1958), then at the University of Newcastle upon Tyne. Peter spent six productive years in Sheffield and was promoted to Senior Lecturer in 1964. His research was mainly concerned with developments in dynamical plasticity (4) and linear thermoelasticity, for example (5, 6), that he had in mind on leaving AWRE. He also worked on a problem in linear elastodynamics involving the wave fields generated by motions of a spherical inclusion (7, 8). Alongside the specific projects in linear thermoelasticity, he began to study the nonlinear theory and, more widely, the important advances in general continuum mechanics which were being made at that time. In Sheffield, he supervised one PhD student and two MSc students. In 1964 two other students started their PhDs under Peter's supervision but then transferred to the University of East Anglia when Peter moved there in 1965.

Peter's teaching at Sheffield was principally in the areas of mathematical methods and theoretical mechanics. The Department of Applied Mathematics had a major commitment to service teaching, directed largely to engineering and applied science students. Consequently, quite a large proportion of his teaching consisted of service courses. He had some departmental responsibilities in connection with examinations and was a member of the Board of the Faculty of Science.

EAST ANGLIA, 1965–1991

In December 1964 Peter was appointed as the second Professor of Mathematics at the University of East Anglia (UEA) in Norwich at the age of only 34. He took up his appointment at UEA at the start of the academic year 1965–6, but was involved in the planning of undergraduate and graduate teaching in the School of Mathematics and Physics (MAP) and in the development of library facilities from the beginning of 1965. The first Professor of Mathematics to be appointed was M.B. Glauert, a fluid dynamicist from the University of Manchester who had taught Peter in his second undergraduate year there.

Before taking up his appointment Peter had also been involved in a round of new appointments as a result of which he started at UEA with two colleagues, L.W. (Leslie) Morland and M.A. (Mike) Hayes, with well-established research interests allied to his own. In addition, two PhD students who had completed their first year under his supervision at Sheffield transferred to UEA. He thus had the makings of a research group, which contributed substantially to the School's output of research in mathematics throughout Peters 26 years at UEA, although its size remained small, with only two further faculty appointments in theoretical solid mechanics. Hayes left in 1974 on his election to the chair of mathematical physics at University College, Dublin. The nucleus of permanent staff was supplemented by PhD students, most of them graduates of an MSc course in theoretical mechanics which, under Peter's strong influence, was introduced in 1965, postdoctoral workers, usually supported by Research Council grants or fellowships, and visitors from abroad. Peter led by example with considerable enthusiasm and with much encouragement for others.

Peter Currie, a PhD student of Mike Hayes, described the close contact that there was between the graduate students, lecturers and professors, which made the students feel very much part of the team at UEA developing the theoretical mechanics section, thus offering the PhD and MSc students insight into the workings of a research department and the development of a distinctive research character and philosophy. He wrote that Peter was largely responsible for creating this situation and was clearly the driving force, and forged a very effective research department which was active in a number of different mechanics areas but was united by a coherent philosophy. A few years later, when working at Ulster University, Peter (Currie) had a very productive six-month sabbatical at UEA, working with both Peter and Mike.

The early years at UEA were in some ways the most rewarding, but they were also very demanding. Planning new courses, examinations and an organisational structure for the school and participating in the governance of the university imposed heavy burdens. Peter had been appointed as an executive editor of the *Quarterly Journal of Mechanics and Applied Mathematics* in 1965, and over the next few years he was invited to join several national committees. In addition, he was constantly in demand as an external examiner, both in the UK and abroad. By the end of the 1960s he realised that he could not go on adding to external commitments while carrying out a full load of teaching and maintaining an active research career. He decided that the standing of mathematics at UEA was more likely to benefit from his research contributions than from his involvement in administrative affairs, and he tried subsequently to follow this precept, although he was a member of Sectional Committee 1 of the Royal Society from 1978 to 1981, chairman in the final year and served on the editorial boards of several journals, relinquished his share of the executive editorship of the *Quarterly Journal of Mechanics and Applied Mathematics* in 1972, and became a trustee in 1977, later senior trustee. His resolution to minimise administrative work suffered a setback, however, between 1979 and 1982 when, against his better judgement, he was persuaded to serve a term as Dean of MAP.

