STEPHEN MOORBATH
9 May 1929 — 16 October 2016
Stephen Moorbath was an intellectual with eclectic interests across the sciences and humanities. In 1939, as a ten-year-old, he fled from Germany to England with his father. Stephen spent almost the whole of the rest of his life—from schoolboy to university professor—in Oxford, where he became one of the world’s leading isotope geochemists. His academic career began with setting up Europe’s first radiometric rock and mineral dating laboratory. In this laboratory, together with numerous colleagues and students, he applied the lead–lead, rubidium–strontium, potassium–argon and, later, samarium–neodymium isotopic dating methods to the solution of many geological problems. He made major contributions in establishing the chronology for the geological and tectonic evolution of Precambrian crust in the Scottish Highlands and Islands, in West Greenland, Zimbabwe, South India, and Ghana. He developed isotopic criteria for assessing the relative contributions of mantle and crustal sources to Tertiary igneous rocks in Scotland, Andean volcanics and the late Archaean granitoids of West Greenland. He established dating methods for sedimentary rocks: Rb–Sr for shales and Pb/Pb for Archaean limestone. Stephen’s abiding geological passion was the study of the early Archaean, especially the Godthåbsfjord and Isukasia areas of West Greenland.

**Early Life**

Stephen Irwin Moorbath was born Stefan Irwin Moosbach, a Jewish German citizen, in Magdeburg on 9 May 1929. His father Hans (later Henry), born in the nearby town of Halle,
was a physician and paediatrician who had fought in World War I and received the Military Cross. His mother, Else, was a Rosenbaum. His paternal grandfather’s sister Henrietta, born in 1861, married into the Eulenburg family, the famous music publishers who printed most of the works of Brahms. He was related to a long line of distinguished musicians and philosophers including Bruno Walter and Karl Popper (FRS 1976). During his happy childhood, he went on walking holidays with his family in the Harz Mountains and spent much time at a Jewish children’s holiday home on the North Sea island of Föhr. His primary education was in a Catholic convent school because, after 1936, Jewish schools were proscribed. He remembered the growing antipathy toward the Jews, formally expressed by the anti-Jewish newspaper Der Stürmer, the torrent of anti-semitic taunts, and the horrors of Kristallnacht. Stephen was an exemplary pupil throughout his schooling in Magdeburg. His father practised medicine in his surgery in their house in Magdeburg but, in 1938, he was taken to the Buchenwald concentration camp. He bribed his way out in 1939, aided by his Military Cross. He was allowed to take his son out of Germany but was forced to leave his wife in the ghetto. The outbreak of World War II on 3 September prevented implementation of plans to bring her to England. Else was in contact with Stephen and Henry through the British Red Cross until 1942, when she was removed, with the rest of the Magdeburg Jews, to the Theresianstadt extermination camp where they were murdered by the Nazis.

**LIFE IN ENGLAND**

Stephen and his father (now Henry) arrived in England on 24 May 1939, by train through Holland, with the help of a refugee organization and a guarantor in Britain. In giving sanctuary to Stephen and so many other refugee Jewish German children at that time, Britain was to gain an intellectual treasure house in many fields. Stephen and his father were given a pound a week by the Jewish Refugee Committee and found a room in Brighton. The room turned out to be too small for both of them, so Stephen was placed with an old lady in Worthing where there was already another Jewish boy from Magdeburg. The old lady found two boys too much, so Stephen went back to live with his father in the cramped room. However, his father was very soon sent to an internment camp on the Isle of Man, and Stephen was placed in a boys’ hostel in Hove, and then in a hostel for German boys in High Wycombe, where he became a lifelong friend of Peter Pulzer. There he was again taunted, this time for being German. Throughout his early life, he had religion and nationalism thrust down his throat, which led to his lifelong atheism and his forgiving international outlook. In 1941, he was sent, with other refugees, to a family in North Oxford. Now at last he began a new, relatively stable and normal life.

At the end of World War II, his father became a doctor, first in the Ministry of Pensions Hospital in Liverpool, and then as a Captain in the Royal Army Medical Corps. Later, he remarried and became a doctor in Newcastle-upon-Tyne. Stephen visited him, gained a half-brother, and enjoyed short holidays in Northumberland.

After primary school, Stephen attended the Oxford High School for boys from 1941 to 1945, where he made many new friends including Ronnie Barker, from whom Stephen may have caught an infection of humour, which was to stay with him for the rest of his life. It was here that he discovered his fascination with chemistry, and he became a fine young scholar in both arts and sciences. His love of chemistry was profound: he thought about it all the time,
and realized that it was his vocation. However, at the age of 16, he was financially unable to continue into the sixth form and was released from formal education to make his way in life.

**Biochemistry technician in Oxford**

Stephen realized that, to fulfil his dreams of becoming a professional chemist, he needed, simultaneously, to get a job and further his education. Thus, he worked as a laboratory technician in the Biochemistry Department in Oxford University for three years. The job offered a day off each week to attend classes and take evening classes at the Technical School in St Ebbe’s. He studied a range of arts and sciences and achieved his Higher School Certificate in 1948.

In Biochemistry, where Sir Howard Florey FRS, Ernst (later Sir Ernst) Chain (FRS 1949) and Edward (later Sir Edward) Abraham (FRS 1958) were working on penicillin and other drugs, he participated in a wide variety of experiments, mainly setting up columns with early versions of ion-exchange resins. He was a very fortunate early recipient of penicillin for the treatment of a severely infected leg, which he sustained from a very bad fall in the department.

He had vivid memories of the departmental glass-blower, Harold Vincent, one of the most important people in the department: he had a brilliant facility for manufacturing all the apparatus upon which their research depended. During this period in Biochemistry, Stephen joined the Youth Hostels Association and explored a great deal of England, Wales and Scotland, especially the mountains. He also visited Norway, where he learnt to ski proficiently.

**Harwell**

In 1948, his Higher School Certificate enabled him to seek a better job in science. He applied for and was appointed to the position of Assistant Experimental Officer at the Atomic Energy Research Establishment at Harwell, in the Inorganic Chemistry Division (figure 1). There he worked on radiation chemistry and the structure of uranium and thorium oxides as fuel for nuclear reactors. He lived in a staff hostel in Abingdon, took the bus to and from Harwell, and was very fulfilled in learning a huge amount of chemistry and having his name on several papers. He described this phase of his life as idyllic, working in a friendly, intellectual environment in which he felt that, for the first time, he was making valuable contributions to fundamental science. He was shocked by the treason of Klaus Fuchs and the putative defection of Bruno Pontecorvo during his time at Harwell; throughout his working life and retirement he was a man of intense loyalty.

