

Stuart Ross Taylor 1925–2021

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ABSTRACT

Stuart Ross Taylor, born and raised in New Zealand, spent most of his career at the Australian National University where his laboratory research focused on trace element geochemistry. He made fundamental contributions toward understanding the composition and evolution of the Moon and Earth, the origin of tektites and solar system evolution. He carried out the first-ever chemical analyses of Apollo 11 lunar samples. Ross Taylor received many awards and honours and was a Companion of the Order of Australia.

Keywords: continental crust, cosmochemistry, geochemistry, lunar science, mass spectrometry, planetary science, solar system, spectrochemical analysis, tektites, trace elements.

Introduction

Emeritus Professor Stuart Ross Taylor AC FAA NAS HonFRSNZ (Fig. 1), who always went by his middle name Ross, died peacefully at Calvary John James Hospital, Canberra, Australia, on Sunday, 23 May 2021 at the age of 95. At the time of his passing, Ross was surrounded by his family and was survived by his wife of 63 years, Noël, his daughters Susanna, Judith and Helen, grandson Angelo, son-in-law Michael, and brother Forbes. He also had extended families in New Zealand and Western Australia.

Ross was born and grew up on a farm at Wakanui on the South Island of New Zealand, and maintained his New Zealand passport throughout his life. He was educated in New Zealand and the United States and pursued most of his career, spanning 65 years, at the Australian National University (ANU). He was one of the most influential geochemists and planetary scientists of his generation and made numerous important contributions, often of a fundamental nature, to understanding the composition, origin and evolution of Earth, the Moon and solar system. Ross exemplified humility; he was soft-spoken, diligent, polite, and respectful to those with whom he crossed paths. We are fortunate that Ross left behind a considerable accounting of his life and career and in preparing this biographical memoir, we have relied on several published sources that include autobiographical writings and published interviews,¹ testimonials and memorials,² and recorded interviews.³ Interested readers are directed to these works for additional details of Ross's life and career.

Ancestry and early life in New Zealand

Ross Taylor was born in Ashburton, New Zealand on 26 November 1925, of Celtic ancestry (Irish, Scottish, Welsh). He was a third-generation New Zealander, his grandfather having emigrated from Northern Ireland at the age of twenty. After his arrival, his grandfather tried his hand at gold mining but soon returned to a family tradition and set

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¹Taylor (1994a, 2016). Crompton (2000). Marvin (2002).

²Burke (1990). Mason (1994). Hofmann (2003). McLennan and Rudnick (2021).

³1994 interview recorded for Lindsay (2001): https://honeysucklecreek.net/audio/interviews/Dr_Stuart_Ross_Taylor_24_May_1994.mp3. 1998 interview recorded for the 1999 NOVA television documentary *To the Moon*: https://openvault.wgbh.org/catalog/V_4F6B3FE27D614A86B34F7BB36EB7B427.

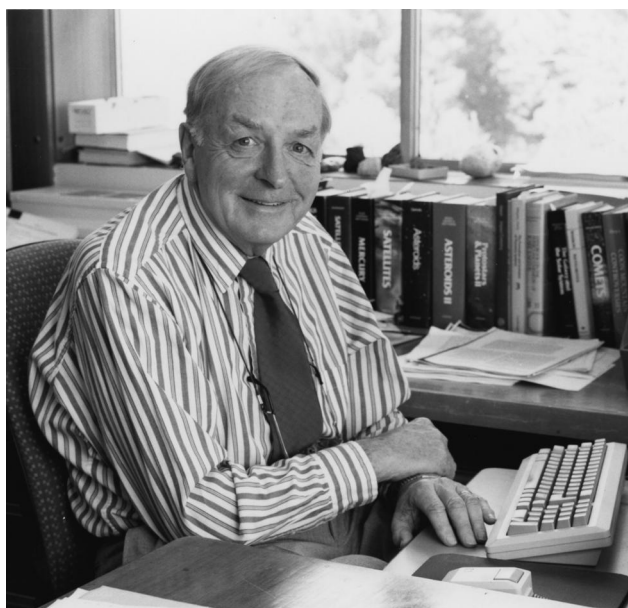


Fig. 1. Stuart Ross Taylor AC FAA NAS in his office at the Australian National University in 1990 (Photo credit: Australian Academy of Science).

up a farm in Ashton, New Zealand, southwest of Christchurch, where Ross's father, Stuart Taylor, the youngest of thirteen children, was born in 1891. The Taylors later moved to the nearby Wakanui district, southeast of Ashburton, and the family farm, where Ross grew up, is in the family's fifth generation. Ross's father and mother, Grace Lloyd, a primary school teacher, met and were married shortly after World War 1.

Ross was one of three brothers. Lloyd, the eldest, was a law student when he enlisted in the Royal New Zealand Air Force during World War 2. He served from 1944 to 1945 as a flying officer with the 490th Squadron in the eastern Atlantic, operating off the coast of west Africa. Shortly after the war, in December 1946, Lloyd was tragically killed in a traffic accident. Ross's younger brother Forbes, who received the British Empire Medal in 1985, saw service in the Korean War as a lieutenant in the signal corps, returning home to become a farmer, hotel owner and chairman of the Waitaki County Council. At the time of Ross's death, Forbes was retired and living in Christchurch.

World War 1 had a considerable impact on Ross's family and no doubt is a major reason why he became so interested in, and knowledgeable about, the history and politics of the Great War. His mother lost a favourite brother in the Battle of the Somme in September 1916. His father served with the New Zealand Division and took part in (and was very fortunate to survive) the disastrous First Battle of Passchendaele

in October 1917 that resulted in over 2700 New Zealand casualties on a single day (0.2% of the nation's population!). By the end of the war, he had served in the trenches for two years and was wounded twice. Despite becoming highly disillusioned with military matters, he went on to command the local Home Guard during World War 2. Ross's father died young in 1948, aged 56, 'worn out by the Great War, the 1930s depression, illness and the loss of Lloyd'.⁴

Ross grew up in a Presbyterian farming community and throughout his youth, farm chores consumed much of his time, an experience he credited for his stamina and work ethic. He was fond of quoting the Canadian American economist John Kenneth Galbraith, who had a similar upbringing in southern Ontario: 'After that, everything was easy'.⁵ Ross attended the Wakanui Primary School (1931–8), a small country school of about forty students divided into two groups of four classes each. From an early age, he performed well in his studies, usually at the top of his class. At age ten, he nearly died from peritonitis resulting from a ruptured appendix. Antibiotics were not then readily available and only emergency surgery by the local doctor saved him from an early demise. He attended Ashburton High School from 1939 to 1943 (Fig. 2) and excelled in English literature, history, and chemistry. Although the school was small, his teachers had masters degrees from the University of New Zealand and the quality of education, even including Latin, was high. For example, Ross noted that his high school science laboratory instruction was superior to that at university.⁶ In his final year (sixth form), he was awarded the Drummond Prize for science, which Ross credited with helping to tip the scales in choosing to pursue science at university over law (as his brother Lloyd had done).