Peter's research activities during his tenure at UEA and after retirement covered a diverse range of topics, details of which will be described under a separate section. His main contributions were to nonlinear elasticity and thermoelasticity, wave propagation in heat-conducting elastic media, shock and acceleration waves in elastic media, small amplitude disturbances of a state of finite deformation or pre-stress, wave propagation in constrained elastic media, bulk waves in anisotropic elastic media, and surface and interfacial waves in elastic bodies. In addition, he made contributions to the theories of heat conduction, linearized interacting continua, the generation of acoustic and elastic pulses, elastodynamic wave function representations, elastic–plastic waves, waves in periodically layered anisotropic elastic composites and material symmetry in linear elasticity. In these areas Peter supervised 11 PhD students at UEA and one MPhil student. A number of postdoctoral researchers worked under his direction, including the writer, and several went on to hold professorial appointments in British universities. It was his research work and interaction with his postgraduate students that brought him most pleasure and satisfaction and it is a testimony to Peter that many of his former students remained in contact with him right up until the time of his death, several becoming close friends. During his years at UEA, Peter travelled extensively to universities all over the world, in Europe, America and Asia, gaining an international reputation as a result of his research work and increasing number of published papers. This included a three-month period in 1972 as a Visiting Professor at the University of Queensland.

His growing reputation led to quite a number of international visitors attracted to his research group. These included Piotr Borejko (University of Karlsruhe), who visited Norwich several times at Peter's invitation and recalls that Peter used to go for long walks in the countryside, always inviting him to join him on day-long walks. Peter had a booklet, as Piotr recalls, entitled 'Norfolk Walks', with each route marked out by the dates on which he walked it. On several occasions (in 1980, 1983 and 1986) Peter attended workshops on Continuum Mechanics of Solids at Oberwolfach, Germany, and twice he also visited Piotr in Karlsruhe. Later Piotr moved to the Technical University of Vienna where Peter gave a seminar in August 1989 followed by attending a performance of 'The Magic Flute' at the Vienna State Opera House. Piotr was very grateful for Peter's support, in 1985 for his application for Austrian citizenship (awarded in 1986), and as a member of the committee for his Habilitation from the Technical University of Vienna in 1997.

In connection with his work on elastic surface waves he had a fruitful interaction, over a period of about 12 years, with D.M. Barnett (Stanford University) and J. Lothe (University of Oslo). David Barnett wrote:

> Peter was the quintessential example of "a gentleman and a scholar", who, at least in my presence, was never known to say an unkind word about anyone. His language and work were always noted for their clarity, precision, and completeness, and from his technical lectures which I was privileged to hear he surely must have been a marvelous teacher.

On the basis of his published work Peter was awarded the degree of ScD by the University of Cambridge in 1973, and his distinguished research led to his election as a Fellow of the Royal Society in 1977, an honour for which he was very proud and humbled. The conferment of a Honorary DSc by the University of Glasgow followed in 1991 with the citation "Nationally and internationally he has had a major influence on the development of his subject—through his numerous scientific writings, through his students and through the help and encouragement that he has given to many young academics". A photograph from the occasion is shown in figure 1.

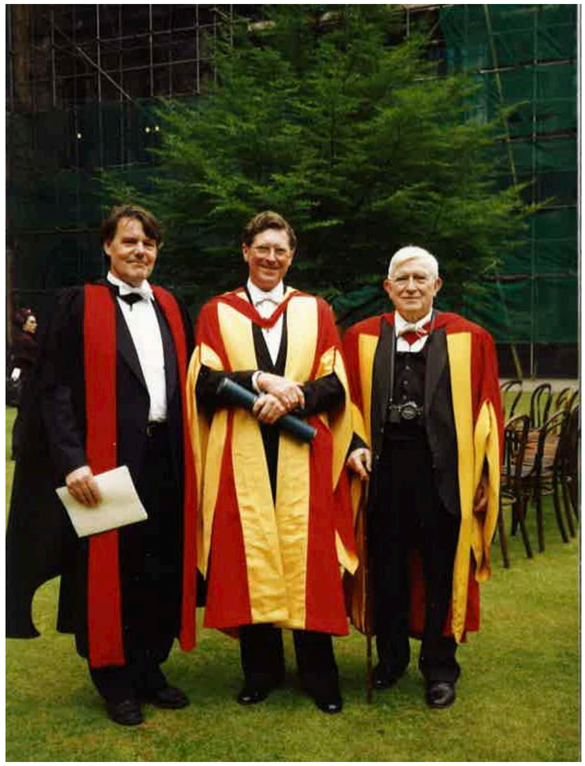

Figure 1: Peter (centre) on the occasion of the award of an Honorary DSc at the University of Glasgow in 1991. On Peter's left is Professor I.N. Sneddon (F.R.S. 1983), for whom Peter composed a memoir, and on his right is the writer of this memoir. Photograph provided by Ray Ogden.

