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Bruce William Chappell 1936–2012

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Bruce Chappell was one of the most distinguished geologists of his generation whose contributions to understanding the origins of granites are both insightful and profound. A pioneer in the application of X-ray fluorescence spectrography to the analysis of geological materials, his radical ideas about magma genesis, still the subject of vigorous debate, have dominated and largely determined the global directions of subsequent research on granites. His *restite model*, the recognition that most granite magmas move bodily away from their source regions as a mixture of melt and solid residual material, the progressive separation of which determines the magma composition, underlies his tenet that granites are images of their source. His consequent recognition, with Allan White, that there are two fundamentally different types of granite magma, I-type (derived from igneous sources) and S-type (derived from weathered sedimentary sources), each with its distinctive evolutionary path and associated mineralization, continues to underpin research into granites worldwide, and the search for granite-related mineral deposits.

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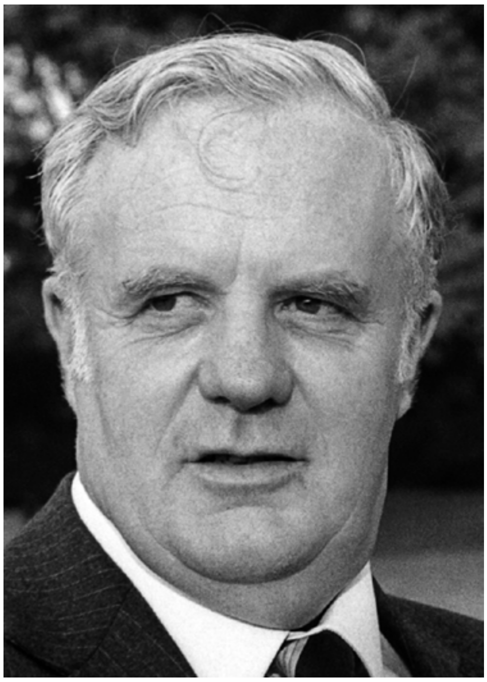
Early Days in Armidale

Bruce William Chappell was born in Armidale, New South Wales, on 20 November 1936, the fourth of five children in the family. He spent his childhood in Arding, a small village 16 km south-west of Armidale, where his father John was the headmaster of the one-teacher country school, and his mother Eva worked in the post office and operated the telephone exchange. He started formal schooling one year earlier than most children, principally as a form of child minding by his father, and as a consequence had to spend a seventh year in primary school in order to be old enough to enter secondary school. His only teacher for those seven years was his father.

From 1949 to 1953 Chappell was a student at Armidale High School. There he excelled, attributing his success in large part to his having exceptional teachers, particularly in mathematics and science. His Leaving Certificate result in 1953 remains the best achieved by a student from that school. He topped the state in several subjects, and was awarded first class honours in mathematics, physics and chemistry. Almost 60 years later, when sorting through his papers just before his death, he confessed to family members how very proud he was of that initial academic achievement.



Formative Years and the University of New England

Limited funds prevented his family from sending Chappell to university in Sydney, so in 1954 he enrolled in Armidale's 'university of the north', New England University College, a college of the University of Sydney. Later the same year the college became fully independent as the University of New England (UNE). Given his strong interest in science, Chappell enrolled in physics (taught by Dr Jack Somerville, a leading researcher), mathematics and chemistry, choosing geology (taught by Dr Alan Voisey) as his fourth subject.

Initially Chappell travelled the 19 km from Arding to UNE on a pushbike, an arduous undertaking, particularly in the bitterly cold Armidale winter, and when classes did not finish until 5.00 p.m. Concerned for his health, Somerville and Voisey canvassed the Geology Department staff and raised the money to buy him a motorcycle.

In his second year at UNE Chappell focused his efforts on physics and chemistry. Finding mathematics relatively straightforward, he had time to pursue his increasing interest in geology, and particularly the role of chemistry in geology. This interest was fostered by Dr John Wilkinson, an enthusiastic young petrologist who had just returned to teaching at the UNE after completing a PhD at the University of Cambridge on the mineralogy and chemical composition of a differentiated 'basaltic' sill near Gunnedah.

* Deceased 17 June 2017.

At the end of his second year, Chappell took a vacation job at the National Standards Laboratory in Sydney. This was to be a major turning point in his life because, on returning to Armidale to resume his studies, he surprised his lecturers by abandoning plans for a career in physics and turning his attention wholly to chemistry and geology. Recognizing that Chappell would need a stronger grounding in geology if that was to be the subject of his honours year, Voisey made it clear that he should study those aspects of geology that he had missed during his second year. This he did by taking several second year geology subjects along with third year chemistry and geology.

