BIOGRAPHICAL
MEMOIRS

Arthur Holmes, 1890-1965

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ARTHUR HOLMES

1890-1965

Elected F.R.S. 1942

With the death on 20 September 1965 of Arthur Holmes, the Society has lost a geologist of great international distinction. Born on 14 January 1890 at Hebburn-on-Tyne, he was the son of David Holmes and Emily Dickinson. His father was a cabinetmaker and his mother a school-teacher, but Holmes was descended on both sides from Northumberland farming stock, of which he was justly proud. He retained all through his life an affection for the Northumbrian countryside.

He was educated at Gateshead High School, here receiving the first glimpse of the world of geology to which he was to devote his life, through the interest of his physics master who introduced him to Kelvin's *Addresses*. From these he learned about the long controversy between Kelvin and the geologists. Kelvin, starting from the assumption that the earth had cooled from a molten state, estimated that no more than 40 million years could have elapsed since it solidified; whereas geological opinion, confronted by the slowness of earth processes, held that a much longer span was needed. Thus, through physics, Holmes was introduced to earth science, in which his interest was further aroused by reading E. Suess's great geological masterpiece, *Das Antlitz der Erde*, at that time recently translated into English.

With the intention of entering Armstrong College, Newcastle upon Tyne, Holmes took Intermediate B.Sc. from his school, and was astonished to learn that on the results of this examination he had been awarded a scholarship to Imperial College. He entered the College in 1907 with the intention of reading physics. Here he soon realized that R. J. Strutt, then Professor of Physics, had found the answer to Kelvin by demonstrating the abundant presence of radioactive elements in the earth's crust; simple cooling from the molten state was no longer a tenable assumption. Meanwhile attendance at the lectures of Professor W. W. Watts opened before him the prospect of becoming a professional geologist. 'From him', he has recorded,* 'I soon learned that Nature is the perfect expert witness—a favourite phrase that implies a whole philosophy of scientific method.' He successfully sat the B.Sc. examinations in 1909, then changed over to geology and became an Associate of the College in 1910, remaining to undertake post-graduate work in the laboratory of Professor Strutt (later Lord Rayleigh). Soon, however,

* *Proc. Geol. Soc. Lond.* (1940), 96, 54.

he had joined an exploring party, organized by Memba Minerals Ltd, bound for Portuguese East Africa. Thus in his post-graduate year were started investigations which were the roots of almost all his subsequent work. Investigation of the applications of radioactivity to geological problems was just beginning. 'The far-reaching possibilities stirred my imagination', he has said; they lasted him through more than fifty years of unceasing endeavour, during which he became, more than anyone else, the focus and exponent of this branch of the subject. In Mozambique, the virgin field of Pre-Cambrian ultrametamorphics and Tertiary lavas led him to petrology, his other main theme 'To get the best out of geology', he was apt to say, 'you should have at least two lines of interest'. He was a major contributor to both his chosen lines, and more than once, one fertilized the other. Nor should contributions to geomorphology, also springing in the first case from the *inselberg*-studded landscape of Mozambique, be forgotten.

When he returned to London in 1912 he brought with him a great collection of petrographical material to work on; he had had adventures in the jungle, and he had had bad attacks of malaria and blackwater fever which were to leave him unfit for military service when the War came. In 1912 he was appointed Demonstrator in Geology at Imperial College, a post he held until 1920. His close association with Watts left him with a profound affection for that eminent geologist. Petrology at that time was in the charge of Dr J. W. Evans, F.R.S., himself a remarkable man, explorer, philosopher and eccentric, who cannot have failed to exert, for good or ill, an influence upon the young Holmes. These were productive and happy years. In 1914 Holmes married Miss Margaret Howe of Gateshead; they settled in Chelsea. Three books, two of them still standard works, and numerous original papers were published. Among his contemporaries especially after the war were men destined to achieve distinction, including the petrologists H. H. Read and Alfred Brammall. But this was not to endure.

In the post-war ferment, he took, out of financial necessity, a step that might have had disastrous consequences for his scientific career, and for geology; he forsook his main interests and became chief geologist of an oil-exploring concern, the Yomah Oil Company, operating in Burma. The exploration was inadequately financed, and failed in spite of Holmes's competent work in the field. In 1924 he was back in England, obliged to take legal action to recover his salary. By this time, the domestic demand for geologists had dried up and oil geologists were returning home one after another. The limited number of industrial posts had been filled; the small expansion of the universities which pressure from returning service men had produced was long over. For a time the situation looked hopeless; then, fortunately, a single academic opening, in the North Country, presented itself.