University education

Ross enlisted in the New Zealand Air Force in early 1944, shortly after turning eighteen, but was not called up until mid-1945 and, as the war ended that August, his service was not required. In 1944 he also enrolled at Canterbury University College in nearby Christchurch, which then was part of the University of New Zealand (becoming the independent University of Canterbury in 1961). Pursuing a BSc in chemistry, he was required to enrol in a fourth subject in addition to mathematics, physics and chemistry, and chose geology, which dovetailed with his interest in history. Robin Allan (after whom the famous Allan Hills meteorite location in Antarctica is named) was the professor of geology and Brian Mason was a lecturer in mineralogy. Ross credited Allan's outstanding teaching style as the inspiration for a newfound fascination with geology. In spite of living in the

⁴Taylor (2016) p. 2.

⁵Taylor (2016) p. 3.

⁶Taylor (2016) p. 3.



Fig. 2. Ashburton High School 1941 class photograph. Ross, who was 16-years-old at the time, is in the back row, second from the right (Photograph provided by the Taylor family).

same college residence (College House, renamed Christchurch College in 1957) where theological courses were offered to students preparing for the Anglican ministry, it was during this period that Ross permanently abandoned any regard for religion. He moved into private accommodations after his second year. During holidays, Ross worked in the product control chemistry laboratory for the local freezing works (slaughterhouses) analysing by-products, such as tallow and blood-and-bone, for the nationally important frozen lamb export market to the United Kingdom. High-quality results were needed in a timely manner and so it was here that Ross claimed he truly learned analytical chemistry and how to produce accurate data under time pressure—skills that would serve him well more than two decades later at the Lunar Receiving Laboratory in Houston. In 1948, Ross graduated with a BSc degree earning a double major in chemistry and geology.

These were exciting times to attend university in New Zealand and especially at Canterbury College.⁷ Karl Popper, an Austrian refugee from the growing threat of *Anschluss* and brilliant philosopher of science, was a lecturer at Canterbury College from 1937 to 1945. Ross overlapped briefly with Popper and attended a couple of his lectures. But more importantly, Robin Allan became close friends (and neighbours) with Popper and imbued into his own teaching much of Popper's thinking about the philosophy of science, something that also influenced Ross. Allan and several other faculty members also worked closely together, initially with Popper, to enact major reform at the university to greatly enhance the roles of science and research and

generally bring the institution into the modern era.⁸ Thus, in Robin Allan, Ross had an early mentor who was a true pioneer in promoting university science research in New Zealand.

With the death of his father, Ross offered to return to the farm to help his mother but she insisted that he continue his studies. Under Allan's supervision, Ross carried out masters research with mapping and stratigraphic analysis of a 250-km² area in the Stonyhurst district of North Canterbury, a structurally and stratigraphically complex region of mostly Cretaceous through Holocene sedimentary rocks.⁹ For Allan's students, field mapping was a self-taught skill and after six months of field work (Allan visited him in the field just once), Ross thought that he had 'finally understood how to carry out geological mapping', an experience he also credited for helping to teach him the difficult issue of how to select field samples for laboratory study.¹⁰ He graduated with an MSc in geology in 1951, with First Class Honours, and also received the Sir Julius von Haast Prize as the best MSc geology student at the University of New Zealand.

Ross briefly returned to the freezing works but decided that he wanted to pursue an academic career and so had to obtain a PhD. The tradition in New Zealand at the time was to go to the United Kingdom (UK) for doctoral-level study, but Ross had other ideas. He considered chemistry, but settled on geology, which he thought had better career opportunities and that the post-war research coming from the United States was particularly exciting. He also thought that traditional geology, such as the mapping he carried out

⁷Gardner and others (1973).

⁸Gardner and others (1973). See Chapter 13, p. 386–408.

⁹Taylor (1950).

¹⁰Taylor (2016) p. 3.

for his MSc, was not the best choice and that he should be looking for something new. Accordingly, he contacted his former mineralogy instructor, Brian Mason, who had taken up a faculty appointment at Indiana University in the United States in 1947, for advice. Mason suggested that Ross come to Indiana and study the relatively new field of geochemistry with him, working on trace element analysis.

This made sense for at least two reasons (quite apart from the scholarship offered). Brian Mason had also bucked tradition and gone to Oslo, arriving in January, 1940, for his PhD with Victor Goldschmidt, widely considered the ‘father of modern geochemistry’.¹¹ Although Mason’s studies were interrupted by Germany’s invasion of Norway in April, 1940, resulting in Brian departing abruptly for Sweden and completing his PhD at the University of Stockholm, the connection to Goldschmidt (with whom he corresponded until 1945) was deeply influential for both Mason,¹² and later Ross. The second reason is that the Indiana State Geological Survey was housed in the Geology Department at Indiana University and within the survey was a state-of-the-art optical emission spectrochemical laboratory for trace element analysis. The head of the survey’s geochemistry section, Dick Leininger, thus became another key early mentor of Ross and first taught him how to carry out accurate spectrochemical analyses on rocks and minerals.

With financial and moral support from his family, Ross travelled to Indiana University in 1951. For his PhD research, he brought with him three suites of New Zealand rocks: Cenozoic volcanic and intrusive rocks from the Banks Peninsula near Christchurch, Cretaceous plutonic rocks from the Mandamus-Pahau area of North Canterbury, and Jurassic-Cretaceous metamorphic rocks from the Alpine Schist Belt in North Westland. Ross’s first task as a PhD student was to proofread the galley proofs of his supervisor’s new book *The Principles of Geochemistry*,¹³ which essentially put him at the ‘cutting edge of the subject’.¹⁴ In his second year, he also presented to the department’s journal club¹⁵ a review of Harold Urey’s exciting new book *The Planets: Their Origin and Development*,¹⁶ often cited as the most important publication in establishing the field of cosmochemistry. Indiana had a foreign language requirement and, after he failed the German examination twice (likely the only ‘F’ ever recorded on his transcript!), Brian Mason tutored him using Goldschmidt’s classic papers written in German leading to a pass with distinction on the third attempt (and a bottle of fine brandy for Brian).¹⁷

Although Ross did not think his PhD thesis led to any significant breakthrough and described it as ‘trace element chemistry of geological materials, rather than geochemistry’,¹⁸ the critical things this research taught him were the analytical techniques; the breakthroughs would come later. He graduated with his PhD in 1954.¹⁹

Early career

Ross worked for nearly a year (July 1953 to June 1954) as a spectrographer at the Indiana Geological Survey. This allowed him to hone his skills as a trace element analyst, an experience that served him well as he began to pursue his academic career. Ross spoke fondly of his time in Indiana as the place where he began to develop his strong affection for the United States and its people.