Voisey taught him the basics of physiography, particularly as it applied to the elevated New England plateau. Other members of the geology staff took him on field trips to Tamworth, Manilla, and other regions further north, each serving to increase his knowledge of the geology of the area, and the western side of the plateau in particular. Chappell had no interest in biology, a subject he had not studied in high school, but as part of broadening his knowledge of geology he was introduced to palaeontology and its application to determining the age of sedimentary rocks. He was taken to Gloucester in southern New England and shown how palaeontology could be used in studying the cooling of the Earth during the widespread glaciation that affected Gondwana in the Late Palaeozoic. These trips served to show Chappell the breadth of geological studies being carried out in New England and he became increasingly aware of the vast area of granite in the region, and how little was known about it. He decided that if he were to have a career in research, he would work on granites.

For his honours year (1958) Chappell mapped the geology of an area of over 500 km^2 in the Tamworth-Manilla region. His work focused on the Devonian sequences in the area and their contacts with the granites of the New England Batholith. It introduced him to the differences between the geological structures in two of the main geological terranes in eastern Australia; the New England Orogen and the Lachlan Fold Belt. He became aware of the significance of the major faults that separated the two terranes and began to think about possible reasons for the geological contrasts between the two.

The year 1958 was seminal in the history of granite studies. The field had just emerged from an extended period of controversy over whether or not granites were igneous rocks, the argument being laid to rest by the partial melting experiments of Tuttle and Bowen (1958).[1] Chappell became engrossed in the problem of how granites formed and, by his own admission, during his honours year read almost everything that had been written on the subject, which at that time was still possible. He was particularly interested in the ideas of Eskola,[2] whose concept of mineral facies broke down the barriers between the mineralogy of metamorphic and igneous rocks, but the paper that he later considered to have influenced his thinking the most was one by Walton,[3] who showed that granite bodies surrounded by narrow high-temperature metamorphic aureoles must be igneous intrusions. In 1959, having written a thesis entitled ‘The Geology of the Tamworth-Manilla-Bendemeer District, New South Wales’, he graduated with first class honours in geology and was awarded a University Medal, the first to a geology graduate at the UNE.

Two important ideas took root in Chappell’s mind during his honours year. First, he realized that the volcanogenic sediments of the Late Devonian Baldwin Formation, which were virtually devoid of detrital quartz were, except for a high Na_2O content due to interaction with sea water, almost unchanged in chemical composition from typical andesite, a volcanic rock common in island arcs. Second, he recognized that the enclaves (dark inclusions) in the granites that he studied were distinctly different from any of the country rocks that the granites intruded, so were not xenoliths (foreign rocks) as commonly believed. He argued that the enclaves were intimately related to the origin of the granites, and that the clots of mafic (Fe- and Mg-rich) minerals and even the zoned plagioclase crystals found in the more mafic granites might be disaggregated enclaves.

In 1959, Chappell took a job as a Demonstrator in the Geology Department at the UNE and began work on a PhD. The situation was becoming difficult for him at his home, however. His father was a man of strong religious convictions, and young Chappell’s work in geology brought him into conflict with his father’s beliefs. In late January, 1960, Chappell decided to make a move. He resigned as demonstrator, withdrew his PhD candidature, and took a job as a Lecturer in the newly established Geology Department at the Australian National University (ANU). The move was made with the support of his UNE lecturers Voisey and Wilkinson, although he never published any of his work with his UNE colleagues.

The Australian National University

Chappell was the second appointment, after Professor David Brown, to the fledgling ANU Geology Department. During 1960–1, while working with Brown to set up the department and lecturing, he studied part-time for his MSc degree. He chose as his topic the petrology of the Late Devonian volcanic greywackes of the Baldwin Formation, developing his ideas about the close chemical relationship between the volcanogenic sediments and the erupted magmas that had given rise to them. Uncharacteristically Chappell was outwardly proud of his work on the greywackes,[4] and in later life never missed an opportunity, when leading a field trip that passed through Tamworth, to take the party up the road to the Oxley Lookout to see the greywacke outcrops.