The University of Durham, which had offered courses in mineralogy under J. F. W. Johnston, F.R.S., from the foundation (1832) to 1856, had afterwards moved all science teaching other than mathematics to its

daughter College of Science in Newcastle upon Tyne; this evolved into Armstrong College. In the post-war period it was realized that if the Durham Division was to maintain its standing as a university institution it was imperative to offer science subjects in addition to divinity and arts. A group of science departments was therefore founded in 1924, under the general headship of Professor (later Sir) Irvine Masson. A Readership in Geology was offered, probably in response to the Durham County Council's interest in the mining industry; and to this Holmes was appointed; receiving professorial rank in 1925. The department consisted of a laboratory for 30 students, a museum shared with the Botany Department, and staff rooms. With great energy he got together the nucleus of a fine teaching collection and the first Honours student was admitted in 1925. Here Arthur Holmes remained for twenty years. The Honours candidates, never more than two or three of whom were accepted each year, received from him and his colleague William Hopkins, a Carboniferous biostratigrapher, what nearly amounted to a personal tutorial training. His research students, always free to consult him for advice, were nevertheless given their heads to develop as much originality as they were capable of showing. The opportunities for research and for writing were considerable, and geology owes much to the contemplative years in Durham, which Holmes splendidly exploited. In ecclesiastical and collegiate Durham he had little interest, though he eventually served on its divisional Council.

In 1938 the first Mrs Holmes died, and in 1939 Holmes married Dr Doris Livesey Reynolds, herself a distinguished petrologist, who had joined the Department as lecturer in 1933. A son of his first marriage, Mr Geoffrey Holmes, and four grandchildren, also survive him.

In 1930 Holmes exchanged visits with Professor Reinhard of the University of Basle, and in 1933 he was Lowell Lecturer at Harvard University, owing his invitation to Professor Reginald Aldworth Daly, who freely expressed the opinion that he was one of the few English geologists with ideas on the grand scale. His work was further recognized by the award to him in 1940 of the Murchison Medal of the Geological Society of London, and by his election to the Royal Society in 1942.

In 1943 he was appointed to the Regius Chair of Geology at Edinburgh. Here, at the Grant Institute of Geology, a more spacious environment offered greater scope but made greater demands upon Holmes for administration and teaching. The hope that could never have been realized in the Durham of his day, that the sophisticated apparatus of mass-spectrometry might become available to enable him to introduce the experimental field into his department was still-born too in Edinburgh; perhaps, as L. R. Wager* has suggested, with fortunate results for the science.

In the closing years at Durham, Holmes had devoted time, much of it while fire-watching, to the writing on a text, *Principles of physical geology*; this book appearing shortly after his move to Edinburgh, placed the seal

* *The Phanerozoic time-scale*, London (1964), p. 11.

upon his already great international reputation. It deserves to rank with Lyell's *Principles* as one of the most successful textbooks of geology ever written. Those who had heard his admirably clear and attractive lectures on geology and geophysics could not fail to realize that the book was no more than an expansion of these, beautifully illustrated. It was adopted widely in many foreign countries as well as at home.

Many honours now came his way. He was elected Correspondent, Geological Society of America, 1936; Honorary Member Royal Geological Society of Cornwall, 1937; Corresponding Member Geological Society of Belgium, 1946, Honorary Member, 1956; Honorary Member Belgian Society of Geology, Palaeontology, and Hydrology, 1947; Foreign Member Royal Swedish Academy of Sciences, 1947; Foreign Member Royal Netherlands Academy of Sciences, 1947; Foreign Member Geological Society of Stockholm, 1952; Foreign Member Academy of Sciences, Institute of France, 1955; Wollaston Medal, Geological Society of London, 1956; Penrose Medal, Geological Society of America, 1956; Fourmarier Medal, Royal Academy of Belgium, 1957; Fellow of Imperial College, 1959. The Royal Society of Edinburgh gave him its Macdougall-Brisbane prize in 1965.