Stephen’s work was sufficiently admired that, in 1951, he was invited to apply to the Competition for University Grants. He was called for a nerve-wracking interview before Sir John Cockcroft FRS and was given an award to enable him to study for three years towards a degree in chemistry at a university of his choice. He naturally chose Oxford, his home town, and was accepted by Lincoln College, where his tutor was Rex (later Sir Rex) Richards (FRS 1959).

**University of Oxford**

Stephen chose physics as his subsidiary subject and settled down to work hard. It was a chance visit to the Department of Geology and Mineralogy with a friend that caused a Damascene conversion on seeing people re-arranging cases of rocks, minerals and fossils. He realized, in a flash, perhaps influenced by his extensive walking in mountains and picking over stones on Brighton beach, that he must switch to read geology. Rex Richards was not too keen on this.
A real struggle ensued with the scientific civil service and with Harwell, but after substantial negotiations, the conversion was agreed and he was allowed, in 1952, to switch to geology with chemistry as a subsidiary. Modern geochemistry was beginning to develop at this time. Stephen thrived and was awarded a first class degree in 1955.

In Oxford, Stephen shared a flat with David Bell and Brian Upton, both of whom went on to distinguished academic careers in igneous petrology. They recall that Stephen became President of the University Psychical Society, famous for ghost-hunting. After one hair-raising expedition, after they all went to bed, a loud crash echoed through the building. Stephen’s response was to pull the covers over his head and moan softly. In the cold light of dawn, the cause of the crash was discovered to be the collapse of a worm-eaten, fragile chest of drawers, overlaid with Stephen’s ammonite collection. As an undergraduate in still-rationed Britain, Stephen supplemented meagre college fare with the signature dish of the Taj Mahal in Turl Street, purportedly the first Indian restaurant in the UK: a hollowed-out loaf filled with vegetable curry.
Following graduation, he returned to Harwell, where he founded an Analytical Geochemistry Group in Alex Smales’ Division of Analytical Chemistry. The role of this Group was to find a way of dating rocks and minerals. Stephen investigated monazite, a rare-earth phosphate, which also contains thorium and some uranium. Dating minerals rich in thorium and/or uranium depends on the radioactive decay of $^{235}\text{U}$ to $^{207}\text{Pb}$, $^{238}\text{U}$ to $^{206}\text{Pb}$, and $^{232}\text{Th}$ to $^{208}\text{Pb}$. Using chemical methods to measure quantities of uranium, thorium and lead, Stephen was only able to calculate rather imprecise ages for the monazite because, without a mass spectrometer, he was unable to distinguish the isotopes of lead. There were mass spectrometers at Harwell, but they were fully dedicated to atomic energy research and unavailable to his group.

Now an amazing stroke of luck occurred: Professor L. R. (Bill) Wager FRS, a geologist with many geological discoveries and mountain climbing feats to his name, had been appointed Professor of Geology at Oxford in 1950, to save a failing Department. He now invited Stephen to return to Oxford as his Personal Assistant to set up a geological age laboratory (later known as ‘The Age Lab’). He gladly agreed and started work on 1 January 1956. In 1957, the first commercially built, solid-source mass spectrometer (Metropolitan–Vickers MS5) was installed, and Stephen started work on calibrating the machine and developing new chemical techniques for separating uranium and lead from rocks and minerals. Stephen admitted to being overawed by this ‘monster of a machine’ and it took him several months to pluck up courage before he dared run lead samples on the triple filaments. It was a very labour-intensive procedure, involving magnetic peak scanning; a pen and ink chart recorder, the output of which had to be measured with a ruler; and mercury diffusion pumps whose cold traps had to be filled with liquid nitrogen every nine hours. He was now courting his wife-to-be, Pauline Varlêt, who willingly helped him with this activity. Stephen and Pauline met in 1957 at art evening classes where they found themselves the only ones enrolled on the pottery course. During their courtship, they had happy holidays in Austria and Italy, hiking and skiing. In 1959, after only two years’ work, he produced his innovative DPhil thesis on the age of British galena deposits.

Bruno Giletti arrived from Lamont in 1958 for a two-year sabbatical. He brought with him the rubidium–strontium method, so that Oxford was the first laboratory in Europe to carry out routine Rb–Sr age determinations, using isochron and intersection plots. Other key players in this period were Martin Dodson and Derek York, who set up the potassium–argon line, Eric Hamilton and Alan Mills. Norman Snelling, an employee of the Overseas Geological Survey, played a key role in rock-dating work and liaising with Harwell.

The dating lab now entered a period of exciting growth and, by 1960, was ‘up and running’. Stephen now took a well-deserved postdoc in MIT, and married Pauline in Boston in 1961. They then faced a dilemma. They considered what could have been a bright future in US academe, but they would have had to leave the USA for one year before returning. Simultaneously, Wager offered Stephen an academic position in Oxford in 1962 to run and continue to develop The Age Lab, which Stephen accepted (figure 2). On their return to the UK, they set up house in a rented, rather primitive, cottage with no bath or toilet in Horspath, just outside Oxford. Pauline developed a career in art and exhibition design, and in 1967 they moved to a house in Kennington, where they raised their children, Nicholas and Susannah. They took regular holidays on the Isle of Wight, where geology and fossil collecting were enjoyed. Nicholas became an important figure in the popular music scene as a member of the group Ride. He developed a music recording studio and owned the popular night club ‘Zodiac’ in Oxford.
Stephen’s major contributions were in the fields of geochronology and isotope geochemistry. He established and developed methods for the analysis and interpretation of K–Ar, Rb–Sr, U–Th–Pb and Sm–Nd age and isotope data, and then applied those methods to a wide range of geological problems. He and his co-workers thereby provided vital age data on the geological development of the continental crust, particularly during the early Precambrian. His work on the early Archaean rocks of West Greenland won him particular renown: at the time of their discovery in 1971, the Amitsoq gneisses were the oldest known rocks on Earth and the earliest-known continental crust (13)*. The subsequent discovery in 1973 of the slightly older (3.75

* Numbers in this form refer to the bibliography at the end of the text.
billion years old) Isua Supracrustal rocks \(17\) has provided important evidence concerning the earliest terrestrial surface processes.