Chappell and White

At the ANU, Chappell met Senior Lecturer Dr Allan White, the start of what became a lifelong scientific partnership, synergy and enduring friendship. White was a vibrant, irreverent young structural geologist/petrologist who had studied granites for his PhD under the supervision of Professor Wally Pitcher at King’s College London, and been a lecturer at the University of Otago with Professor Brown. In 1962 Chappell enrolled to study for a PhD that he worked on part-time under White’s supervision, completing the project in 1966. The topic of his research was the granites of the Moonbi region, in the southern part of the New England Batholith (Fig. 1). When he started his work on the granites, fundamental questions about what granites represented and how they formed remained unresolved. Following the experimental work of Tuttle and Bowen (1958)[5] it was widely agreed that granites were igneous rocks formed from magmas, but the source of those magmas was assumed to be metasedimentary rocks, and assimilation of country rocks was thought to be an important factor in granite magma genesis. Plate tectonics was an unknown concept, so the global distribution of granites remained unexplained, but it was firmly believed by most

Figure 1. Collecting granite samples requires hard physical labour. Broken rock thrown up by roadworks makes the job easier, as at this roadside site near Bendemeer, where Chappell collected material in 1966 for his PhD study of the granites of the Moonbi district.

igneous petrologists that there was no connection between granites and volcanic rocks.

X-ray Fluorescence Spectrography

A critical component of Chappell's PhD research was the chemical analysis of granites using X-ray fluorescence spectrography (XRF). Chappell had never been interested in chemistry for its own sake, but with his background in physics, he developed an interest in the physical methods of chemical analysis. In 1963 he was given responsibility for the operation of the ANU Geology Department's XRF laboratory, a position that he held for a period of 34 years. The XRF equipment that he used for his PhD analyses was very basic, but under the expert guidance of Dr Keith Norrish from the CSIRO Division of Soils, Adelaide (who also became a lifelong friend) he was able to produce rock analyses with a level of accuracy not previously achieved. These analyses included determinations of elements such as Al, Na and K that were notoriously difficult to measure by classical chemical methods. His paper with Norrish on XRF published in Zussman's *Physical Methods in Determinative Mineralogy* (1967) remains a benchmark in the development of the technique and a basic reference in its application.[6]

The accuracy of Chappell's analyses made it possible for him to see patterns and relationships in the chemical compositions of granites that had never been seen before. He recognized that bulk chemical composition is a basic parameter by which a granite must be defined and that the composition of a granite is the most useful parameter for studying its genesis. He showed that there is a very close relationship between the bulk chemical composition and the mineralogy of a granite that can be defined precisely, his use of ACF (Al_2O_3, CaO, MgO + FeO) diagrams for granites following directly from the ideas of Eskola.[7] He found that each of the Moonbi granite bodies (plutons) had a distinctive range of compositions, and that it was possible to recognize groups of plutons (that he later termed *suites*) that shared common mineralogical and chemical features that distinguished them from other groups.[8]

The Restite Hypothesis

Chappell showed that within each pluton and suite, except for one unusual group of cordierite-bearing granites, there were strong linear correlations between the abundances of different elements. He interpreted this to indicate that the source region for each suite was igneous rock of very uniform chemical composition, and that the granite magmas consisted of a mixture of partial melt and solid material (ten years later he termed this *restite*) that became separated to different extents (unmixed) during magma transport, producing the range in compositions within a pluton or suite as observed. Clots of mafic minerals within the granites were interpreted as remnants of restite, and the most mafic granites in a suite were considered to be the closest in composition to their igneous source rocks. In essence Chappell recognized what he stated directly over a decade later—granites are images of their source.[9] These findings and ideas were radical for the time, but because work on the Lunar program then intervened, they were not published until several years later.[10]

In 1967, the ANU XRF laboratory was re-equipped with a new generation of instruments and over the next several years Chappell spent a huge amount of time and effort improving the instruments and developing techniques for the analysis of trace element abundances with parts per million accuracy. He was the first person to use XRF to measure trace elements accurately on large numbers of samples of a wide range of rock types. Working with technical staff from the Geology Department and Mr Steve Butler of Torrens Industries Pty Ltd, he designed and built a large automatic sample loader for the XRF spectrometer, for which he was jointly awarded a Certificate of Merit by the Australian Industrial Design Council for the best industrial design in the field of electronics in 1971, and was a finalist for the Prince Phillip Prize for Industrial Design. This equipment made it possible for the first time to make large numbers of highly precise geochemical analyses and is now standard on most XRF spectrometers.