In 1956 Holmes decided that the deterioration in his health was such that he ought no longer to continue in the Chair; he was elected Professor Emeritus by Senatus, and his work in Edinburgh was recognized by the conferment of the honorary degree of Doctor of Laws in 1960. In 1964 his career was crowned with the Vetlesen Prize, awarded 'for scientific achievement in a clear understanding of the earth; its history and its relation to the universe'; and of standing similar to that of a Nobel Prize.

He will be remembered by all who knew him for his quiet unassuming charm, and as his successor in Edinburgh, F. H. Stewart, puts it, for his willingness to go to enormous trouble to help lesser mortals with their problems. He never wished or attempted to be a public figure, but vast numbers of geologists will realize that he has influenced their thinking through his writings, and international correspondence, and even larger numbers will owe to him the inspiration which gave them an interest, even if only a passing one, in geology. His interests outside his subject were in music, literature and the visual arts, music being his main form of relaxation. He was a capable performer on the pianoforte and he delighted in spending hours playing the compositions of Beethoven, Schumann, Chopin, Debussy and Ravel. Although in his middle years he once remarked that his development had stopped short between Cesar Franck and Stravinsky, he came in later years to be a great admirer of the Russian composer. He would travel up to London for Stravinsky concerts and it is said that there are still some in Edinburgh who remember a Festival performance of Stravinsky's works with Ansermet conducting, at which Holmes stood on his seat and shouted his applause as if he were at a football match. A few days later he very effectively tackled the writings of the grudging music critic in *The Scotsman*, receiving support from many other music lovers. His tastes in painting were

consonant with his interests in music; he had a particular enthusiasm for the Impressionists. A stylist himself, he appreciated good writing and read a great deal. His popular books are enlivened with apt quotations.

Radioactivity in geology

Arthur Holmes entered this field at the historic moment when the discoveries of Bequerel, the Curies and Rutherford had revolutionized the whole conception of matter, and when Strutt had demonstrated the widespread presence of radioactive minerals in rocks. The time was propitious for a thorough examination of the geological implications. Only a few years previously Boltwood had suggested that the end-product of the decay of uranium was lead, and that a comparison of the quantities of the two elements in a rock would give a measure of its age. Soddy had identified helium as a second disintegration-product, and Strutt had determined U/He ratios in minerals.

Geological time

Holmes's first paper (1911) giving the results of his work in Strutt's laboratory, dealt with the association of uranium and lead in rocks, and its application to the measurement of geological time. His first book followed only two years later, notwithstanding the Mozambique expedition, reviewing the history of attempts to ascertain the age of the earth, from the speculations of the Chaldees to Archbishop Ussher, and setting forth the evidence from astronomy, rates of denudation, the sodium-content of the oceans, from sedimentation and from radioactivity. Contrasting the results obtained from the 'hour-glass' methods such as total thickness of sediments and oceanic sodium with those from the lead-ratios and helium-ratios, a substantial discrepancy was noted which could not be resolved if the rate of disintegration of uranium is not constant, or if that principle cherished by geologists since Lyell, that of uniformitarianism, fails to apply in detail to rates of sedimentation and denudation. Unhesitatingly Holmes argued that since the half-periods of the short-lived elements had proved to be constant, that of uranium must be expected to be constant also; and adduced as reasons for adopting the second alternative the abnormal character of present time, in the wake of the great Cordilleran-Alpine mountain-building episode. The maximum age deduced for any mineral examined up to this stage was 1600 million years; previously geologists had found Kelvin's estimate of 20 to 40 million confiningly short; now they were presented with an embarrassingly long history for the earth. Many were critical, as Barrell had been of Boltwood's results; but Holmes had already played a part in what was to become accepted as a major revolution in thought.

In 1914 appeared the first results of a fruitful collaboration destined to last many years, with R. W. Lawson, a boyhood friend, then at the Radium