University of Oxford

The year before Ross completed his PhD, his advisor Brian Mason accepted a position as Curator of Mineralogy at the American Museum of Natural History in New York. His temporary replacement was a visiting professor and Brian’s friend, Henrich Neumann, Head-Curator at the Mineralogical-Geological Museum, University of Oslo. Neumann advised Ross to apply for a position at the University of Oxford, an idea that Ross found rather daunting given Oxford’s reputation. Nevertheless, he persevered and accepted an offer of a department demonstratorship in mineralogy (equivalent to a junior lecturer) and moved to Oxford in 1954. He found out much later that Neumann had written a strong supportive letter. He was hired and mentored by the famous igneous geologist (and mountaineer) Bill Wager, the professor of geology who himself arrived at Oxford in 1950 and was engaged with modernising the department. Less than two years later, in January, 1956, Ross was promoted to a permanent position (university demonstratorship and lectureship) and joined Christ Church College.

As chronicled by David Vincent, who first arrived at Oxford shortly before Ross and in 1967 succeeded Wager as the professor of geology, in his history of the Department of Geology and Mineralogy, Ross’s ‘influence in the Department was very considerable right from the beginning’ and that Ross ‘showed a penetrating mind and a quite unusual enthusiasm and capacity for hard work ... while

¹¹Mason (1992).

¹²Mason (1992) pp. 1–6, 110–111.

¹³Mason (1952).

¹⁴Crompton (2000).

¹⁵Thornbury (1953).

¹⁶Urey (1952).

¹⁷Mason (1994).

¹⁸Crompton (2000).

¹⁹Taylor (1954).



Fig. 3. Ross Taylor (right) with Louis Ahrens at the University of Oxford in 1956. Ross was a demonstrator in the Department of Geology and Mineralogy and worked closely with Ahrens to set up a spectrochemical laboratory (Photograph provided by the Taylor family).

(he) quickly proved a natural teacher. Moreover, he was a delightful person with whom everyone quickly made friends'.²⁰

Ross worked mostly with Louis Ahrens (Fig. 3), a world-renowned geochemist and leader in the field of trace element spectrography, and later with Knut Heier, a Norwegian geologist who was also a department demonstrator and became a lifelong friend. Along with teaching and tutorial duties (to allow him to lecture, he was presented with an Oxford MA degree in 1956), Ross worked with Ahrens to set up the spectrochemical laboratory with equipment more primitive than what he was used to at Indiana, which ironically allowed him to understand the fundamentals of the method better. With Ahrens, Heier and other members of the geology and mineralogy department (Stuart McKerrow, Steve Moorbath, Colin Exley) he began working on the trace element distributions in materials as diverse as feldspars and fossils. These were exciting times to be an analytical geochemist and he 'enjoyed the fact that almost everything you looked at was new—nobody had done it before'.²¹

An important influence on Ross was his chance interaction with Harold Urey who spent 1956 at Oxford on sabbatical. A Nobel laureate (for discovering deuterium), Urey had turned his attention to cosmochemistry and became very interested in the Moon. From him, Ross learned that an analytical geochemist could investigate the Moon through the study of tektites. These small glassy and often aerodynamically shaped objects were at the center of the debates about the composition of the Moon. Although they were recognised as the splash product of meteorite impacts,

whether such impacts were on Earth or the Moon was highly controversial. Thus began Ross's own 'love affair' with the Moon.

University of Cape Town

In 1956, Louis Ahrens, South African by birth, was recruited to the Chair of Inorganic and Physical Chemistry at the University of Cape Town. Ross later followed Ahrens to Cape Town, departing from Oxford in 1958, to take a position as senior lecturer in the geology department. As they were leaving Oxford, Ahrens invited Ross to join him as co-author on the second edition of his comprehensive book on spectrochemical analysis, which was published a few years later,²² and became the first of ten books that Ross would publish. Nearly a decade later, this experience would also have profound implications for Ross's career. Ross started a small sub-department of geochemistry and set up another spectrochemistry laboratory, similar to the one in Oxford. Here he began to work on tektites in earnest and also supervised his first PhD students: Tony Erlank and Peter Kolbe (who completed his PhD at ANU).

Although Ross and Noël were fond of Cape Town and the people they worked and socialised with, the political situation in South Africa was deteriorating. The University of Cape Town was an 'English' university that enrolled a significant black student population and employed black staff members. However, the government's apartheid policies relentlessly undermined this (with varying success) and political discussion and activity were commonplace on campus (Fig. 4). During these times, Ross came to deeply appreciate the true significance and importance of academic and university freedom and independence, issues on which he always held strong views. Even by 1959, Ross and Noël concluded that Cape Town was not where they wanted to bring up a family and pursue careers.

The Australian National University

Department of Geophysics and Geochemistry and the Research School of Earth Sciences

At this time, John Jaeger was increasing the presence of geochemistry at the recently formed (1952) and rapidly growing Department of Geophysics in the Research School of Physical Sciences (RSPhySci) at the Australian National University.²³ In addition to growing the fields of petrology and isotope geochemistry, he was interested in a trace element geochemistry group and in 1960 offered a professorship to Louis Ahrens and another position to Ross. After

²⁰Vincent (1994) p. 76

²¹Crompton (2000).

²²Ahrens and Taylor (1961).

²³Paterson (1980).



Fig. 4. Ross with wife Noël (left) and gifted laboratory assistant Maureen Sachs (later Maureen Kaye) attending a demonstration against apartheid, University of Cape Town, 1959. It would surprise no one who knew Ross well to see that he is wearing his academic dress to the event (Photograph provided by the Taylor family).

considerable deliberation, Ahrens declined but Ross informed Jaeger that he was still interested in coming to ANU. Ross moved there in 1961 as a senior fellow and, as a consequence of being offered a readership at Oxford, was promoted to professorial fellow (equivalent to Reader) in 1962, a position he held until retirement. As the focus on geochemistry grew, the department was renamed the Department of Geophysics and Geochemistry in 1964 (and breaking from physics as the separate Research School of Earth Sciences (RSES) in 1973).