The Apollo Samples

As an essentially non-destructive analytical technique with high sensitivity, accuracy and precision, XRF was ideal for the analysis of samples returned from the Moon. Chappell was an Associate Investigator for the entire Lunar program, and undertook chemical studies of samples returned from all six manned Lunar missions.[11] Of the first 65 Lunar sample analyses reported by twelve laboratories at the Apollo 11 Lunar Science Conference, Chappell contributed ten, more than any other laboratory.[12] Only four laboratories, including Chappell's, reported full analyses of major elements plus trace elements. Because several laboratories analysed the same samples by a range of analytical techniques a rigorous comparison of the various datasets could be made. Chappell's results stood up well, and although some other laboratories determined a larger number of trace elements, for some elements, such as Y, Nb and Ga, Chappell's values were the most definitive. Much of each small sample that Chappell used for his determinations ($\sim$1 g) was recovered afterwards and used by his ANU collaborator, Principal Investigator Dr William Compston, for isotopic analyses.[13]

Chappell's chemical data on the Apollo 11 basalts reported at the First Lunar Science Conference showed that the samples fell into two chemical groups.[14] He interpreted this to indicate that the samples represented two distinct rock units, although the groups differed from the two recognized by the NASA preliminary examination team. In a sample of soil that had a composition intermediate between the two, he detected the presence of a small amount of a discrete component enriched in Ni, Cu and Zn. Analyses of nine Apollo 12 basalts showed much more diversity, with at least six distinct groups being recognizable. Chappell modelled the basalt compositions in detail to determine the best groupings, then in one of the first attempts of its kind, used a primitive computer program to model the process of fractional crystallization (sequential crystallization of different minerals) quantitatively. He successfully distinguished the samples produced by different melting events in the Lunar mantle and showed how the compositional variation within each group resulted from the crystal fractionation (progressive removal from the magma) of olivine and spinel.[15] Largely as a result of his work, XRF soon replaced emission spectroscopy as the preferred technique for the analysis of Lunar rocks.

Computerization and INAA

Chappell pioneered the use of simple minicomputers to process XRF data online and developed all the software for doing so. With the advent of personal computers he developed software for processing trace element data in which every sample was identified in the system by a unique number, and different elements (as well as duplicates of the same element) could be analysed with different X-ray tubes with different groups of calibrations at different times. The date and time of each analysis were recorded, and each analysis processed with the appropriate calibration on that basis, in combination with all of the necessary inter-element corrections.

In 1978, Chappell made the major decision to supplement his XRF analyses by entering the field of Instrumental Neutron Activation Analysis (INAA). This provided the ANU Geology Department with a combination of analytical techniques that was available in very few other institutes, and led to significant improvements in the use of both. The combination also made it possible to make very precise corrections for variation in the neutron flux during the irradiation for INAA, opening up additional possibilities for applications requiring highly accurate geochemical data.

The experience that Chappell gained with solid state detectors when working with INAA led him to appreciate the potential of XRF analysis using polarized X-rays. The method, developed mainly for use in industrial and environmental laboratories, provided much greater sensitivity than conventional XRF for many of the elements of interest to geochemistry. In 1998, Chappell purchased an XRF spectrometer from Spectro Analytical Instruments in Germany and, linking up with the manufacturers, became the first person to investigate its performance and push it to its limits in a geological research environment. This collaboration, in which Chappell visited Germany regularly to provide practical advice on how the spectrometer could be improved, and assisted in the installation and commissioning of several Spectro spectrometers in Australia, continued almost until the time of his death.

I- and S-type Granites

Over the period that Chappell was mostly focused on refining his techniques for XRF analysis and his work for the Lunar program (1966–74), Allan White and BSc honours students from the ANU Geology Department were systematically mapping and characterizing Lachlan Fold Belt granites in the Berridale region of southern NSW. They found that there were two different types of granite in the region, hornblende-bearing granite that was metaluminous to weakly peraluminous (ASI = molecular $Al_2O_3/(Na_2O + K_2O + CaO) \leq 1.1$), and cordierite-bearing granite that was strongly peraluminous (ASI $>$ 1.1). Chappell and White visited the area together in 1972 and, in discussions on the outcrops, came to the realization that the difference between the granite types was fundamental, the metaluminous to weakly peraluminous granites probably being derived from igneous source rocks, and the strongly peraluminous granites being derived from sedimentary source rocks. In retrospect this explained the origin of the curious cordierite-bearing granites in the New England Orogen that had worried Chappell during his PhD because their composition was inconsistent with derivation from an igneous source.