Institute in Vienna, and subsequently at Sheffield University. It is maintained that lead is now practically established as the end product of disintegration of the uranium family; and the following significant phrase occurs: 'Atomic weight estimations can now be used to correct the crude determinations of the age of a mineral by means of its present lead and uranium content', foreshadowing the use of isotopic estimation to refine the method. The expectation at this time that bismuth might prove to be the stable end product of the decay of thorium was not realized; this also yields lead, introducing a further complication. The construction of a geological time-scale, given sufficient fixed points provided by lead-ratio and helium-ratio determinations on minerals of known stratigraphic position could now be contemplated. By 1927, when a revised and shortened version of *The age of the Earth* was prepared for Benn's Sixpenny Library, it was possible to list 23 fixed points, ranging from Lower Pre-Cambrian (1260 My) to Oligocene (35 My). The following approximate empirical expression could now be stated

$$T = \frac{\mathrm{Pb}}{\mathrm{U}+0\cdot 38\mathrm{Th}} \times 7400\ \mathrm{My} \tag{1}$$

Between 1927 and 1937, mass spectrography made possible the identification of the isotopes of uranium and lead. An enlarged, and final edition of *The age of the Earth* (1937) discussed both the helium and lead methods, giving new results produced by workers in many different countries, and modifying the general expression to take account of the uranium and thorium lost during disintegration:

$$T = 15\,150\,\{\log_{10}\,(\mathrm{U}+0\cdot 36\mathrm{Th}+1\cdot 155\mathrm{Pb}) - \log_{10}\,(\mathrm{U}+0\cdot 36\mathrm{Th})\}\ \mathrm{My} \tag{2}$$

The helium and lead methods were combined to produce the first scale for time since the beginning of the Cambrian period (1937, Fig. 3), the starting of the Palaeozoic being placed somewhat greater than 453 My ago. By 1931 a stage had been reached when Holmes could review in a contribution 336 pages long, the basic data of radioactivity and geological time, in the report of a (U.S.) National Research Council Committee.

In the next general statement (1933), a return was made to the question of total thickness of sedimentary rocks. Plotting the maximum thicknesses of the various systems against the best time-scale produced a curve convex upward, justifying Holmes's contention of an increasing rate of erosion, but it became apparent that the discrepancy between maximum rates of sedimentary accumulation and time as determined from Pb and He ratios was by no means as great as once appeared. In 1947 he employed more refined estimates for the preparation of new curves, again using the maximum thicknesses of sediments to provide a means of correlation between a limited number of age determinations. New methods now began partly to supersede the lead and helium ratios; in particular potassium/argon and rubidium/

strontium have been found to be applicable to common minerals such as micas and feldspars, instead of comparatively rare radioactive minerals. The last time-scale appeared in 1959. It is interesting to compare Holmes's four scales; the tendency has been to recognize geological time as longer with each successive estimate. Cambrian time is now considered to have begun 600 ± 20My ago; the age of the earth's primaeval crust is now placed at about 4550 My (Holmes 1964).

The use of radioactive decay to measure geological time has proved to have some formidable difficulties; the loss of parent or daughter elements, especially where, as in the case of helium or argon, these are gases; the alteration of the minerals concerned by metamorphism or weathering. Holmes never minimized these difficulties, and from 1913 onwards his insistence upon them has been salutary. There can be no doubt that he performed a most valuable role, at once critical and catalytic. One of the most interesting studies in which he was concerned was directed to the xenoliths in the diamond pipes of South Africa. These deep-seated diatremes, generated by pressures high enough to produce the close-packed form of carbon, contain fragments of eclogite which many regard as the stuff of the Upper Mantle. In collaboration with F. A. Paneth, F.R.S., distinguished for his beautifully delicate determination of inert gases in small quantity,* the existence of the eclogite long prior to eruption was demonstrated, using helium-ratios (1936). Professor Paneth subsequently became Professor of Chemistry at Durham, where he undertook, among other exacting investigations, studies of the ages of meteorites.

In addition to R. W. Lawson and F. W. Paneth, Holmes worked closely with a number of other physicists and radiochemists: V. S. Dubey, W. D. Urry, A. A. Smales, H. A. Shillibier, J. Tuzo Wilson, W. T. Leland and A. O. Nier. It was fitting that the last mentioned was honoured in 1956 by the Geological Society of America at the same time as Holmes. Holmes's achievement in what is now called geochronology was crowned with the publication in his honour of an authoritative volume by the Geological Society of London in 1964 under the title of *The phanerozoic time scale*.