The first order of business was to set up a modern optical emission spectrochemical laboratory. Unlike Oxford and Cape Town, cost was not an issue and so Ross set up a facility with the most modern instruments available. However, he had already realised that this technique had reached its limits for addressing modern questions in geochemistry, in terms of sensitivity and precision, and that many low-abundance trace elements, especially the rare earth elements (REE), were increasingly important. Ross concluded that spark source mass spectrometry (SSMS), which was being developed for trace element analysis of semi-conductors, was a technique worth pursuing because it simultaneously recorded the isotopes of all of the elements (Li to U) in tens of milligrams of sample on a medium that he understood well (photoplates) and had sub-parts per million sensitivities. The double-focusing mass spectrometer (AEI-MS7), installed in 1964, used a high-frequency spark (25 kV) between mixed sample-graphite pressed rods to produce an ion beam.²⁴ This was an inherently difficult

technique for quantitative analysis because it was not possible to measure the wildly varying ion beam intensities accurately during data collection. Ross applied a two-pronged strategy to solve this problem: an internal standard of one of the REE (Lu) and ‘calibrating’ each photographic plate response (Seidel function) using known relative abundances of isotopes in selected elements (Yb, Nd, Hf, Ba). He also focused on elements with $Z \geq 39$ (Y) because interferences were more readily quantifiable. Ross’s laboratory thus became the first and most successful to apply the SSMS method quantitatively to rocks and minerals. Laboratories around the world that succeeded in using SSMS instruments for quantitative results generally adopted his approach.

In about 1980, with laboratory assistant Mike Shelley, Ross set up an inductively coupled argon plasma emission spectrometer (ICP-OES) as a more sensitive and precise replacement to the arc-source emission spectrometer,²⁵ and was also able to analyse low- Z elements unavailable to SSMS. At the time, most commercial instruments had multi-element configurations (polychrometers) allowing for rapid analysis, but with low spectral resolution. From his experience with emission spectroscopy, Ross recognised that for complex geological samples, low resolution resulted in numerous spectral interferences degrading analytical quality, and instead installed two computer-controlled high-resolution scanning monochrometers, configured at right angles to the plasma source and thus able to simultaneously collect data for two elements. Although more time-consuming for analyses than polychrometers, higher resolution and ability to better monitor backgrounds, resulted in improved data quality.

The Trace Element Group was small by RSES standards and, since Ross was not a fan of ‘big science’, this suited his approach very well. His group typically consisted of a research fellow, one or two graduate students and one or two technical assistants (Fig. 5). Despite the small size, the vitality of the group was assured by having numerous visitors in any given year. For those visiting to collect data, the rules were the same for all: a viable scientific problem, a reasonable length of stay (preferably three months or more), and collecting and processing their own data.

Ross’s trace element laboratory flourished for over thirty years. The analytically-based research programs pursued by his group were remarkably diverse. Although the origin of tektites was resolved with the Apollo sample return, his interest remained and he continued to publish many papers on the topic while at ANU. He was a NASA Lunar Sample Principal Investigator for twenty years (1970–90) and received and analysed lunar samples from NASA for more than a decade following his preliminary analyses for Apollo 11 and 12. His early days at ANU also coincided with the plate tectonic revolution and Ross became very interested in

²⁴Taylor (1965).

²⁵RSES (1981) p. 282.



Fig. 5. The RSES 'Trace Element Group' in 1979, celebrating the exposure of the 5000th spark-source mass spectrometer photographic plate (mass intensities were obtained from 16 variably timed mass spectra exposed on each glass plate with 2–3 plates used for most samples). From left are Ross, Mike Shelley (Senior Technical Officer), Mike Perfit (Research Fellow), Scott McLennan (PhD student) and Pat Oswald-Sealy (Technical Officer). Pat is sitting in the SSMS operator's chair, where normally there were no champagne bottles, although usually several recent issues of the *New Yorker* (Photograph provided by M. Perfit).

the composition, origin and evolution of the continents. His group carried out extensive work on island arc volcanic rocks, sedimentary rocks of all ages, and samples from the lower continental crust (xenolithic and terrane granulites) to gain a broad understanding of the crust. Indeed, all of his graduate students at ANU were put to work on these problems: Peter Kolbe (PhD, 1965), who began at Cape Town, worked on granites; Jim Gill (PhD, 1972), Mike Gorton (PhD, 1974) and Dave Whitford (PhD, 1975) all worked on island arc volcanic rocks; Weldon Nance (MSc, 1975) and Scott McLennan (PhD, 1981; Fig. 6) worked on sedimentary rocks; and his last student, Roberta Rudnick (PhD, 1988; Fig. 6) studied the lower crust. He also co-advised Graham Bradley (PhD, 1972) in the Department of Geology with Alan White, who examined Precambrian granulites. In addition to graduate students, Ross supervised three research fellows (three-to-five year post-doctoral positions): Mike Perfit (1976–81; island arc geochemistry); Scott McLennan (1981–6; sedimentary geochemistry); and Marc Norman (1987–90; lunar geochemistry).

Other collaborators he worked with while at ANU included Robin Cherry and Chris Koeberl on tektites; Dick Arculus, Ian Campbell, Andy Duncan, Ken Eriksson, Tony Erlank, Tony Ewart, Jack Hallberg, Knut Heier, Lynton Jacques, Wally Johnson, Malcolm McCulloch, Ian Nicholls, Angelo Peccerillo, Dick Price, Ian Smith, Charlie Vitaliano, Alan White and John Wilkinson on crustal geochemistry;