After the field trip, having been exposed to the hype of the Apollo program, Chappell felt that catchy names were needed for the two granite types. It was decided to call the granites with infracrustal igneous sources *I-type*, and those with supracrustal weathered sedimentary sources *S-type*. A distinction and nomenclature that now underpins much of the work on granites worldwide was born. In October 1972, Chappell outlined the I-S concept at a meeting of the International Geoscience Program (IGCP) Circum-Pacific Plutonism Project in Santa Cruz, California. He was urged to publish the idea, so an abstract was written for the meeting of the Project in Chile the following year, and appeared among the conference papers in the now-discontinued journal *Pacific Geology*.[16] By early 2017, this little abstract had attracted over 3000 citations. It was listed by Yoder (1993) in his article *Timetable of Petrology*[17] as one of only seven critical discoveries in the development of ideas in petrology that originated in Australia.

Chappell's visit to California was the start of a collaboration with Dr Paul Bateman (United States Geological Survey), leader of the IGCP project, and later Professor Leon T. Silver (California Institute of Technology) in the study of the Cordilleran granites of the western USA. He found those granites to be completely different in basic features such as rock texture, intrusive relationships and chemical trends, from those that he had studied in Australia. Unlike the relatively homogeneous granite plutons in Australia, those in the western USA commonly were zoned from more mafic (Fe- and Mg-rich) rocks at the margins to more felsic (Fe- and Mg-poor) rocks at the centre, the Tuolumne intrusive series in the Sierra Nevada being a prime example. In addition, rather than there being strong linear relationships between the abundances of different elements in the granites, some elements such as Rb, Ba, Zr and Ni commonly defined curved trends when plotted against SiO_2 or total Fe.[18] This he realized was due to the process of fractional crystallization, in which particular more compatible elements are extracted from the cooling granite magma as different minerals crystallize, while other more incompatible elements become concentrated in the melt phase, some such as Zr and Ba being removed only when a new mineral starts to crystallize.

High and Low Temperature Granites

Chappell had embarked on what became a lifelong quest, to understand the petrogenesis of granites through their chemical compositions. In the course of his career he analysed, with unprecedented accuracy, many thousands of samples of granites and their associated volcanic rocks carefully collected and documented by himself, his students, post-docs and collaborators. The scientific concepts that he developed were underpinned by extensive geological mapping of large areas of eastern Australia that he, White and their students undertook as a basis for understanding the relationships between, and distribution patterns of, the different types of granite and granite suites. That work culminated in the preparation of a 1:1,250,000 scale map, published by the Bureau of Mineral Resources, Geology and Geophysics in 1991, in which all the main granites and related rocks of the Lachlan Fold Belt were distinguished, delineated, named and, where possible, classified.[19] Substantial portions of that mapping were subsequently integrated into the geological maps of the Geological Survey of New South Wales and Geoscience Australia (and its antecedents).

As well as analysing nearly every significant granite body in eastern Australia, from Torres Strait to southern Tasmania, Chappell carried out major studies on the igneous rocks of Papua New Guinea, Japan, the western USA, Scotland and Cornwall. Through this work he refined his ideas and recognized the similarities in, and differences between, the source rocks and magma-forming processes in different tectonic settings. The granites of the western USA, for example, were formed by the high temperature melting of igneous sources, the very high degrees of partial melting commonly leading to changes in magma composition due to fractional crystallization during magma transport and after emplacement. Many of the granite magmas in Cornwall also were modified by fractional crystallization, but because their source rocks were predominantly sedimentary, the end products were different resulting, for example, in major enrichments of Sn.[20]

Amongst the granites of the New England Orogen and Lachlan Fold Belt fractional crystallization was relatively uncommon. The temperature of the magmas mostly was relatively low, so they moved bodily away from their sources deep in the crust as crystal-rich mixtures of melt and residual solid material. Although solid and melt could begin to separate (restite unmixing), by the time the granites began to crystallize the melt component was too viscous for the complete removal of crystals. Exceptions were rare granites, mostly I-types, in which the source reached much higher temperatures before the magma mobilized. These high temperature magmas were less viscous and had a much higher melt fraction, allowing fractional crystallization to occur and compositional zoning to develop.[21]