The thermal history of the Earth

During the later years of the nineteenth century Lord Kelvin's calculations, based upon a cooling earth had led to what seemed to be an unassailable estimate of 20 to 40 My of all geological time. Geology was liberated from this straight-jacket by the discovery by the Curies that radioactive elements impart heat to their environment; thus a source of spontaneous internal heat existed inside the earth. Holmes proposed (1913) that Kelvin's argument should be reversed; given the time, the thermal condition could be calculated. The result left open the possibility that, far from cooling down, our planet is heating up. But both a cooling (and therefore contracting) earth and a heating (and expanding) earth are difficult to reconcile with the

* *Biog. Mems. Roy. Soc.* (1960), **6**, 227-246.

facts of tectonics, which plainly point to periods both of regional compression and regional tension. In 1925 Holmes was particularly interested in a suggestion of J. Joly that the problem could be overcome by postulating cyclical heating up, followed by crustal sliding and cooling down. He had always been fascinated by the apparent periodicity of events in the geological record. The cyclical conception was elaborated in the last of five interesting papers on the earth's thermal history (1925) in which it was demonstrated that the known distribution of radioactivity was such that magma-generation must take place in the substratum, and not in the crust; a major 'peridotite cycle' was conceived, with many minor basaltic cycles. The most important aspect of the paper was, however, that it showed how unsatisfactory were existing concepts of the thermal regime of the earth, and prepared the way for a later major contribution to the subject.

Meanwhile, with Lawson, the role of potassium as a source of radioactive heat, hitherto neglected, was examined. The element is so much more common than uranium and thorium in crustal rocks, that as a source of radiothermal energy, it was shown to be of the same order of importance as the other two combined.

Earth movements

The stage was now set for the next forward movement. In 1929 Holmes announced to the Geological Society of Glasgow his conviction that heat in the substratum was transferred by means of convection currents, and that these were the principal cause of major earth movement. The first influential advocate of this hypothesis, he was followed later by Vening Meinesz and later still by Runcorn. It has the major advantage that it permits simultaneous tension and compression in different regions of the crust and thus closely fits the facts of tectonics. The implications of the proposal were examined in some detail; one of them was the acceptance of continental drift, if not in exactly the form proposed by Wegener, at least in a modified form; in a review of a symposium organized by the American Association of Petroleum Geologists (1929), Holmes threw in his lot with A. L. du Toit and E. B. Bailey in their championship of it. Subsequently continental drift encountered severe opposition from geophysicists and geologists alike, but in the past decade Holmes has had the satisfaction of seeing the hypothesis revived with strong support from palaeomagnetic evidence, and from the remarkable 'fit' of the continental shelves on opposing sides of the Atlantic where plotted in spherical projection.

Ore-genesis

Arthur Holmes's interest in the origin of lead in rocks led him to make one excursion into this field. In 1931 G. Hevesy and R. Hobbic had carried out estimations of the lead-content of 220 representative rocks supplied by him; their figures form the basis for the value of 16×10^{-6} g/g accepted today as the average content of the crust. Comparing the amount of lead found in

granites with that calculated as generated in them by radioactive decay showed a ratio of 8 : 1. Extending the calculation to atomic weights, and comparing the result with the available information for the lead of ore deposits showed no significant difference; but further data which had become available by 1937 led him to the belief that rock-lead had a significantly lower atomic weight than ore-lead; which appeared to have remained constant through geological time. The conclusion was therefore drawn that lead ores could not have been generated from granitic magmas, as was generally supposed at that time. The conclusion was criticized by A. Knopf and severely attacked by L. C. Graton; on the whole it is true to say that later isotopic studies of ore-lead have not vindicated Holmes's views, though his general conclusion that metalliferous ores come from the mantle rather than the crust has influential supporters today.

It will be evident from this brief review that Arthur Holmes was involved in some of the deepest controversies of geophysics of his day. This account would not be complete without some reference to his arguments with another geophysicist born on the Durham side of the Tyne, Sir Harold Jeffreys. The mutual reactions of these two exceptional men had a profound effect on the development of the subject even if at times they were in deep disagreement. Referring to his thermal contraction hypothesis, Jeffreys* says . . . 'my original work on it was published in 1916, just after Holmes's first theory of the Earth's thermal history, on which my work was based . . . '; and a little later, on Holmes's convection hypothesis 'So far as I can see there is nothing inherently impossible in it, but the association of conditions to make it work would be rather in the nature of a fluke'.