Stephen also developed and applied radiogenic isotopic criteria to questions concerning the petrogenesis of igneous rocks, both ancient and modern. His extensive use of strontium and lead isotopes to demonstrate convincing evidence for the interaction of mantle-derived magmas with the lower continental crust was perhaps his signature contribution in this field. The results are especially compelling when the lower crust consists of ancient uranium-depleted basement rocks.

**Lead isotope studies of British lead ore deposits and models for the Earth's lead isotopic evolution**

Stephen’s career in isotope geology began with his DPhil project, a large and comprehensive study of the isotopic compositions of lead in galena specimens from the mineral deposits of the British Isles \(1, 4\). For a few of his galena samples, he was able to establish the age of the mineral deposits by reference to K–Ar, Rb–Sr and U–Pb dates for associated igneous rocks. He reviewed the then current models for terrestrial Pb isotopic evolution and concluded that the Holmes–Houtermans model provided the most reliable basis for estimating the age of galena mineralization. A large proportion of his galena samples gave model ages consistent with published geological constraints on their ages of mineralization. Stephen identified six periods of mineralization in the British Isles between Lower Palaeozoic and Upper Mesozoic times. The two most important of these were associated with the Caledonian and Hercynian orogenies.

Analytical and model uncertainties on the Pb/Pb model ages of galenas are too great for this ever to be regarded as a precise geochronological method: the main value of Stephen’s study was to provide a large body of data to test and constrain models of whole-Earth Pb isotopic evolution, including the assessment of the Earth’s U/Pb and Th/U values. These model parameters informed much of Stephen’s later work using the Pb/Pb method on the trace lead in whole-rock samples.

**The Pb/Pb whole-rock dating method and the use of Pb isotope geochemistry in igneous petrogenesis**

The Pb/Pb geochronological method depends on the radioactive decay of \(^{238}\text{U} \rightarrow ^{206}\text{Pb}\) and \(^{235}\text{U} \rightarrow ^{207}\text{Pb}\). Pb isotopic compositions of rock samples that have formed at the same time and with the same initial Pb isotopic composition, but with a range of U/Pb ratios, evolve through time to plot on the same straight line in a \(^{207}\text{Pb}/^{204}\text{Pb}\) versus \(^{206}\text{Pb}/^{204}\text{Pb}\) isochron plot, provided that the samples remain closed systems with respect to uranium and lead from the time of their formation to the present. The age of the rock unit is then determined by the gradient of the isochron line. The Pb/Pb method is most effective for dating Archaean and early Proterozoic rocks. Stephen became one of the foremost proponents of this method of dating igneous and metamorphic rocks.

In a remarkable series of related publications over the course of a few months in 1968–1969, Stephen, together with Hans Welke and others, reported on the lead isotopic compositions of a substantial collection of Lewisian gneisses from northwest Scotland \(12\), an extensive suite of Tertiary igneous rocks from the Isle of Skye in northwest Scotland \(10\), samples of the Tertiary granite on Rockall \(9\), and a suite of igneous rocks from Iceland \(8\).
Lead from the Lewisian gneiss samples defined a Pb/Pb isochron which gave a late Archaean age and indicated an origin from an upper mantle source (12). The Lewisian gneisses all had lead isotopic compositions that demonstrated severe uranium and thorium depletion already from late Archaean times when these rocks were formed. This feature has subsequently been seen in other areas of high-grade gneisses, particularly in granulite terrains. Thus, Precambrian gneisses and granulites may have remarkably distinctive lead isotopic fingerprints in the form of unusually low $\text{Pb/204Pb}_\text{206}$, $\text{Pb/204Pb}_\text{207}$, $\text{Pb/204Pb}_\text{208}$ ratios.

Those Lewisian fingerprints manifested themselves very clearly in the study of the Tertiary igneous rocks from the Isle of Skye (10). Skye was a major centre of Tertiary igneous activity about 60 million years ago, associated with the opening of the North Atlantic Ocean. There are basalt lava flows, large bodies of basic and ultrabasic igneous rocks, granites, granophyres and felsites, and an extensive swarm of dolerite dykes. Stephen and his colleague, Hans Welke, extracted and isotopically analysed the lead from a large suite of these rocks. All the Skye Tertiary igneous rocks, from ultrabasic and basic rocks of undoubted mantle origins, through intermediate to silicic compositions, show clear evidence of interaction with Lewisian basement rocks. The lead isotopic compositions of the Skye igneous rocks plot on a mixing line between lead characteristic of the upper mantle in the early Tertiary and the very distinctive lead typical of late Archaean uranium- and thorium-depleted Lewisian high-grade gneisses. In general, the silicic igneous rocks have a larger proportion of Lewisian lead than the mafic rocks. However, even the ultramafic rocks have assimilated some of the isotopically distinctive Lewisian lead. Whenever high temperature basaltic magmas sit in chambers in the lower crust it is more or less inevitable that some interaction or assimilation of crustal material takes place.

From their lead isotope study of the samples of the Rockall aegirine granite, Stephen and Hans Welke demonstrated that these rocks also plotted on a mixing line between early Tertiary mantle-derived lead and the distinctive Lewisian-type lead (9). The important conclusion of this study was that the Rockall Bank is underlain by ancient uranium- and thorium-depleted crust, which has contributed lead to the magma from which the Rockall granite crystallized, thus demonstrating the continental affinities of the Rockall Bank.

Theories of sea-floor spreading and plate tectonics were still in their infancy in 1968, so it was natural that Stephen should also turn his attention to Iceland, which consists almost entirely of Tertiary and Quaternary igneous rocks. Together with Haraldur Sigurðsson, Stephen carried out K–Ar dating to find out how old Iceland’s oldest rocks were and where they were located (7). The oldest rocks, at 16 million years, were found at the northwest extremity of the island. The youngest rocks are those located nearest the rift or spreading axis. The rocks at the southeastern extremity are 12.5 million years old, and 150 km from the spreading axis. Thus they proposed a model for the growth of the Icelandic crust to the southeast of the rift at an average spreading rate of 1.2 cm per year.