Chappell considered the restite model to be his most important contribution to the study of granite petrogenesis. After first publishing the concept with White in 1977,[22] he developed the model and explored its implications, publishing his findings in a carefully reasoned article in the *Journal of Petrology* (1987)[23] and expanding them further in his Mawson Lecture for the Australian Academy of Science, delivered in 1998.[24] The key point of the restite model is that granites image their source rocks—their compositions and the paths by which the magmas evolve are determined by their source 'DNA'. The model recognizes that many granites exposed at the surface of the Earth closely reflect the nature and composition of their deeper source materials, and from the patterns of compositional variation within granites, the nature of the source rocks can be inferred. The fact that many granite magmas are formed at relatively low temperatures has important implications for the amount of heat required to induce magmatism, the mechanism by which the composition of the Earth's crust has become vertically fractionated, the water content of magmas, and the role of granite magmatism in forming mineral deposits. In Chappell's opinion, the restite model was 'the only fundamentally new process dealing with the evolution of igneous rock suites since [the publication of the book *The Evolution of the Igneous Rocks*[25] by] Bowen in 1928'.[26]

Towards a Unified Model of Granite Genesis

By 2004, Chappell had made significant progress towards a unified model for granite genesis.[27] The model was based on premises that he held to be true: most granites form by processes initiated by partial melting of the crust; source rock compositions provide the genetic code for granites, predetermining to a significant degree the physical and chemical properties of magmas, and their physical and compositional evolution; each granite source responds to heating in a manner that is a physicochemical expression of its composition; crystal fractionation, either of entrained or previously precipitated crystals, is the dominant mechanism by which the compositions of individual samples of granite have evolved.

Chappell's unified model used as its basis the work of Tuttle and Bowen (1958)[28] who showed that partial melting produced a low temperature melt of granitic composition, crystallizing approximately equal amounts of quartz, albite and orthoclase (haplogranite), only if the starting material contained a sufficient abundance of four critical components: SiO_2, K_2O, Na_2O and H_2O. Chappell took the idea one step further and asked the question—what would the composition of the melt be, and what sort of magma would be produced, if higher temperatures were needed to form a mobile magma because the source rock was deficient in any one of those components? His answer provided an explanation for much of the range in the compositions of granites around the world.

A deficiency in SiO_2 produces mafic magmas (high CaO, MgO, FeO) that crystallize to form monzogranites enriched in Na_2O and K_2O like some in the New England Orogen and the USA Cordillera. These magmas have low viscosity and carry little restite or inherited older zircon. If the SiO_2 deficiency is severe, the magmas will be very high temperature with a high melt fraction, so will evolve by fractional crystallization.

A deficiency in K_2O produces the most common low to medium temperature I-type magmas, crystallizing as granodiorites and tonalites, such as found in the Lachlan Fold Belt, New England

Orogen, the USA Cordillera and some island arcs and ocean islands. These magmas are restite rich, and commonly contain inherited older zircon. A severe deficiency produces high temperature tonalites like those characteristic of the early part of Earth's history, the Archaean tonalite-trondhjemite-granodiorite (TTG) suite of rocks.

A deficiency in Na_2O is usually found in sedimentary rocks from which Na_2O has been removed when plagioclase has been destroyed by weathering. Magmas produced by the partial melting of such source rocks produce the S-type granites, with their characteristic depletions in Na_2O and CaO. If the deficiency in Na_2O is severe, insufficient melt will be produced to form a mobile magma at any reasonable geological temperature—the source rock is infertile.

A deficiency of H_2O is one of the most severe limitations on partial melting. Magmas initially produced at high temperature from such sources crystallize as granite with a similar bulk mineralogy to that produced by low temperature minimum melts (haplogranite), but with significant enrichments in diagnostic trace elements such as Zr, Ga and Y. These so-called A-type ('anhydrous'—anorogenic) granites were recognized by Chappell and his students as comprising a minor third granite group in south-eastern Australia,[29] examples of which subsequently were characterized elsewhere in the world.[30]

Despite their applicability to a range of granites worldwide, both the restite model and the concept of I- and S-type granites have been highly controversial, attracting a great deal of at times vitriolic criticism from petrologists and geochemists who have a steadfast belief that most granites must have an origin involving mixed sources or mixed magmas, most with a significant contribution from the Earth's mantle. Part of the problem is that, in the minds of some researchers, the restite model and the concept of I- and S-type granites have become linked, when in fact they are two completely separate ideas. Some of the most vehement criticism has come from those whose ideas are based largely on isotopic evidence, not understanding that any theory of granite petrogenesis must explain both the chemical and isotopic data simultaneously. Chappell was intensely frustrated by some of this criticism, particularly when it became personal and his critics clearly had not understood the key papers in which he had set out in carefully reasoned detail the evidence behind his ideas. Much of the criticism came from conservative petrologists with little or no experience of granites outside America. Chappell defended his ideas in person and in print[31] with characteristic ferocity and tenacity, winning over some, but not all, of his detractors.