Petrology

The evolution of ideas which is so striking a feature of Arthur Holmes's record in geophysics is equally to be found in his petrological studies. The rocks collected on the Mozambique expedition of 1911 were Pre-Cambrian granites and gneisses, and Tertiary volcanics of alkaline affinities. These two themes recur through a life-time's work. But before discussing them, a tribute must be paid to his contributions to the technique of petrographical investigation. During his years at Imperial College he wrote two books which continue to be among the standard works any petrographer should possess. His *Petrographic methods and calculations* (1921) remains the student's best guide to some aspects of the subject; for example, it emphasizes the value of the expression of rock analyses in the calculated mineral 'norm' of Clarke, Iddings, Pirsson & Washington, and gives standard procedures. His *The nomenclature of petrology* (1920) gives a most valuable summary of the origins and significance of rock names. Also to be regarded as a general contribution is his classification of igneous rocks (1917) based on the silica-saturation principle, still very useful in teaching.

* *Geol. J.* (1931), **78**, 20-21.

Holmes did a great number of determinations of the radioactivity of igneous rocks in connexion with his earlier petrological studies, using Strutt's solution method. These established the relatively higher concentration in granitic and alkali rocks, compared with basic and ultrabasic rocks. Although in the case of the Mozambique work Holmes did many of the full chemical analyses of the rocks himself, he was fortunate to have from this time for the next twenty years the collaboration of H. F. Harwood, of Imperial College.

Basalt and alkali volcanics

The first major paper on petrology (1917) describes the basalt, andesite, sölvsbergite, phonolite, aegirine-trachyte and other lavas of a portion of the coastal belt of Mozambique. The diversity of alkali rock types was ascribed to crystallization differentiation, but desilication of the parent magma was attributed, not to assimilation of limestone but to reaction between an ultrabasic magma rising from the substratum and the basalt layer. The process envisaged physical separation of a pyroxenic phase from the liquid.

In the following year he described material from the basalts of the Arctic region, discussing the question of petrographic provinces; some shorter contributions from the same period dealt with lavas in Angola.

His interest in the basaltic intrusions in the North of England had already been aroused when he had collaborated with S. Smith on the Wackerfield dyke. Soon after his appointment to Durham he began to collect material for a new investigation of all the post-Carboniferous dykes and sills, including the Whin Sill which gave its name to that intrusive form. Little had been done since the work of Sir J. J. H. Teall, in the 1880s. Lady Teall generously presented her husband's specimens to assist in the work. The result (1928, 1929) was an orderly account of the Whin suite, and a clear discrimination between this and the dykes related to the Tertiary centres in West Scotland. When he was doing the work Holmes was unaware that J. A. Smythe, of Newcastle, had for several years been collecting material from the Whin Sill for what was probably the most comprehensive sampling ever carried out on any igneous body. When this work appeared, however, in 1931, it complemented perfectly that of Holmes and Harwood. It has only this year become possible to add anything of fundamental significance to these studies of nearly forty years ago.

In 1931 was begun another considerable study of African volcanics, this time from south-west Uganda. The field work was done by officers of the Uganda Geological Survey, particularly A. D. Combe, the petrography by Holmes, the chemical analyses by Harwood. The material was exciting, raising in an acute form the question of the origin of highly undersaturated rocks such as those carrying leucite and melilite. Interesting use of barium and strontium as geochemical indicators was made in the early stages of this work (1933) and the varied rocks of the Toro-Ankole field were attributed to

mica-peridotite and olivine-leucitite magmas formed essentially by the abstraction of eclogite and olivine from a primary peridotite magma under high-pressure conditions, due to great depth or high concentration of volatiles. Possible relationships with the diamond pipes were noted; the eclogite nodules were regarded as particularly significant. This petrogenetic hypothesis was very short-lived. The first stage in its abandonment was the discovery, already mentioned, that the eclogite and dunite nodules in Kimberlite are accidental, not cognate, therefore providing no clue to differentiation of the peridotite. Further, the remarkable series of lavas from Bufumbiro (1937), leucite-bearing types including ugandite, olivine-leucitite, mikenite, melilite-leucite nephelinite; leucite-feldspar rocks such as murambite, kivite, leucite-basanite, vesuvite and feldspathic alkali rocks such as absarokite, shoshonite and banakite, were found to present striking evidence of metasomatism, that is, of solid-state substitution.