But was Iceland all brand new, mainly basaltic crust, or was it underlain by any ancient continental material? Whereas basaltic rocks are by far the dominant exposed rock-type in Iceland, there are some occurrences of andesite, dacite, obsidian and granophyre. Stephen and his colleagues carried out Pb isotopic analyses on a large suite of samples of these various rock-types. Their results (8) were markedly different from what they had found with the Tertiary igneous rocks of Skye (10) and Rockall (9). Of Lewisian-type lead there was not a trace. All the Icelandic rocks, even those of intermediate and silicic compositions, had lead isotopic compositions characteristic of rocks very recently derived from the Earth’s upper
mantle. Even the acid igneous rocks had evolved by differentiation of basaltic magmas derived from the mantle. They were thus able to conclude that Iceland has no ancient continental basement. Rather it is a very young and wholly oceanic island.

The studies of the Tertiary igneous rocks of Skye and Rockall have led to the recognition that magmas that have any interaction with ancient continental basement are likely to have their lead isotopic compositions significantly modified as a result. Where there is no ancient basement, as is the case on Iceland, the igneous rocks have initial lead isotopic compositions characteristic of the upper mantle sources from which they were derived.

**Timescale of events in the development of the Scottish Highlands**

In the early days of Rb–Sr geochronology, Stephen and his co-workers undertook a key reconnaissance study of the Scottish Highlands (2, 3). For the Lewisian, within the area of well-preserved Scourian basement, pegmatites gave results indicating an age of at least 2460 million years, whereas the Laxfordian metamorphism and deformation occurred at around 1600 million years ago.

Muscovite from pegmatites in the Knoydart–Morar area gave a minimum age of approximately 700 million years for the pegmatites, and hence for the Moine Series into which they were emplaced. Micas from several Moine Series rocks indicated that the metamorphism of the Moine Series took place around 420 million years ago, while Dalradian specimens from Perthshire, and from the Connemara Schists from western Ireland, underwent their metamorphism some 475 million years ago.

This study provided valuable insights into the timescale for the geological evolution of the Scottish Highlands, which has been gradually refined by later, more detailed studies with improved analytical and interpretative methods.

The Torridonian conglomerates, sandstones and siltstones of northwest Scotland rest unconformably on Lewisian basement, and are themselves unconformably overlain by Cambrian quartzites. Stephen carried out K–Ar and Rb–Sr dating of detrital feldspars, micas and pebbles with suitably high Rb/Sr ratios and showed that the Torridonian sediments were derived from a geologically complex source region (6). Dates ranged from 1700 to 1150 million years. The older dates suggested derivation from Laxfordian sources, but the younger dates are otherwise unknown in the near vicinity of northwest Scotland and are probably Grenvillian from Canada. Rare shale samples with high Rb/Sr ratios gave maximum ages in the range 815–905 million years.

A couple of years later, Stephen revisited the question of the depositional age of the shales and siltstones of the Torridonian (11). Lower Torridonian Stoer Group samples gave the Rb–Sr whole-rock isochron age as 930 million years. Samples from the Upper Torridonian Applecross Formation near Gairloch gave a younger age of 760 million years. That 170 million year age difference between Lower and Upper Torridonian was an important result, in full accord with a profound difference in palaeomagnetic pole positions for these units. This study was one of the first to establish the depositional age of sedimentary rocks by directly dating the strata themselves.

**Precambrian crustal evolution: Lewisian of Scotland**

Throughout the course of his geological career, Stephen, with his research students and colleagues, made a great contribution to our understanding of the development of the Lewisian of northwest Scotland. Rb–Sr and Pb isotopic analysis of large suites of samples of the
Lewisian grey (granitoid) gneisses from the Outer Hebrides (14, 25), from the mainland of northwest Scotland (12, 32, 55), and even from the Scardroy Mass to the east of the Moine Thrust (20), have established that a major episode of crust formation and high-grade metamorphism took place during the late Archaean between 2.9 and 2.6 billion years ago. Some areas of the Lewisian have suffered very little modification since that time. In other areas the effects of later metamorphism and crustal reworking approximately 1.7 to 1.5 billion years ago have been profound, not least in the vicinity of Loch Laxford. There granitic sheets within the Lewisian complex gave Rb–Sr and Pb/Pb isochron ages of about 1.7 billion years. The Badcall Quay granite has Sr, Pb and Sm–Nd isotopic characteristics that indicate an origin by remelting of Archaean high-grade gneisses that had been severely depleted in Rb, U and Th since about 2.7 billion years ago. The Sm–Nd model age \( T_{\text{CHUR}} \) for this granite was 2.75 billion years, closely comparable with that of Scourian gneisses and granulites of the area. Other Laxfordian granite sheets apparently include components derived from the Lewisian basement and from mantle sources. Sm–Nd data for the Rubha Ruadh granite were consistent with a mixture of late Archaean crust-derived component and a Proterozoic mantle-derived component (51).

The discovery of the world’s oldest known rocks: Godthåb–Nuuk region and Isua, West Greenland

Soon after Stephen’s Pb/Pb study of the Lewisian was published (12), Kent Brooks put Stephen in touch with Vic McGregor, a young New Zealander who was mapping the Godthåb region for the Geological Survey of Greenland (GGU). Vic had noted that some of the grey gneisses (Amîtsoq gneisses) of the region had been intruded by a swarm of basic (Ameralik) dykes, whereas there were other gneisses (Nûk gneisses) in which no basic dykes were found. He reasoned that the gneisses that contained the dykes must be older than those without them. He sent a small collection of Amîtsoq gneisses to Oxford for Stephen and his colleagues to analyse. In 1971 they published the extraordinary results (13). Rb–Sr and Pb isotopic analyses of the whole-rock samples defined isochrons that clearly demonstrated early Archaean ages, older by several hundred million years than any terrestrial rocks discovered up to that time (figure 3). Further, the Amîtsoq gneisses have a low initial \( ^{87}\text{Sr}/^{86}\text{Sr} \) ratio, considered characteristic of rocks extracted from upper mantle sources very early in the Earth’s history.

The very low \(^{206}\text{Pb}/^{204}\text{Pb} \), \(^{207}\text{Pb}/^{204}\text{Pb} \), and \(^{208}\text{Pb}/^{204}\text{Pb} \) ratios of these rocks also showed that from 3.6 billion years ago they have been severely depleted in uranium and thorium (a fate similar to that suffered by the Lewisian gneisses in late Archaean times).