Peter's teaching at UEA, as at Sheffield, was mainly in the fields of mathematical methods and theoretical mechanics, but the element of service teaching was very much smaller. He gave courses in all three years of the undergraduate programme and as part of the MSc course in theoretical mechanics. The postgraduate lectures that he gave were on partial differential equations, continuum mechanics, elasticity theory, elastic waves and viscoelasticity. In 1973 he developed his lecture notes on continuum mechanics into an elegantly written book *Continuum Mechanics: Concise Theory and Problems*, which was published in 1976 and reprinted by Dover in 1999. About this book, James Casey (University of California, Berkeley) wrote:

> For those of us who were learning continuum mechanics in the 1970s, Chadwick's book was a beacon. It dispensed with the jumble of indices that obscured tensor calculus and replaced it with a direct, clear, and elegant formalism based on 20th century tensor algebra. It cut to the heart of the subject.

Another characteristic of Peter's teaching was his renowned immaculate and meticulous blackboard writing. Ray Atkin was one of the many students over his career who appreciated his detailed notes and board writing. In later years they used to compare handwriting, each thinking theirs was the neatest. He reflects that his three PhD years went very smoothly, in no small part due to Peter's guidance and his generosity with his ideas and time, and has always appreciated Peter's encouragement, support and friendship and regards it as a privilege to have known Peter. A related comment from Leslie Morland:

> We saw that immaculate blackboard writing was possible, and how office shelves, table and desk could be neat and tidy, though not adopted by most of us.

Soon after moving to Norwich in 1965 Peter began to suffer from asthma. His health deteriorated seriously in 1984 when he was diagnosed with Churg–Strauss Syndrome. The treatment, with steroids, was prompt and effective, but he found it difficult afterwards to operate at the level he had maintained previously. He came to feel, moreover, that he had perhaps been at UEA too long. There had been opportunities to move, but his family, his wife especially, was very happily settled in Norwich and this seemed to him a more important consideration than academic advancement. For these and other reasons he decided to seek early retirement and this was granted in 1991 when he reached the age of 60. To mark this occasion a conference was held in Peter's honour at University College Dublin in November 1991, initiated by Mike Hayes, David Barnett and Tom Ting, during which there were 30 presentations. A photograph of the participants at the event is shown in figure 2. Based on the presentations a special issue of the *Journal of the Mechanics and Physics of Solids*, edited by John Willis (F.R.S. 1992), with 20 papers was published and dedicated to Peter.

Figure 2: Participants at the conference in Dublin on the occasion of Peter's retirement in 1991. Photograph kindly provided by the Chadwick family.

MARRIAGE AND FAMILY

Peter was married to Sheila Gladys Salter in Colchester, Essex on 2 April 1956. Sheila was born in Colchester on 13 April 1931. She was educated at Colchester High School for Girls, the University of Sheffield and Homerton College, Cambridge. They had met during his time in Cambridge whilst she was doing her teacher training at Homerton College. By all accounts there was instant attraction and they became inseparable, cycling great distances across East Anglia to see each other. They shared a love of music, dancing and the countryside and Peter was for many years an enthusiastic Morris dancer. At their wedding, Peter and Sheila had a guard of honour of Morris men at the church door. Peter and Sheila enjoyed a very close relationship; most of their interests were shared and they were totally devoted to each other. The photograph in figure 3 was taken in the early 1950s prior to their marriage.

Figure 3: Peter with Sheila in the 1950s before their marriage. Photograph kindly provided by the Chadwick family.

Sheila taught in Junior Schools in Essex and Berkshire up to the birth of their first child, Janice Mary (born 15th February 1958). Janice was educated at Norwich High School for Girls and the Universities of Nottingham and Loughborough. She married in 1981 and has three sons. She has worked as a bookshop manager and school librarian. The Chadwicks' second child, Susan Alys was born on 7th April 1970. Susan attended Norwich High School for Girls and the Oxford and

County Secretarial College. She started working for the Cambridge University Press in 1989 prior to her marriage in 2000, and continues to freelance for the Press, working on a portfolio of journals. She has two daughters.

The year after Janice's birth Peter took up his post as Lecturer in Applied Mathematics at Sheffield University, thus returning to the familiar territory of Yorkshire, but this was quite a step into the unknown for Sheila. After six years in Sheffield Peter moved to the professorship at UEA, and Sheila was very happy to be back in her native East Anglia. They both settled there very quickly, although Peter always yearned for the hills of the north. In 1972, the whole family travelled to Australia when Peter accepted an invitation to join the Department of Mathematics at the University of Queensland for three months, as a Visiting Professor.

RETIREMENT, 1991–2018

On his retirement from UEA Peter was appointed Emeritus Professor. He gave up all his scientific activities except research, which continued quite strongly for another ten years or so, and his research was supported by a Leverhulme Emeritus Fellowship during the period 1991–93. By this time Peter had three grandsons, Christopher, Jonathan and Alistair, all born in Yorkshire, which gave him and Sheila the perfect excuse to travel up to visit his favourite county more often, combining visits with some walking.