Holmes had now reached a stage when a revolution was to take place in his thinking about petrology. Up to this stage, he had conscientiously, and sometimes ingeniously, applied hypotheses which could be founded upon the growing body of data about the physical chemistry of crystallization of minerals from melts. Now he was satisfied that these could not adequately explain the facts. 'The fundamental source of the difficulties lies in the fact that petrology is concerned with an integration of complications which lies far beyond the scope of present-day physical chemistry', he wrote (Bufumbira Memoir, 1937, p. 243). 'We must therefore be temporarily content with empirical hypotheses and we must regard them, not as a substitute for thought, but as a stimulant to further research, comparison and correlation.' In addition to the activity of magmas (melts of rock-material) he was now driven to contemplate metasomatism and 'transfusion' of pre-existing rocks by differential introductions of fluxes of emanations; and also the effects of differential fusion of pre-existing rocks. 'The factors concerned in metasomatism (*ibid*, p. 253) and in the related process—at a higher energy level—of syntectic or diatectic magma formation, may be expressed in a general way, as follows: (a) *Incoming emanations*—(from other "active" magmas or the "substratum") *plus* (b) *Energy* (secular, radioactive, ionic reactions, etc.) *plus* (c) *Crustal rock-material*, metasomatized, migmatitized, or more or less magmatized by (a) and (b); *minus* (d) *Outgoing emanations* and associated energy (magmatizing agents transforming other crustal rocks into magma; migmatizing agents generating migmatites, skarns and other syntectic rocks; pneumatolytic and hydrothermal fluids generating ore deposits and mineral veins, volcanic gases, etc.).'

The specific evidence of metasomatism in the Bufumbira volcanics was the presence, in quartz and quartzite xenoliths, of glassy veinlets which analysis showed were neither fused silica nor a solution of silica in the material of the enclosing lava; they represented the selective introduction into quartz of constituents in proportions surprisingly different from those in the lavas.

It happened that in 1934, on a joint visit to Kiloran Bay, Colonsay, with

Dr Reynolds, particularly clear examples of the transfusion of quartzite enclosed in hornblendite to glass, micropegmatite, syenite had been discovered,* and a further visit was made in 1936. 'The evidence is complete', wrote Holmes, 'that metasomatism and magma formation are intimately related processes, the active agent being a flux of emanations'. The Uganda volcanics were regarded as being formed, essentially from pre-existing sialic rocks, including sediments, plus emanations; that is, they were held to have been generated *in situ*. Further, it was maintained that the emanations were by no means necessarily derived from magmas; 'Recognition of the "flux of emations" as a working petrological concept—a concept which is more fundamental than that of magma—opens up a new world of possibilities' (*ibid*, p. 277).

To the petrological world these proposals were by no means universally acceptable; the postulated emanations were felt by some to be in the nature of a *deus ex machina*, and particularly suspect because they seemed to be fluids outside the scope of experimental investigation. A controversy between the magmatists and the metasomatists ensued which stimulated and enlivened the subject in Europe and America for a decade; but in this it was not Arthur Holmes but Dr Reynolds—now Mrs Holmes—who became a central figure. Experimental investigation has now been extended to hydrothermal systems at high temperatures and pressures, and supercritical phenomena are being investigated; metasomatism in igneous rocks is now widely recognized, even by some former bitter opponents of the emanationists; but it is still too soon to say that Holmes's contention that emanations from the mantle are of more fundamental importance than magma has been vindicated.

Granite

From the interior of Mozambique, Holmes (1919) described Katazone metamorphics and granites, suggesting that the gneisses were produced by the concordant injection of granitic magma into a series of pre-existing sediments. 'Of the latter, the argillaceous facies became granulized and controlled the formation of biotite-gneisses, while the calcareous or dolomitic facies formed . . . hornblendic and garnetiferous rocks' (1919, p. 95). 'Limestones tend to persist, since they are not easily granitized, like argillaceous rocks, but become enclosed within a blanket . . . of amphibolite . . .' It seems that even at this early stage, Holmes contemplated reaction as well as *lit-par-lit* injection of granitic magma, but the time was not yet ripe for this subject to be developed.