This discovery took place at the time when most of the world’s premier geochronology labs were busily engaged in the analysis of all the lunar material returned to Earth by the Apollo missions. It proved to be a blessing in disguise that the Oxford Lab was not involved in the Lunar Programme and was able to devote its attentions to the exciting discoveries in West Greenland.

In the early 1970s Stephen spent several summers in the Godthåb area with Vic McGregor to collect samples of the Amîtsoq and Nûk gneisses and various other units for further isotopic studies (15–19, 24, 27, 31, 41, 44, 51).

The Amîtsoq gneisses were subjected to a thorough campaign of Rb–Sr whole-rock isochron dating in several of the areas where they crop out. This confirmed the great antiquity of these gneisses and established that, from early Archaean times (3.6–3.7 billion years ago),
the Earth has been producing dioritic, tonalitic and granodioritic rocks that have remained as part of the continental crust to this day (15).

In the summer of 1971, Stephen and Vic had the opportunity to visit a locality at the edge of the inland icecap beyond the head of Godthåbsfjord, now known to the geological world as Isua. A major magnetic anomaly had attracted the attention of a mining company, which then discovered a mountain of high-grade magnetite ore, the Isua Banded Iron Formation. The Banded Iron Formation (BIF) is part of a suite of supracrustal rocks (i.e. rocks of sedimentary and/or volcanic origin, formed at the surface of the Earth) that form a horseshoe-shaped belt surrounded by quartzo-feldspathic gneisses very similar in character to the Amítsq gneisses. At several locations along the contact, there is evidence that the igneous protoliths of the gneisses intrude the supracrustals. Both gneisses and supracrustals are cut by a swarm of metadolerite dykes that closely resemble the Ameralik dykes. The Pb/Pb age of 3.75 billion years for the BIF samples reported by Stephen and his colleagues (17) gave important insights into the surface processes operating in the early history of the Earth: associated with the BIF in the Isua Supracrustal Belt, there are both acid and basic meta-volcanic rocks, as well as pelitic metasediments that started life as water-laid clays and shales. The sedimentary and
volcanic processes that we see in action today have been around for a very long time. Ever since the discovery of the early Archaean age for the Isua supracrustals, there has been intense scrutiny of these rocks for what they can reveal of surface processes on the early Earth. Stephen revisited Isua many times over the course of his life: it remained an endless source of fascination to him.

In 1978, Stephen’s colleague, Peter Appel, discovered a mineral vein in the Isua supracrustals from which he obtained some galena. Stephen received this with great excitement; it proved to have the least radiogenic Pb isotopic composition ever measured on a terrestrial sample—Amítsoq gneisses included—and gave a Pb/Pb model age fully consistent with its early Archaean setting (37), a rare return to the theme of his first isotopic studies of lead mineralization.

The gneisses that enclose the Isua supracrustals also yielded an early Archaean Rb–Sr whole-rock isochron age, confirming their equivalence with the Amítsoq gneisses (31).

Late Archaean crustal evolution in West Greenland

In addition to the early Archaean rocks (Isua supracrustals and Amítsoq gneisses), there were further extensive additions to the continental crust of West Greenland during the late Archaean (16, 27, 41, 51). Stephen and his co-workers applied the Rb–Sr and Pb/Pb whole-rock methods to establish the timing and extent of these events. They showed that, over a large area from Sukkertoppen in the north to Fiskenaesset in the south, between 3.0 and 2.8 billion years ago, granites, granodiorites, tonalites and diorites were added to the West Greenland crust and subjected to deformation and high-grade metamorphism. To the northwest of Godthåbsfjord, no outcrops of early Archaean rocks are known: the area consists solely of late Archaean granulite facies orthogneisses (16, 41). To the south, around Fiskenaesset, the area was also devoid of early Archaean rocks. However, in the Godthåbsfjord area itself, large volumes of Nûk gneisses were emplaced through and into the early Archaean crust (27, 41). The criteria for recognizing these as late Archaean additions to the crust were their low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (typically ca 0.702) and Pb isotopic characteristics for the granulites typical of rocks freshly derived from an upper mantle source. The Nûk gneisses of Godthåbsfjord, however, have Pb isotopic compositions that indicate interaction with the ancient early Archaean uranium-depleted crust through which they were emplaced (41, 51), a similar story to that of the Tertiary igneous rocks of Skye interacting with their Lewisian basement.

The long history of crustal evolution in the Archaean of West Greenland concluded with the intrusion of the Qôrqut granite in the Godthåbsfjord area (18, 44, 51). Stephen and his co-workers first established a very late Archaean age for that event by Rb–Sr isotopic analysis of the minerals of a pegmatite associated with the granite (18). In a later study (44), Rb–Sr and Pb/Pb whole-rock analyses of a large suite of granite samples confirmed the very late Archaean age (2.5 billion years) of the granite and provided clear isotopic evidence that the Qôrqut granite was the product of crustal reworking. The high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the granite (0.708) and its Pb isotopic characteristics were best modelled as the result of partial melting of a mixture of early Archaean Amítsoq gneisses and late Archaean Nûk gneisses (44, 51). This study demonstrated that the combined use of initial $^{87}\text{Sr}/^{86}\text{Sr}$ and Pb isotope data provides powerful criteria for the recognition of crustal reworking events and the crustal origins of some granites.
Further discoveries of ancient gneisses in Zimbabwe

The areas of Archaean surrounding the North Atlantic (Lewisian of Northwest Scotland; Lofoten–Vesterålen, North Norway; East and West Greenland; Labrador) consist of high-grade gneisses in amphibolite or granulite facies. By contrast, many other Archaean cratons consist substantially of granites and greenstone belts. One such region is the Archaean Craton of Zimbabwe. Encouraged by Jim Wilson, professor of geology at the University of Harare, Stephen together with Chris Hawkesworth (FRS 2002) made collections of samples from some of the main rock units to establish the chronology of events in the Craton’s geological development (23, 28, 34, 61). Rb–Sr whole-rock studies established that two areas of gneiss (Mashaba and Shabani) have early Archaean ages (3.6 billion years) and low initial $^{87}$Sr/$^{86}$Sr ratios, which imply new additions to the crust from early Archaean mantle sources (23, 34). Volcanic rocks of the main, Bulawayan, greenstone belts were erupted in the late Archaean (2.7–2.6 billion years). Late tonalite intrusions were also emplaced at that time. There are also late Archaean gneisses and migmatites, very slightly older, which just predate the eruption of the main greenstone belt volcanics.