Peter embraced retirement by pursuing some of his lifelong interests, along with Sheila. They loved walking, exploring places of historic interest, attending classical concerts, reading and travelling all over the UK for holidays, accompanied by their succession of beloved Lakeland Terriers. Peter's deep love of music continued all through his life and he was very proud of the strain of strong musical talent within a different branch of his family. On retiring he took up piano lessons and practiced with typical conscientiousness, but being such a perfectionist was never satisfied with his performance and felt that he had come to the practical side of music too late in life. Peter also loved to visit village cricket matches around Norfolk and retained a dogged devotion to Yorkshire cricket throughout his life, with a truly impressive knowledge of players, scores and statistics.

Peter was a reluctant gardener, preferring to leave management of their large garden to Sheila, but he did tackle the heavier jobs of lawn cutting, hedge trimming and battling to prune rambling roses. His mathematical side came to the fore in using a spirit level to achieve level hedges and insisting that nobody else ever ventured near the lawnmower as their stripes on the lawn wouldn't be perfectly straight. In 2000 Peter's fourth grandchild, Emily, was born, followed in 2003 by Olivia, and as his granddaughters lived locally they were able to enjoy visits to see their granddad on a regular basis, especially loving to play in and explore the garden.

Sadly Sheila became ill just after this and died in Norwich on 21 December 2004, leaving Peter utterly desolated. Gradually, with the support of his family and some very strong friendships that he and Sheila had forged, he gradually started to immerse himself in some new activities and the best decision he made was to accept an invitation to go along to a meeting of the UEA University Retirement Association. He signed up immediately and joined the walking group, which gave him the opportunity to meet like-minded people, some former colleagues, and many completely new friends. Regular walks with them around Norfolk and walking holidays around Britain followed, and Peter soon joined in with other activities such as social events and visits to places of special interest, art talks and holidays in Yorkshire and on the south coast. Membership gave him a completely new lease of life, and he was soon attending concerts with some of his friends from the association and taking on organisational duties within the group. He also threw himself wholeheartedly into membership of the Cringleford Historical Society, stepping into the shoes of Sheila who had been an enthusiastic member. Friendships from this stage of Peter's life lasted until his dying day and those friends have been a tremendous support to Janice and Susan too over the years.

In 2010 Peter suffered a major stroke on Boxing Day whilst staying with the family in Yorkshire for Christmas, and owed the ensuing years of his life to the swift actions of the Upper Wharfedale Fell Rescue Association who were able to reach him up a snowy track in Gargrave with their vehicles. Peter made a remarkable recovery physically, but his mobility was drastically reduced and he suffered a series of falls and accidents which worried the family. In 2013 it was suggested to him that he might consider moving back to his native Yorkshire as a bungalow had become available just down the road from Janice. Peter accepted this proposal more readily than anyone had anticipated and in August 2013 Peter moved to the village of Cononley, where he immediately felt at home with plenty of space for his possessions from Norwich and a beautiful garden to look out at, with a mature apple tree as centrepiece, just like his old garden in Norwich. With the support of family Peter soon settled into his new life, enjoying being taken out in the Yorkshire Dales, attending concerts and village events. Peter was a smart man, never seen without a shirt, tie and jacket until well after Sheila's death, and in recent years the family loved to see him dressed up for a special occasion and looking like the Peter of old (see figure 4).

Figure 4: Photograph of Peter taken by his grandson and kindly provided by the Chadwick family.

In 2016 Peter attended the wedding of his eldest grandson, Christopher, and wore a huge smile all day long. His first great grandchild, Evelyn, was born in 2017.

Peter's underlying illness caught up with him in 2018. Having celebrated his 87th birthday in great style, lunching out with his carer, enjoying tea and cake with family and then spending the evening at a village event with family and friends, he was admitted to hospital in the night, made it back home for Easter, but was soon admitted to hospital once more where he remained for several weeks until a final couple of weeks spent in Threshfield Care Home.

The family have been overwhelmed by the comments about Peter that they have received from both relatives and friends. Gentle, kind, respected, delightful, generous, a real gentleman, interesting, quiet, modest, are just some of the descriptions of Peter. Talented, distinguished, humorous, proud of his Yorkshire roots, devoted to his family are a few more. He loved to receive visits from friends old and new and was delighted when friends from his past dropped in to see him in Cononley. It is a true testimony to Peter that so many of his friends (old and new), past students and colleagues, neighbours, those who helped to care for him in later years, friends of Janice and Susan and residents of Cononley have described him in these terms. He has made a mark on many lives and will be sorely missed. He will live on in many hearts for ever.