During the 1920s increasing attention was being paid by petrologists to the importance of crystallization-differentiation in producing varied suites of igneous rocks. Some importance attaches to the demonstration by Holmes that the quartz-dolerite magma of the Whin Sill was able to produce only about 5 % of quartz-orthoclase residuum by this process; the micropegmatite

* Reynolds, D. L. *Mineral Mag.* (1937), **24**, 367-407.

remained trapped in the crystal mesh and produced no significant acid intrusions. After the Geological Survey Memoir on Ardnamurchan* appeared in 1930, he used this and other evidence to suggest that it was quantitatively impossible for the amount of acid rocks in the Hebridean volcanic complexes to arise from the differentiation of basaltic magma, as Richey & Thomas implied, and suggested that palingenetic fusion of the granitic layer adjacent to the volcanic centres was a more satisfactory conception (1931). In the following year an examination of magma-generation in the light of crustal structure led him to propose three primary magmas, each derived from the fusion of appropriate layers: peridotite, basalt, granite. However, with his adoption of emanation petrogenesis, the crustal fusion hypothesis was relegated to a local role only; transfusion by highly energized emanations was considered to be of much more general application than fusion brought about by ascending heat alone. 'There is abundant evidence from every continent.' Holmes wrote (Bufumbiro, 1937, p. 249) 'that many granitic rocks, especially in orogenic belts, are themselves largely replacements of pre-existing sediments, schists and other sialic rocks, the granitization being due to a process of metasomatism by alkali emanations. The "granite" is the balance of what was there originally, *plus* what has migrated in, *minus* what has been driven out. Granite magma is held to disappear as a fundamental postulate; if it occurs it is merely granite plus emanations.'

Correlation of the Pre-Cambrian

The lack of control of correlation of formations older than the Cambrian by means of fossils meant that any attempt to understand Pre-Cambrian history and structure rested upon very slender foundations. The applications of radiometric data has revolutionized this position, and Arthur Holmes has played a leading part in synthesizing, on a world scale, the geochronological data, and in combining it with structural information. From this emerges a series of dated structural belts, showing how ancient orogenies gradually built up the shields and continental nuclei.

Holmes was well qualified to do this work. He had had first-hand acquaintance with the problems of field mapping of the ancient rocks in East Africa, and in 1931 he had visited Finland, to gain first-hand knowledge of Sederholm's work and that of his colleagues. Holmes's work on India began to appear in 1951, and on Africa the following year. Fruitful collaboration with Louis Cahen led to great advances in the general picture for the African continent. In his last work, the revised edition of *Principles of physical geology*, maps and a correlation chart for all the continents appear (1964) and form the most concise picture yet attempted for the ancient crustal formations.

Physical geology

A brief account of the main contributions of Arthur Holmes to the literature of the geological sciences through the learned journals has now been

* Richey, J. E. & Thomas, H. H. (1930), *Mem. Geol. Surv. G.B.*

attempted. Yet it is probably not chiefly for these that he will be remembered, great as they have been, but for his general texts on the *Principles of physical geology*.

In the earlier years of the second world War, when few students of geology other than R.A.F. cadets remained in Durham, he set himself the task of writing a book which would bring together the basic discoveries of geophysics, of geology in all its branches (save perhaps that of economic geology) and which would show how the landscape, the configuration of continents and oceans and the history of our planet could be understood in their terms. He set out to do this with a minimum of jargon, with constant reference to observational evidence, and with copious illustration. The book was aimed at the university student and the senior schoolboy, but the hope was expressed that it would also appeal to the wide range of general readers whose wonder and curiosity are excited by our mysterious world. 'My hopes have been surprisingly surpassed,' he wrote, twenty years after the first edition appeared (1964, p. v).

From the point of view of the scientific reader, the importance of the text is that it is no mere compilation of other men's ideas, though it pays full respect to these. It is a philosophy of the earth, constantly informed with Holmes's own ideas, often challengingly original. He had written little, other than his study of East African inselberg, on geomorphology, yet his Durham lectures both used this as part of the evidence for uniformitarian interpretation, and interpreted its processes in geological terms. The *Principles* gave written expression to a lifetime of interest in physical geography. On the other hand, the text contains far more on the geophysical side than is usually found in an introduction to geology.

'Rocks, like everything else, are subject to change and so also our views about them', wrote Loewinson-Lessing. Arthur Holmes in his sixty years as a geologist recorded many such changes of ideas; some of the most important like those concerning the age of the Earth, and its thermal history were profoundly influenced by his work.

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