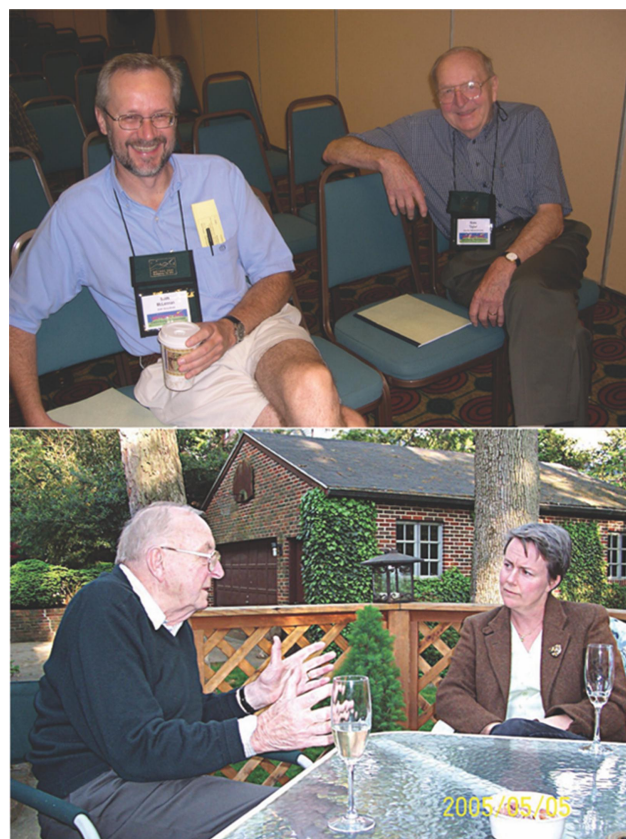


Fig. 6. Top. Ross with his former student and long-time collaborator Scott McLennan (PhD, 1981) at the Meteoritical Society Annual Meeting in Gatlinburg, Tennessee (2005). Bottom. Ross in deep conversation with his last PhD student, Roberta Rudnick (PhD, 1988) in Maryland, USA, also in 2005 (Photographs provided by Taylor family).

and Ted Bence, Tezer Esat, Petr Jakeš, Amir Khan, Al Levinson, Brian Mason, Mike McElhinny, Horton Newsom, Dave Stevenson, Jeff Taylor and Larry Taylor on problems related to lunar and planetary science.

The Lunar Receiving Laboratory and the Lunar and Planetary Institute

The most important sequence of events in Ross's career took place in 1969,²⁶ and can be summed up with one of Ross's favourite aphorisms, that fortune follows the well-prepared. In April, 1969, Ross attended an international conference on tektites in Corning, New York. An old friend, Robin Brett, chief of the geochemistry branch at the NASA Manned Spacecraft Center (now Johnson Space Center) in Houston, invited Ross to visit the newly formed (1968) Lunar Science Institute (LSI; renamed Lunar and Planetary Institute, LPI, in 1978) for a few weeks (Ross always believed that Robin had an ulterior motive, to involve Ross with the Apollo project,

²⁶See Taylor (1994a, 2016) and Marvin (2002) for complete details.

that played out exactly as planned). Ross thus became the first visiting scientist at LSI/LPI.

Near the end of the visit, Ross was summoned by William Hess, one of the center's directors. The Lunar Receiving Laboratory (LRL) had installed an emission spectrograph, similar to the one Ross had at ANU, to carry out the initial chemical analyses on Apollo 11 samples, scheduled to arrive in July. However, the laboratory was being operated by a commercial construction company that hired technicians with no experience of working with rock samples, which are among the most complex materials encountered by analytical chemists. Preparations were not progressing at all well and time was running out. Because of Ross's experience with spectrochemical analyses of rocks and minerals (setting up three laboratories and co-authoring the definitive text) and his knowledge of lunar science resulting from tektite research, he was asked to stay and join the Lunar Sample Preliminary Examination Team (LSPET) and take over the spectrochemical laboratory to prepare it for the impending sample return. He thus became one of only two members of this select group of about fifty scientists from a non-US institution.²⁷ This led to a famous phone call that Ross made to Noël, who was expecting him home imminently, to tell her of the offer, which meant that he would not return home for at least five months and that she would have to oversee completion of their half-built house on her own. Ross noted that Noël 'immediately said, yes dear, of course you have to do this'.²⁸ A great irony was that several colleagues in Ross's department at ANU had formed a team to obtain and analyse Apollo samples but had completely excluded Ross from their proposal.²⁹

Ross then spent the most gruelling six weeks of his life, averaging about three hours of sleep daily, to set up the laboratory. Standards had to be selected and obtained, ancillary equipment purchased or sent from ANU, graphite-sample mixing procedures developed, internal standards produced, analytical lines selected and calibrations made. Ross commented that 'I needed every item of knowledge that I had acquired during the previous 15 years working with spectroscopic analysis'.³⁰ Having completed the final calibrations about an hour before, the first samples arrived at the laboratory at 11:45 am on 28 July and just after midday the first sample was loaded into the spectrograph. The initial results were unexpected (very high Ti, Fe and Cr), creating unanticipated interferences thus necessitating a recalibration (done in a matter of hours) before final release

of the first analyses to the public (Fig. 7). Over the next three weeks the laboratory analysed about two dozen lunar rocks and soils and produced data that have withstood the test of time. Among the many early highlights is that with Oliver Schaeffer (Stony Brook), the LSPET rare gas geochemist, they produced the first radiometric date of a lunar rock (3.0 ± 0.7 billion years old by the potassium-argon method), which resolved a controversy about the age of mare basalts.³¹ In November, Ross returned to Houston and repeated his efforts for Apollo 12. During this time, he was often interviewed by a reporter (Henry Cooper) from his favourite *New Yorker* magazine, who later also published a popular account.³²

Retirement, Nuclear Physics and Earth and Marine Sciences (Geology)

Ross formally retired from RSES in 1990, retirement at ANU being then mandatory at age 65. His retirement was marked by The Taylor Colloquium: Origin and Evolution of Planetary Crusts, a two-day conference sponsored by the Australian Academy of Science, Geochemical Society, International Union of Geological Sciences, and RSES.³³ More than fifty scientists from nine countries attended, and over twenty papers and testimonials were presented, resulting in the publication of a special issue of *Geochimica et Cosmochimica Acta*.³⁴

Ross had never fitted in well with the highly competitive group structure at RSES. Consequently, in spite of many successes, his political situation had always been tenuous, and at times was described as being 'bleak'.³⁵ Throughout his career, he made full use of his research leave opportunities and travelled extensively. In 1967, he took leave at the University of California, San Diego, where he again encountered Harold Urey, who was on faculty and involved with persuading NASA to mount a lunar mission. He regularly attended the annual Lunar (later Lunar and Planetary) Science Conference (LPSC) in Houston. He held visiting appointments in Germany, Italy, Austria, India and several US institutions. Al Hofmann, Director of the Max Planck Institute in Mainz, described him as 'the human demonstration of the Heisenberg uncertainty principle' in that when you encountered him, you knew exactly where he was, but you could not predict where he might be the very next moment.³⁶ During his years at RSES, he spent much time

²⁷Lunar Sample Preliminary Examination Team (1969) Note 1 p. 1227.

²⁸Marvin (2002) p. B51.