A special event to mark a "Celebration of Peter Chadwick's Life" was held at the Sainsbury Centre, University of East Anglia, on 28 October 2018 and was attended by more than 100 family members, former colleagues, academic associates and friends, many of whom travelled considerable distances to be present.

SCIENTIFIC WORK

Particular characteristics of Peter's work were the clarity, conciseness and elegance of his writing, which was always a joy to read. His precisely crafted mathematical formulations, with meticulous attention to detail, were based on a deep knowledge of a wide range of topics within continuum mechanics and demonstrated that he was a master of his subject.

Peter's work in wave propagation provides the theoretical foundations for understanding various applications, such as non-destructive testing, including detection of defects in materials, and the characterization of material properties, seismic wave propagation, in particular surface waves. There are also more modern application to medical diagnostics through the technique of elastography, which is used to detect changes in tissue stiffness that can be indicative of the presence of, for example, tumours.

His work in rubber thermoelasticity, although less extensive than that on elastic waves, underpins the characterization of the properties of rubber, which is used extensively in industry for vibration isolation, for example in bridge bearings, and in vehicle tyres.

The topics in the following appear essentially in the same order as listed in Peter's personal record lodged with the Royal Society.

Nonlinear elasticity

The subject of nonlinear elasticity happens to be the one with which I was most closely involved in collaboration with Peter during my time at UEA as an SRC Research Fellow (1970–1972). The paper (9) developed a general theory of first- and second-order elastic moduli, highlighting connections between moduli associated with different measures of stress and strain and connections with the propagation of waves. In particular, a concise derivation of the propagation and growth conditions for acceleration waves travelling in a general finitely deformed elastic solid was presented. The general theory was then applied to isotropic materials in (10) with a focus on deriving explicit expressions for the components of the first- and second-order moduli with respect to the principal axes of the prevailing finite deformation. These results are cast as a theorem of tensor calculus and highlight the advantages of so-called "principal axes methods" for isotropic materials advocated by Hill (1970). The results were applied to the propagation of acceleration waves in isotropic materials, providing, in particular, a succinct account of the properties of principal waves.

So-called controllable finite deformations of incompressible isotropic elastic materials for circular cylindrical tubes and solid cylinders were treated on the basis of a systematic referral to the common principal axes of stress and strain in (11), (12) and (13), including inflation, extension, axial and torsional shear of a tube of incompressible isotropic elastic material.

The connection between conservation laws in nonlinear elasticity and an energy–momentum tensor, the Eshelby tensor, was elucidated and highlighted in (14). This is a paper that particularly impressed James Casey, who commented:

> I had been unable to follow Eshelby's own account of this concept, clothed as it was in somewhat idiosyncratic intuitive arguments. Chadwick completely swept away the cobwebs and gave an impeccably clear definition of the Eshelby tensor in the context of elastic media. I use this paper as a model of clarity and method in my graduate courses on continuum mechanics.

Nonlinear thermoelasticity

One of Peter's major contributions was the development of a phenomenological theory of the thermomechanics of rubberlike solids (15), which involved the formulation of constitutive equations describing the thermo-mechanical response of solid polymers in the temperature range in which they exhibit rubberlike behaviour. On the basis of assumptions motivated by physical arguments the Helmholtz free energy of the considered material was constructed, from which the associated stress-deformation-temperature relations involved three response functions. The resulting predictions of these relations provided qualitative consistency with observed behaviour in experiments over the full range of deformations and temperatures for which measurements have been reported.

It was found that for the constitutive equations to be able to characterize anomalous thermomechanical effects of solid elastomers such as the thermoelastic inversion phenomenon restrictions on the response functions are required that are no more severe than those which ensure that the purely mechanical behaviour of the material is physically realistic. The paper then addresses the capability of the basic theory to predict results that agree quantitatively with experimental results. For this purpose empirical forms of the three response functions were presented which accurately represent measurements made in tests involving different fixed temperatures and stretches. An analysis of the extension of a cylinder subject to different temperatures was then provided to exemplify the theory, and numerical results were obtained which compared favourably with the results of experiments in which thermoelastic inversion occurred.

At fixed temperature rubberlike materials are typically recognized as approximately incompressible, and their mechanical response is normally treated on the basis of the incompressibility assumption so that volume changes can then only be effected by changes in temperature. However, as highlighted in the final section of (15), incorporation of the mechanical incompressibility constraint within the theory of rubberlike thermoelasticity is not straightforward and places an undesirable limitation on the scope of the theory.