Granites and Metallogenesis

From a very early stage Chappell and White (Fig. 2) realized that there were economic implications to the recognition of two main types of granite—Sn mineralization, for example, appeared to be confined to the most felsic of the S-type granites, whereas W and porphyry-type Cu and Mo deposits were associated with the I-types.[32] These ideas were developed in following years as Chappell's eastern Australian geochemical database was expanded, vast amounts of information being disseminated to assist the mineral exploration industry through workshops and meetings, particularly through the Australian Mineral Industry Research Association (AMIRA). AMIRA provided considerable financial support. Over a stressful period of nearly twenty years, meetings with industry were held at least every six months, most preceded by a mad rush to finalize analytical work and have new ideas and results ready for presentation. Larger workshops and field visits were held at sites as widespread as Canberra, Sydney, Melbourne, Hobart, Townsville, the Australian Alps, inland far north Queensland, and the central west and New England regions of NSW.

Figure 2. The symbiotic collaboration between Bruce Chappell (right) and Allan White (left), seen here in 2001, led to some of the most significant advances in the understanding of granite petrogenesis in the 20th century.

Chappell's first AMIRA project (P147: Geochemistry of Granites as an Aid to Mineral Exploration) ran from 1984 to 1986. It brought together all the geochemical results on granites of the Lachlan Fold Belt that had been obtained at the ANU by Chappell and his students up until that time. The project was subsequently extended twice to encompass analyses of granites from the New England Orogen and North Queensland, providing coverage of much of the exposed Palaeozoic crust in eastern Australia.

The work on granite-related mineralization received a significant boost when economic geologist Dr Phillip Blevin joined the team. Starting with a ground-breaking paper in 1992[33] Blevin and Chappell set about establishing a range of criteria by which the mineral industry could use granites and their related volcanic rocks to assess the prospectivity of a given district or region, particularly in eastern Australia, for a range of different types of mineral deposits. These criteria, progressively refined over the following two decades, were based on a deep understanding of the chemical processes that govern the transport and concentration of metals in the context of the different chemical environments present in granite magmas and magma sources of different compositions.[34]

The style of mineralization associated with a given granite suite was found to be related primarily to silica content, oxidation state, degree of compositional evolution and fractionation, and halogen content. Sn mineralization is associated with granites, both I- and S-type that are reduced and have undergone fractional crystallization. Cu and Au are associated with magnetite- and/or titanite-bearing, oxidized, I-type granites with intermediate SiO_2 contents. W is associated with a variety of granite types, apparently independently of oxidation state. The relationship between style of mineralization and redox state was attributed to the sequestering of ore elements by sulfides and Fe-Ti phases, the stability of which is dependent on the O_2 fugacity (f_{O2}). Fractional crystallization amplifies the process by concentrating in the melt phase those elements that are incompatible in the new-forming crystals. The low Cl content of S-type granites accounts for the rarity of Mo, Cu, Pb and Zn mineralization associated with those rocks.

For AMIRA Project P425 (1994–7: Intrusion Related Gold and Copper Deposits of Eastern Australia) Chappell and Blevin joined forces with Dr Gregg Morrison (Klondyke Exploration Services) to examine the relationships between regional-scale igneous associations and many of the major Cu and Au deposits in eastern Australia. Young researchers Simon Beams (later Director of Terra Search Pty Ltd) and Doone Wyborn (later a Director of Geodynamics Ltd) were major contributors to this large project.[35] AMIRA project P515 (1999–2002: Igneous Metallogenic Systems of Eastern Australia) brought the long-running collaboration with industry to a conclusion. The confidential final report for the project written by Blevin ran to over 200 pages. It provided a first-pass synthesis of the granite geology and related metallogeny throughout eastern Australia and an assessment of the prospectivity and likely styles of granite-related mineralization, region by region, from far North Queensland to southern Victoria.