²⁹Taylor (2016).

³⁰Taylor (2016) p. 9.

³¹Marvin (2002). Lunar Sample Preliminary Examination Team (1969) p. 1223.

³²Cooper (1970).

³³McLennan and others (1990).

³⁴McLennan and Rudnick (1992).

³⁵Taylor (2016) p. 9.

³⁶Hofmann (2003).



First lunar sample analysis. Apollo 11.
 Lunar Sample Number 10015
 (Sample from gas reaction cell)
 Chemical Compositions

Wt. %		Not detected
SiO ₂	48.0	Pb < 2 ppm
Al ₂ O ₃	10.0	Tl < 1 ppm
FeO	15.0	S < 5 ppm
MgO	8.0	Be < 3 ppm
CaO	11.0	Ga < 10 ppm
Na ₂ O	0.50	Zn < 30 ppm
K ₂ O	.12	Os < 1 ppm
TiO ₂	6.0	La < 30 ppm
Total	98.2	Nd < 30 ppm
		Sn < 10 ppm
		Ag < 1 ppm
		Hf < 50 ppm
		Nb < 30 ppm

Parts per million

Cr	2400
Zr	300
Sr	250
Ni	180
V	85
Sc	55
Ba	50
Co	35
Cu	30
Li	10
Rb	2

Analysts: S.R. Taylor
 P.R. Johnson
 R. Martin
 D. Bennett
 J. Allen

Ratios

K/Rb	500
Rb/Sr	.008
Ba/Rb	25
Ni/Co	5
Cr/V	28
V/Ni	.47

July 29, 1969

Ross Taylor

Fig. 7. Left. Ross Taylor (left) at the Lunar Receiving Laboratory in 1969, supervising the chemical analysis of an Apollo 11 sample with an optical emission spectrograph (similar to the one in his ANU laboratory, but with a quarantine glovebox enclosure). Right. Analyst's report of the first chemical analysis of a lunar sample, annotated and signed by Ross. Note Ross's last-minute revision to the Na₂O concentration (to an improved value) (Photo and image credits: NASA).

at the Lunar and Planetary Institute in Houston Texas, as a visiting scientist, where he wrote three of his books.³⁷ In total, Ross held 17 visiting appointments at LSI/LPI between 1969 and 2005, a place where he 'was always made very welcome'.³⁸

Following his retirement, there was never any offer to remain at RSES as a visiting fellow, as was common for senior retirees. He was, however, offered such a position in the Department of Nuclear Physics in RSPhySci and there spent a productive decade (1990–2000). No longer able to make new measurements in his laboratory, Ross recognised that in retirement, 'you cannot compete with young post-docs in producing more and more data on detailed subjects, but you can broaden your interests into more philosophical considerations'.³⁹ Accordingly, he turned his attention to broader questions of solar system evolution, writing the first edition of *Destiny or Chance*,⁴⁰ examining the likelihood that a solar system like ours (including intelligent life) might exist elsewhere, and beginning work on a fully revised

second edition of *Solar System Evolution*.⁴¹ During this decade, Ross (and Noël) often travelled to the University of Vienna, visiting his friend and colleague Chris Koeberl, and where Ross would present a series of lectures.

As Ross's second term as a visiting fellow in nuclear physics was coming to an end, he was approached by Dave Ellis, head of the Department of Geology (becoming Earth and Marine Sciences (EMS) in 2004), and invited to join that department as emeritus professor and visiting fellow⁴² to which Ross agreed. During his time in Geology/EMS, Ross re-discovered the classroom and, with Dick Arculus, taught a popular senior course in planetary science and also mentored several undergraduate students.

Return to RSES

In 2008, EMS was merged with RSES and Ross's career essentially came full circle. RSES had changed greatly during his two-decade absence and Ross remained there as a

³⁷Taylor (1975, p. xvii, 1982, p. ix, 1992, p. xv).

³⁸Taylor (2016) p. 9.

³⁹Marvin (2002) p. B54.

⁴⁰Taylor (1998).

⁴¹Taylor (2001).

⁴²Rickard (2010).



Fig. 8. Participants of the S. R. Taylor Planetary Crusts Workshop held in honour of Ross's 90th birthday in May 2015. Ross is sitting in the front row between his wife Noël and eldest daughter Susanna (Photograph provided by RSES).

visiting fellow until his death and (nearly to the end) 'continued working under more favourable conditions'.⁴³ During this time, Ross worked on his final book, *Destiny or Chance Revisited*.⁴⁴ One highlight of this time was the celebration of his 90th birthday (together with longtime RSES colleague, Mervyn Patterson) at RSES in 2015. Celebrations included a workshop on planetary crusts with invited speakers from the university and overseas (Fig. 8),⁴⁵ organised by Trevor Ireland and Marc Norman with much support from Ian Jackson, the RSES director. At the end of the various invited talks, Ross provided a remarkably detailed extemporaneous critique of each of the presentations, much to the delight of the audience. Everett Gibson, representing the Director of the Johnson Space Center in Houston, presented Ross with a plaque that included a New Zealand flag that had flown aboard the space shuttle Columbia in 1981 and the inscription: 'In recognition of your many scientific contributions across six decades. Your assistance in analysing the returned Apollo samples and interpreting the analytical data from NASA's planetary missions continues to contribute to our exploration efforts'. Around this time, external donations and RSES matching funds led to the founding of the Ross Taylor PhD Supplementary Scholarship in Geochemistry, available to both Australian and international students undertaking PhD studies in geochemistry at RSES.

Family and other interests

While at Oxford, Ross had met Noël White, originally from Perth, Western Australia. Noël was a PhD student in the Department of Chemical Crystallography (although her laboratory was in the Museum of Natural History, essentially next door to geology and mineralogy), supported on a CSIRO Overseas Studentship. Her supervisor was Dorothy Hodgkin, a future Nobel laureate, and her thesis dealt with



Fig. 9. Ross and his immediate family in 2015. From left are Judith, Noël, Ross, Susanna and Helen. Ross is holding a plaque presented to him by NASA in recognition of his efforts in lunar and planetary science. On the plaque is a New Zealand flag that was carried into space in April 1981 by the space shuttle Columbia (Photograph provided by RSES).

organic X-ray crystallography. Ross and Noël were married in Christ Church Cathedral on 21 May, 1958, shortly before departing for Cape Town. Noël found a research position in X-ray crystallography in the physics department at the University of Cape Town but when they moved to Canberra in 1961, there were no opportunities for Noël to further pursue a scientific career. She later pursued a career in intellectual property law at the Australian Patent Office (now IP Australia), where she was employed for more than twenty years.