In addition to the Bulawayan greenstone belts, there was an earlier generation, the Sebakwian. In the vicinity of Selukwe, the Mont d’Or granite was intruded into the Sebakwian greenstone belt. Stephen’s Rb–Sr and Pb/Pb age and isotope studies showed that the Mont d’Or granite is 3.35 Gyr old and has a high initial $^{87}$Sr/$^{86}$Sr ratio of 0.711 and unusual Pb isotopic characteristics, both of which indicate that the granite was derived by partial melting of still older continental crustal rocks that had not been depleted in Rb, U or Th (28, 51).

In terms of models for crustal evolution, all the rock units of late Archaean age have low initial $^{87}$Sr/$^{86}$Sr ratios: they were all new additions to the crust: none of the late Archaean magmas was the product of ancient crustal melting. This was a major episode of late Archaean crustal accretion.

The discovery of stromatolitic structures in a limestone in the Mushandike National Park prompted an investigation to measure the age of the limestone to determine when these stromatolites were formed. Stephen and his co-workers used the $^{207}$Pb/$^{206}$Pb method to determine a late Archaean isochron age for its deposition (56). Limestones with little or no detrital component have very low contents of original lead, but they do include significant uranium. Consequently, some ancient limestones develop extremely radiogenic Pb isotopic compositions, conducive to precise age determinations. This was the first direct isotopic dating of a limestone by the Pb/Pb method. The method has subsequently proved useful for carbonate rocks of sedimentary, metamorphic (marbles) and igneous origin (carbonatites).

A time-frame for the development of the Karnataka Craton, South India

Like Zimbabwe, the Karnataka Craton of South India consists substantially of granites and greenstone belts with a basement of gneisses. Stephen undertook a project to investigate the chronology of events in the development of the Karnataka Craton in collaboration with Brian Chadwick of the University of Exeter and Dr M. Ramakrishnan of the Geological Survey of India (49, 50).

In the Karnataka Craton, the Peninsular gneisses and granitoid intrusions that underlie the Dharwar Supergroup (greenstone belts) have ages in the range 3.1–3.0 billion years, with Sr and Pb isotopes characteristic of rocks derived from upper mantle sources at or shortly before that time. The Dharwar Supergroup, in the Chitradurga Belt, was intruded by the
2.6-billion-year-old Chitradurga granite, also a new addition to the crust. The Pb and Sr isotopic compositions of the Peninsular gneisses and granitoids show no evidence of the extreme uranium, thorium and rubidium depletion that is characteristic of some Precambrian high-grade gneiss terranes.

**Early Proterozoic crustal growth: the Birimian of Ghana**

Much of western and central Ghana is underlain by NW–SE trending belts of meta-volcanics and meta-sedimentary rocks, and a suite of granitoids. Stephen’s extensive programme of Rb–Sr, Pb/Pb and Sm–Nd whole-rock isotopic analyses of suites of these rocks established that they were formed in a fairly short-lived episode of early Proterozoic crustal accretion (62). The meta-volcanic samples gave a Sm–Nd whole-rock isochron age of about 2.15 billion years. The granitoids from the Kumasi and Upper West areas gave consistent Rb–Sr and Pb/Pb whole-rock isochron ages at around 2.1 billion years, all with Sr and Pb isotopic characteristics typical of rocks newly derived from upper mantle sources. Sm–Nd model ages for the meta-sedimentary rocks indicate that they consist of detritus derived from the early Proterozoic igneous rocks. The granitoids of the Winneba area provided the only isotopic evidence for a magmatic contribution from older crust, a presumed Archaean basement in that area. Stephen and his co-authors concluded that the 2.1–2.2 Ga Birimian terranes in Ghana and neighbouring West African countries represent a major episode of new crust formation not widely known elsewhere. Stephen thought that it may be the product of the first plate tectonic regime on Earth as an assemblage of volcanic arcs colliding with micro-continents.

**Petrogenesis of Tertiary and Quaternary igneous rocks**

Although Stephen was best known for his work on some of the world’s oldest rocks, he was just as devoted to the application of isotope geochemistry for better understanding the petrogenesis of much younger igneous rocks. No student of geology at Oxford during the days of Professor Wager could possibly avoid exposure to the Tertiary igneous rocks of the Isle of Skye in northwest Scotland. Stephen and his good friend and contemporary, David Bell, were two who came under that particular spell.

**Skye and the Tertiary igneous province of northern Britain**

In an innovative study for its time, Stephen and David Bell (5) reported Rb–Sr isotopic analyses for a substantial suite of igneous rocks from the Isle of Skye. These included basalts, dolerites, gabbros and peridotites from the Cuillins, and granites from the eastern and western Redhills Complexes and samples of the marscoite suite—considered to be the products of mixing of acid and basic magmas. They established an age of $54 \pm 3$ million years for the Redhills granites and used that age to calculate initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for the whole sample suite. The basic igneous rocks generally had the low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios typical of magmas derived from mantle sources. By contrast, the granite samples and the rocks of the marscoite suite had much higher initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, and these indicate that the granites and marscoite suite were produced by partial melting of an ancient source with Rb/Sr ratio significantly higher than that of the basaltic magma source. Lewisian rocks, which form the underlying basement in the area, seemed the most plausible candidate. Not long afterwards Stephen and Hans Welke (10) carried out their study of the Pb isotopic characteristics of the Skye igneous rocks and reached similar conclusions (see above), though they noted that even the mafic igneous rocks had acquired a significant component of Lewisian lead.
In 1980, Stephen reported further on the Sr isotopic composition of the Early Tertiary lavas of Skye in association with Bob Thompson (42). They analysed a large suite of samples from the Skye Main Lava Series (SMLS) composed of basalts, hawaiites, mugearites, benmoreites and trachytes, and also from the olivine tholeiites of the Preshal Mhor type, together with associated dykes. The SMLS had initial \( {^{87}Sr/^{86}Sr} \) ratios ranging from 0.70308 up to 0.70571; the Preshal Mhor basalts from 0.70307 up to 0.70621. These variations indicate that, for both suites, there has been significant interaction of parent magmas with the Lewisian basement, with contamination increasing as basalt magma fractionation progressed.