An alternative formulation of a model of rubberlike thermoelasticity in (15) was proposed in a later paper (16) wherein the concept of strictly entropic elasticity as applied to elastomeric materials was modified. This was developed to account for the observed experimental findings that the deviatoric stress is not entirely entropic in origin but includes a contribution from the internal energy, in contrast to the classical theory that regards rubber elasticity as entirely entropic. In particular, the modified theory predicts the observation of an energetic contribution to the axial force in a stretched cylinder.

Wave propagation in heat-conducting elastic media

Peter made several key contributions to the propagation of waves in heat-conducting elastic materials. First, in the paper (17), from the point of view of thermo-elastic interactions, plane harmonic disturbances in a transversely isotropic elastic material that is able to conduct heat were studied. It was found that the three body waves that can be transmitted in each direction with small amplitude in the non-conducting case, a quasi-longitudinal wave, a quasi-transverse wave, and a purely transverse wave, are modified and that the modified quasi-waves exhibit frequency-dependent dispersion and damping of the kind known to affect dilatational waves in isotropic heat-conducting elastic materials.

In the paper (18) the propagation of plane harmonic waves of small amplitude was examined without any restriction on the material symmetry and without the assumption that the undisturbed state is stress free. The secular equation was derived in a form that made clear the association of low- and high-frequency behaviour with isentropic and isothermal conditions, respectively. It also allowed the introduction of a multivalent modal function whose regular branches determine the complex arrangement of the possible modes of wave propagation in a given direction. The development of a general analysis of harmonic waves on this basis yields a natural classification of the modes and leads, via a standard result in the theory of algebraic functions, to series representations of modal properties that are valid near the extremes of the frequency range.

The substantial paper (19) focused on the linear theory of thermoelasticity with a view to generalizing the classical elastic wave theory results that all degeneracies of the waves are associated with directions (so-called acoustic axes) in which two or all three plane bulk waves have equal speeds. For a thermoelastic material four plane harmonic waves can travel in an arbitrary direction, and there are two types of degeneracy. The first type arises when two or more waves have equal wave speeds, and the second type when the coefficient matrix of the governing system of differential equations has a repeated zero eigenvalue. Each type of degeneracy is of two possible kinds, so the number of cases in which at least one degeneracy occurs is eight. It was shown that only three of these possibilities can actually exist and in only one of them are both types of degeneracy present, as a result of which the effects of thermomechanical interaction on the modes of wave propagation are minimal. The paper provided a detailed analysis of the degeneracies, their interconnection, their influence on the nature of thermoelastic waves, and the relationship between classical elastodynamics and linear thermoelasticity in respect of degeneracy.

In (20) the most general form of the (conventional) theory of thermoelasticity was considered, with no assumption on material symmetry and without the constraint that must be placed on the heat flux that ensures acceleration waves conform to a propagation condition of Fresnel–Hadamard type. The paper provides a classification of elastic heat conductors dependent on the properties of the heat flux, as non-conductors, normal conductors and anomalous conductors, and proves several theorems related to the propagation and growth of acceleration waves under each of these categories.

Without any restriction on material symmetry and for an arbitrary choice of homogeneously deformed equilibrium configuration of an unbounded body of heat-conducting elastic material, the equations were derived in (21) for a superimposed infinitesimal disturbance for the situation in which a deformation–temperature constraint was imposed. The disturbance consisted of plane harmonic waves in order to examine the stability of the equilibrium configuration. It was found that at least one of the four possible modes of wave propagation is always unstable when the basic material constants are subject to very mild restrictions, thus calling into question the validity of the considered form of constraint.

Acceleration waves in elastic media

It was mentioned in the context of nonlinear elasticity that the papers (9) and (10) featured discussions of acceleration waves. In particular, a concise derivation of the propagation and growth conditions for acceleration waves in a homogeneous finitely deformed general elastic material was given in (9) and then specialized for the case of isotropy in (10), with particular applications to the Hadamard–Green material model strain-energy function, which has the special property of admitting a longitudinal and two transverse waves for every direction of propagation when the material is subject to an arbitrary finite deformation.

In 1977 Piotr Borejko, then a PhD student in the Polish Academy of Sciences, Warsaw, met Peter and attended a series of lectures on elastodynamics given by Peter at the invitation of the Academy of Sciences. Piotr also attended a lecture given by Peter on recent applications of the elastic wave theory to anisotropic media at the 20th BTMC in Sheffield in which the topic of the physical significance of the energy flux produced by the harmonic plane wave in an anisotropic elastic medium was addressed. This led to correspondence on the topic and a collaboration which lasted several years and their first joint publication (22) on energy relations for acceleration waves. Piotr regarded working with Peter as a great pleasure.