Ross and Noël had three daughters (Fig. 9), Susanna Margaret, born in 1962, Judith Caroline, born in 1964, and Helen Rosalind born in 1966, and one grandson, Angelo Liangris, born to Helen in 2005. At the time of Ross's passing, Susanna, Helen and Angelo were living in

⁴³Taylor (2016) p. 12.

⁴⁴Taylor (2012).

⁴⁵RSES (2015).



*"Oh, I give him full credit
for inventing fire, but what's he done since?"*

Fig. 10. Ross was an avid reader of the *New Yorker* magazine and had a subscription for over fifty years. This cartoon, by Robert Kraus, was published in the 30 July 1960 issue and was posted outside Ross's office at ANU for many years, providing a good reflection of Ross's view that when conducting science, you should take your work very seriously, but not yourself (Used with permission of the *New Yorker*).

Canberra with Judith and her partner Michael living in northern Queensland.

Ross had many interests beyond science. As noted, he was a passionate student of history, especially military history, and was very knowledgeable about the battles and politics of World War 1. He was an avid reader of the *New Yorker* magazine and had a subscription for over fifty years. He would routinely bring copies into the laboratory for students and visitors to read during quiet times of operating the various instruments. Many mornings in the laboratory began with his group poring over the famous cartoons (Fig. 10) and column fillers in a newly arrived issue. Another life-long interest was classical and baroque music, mostly that written prior to 1820, and he especially enjoyed the works of Mozart. At home, he spent time working around the house and garden and always owned a tractor, nicknamed 'Tractor Ross', that he greatly enjoyed using both for working around the garden or just giving visiting children rides.

Major research contributions

Ross Taylor had broad academic interests and, with his students and collaborators, carried out analytical research

programs on topics as broad as trace elements in fossils and minerals, tektites, lunar samples, island arc volcanic rocks, sedimentary rocks, lower crustal xenoliths, and meteorites. His work was highly influential and in many cases provided fundamental contributions to our knowledge of Earth, the Moon and the solar system. He published his first paper in 1955,⁴⁶ on the petrology of rocks from one of his PhD field areas, and his last 64 years later at the age of 93,⁴⁷ a final contribution to lunar studies and tribute to his friend Larry Taylor. In between he authored about 375 publications, including 10 books, over 245 scientific papers in journals and multi-authored volumes and numerous others, including book reviews, commentaries and minor publications (see Supplementary material).

Ross was well known for his clear and highly engaging writing style (even a primary school teacher complimented Ross's writing style). He was economical with words and on several occasions received that rare editorial direction of elaborating further and so making his paper longer! Although he understood the importance of precision in scientific writing, he had a strong aversion to unnecessary jargon. Ross often brought his deep knowledge of history to his scientific writings: providing some appropriate historical context, a witty or wry reflection, or an ironic comparison. To give just one example, when highlighting the challenge of keeping in mind the big picture in geological investigations, Ross quoted the diplomat and naturalist Sir William Hamilton: 'We are apt to judge the great operations of Nature on too confined a plan' and then following this up with a footnote reminding readers that Hamilton was the husband of Emma Hamilton, who was even more famous for her long and (at the time) scandalous love affair with Admiral Horatio Nelson.⁴⁸

Tektites and impact glasses

While tektites were widely regarded as originating from meteorite or cometary impacts, a major controversy concerned whether the impacts were on Earth or the Moon (or even from outside the solar system). Of course, if tektites represented lunar samples they were of enormous importance. During his time at Oxford and Cape Town, Ross set upon a major analytical research project—which lasted over three decades—to evaluate the chemistry, origin and significance of tektites and other impact glasses. Focusing first on the alkali elements (K, Rb, Cs), Ross demonstrated that the K/Rb ratio of tektites was similar to that of the Earth's and, since those two elements formed by different nucleosynthetic processes, any extra-solar system material was unlikely to have a terrestrial K/Rb ratio. Ross concluded that the geochemistry strongly supported a terrestrial origin

⁴⁶Mason and Taylor (1955).

⁴⁷Taylor (2019).

⁴⁸Hamilton (1773). Taylor and McLennan (1985) p. xi.

for tektites because all major elements, and especially potassium, exhibited negative correlations with silicon, trends commonly observed in sedimentary rocks but rarely in igneous rocks. Up until that point, even proponents of a terrestrial origin had thought tektites were of igneous origin. These data provided one of the most compelling lines of argument for a terrestrial origin by impact of sedimentary rocks, since chemical weathering to form sediments on the Moon was highly unlikely.⁴⁹ The debate continued to rage for many years until the return and analysis of Apollo samples leading one observer to remark ‘The lunar origin of tektites, a controversial and stimulating theory ... died on July 20, 1969. The cause of death has been diagnosed as a massive overdose of lunar data’.⁵⁰

Lunar science

Although Ross had said that his work on the preliminary analyses of Apollo 11 and 12 samples was the ‘most important and critical thing that I have done’,⁵¹ he also made major advances in our understanding of the origin and evolution of the Moon, and Ross was highly regarded for his authoritative books summarising the state-of-the-art of lunar science,⁵² which remain must-reading to this day.

Working with Petr Jakeš, and later Ted Bence, Ross developed the Taylor-Jakeš (-Bence) model for the evolution of the Moon.⁵³ Ross recognised that to explain both the highly variable mare basalt compositions and the feldspar-dominated highland rocks you needed to start with a completely (or at least largely) molten Moon. Once melted and beginning to cool, minerals would crystallise out in a well-understood order, with early-formed, denser olivine and pyroxene sinking and lighter feldspar rising to the top—essentially a planetary-scale layered intrusion with a thick feldspathic crust. Mare basalts could then be derived by later re-melting of compositionally distinct layers within the Moon. Although many refinements have been made over the years, this remains a standard model for lunar evolution.