The interaction of mantle-derived basaltic magmas with the ancient Lewisian basement manifested itself in two ways. First, the magmas themselves assimilated isotopically distinctive Sr and Pb from the crustal rocks in which they were ponded. The magmas also gave rise to partial melting of the ancient crustal rocks. Those melts, the product of crustal reworking, gave rise to the numerous bodies of granite on Skye. These discoveries had a profound influence on much of Stephen’s subsequent work on the petrogenesis of igneous rocks, both ancient and modern.

**Volcanoes of the Andes**

Between 1977 and 1996, Stephen was involved in numerous studies of Andean volcanic rocks along the entire length of the chain (33, 38, 40, 46, 48, 57–60, 63–68). From the first study with Francis and Thorpe (33), comparing Sr isotopic compositions of andesites from five Ecuadorean volcanoes with the San Pedro–San Pablo volcano of northern Chile, a pattern emerged which further studies confirmed and refined: the thickness of the continental crust beneath a volcano exerts a major influence on the isotopic composition of Sr in the lavas erupted. Beneath Ecuador, the crust is 40–50 km thick, whereas that beneath Northern Chile is 70 km. The relatively high \( {^{87}Sr/^{86}Sr} \) ratios of andesites in Northern Chile show clear evidence of more extensive interaction of their mantle-derived parent magmas with the thicker crust through which they rose than their Ecuadorean counterparts.

In a later study, with Déruelle and Harmon (46), Stephen compared the Southern Volcanic Zone (SVZ) in Chile (36°S–42°S), with the southern part of the Central Volcanic Zone (CVZ) (21°S–24°S). \( {^{87}Sr/^{86}Sr} \) ratios of the SVZ volcanic rocks have low values typical of mantle-derived magmas. The underlying crust in the SVZ is less than 40 km thick, slightly thinner than that beneath Ecuador. Beneath the CVZ, however, the crust is 70 km thick and, as in Northern Chile, \( {^{87}Sr/^{86}Sr} \) ratios are significantly higher. Stephen and his colleagues concluded that, in the CVZ, crustal contamination of mantle-derived magmas was taking place at depth in the lower crust, which had been thickened by Mesozoic and earlier plutonism.

In an important review of the Sr, Pb and O isotopic compositions of Recent volcanic rocks along the length of the Andean chain, Stephen and colleagues documented the contrasts between the northern, central and southern volcanic zones, respectively NVZ, CVZ and SVZ (48). Volcanics of the SVZ (45°S–33°S) have the lowest \( {^{87}Sr/^{86}Sr} \) ratios and the least variable Pb isotopic compositions, closely comparable to the characteristics of volcanics in intra-oceanic arc settings where there is no continental crust. Parent magmas were derived primarily from the asthenospheric wedge of mantle above a shallow Benioff zone. The continental crust in the SVZ is relatively thin and there appears to have been no significant crustal contamination of mantle-derived magmas in this sector of the Andean chain. In the NVZ (2°S–5°N), where the continental crust is also relatively thin, \( {^{206}Pb/^{204}Pb} \) ratios are somewhat higher than those of the SVZ, indicative of a greater subduction-zone component in the parent
magnas. It is in the CVZ (28°S–16°S), where the continental crust is very thick, that the highest \(^{87}\text{Sr} / ^{86}\text{Sr}\) ratios are found and also the greatest variations in Pb isotopic composition. There is nothing to suggest that the parent magnas of the CVZ volcanoes differ significantly from those of the NVZ and SVZ to either side, but the marked differences in Sr and Pb isotopic characteristics are rather the result of significant bulk contamination by the lower crust with further modification by fractional crystallization (AFC) processes at higher levels in the crust.

In a seminal study of the northern half of the SVZ (37°S–33°S), Stephen and Wes Hildreth of the US Geological Survey (57) demonstrated a striking pattern of geochemical and isotopic variations in fifteen andesite–dacite volcanic centres on the volcanic front. That volcanic front is consistently 280 ± 20 km behind the trench axis and 90 km above the Benioff zone. The rate of subduction, the composition and age of subducted sediments and sea-floor are more or less constant along the length of the sector. Effectively, all the relevant lower plate properties are similar along the whole front considered. They were thus able to conclude that the marked chemical and isotopic variations from south to north along the front must relate to the characteristics of the upper plate. The key variations there are:

- a northward increase in the basal elevations of the volcanic centres, from 1350 m in the south to 4500 m in the north; a thickening of the crust from 30–35 up to 50–60 km; and a corresponding thinning of the mantle wedge from 60 to 30–40 km. In the south, the crust consists substantially of young arc intrusive rocks, whereas, further north, Palaeozoic and Triassic basement predominates. The main features of the variations in chemical composition, comparing volcanic rocks with closely similar SiO\(_2\) contents (57.5%), were marked increases in K, Ba, Ce, Rb, Cs, Th and U from south to north. \(^{87}\text{Sr} / ^{86}\text{Sr}\) ratios increase from 0.7036 to 0.7057, while \(^{143}\text{Nd} / ^{144}\text{Nd}\) ratios fall from 0.5129 to 0.5125 from south to north. No primitive basalts are known from anywhere in the studied sector. Stephen and Wes concluded that the main characteristics of the volcanic rocks are the result of blending of sub-crustal and deep crustal magnas in zones of melting, assimilation, storage and homogenization located at the crust–mantle transition: these they christened MASH zones. The MASH process involves more than simple contamination of basalts in the lower crust. Rather, true magma generation induced by intrusion and crystallization of basalt occurs on a scale large enough that tens of per cent of subsequently ascending magnas can be of deep-crustal derivation. Basaltic magnas, rising from the mantle wedge, stall at the crust–mantle transition, and there mix with each other and with magnas derived from the induced partial melting of heterogeneous deep-crustal rocks. Further modification of magma compositions can occur during ascent of magma through higher levels of the crust as a result of AFC processes (assimilation–fractional crystallization). The detection of isotopic variations from MASH processes is dependent on the deep crust being sufficiently old to have evolved to isotopic compositions distinct from sub-crustal magma sources, a condition not fulfilled at the southern end of the studied sector.