Small amplitude disturbances of a state of finite deformation or pre-stress

The effect of pre-stress and accompanying strain on the propagation of small amplitude waves attracted a good deal of Peter's attention. In (23) he used the Barnett–Lothe formulation (Barnett & Lothe 1973, 1974) of the theory of elastic surface waves in considering surface motions of a pre-stressed elastic body. This led to a general uniqueness theorem and the notion of a neutral set, the latter defining the boundary of the domain of existence of surface waves, thus identifying configurations in which standing wave solutions can exist.

In the two papers (24) and (25) conditions were identified under which an interfacial wave can propagate along the boundary between two adjoined half-spaces of neo-Hookean elastic material subjected to triaxial extensions of different magnitudes in directions in and normal to the interface. In (24) the in-plane stretches (in directions parallel to the interface) were taken to be equal in each of the constituent half-spaces, while in (25) the two half-spaces were subjected to different stretches along common axes, one of them normal to the interface, without restriction on the magnitudes of the in-plane stretches. The domains of existence of interfacial waves were catalogued in detail.

The paper (26) focused on the effects of internal constraints and an arbitrary homogeneous pre-strain on small-amplitude motions and the associated energy changes, which were found to differ in character from those that arise in linear elastodynamics. A study of solutions of the governing equations of the linear theory representing homogeneous plane waves of arbitrary profile then followed. For this type of wave the set of internal constraints was described as being "fully active" if the actions of the reaction tensors on the wave normal were linearly independent. For a direction in which the constraints are not fully active it was found that there exist one or more "ghost" solutions in addition to the plane-wave solutions. Ghost solutions perturb the scalar constraint multipliers without causing any deformation of the material. Degenerate solutions of this type had been shown earlier in (27) to be essential for the construction of surface waves in particular types of constrained elastic bodies.

For an incompressible pre-stressed elastic material, it was shown in (28) that the sextic eigenvalue problem arising from the Stroh formalism (Stroh 1962), a six-dimensional representation of the equations governing plane motions of an elastic body, can be constructed, extending a known result for unconstrained materials. The theory was applied to the analysis of surface waves in a homogeneously pre-stressed semi-infinite body of incompressible elastic material, and included the derivation of the secular equation that determines the speed of propagation. Explicit results were then obtained for the case of material orthotropy with the symmetry axes aligned with the principal axes of pre-stress.

Bulk waves in anisotropic elastic media

Peter made important contributions to our understanding of the propagation of homogeneous plane waves in anisotropic elastic materials through the geometric properties of the so-called slowness surface. Briefly, the slowness surface is traced out by the slowness vector, which is defined as $\mathbf{n}/v$, where $\mathbf{n}$ is a unit vector in the direction of wave propagation and v is the wave speed. There are in general three distinct values of v for a given $\mathbf{n}$ and hence three concentric branches of the slowness surface. Tangents to the slowness surface at the point of contact identify so-called *transonic states*, which were characterized in considerable detail in (29). At such points the wave speed is referred to as the *limiting speed* in the sense that it separates regions within which the wave speed is subsonic or supersonic. Particular attention was devoted to *exceptional waves* in (30), those that do not affect the traction on a family of parallel planes within the considered material body. The case of transversely isotropic materials was elaborated in (31) and (32) for compressible and incompressible materials, respectively. In (33) fundamental solutions were developed in terms of the associated Green's functions for the case in which the slowness surface of an anisotropic material is ellipsoidal.

Surface and interfacial waves in elastic bodies

Peter made substantial contributions to the analysis of surface and interfacial wave propagation. The paper (34) on the general theory of surface waves in an anisotropic body is perhaps his most influential paper and certainly the most highly cited. Of this paper, David Barnett (Stanford University) wrote:

> I knew of Peter by reputation and from his research when in 1977 I received a letter from him containing a copy of his wonderful paper with his doctoral student George Smith on "Foundations of the Theory of Surface Waves in Anisotropic Elastic Materials" which had just been published in Advances of Applied Mechanics. Since much of that work had been based on two previous papers by Jens Lothe, Kazumi Nishioka, Bob Asaro and me, I was quite eager to read it and stayed up the entire night doing so. Peter and George were kind to include everything we did, and they did so in a fashion which would appeal to better mathematicians than I, including a better discussion and proof of the conditions under which a certain integral, which was central to the existence conditions for a surface wave, was either bounded or unbounded. Simply put, the Chadwick and Smith paper was a wonderful addition to the surface wave literature, and I was at least pleased that our own work was deemed worthy enough by them to have been further expounded upon.