The question then became how to entirely melt the Moon in the first place, which in turn led to the difficult issue of lunar origin—a question that, contrary to expectations, lunar sample return had not resolved. This continued to perplex lunar scientists for well over a decade after Apollo, leading to Sean Solomon paraphrasing Ross when defining ‘Taylor’s Axiom: the best models for lunar origin are testable ones’ and ‘Taylor’s Corollary: the testable models for lunar origin

are wrong’.⁵⁴ The solution had to wait until theoretical modelling caught up with the massive amount of lunar data, giving way to the Giant Impact Model whereby the Moon formed as a result of a glancing blow by a Mars-sized impactor. Ross calculated that the Moon was enriched in iron and refractory elements (notably aluminium) and so Earth and the Moon had significantly different compositions, consistent with the Giant Impact Model as then understood. Ross’s model relied on early data indicating that the Al-enriched lunar crust was very thick, but results from the 2012 Gravity Recovery and Interior Laboratory (GRAIL) lunar orbiter mission demonstrated that the lunar crust was much thinner than thought. Ross accordingly revised his long-held views on the Moon’s bulk composition and accepted that lunar and terrestrial silicate compositions were nearly identical (with implications for the Giant Impact Model that are still debated). With a typical historical perspective, he commented in a 2015 note added to his final book: ‘But as Heraclitus of Ephesus (ca 500 BCE) remarked “There is nothing permanent except change” and science is a movable feast’.

The continental crust

From the earliest days of geochemistry, there was great interest in determining the chemical composition of Earth’s continental crust. The early 1960s witnessed the climax of the plate tectonic revolution and so it was not surprising that soon after arriving at ANU, Ross began to think about the composition and origin of the continental crust. He began with an old idea of Goldschmidt, that sedimentation efficiently sampled and homogenised the exposed crust, and connected that to a newer idea, that rare earth element (REE) distributions in sedimentary rocks were uniform. He then modelled the crust as a mixture of granite and basalt, in proportions that resulted in the sedimentary REE distribution. The resulting composition was by far the most comprehensive to date (including 68 elements) and widely cited for many years.⁵⁵

At about this time, Ross also worked with Alan White (ANU Department of Geology) to note the similarity between the composition of andesites, commonly being formed at orogenic belts (subduction zones), and previous estimates of continental crust composition.⁵⁶ This gave rise to the so-called andesite model whereby continents grew over time by the addition of andesites and related calc-alkaline rocks during subduction processes.⁵⁷ In turn, this

⁴⁹Taylor (1973).

⁵⁰Schnetzler (1970).

⁵¹Taylor (1994b) p. 3760.

⁵²Taylor (1975, 1982).

⁵³For example, see Taylor and Jakeš (1974) and Taylor and Bence (1975).

⁵⁴Hartmann and others (1986) p. vi.

⁵⁵Taylor (1964).

⁵⁶Taylor and White (1965).

⁵⁷Taylor (1967).

led to a two decade-long research effort in Ross's laboratory to gain a better understanding of the geochemistry of subduction-related igneous rocks. Although models for crustal composition and growth have always been controversial, the andesite model (and variations on it) continues to remain popular.

Dating from his work on tektites, Ross recognised a serious dearth in the amount of trace element data available for sedimentary rocks. Therefore, he and his students collected data for sedimentary rocks of all ages. A critical part of this effort was to use the sedimentary data as a sample of the upper continental crust and then explore how the composition of the crust evolved over geological time. They concluded that the Archean-Proterozoic transition (between about 3.2 to 2.5 billion years ago) represented a key benchmark in the evolution of the crust (and Earth in general). This culminated in one of the most influential books written in crustal geochemistry: *The Continental Crust: Its Composition and Evolution*,⁵⁸ which, nearly forty years after publication, is being cited more than 1200 times annually. He later also explored the composition of the lower continental crust.⁵⁹

Meteoritics and the solar system

Ross was also interested in meteoritics and wrote several early papers on the composition of the solar nebula. His most consequential work was with Brian Mason, where they characterised and classified the refractory calcium-aluminium-rich inclusions in the Allende Type CV3 chondritic meteorite that fell in Mexico in 1969.⁶⁰ These materials provided the clearest evidence, largely from highly unusual REE distributions, for complex, very high-temperature chemical fractionation processes taking place locally within the early solar nebula.

Another influential contribution was Ross's scheme to classify the crusts of planetary bodies (planets, dwarf planets, moons), into Primary, Secondary and Tertiary,⁶¹ which still remains in common usage. Although planetary crusts could be reasonably classified in this manner, when examined in detail for Ross's penultimate book *Planetary Crusts: Their Composition, Origin and Evolution*, he concluded that 'this does not imply any logical or inevitable sequence of development' because of the large number of variables, often acting stochastically, that influence crustal development and evolution, summed up as 'there are more variables than there are planets'.⁶²

In Ross's final major work, his book *Destiny or Chance Revisited*,⁶³ he again turned his attention to the large number of stochastic processes giving rise to the extreme diversity of the bodies of our solar system and a growing number of extrasolar planets. This examination reinforced his skepticism of whether or not intelligent life has ever existed elsewhere in the universe.

Professional service

Ross contributed in many ways to the professional community. He took part in the governance and administration of international societies and organisations, including the Geochemical Society, Meteoritical Society, International Association of Geochemistry and Cosmochemistry and the Planetary Society. He served for thirty-five years as an associate editor for the premier journal in the fields of geochemistry and cosmochemistry, *Geochimica et Cosmochimica Acta* (1964–2000). Details of his editorial appointments and other professional service are provided in the Supplementary material.

Honours and awards

Ross's accomplishments were widely recognised and a full list of his honours and awards are provided in the Supplementary material. Most notable among these is his election to the Australian Academy of Science (1978), Royal Society of New Zealand (1989), and the United States National Academy of Sciences (1995), receipt of the Goldschmidt Medal (1993)⁶⁴ and Leonard Medal (1998), the highest honours from the Geochemical Society and Meteoritical Society, respectively, and the Walter H. Bucher Medal (2002),⁶⁵ awarded by the American Geophysical Union. In 1997, The International Astronomical Union approved the naming of the 30 km diameter Main Belt asteroid '5670 Rosstaylor', discovered by Carolyn and Eugene Shoemaker in 1985.⁶⁶

In a crowning achievement, and a fitting end for this biography, the 2008 Australian Honours List named Stuart Ross Taylor a Companion of the Order of Australia (AC), which at the time was the highest Australian civilian award, 'for outstanding service to science, particularly in the fields of geochemistry and cosmochemistry as a researcher, writer and educator'.

⁵⁸Taylor and McLennan (1985).

⁵⁹For example, see Rudnick and Taylor (1987).

⁶⁰Mason and Taylor (1982).

⁶¹Taylor (1989).

⁶²Taylor and McLennan (2009) p. 352.

⁶³Taylor (2012).

⁶⁴See Mason (1994) for award citation.

⁶⁵See Hofmann (2003) for award citation.

⁶⁶The International Astronomical Union Minor Planet Center: https://minorplanetcenter.net/db_search/show_object?object_id=5670.

Supplementary material

Supplementary material is available [online](#).

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