**Overview**

Stephen, throughout his career, was an enthusiastic participant in the scientific discussions of the day. Over many years, he was one of the editors of *Earth and Planetary Science Letters*. He greatly enjoyed participating in the Royal Society’s Discussion Meetings (35, 51), for some of which he was a convenor: ‘On the origin and evolution of the Earth’s continental crust’ (with Brian Windley; 1980) and ‘The relative contributions of mantle, oceanic crust and continental crust to magma genesis’ (with Bob Thompson and Ron Oxburgh FRS; 1984).
Stephen had a long-term interest in the nature of the lower crust (22, 47, 53). In this, he was strongly influenced by his friendship with Knut Heier, who did so much to demonstrate that granulite-facies rocks were characteristically depleted in large ion lithophile and heat-producing elements. Stephen documented the consequences of those depletions for radiogenic isotope evolution, particularly in Archaean high-grade gneiss terranes.

He was also deeply involved in models for the evolution of the continental crust (21, 26, 29, 30, 35, 36, 39, 43, 45, 52). Stephen was convinced that the continental crust has continued to grow in volume to the present day. That growth may have been episodic and its rate has probably diminished since the Archaean, but Stephen was strongly opposed to the recycling of continental crust into the deep mantle: with its relatively low density, continental crust is too buoyant to undergo deep subduction and recycling.

It was always a matter of great importance to Stephen that all claims to new discoveries of very ancient rocks should be reviewed with the utmost care, especially when they were related to evidence for early life. He scrutinized all such claims meticulously and on occasion felt the need to reinterpret data that did not pass muster (54).

Ever since the discovery of the great age of the Amitsq gneisses in 1971, Stephen was devoted to the Godthåbsfjord area of Greenland, and to Isua especially. Over the course of many summers, Stephen amassed a valuable suite of well-collected and curated specimens of the various constituent rock-units of the Isua supracrustals (figure 4). He knew the area like the back of his hand and worked there with many distinguished geologists to try to wrest the secrets from the world’s oldest known greenstone belt. That collection has fuelled many important scientific experiments and discoveries in which Stephen was actively interested and engaged until finally his health failed him (69–82).

WIDER INTERESTS, HOBBIES AND PERSONAL LIFE

Stephen was a profoundly intellectual person of wide interests and hobbies from geology to archaeology, philately, linguistics and music—a great geoscientist and renaissance man. He was at once faintly reserved and withdrawn yet friendly, warm, kind, and ready to give help to anyone. He had a strong sense of social purpose and fairness: all his life he was a staunch Labour supporter, always thought the best of people, and was ready to forgive any transgression except extreme intransigence in the light of clear data. In research, he showed great commitment, single-mindedness, intensity, accuracy and precision, as a result of which he leaves a fine legacy of ground-breaking publications written in flawless English. He appreciated gourmet food and fine wines; perhaps his only weakness was a serious addiction to almond croissants, New Berry Fruits, and Garibaldi biscuits.

For many summers, Stephen visited his Linacre College colleagues, Bill and Jackie Waldren, to help with their archaeology digs on Mallorca (figure 5). Here, he also became friendly with Robert Graves, who lived nearby. He delighted in helping to establish archaeostratigraphy with the warm sun on his back in a rural Mediterranean environment. He had a great interest in postal communication around the world, and a special interest in the Baltic states, for which he built a superb collection of stamps. His fascination with etymology and the flow and beauty of language led to studies of linguistics, particularly Finnish, Hungarian, Lithuanian, Old English, and Inuit. For each new language he encountered, he strove to acquire the correct rendering of the classic phrasebook sentence, ‘The sleeping car attendant has
been struck by lightning!’ He was particularly delighted to learn the Inuit rendition of this expression, in spite of the absence of railways in Greenland.

With his prodigious memory, he could quote huge tracts of Shakespeare and Chaucer. He had an exhaustive knowledge of classical music, especially that of Mozart and Alkan. He could hum or whistle almost any of Mozart’s music, called up at will. He had a lasting admiration
Stephen Moorbath

Figure 5. Archaeological holiday with the Waldrons in Mallorca, 1994. (Online version in colour.)

for Sir Thomas Beecham and was fond of quoting his many droll remarks, such as ‘I hear that Wagner’s music is much better than it sounds’ and, ‘Ah yes, Adrian Boult; a kind of musical Malcolm Sargent’.

Stephen’s wit and humour are memorable and legendary, especially his masterful command of the pun. One of his finest, while waiting for prints from our photography technician, was ‘someday my prints will come’. He believed that if a pun was worth making, it was worth repeating many times. He certainly composed hundreds, if not thousands; many became old friends, as amusing as ever.

He had a great capacity to adapt to almost any situation. Stephen, Chris Hawkesworth and J.F.D. were at a conference on Andean geology in Berlin in 1989, when the Wall was coming down. We collected bits of it and tried to take the train to Potsdam, where we were refused entry. We went to a Greek restaurant, following which we enjoyed a Brahms concert at the Berlin Philharmonic. Steve and I were sharing a room at a small hotel, on the strict understanding that snoring was forbidden. In the morning, he and his mattress and bedclothes were nowhere to be seen. I panicked, thinking ‘famous scientist, collecting pieces of Wall coming down, suspicious attempt to enter East Germany, Stasi, kidnap, ransom’. I got up, opened the window onto the balcony and found Stephen quietly sleeping tucked up on his mattress. When, in great relief, I woke him up, he fixed me with a mournful stare and said, in his gentle way, ‘you were not entirely truthful last night’. My abiding memory of Stephen was of cycling into Oxford behind him; in his pale raincoat and brown hat, he could easily be mistaken for Inspector Clouseau. In spite of his quick and agile mind, Stephen was not
the most practical of men in physical dexterity. He never learned to drive a car, and travelled only on foot, by bicycle, by rail and in the air. Two phrases alarmed his colleagues, in the Department and while camping, respectively, ‘I really must get back into the lab’ and ‘Is there anything that I can do to help?’

Stephen became the doyen of British radiogenic isotope dating (figure 6) and was beloved by his colleagues and friends. He travelled the world in search of research problems, especially the oldest rocks. He died peacefully on 16 October 2016 at the age of 87. He leaves Pauline, his wife of 55 years, and their children, Nicholas and Susannah.

**Awards**

1977  Fellow of the Royal Society
1978  Murchison Medal of the Geological Society of London
1979  Steno Medal of the Geological Society of Denmark
ACKNOWLEDGEMENTS

We are grateful to the many friends and colleagues of Stephen, especially Brian Upton, who contributed their reminiscences.

The portrait photograph was taken in 1978 and is copyright © Godfrey Argent Studio. All photographs were provided by the Moorbat family.

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