The corresponding general theory of interfacial waves in anisotropic bodies was developed in (35) and (36), while (37) was devoted to an elucidation of the structure of the Barnett–Lothe tensors, which are key ingredients for the analysis of surface waves. The particular case of surface waves polarized in a plane of material symmetry was analyzed in detail in the papers (38) and (39). In connection with (38), referring to Peter, Barnett wrote

> I was fortunate enough to interact with him via snail mail and at technical meetings. One such meeting, a workshop on Anisotropic Elasticity and its Applications, had been arranged by Tom Ting and me for the mathematics division of the US Army Research Office in Durham, North Carolina, from June 4–6, 1990. I had just finished reading Peter's latest work ... (38) ... and noticed that his proof in Appendix A that a single inhomogeneous plane wave could not be a free surface wave was incorrect, and that the satisfaction of a particular condition admitting such a "single partial wave" (Rayleigh wave) could at least be possible, though it had to be a "supersonic" surface wave. Peter returned to East Anglia, and wrote a beautiful lengthy paper ... (40) ... which occupied Chapter 14 of the book based on the workshop proceedings. Although he generously listed me first on the co-authorship, the work was his and included the construction of a one-parameter family of stable 6×6 elastic stiffness matrices for a linear elastic media of triclinic symmetry which allowed for these one-component free surface waves. He sent me a handwritten copy of the work to preview and comment upon, and, as anyone who ever received anything handwritten by Peter can attest, this copy was more pleasing to the human eye than any typeset version.

This reflected Peter's generous scientific spirit and appreciation of his well-known immaculate handwriting.

For the case of isotropic symmetry the general theory was specialized in (41) for both surface and interfacial waves, and for surface waves it was applied to cubic (42), orthorhombic (43) and transversely isotropic (44) symmetries. For materials that are either pre-strained or pre-stressed a detailed analysis of surface waves, including the establishment of a general uniqueness theorem, was developed in (23) based on the Barnett–Lothe formulation, for both surface and interfacial waves in (45), and with particular application of the Stroh formalism in (28). Examination of the existence of one-component surface waves was the subject of (46). Interfacial waves were investigated for pre-strained (incompressible, isotropic) neo-Hookean elastic bodies subject to biaxial or triaxial deformations in (24) and (25), as described under the section on small amplitude disturbances.

Other topics

Peter contributed to a variety of other topics, including the generation of acoustic and elastic pulses, the propagation of elastic-plastic waves, and waves in periodically layered anisotropic elastic composites. Of particular note are his papers on the establishment of uniqueness theorems for linearized theories of interacting continua (47), and the development of representations for scalar elastodynamic wave functions (48). His final technical paper (49) produced an elegant new proof concerned with the number of material symmetries in linear elasticity.

Peter completed his publication list with three fine portraits of Fellows of the Royal Society, namely Albert E. Green (F.R.S. 1958) in 2001 (50), Ian N. Sneddon (F.R.S. 1983) in 2002 (51), and Anthony J.M. Spencer (F.R.S. 1987) in 2015 (52) published in Biographical Memoirs of Fellows of the Royal Society.

HONOURS AND AWARDS

1965 Fellow of the Cambridge Philosophical Society
1973 ScD, University of Cambridge
1977 Fellow of the Royal Society
1991 Honorary DSc, University of Glasgow
Honorary Member of the British Society of Rheology

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I am especially grateful to Peter's daughters, Janice and Susan, for providing an account of Peter's life, on which I have drawn extensively. The Royal Society kindly sent me Peter's personal record and list of publications from their archive. Insight from Peter's former PhD students, colleagues, collaborators and correspondents, Ray Atkin, Leslie Morland, Piotr Borejko, David Barnett and James Casey helped to paint the overall picture of Peter's professional interactions.

The portrait photograph was provided to the Royal Society by the subject. It was taken in 1992 by J. R. West.

A personal note: Peter was my external PhD examiner in Cambridge and was instrumental in my appointment to UEA as an SRC Research Fellow, between 1970 and 1972. I always appreciated Peter's kindness and encouragement, which led to the publication of four co-authored papers from that period.

AUTHOR PROFILE

Raymond Ogden

Professor Ray Ogden has been George Sinclair Professor of Mathematics at the University of Glasgow since 1984 apart from a two-year period at the University of Aberdeen between 2010 and 2012. He graduated in Mathematics from the University of Cambridge, from where he obtained a PhD in 1970, and his first academic appointment was as a Research Fellow at the University of East Anglia under the guidance of Peter Chadwick. His main research interest is in the theory of nonlinear elasticity with applications to the mechanics and electromechanics of soft material, areas in which he has collaborated extensively with colleagues in many countries, including Austria, Ireland, Italy, Spain and the USA.

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