Chappell's work for AMIRA was only one of his many contributions to industry. The XRF and INAA techniques that he developed made it possible for him to analyse samples of unusual composition, such as commonly are associated with alteration and mineralization, with great accuracy. He was called on from time to time by various mining companies that were having problems with their assays, and samples that he analysed are still being used by some companies to calibrate their assay results. Work that Chappell did with Western Mining Corporation geologist Dr Doug Haynes has been acknowledged by the company as playing an important role in its discovery of the large Olympic Dam Cu-U-Au deposit in South Australia. Over three decades Chappell and Norrish ran annual courses on X-ray spectrometry for analysts from industry, training over 200 analysts from major mining companies, mineral processors, cement and metals producers, CSIRO, the Australian Nuclear Science and Technology Organisation (ANSTO), The Australian Geological Survey Organisation (AGSO) and a range of universities. In addition, Chappell advised companies such as Philips, Siemens and Spectro Instruments on the development of X-ray and related equipment and its use for specific applications.

Wider Research Interests

Although best known for his contributions to the study of granite petrogenesis, Chappell actually worked on a broad spectrum of petrological and geochemical projects, largely because of his ability to provide accurate analytical data on a wide range of rock types. These projects included work on sea floor basalts,[36] sediments and sedimentary rocks,[37] granulites,[38] the Murchison meteorite,[39] Lunar rocks,[40] volcanic rocks from eastern Australia,[41] Melanesia[42] and New Zealand,[43] kimberlites and lamproites,[44] ophiolites and mantle rocks,[45] oil shales[46] and carbonatites.[47] The most important of these projects were those on kimberlites and Melanesian volcanic rocks. The study of lamproites from the Kimberley region of Western Australia was carried out with Dr Lynton Jaques from the Bureau of Mineral Resources, Geology and Geophysics (now Geoscience Australia). The work demonstrated the national value of the ANU laboratory in its ability to analyse rocks of unusual compositions. Without it much of the geochemistry of this economically important suite of rocks could not have been studied in Australia. All known occurrences of lamproite suite rocks in north-western Australia were thoroughly documented, including the most diamond-rich igneous rocks known, the lamproites from Argyle.[48]

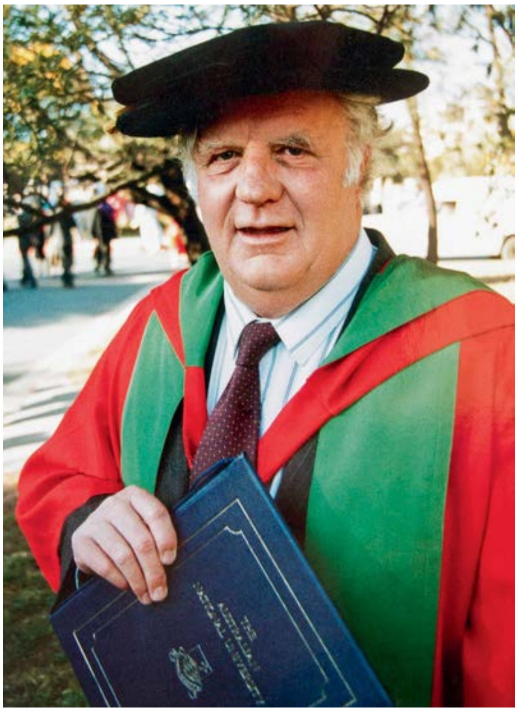


Figure 3. Bruce Chappell on the occasion of the conferring of his DSc degree, 1990.

Honours and Awards

Chappell received several honours and awards in recognition of his contributions to geoscience. He was elected a Fellow of the Mineralogical Society of America in 1983. His paper with Allan White and Rick Hine on granite provinces and basement terranes in the Lachlan Fold Belt[49] was awarded the Stillwell Medal for the best paper published in the Australian Journal of Earth Sciences in 1988. In 1990 he was awarded a DSc by the ANU (Fig. 3). In 1993 he gave the biennial Clarke Memorial Lecture to the Royal Society of New South Wales,[50] and in 1994 was elected a Fellow of the Geological Society of America. He was elected an Honorary Fellow of the Geological Society (London) in 1995, one of only six Australians with that honour at the time. In 1998 he was awarded the Mawson Medal by the Australian Academy of Science, delivered the Mawson Lecture at the convention of the Geological Society of Australia in Townsville,[51] and was elected a Fellow of the Academy. The citation for his election to Fellowship read as follows:

> Professor Chappell is an authority on the geochemistry and origin of granitic rocks. His basic contribution was the recognition that many granite magmas move bodily away from their sources deep in the

crust as a mixture of melt and solid residual material, at relatively low magmatic temperatures. This implies that many granites exposed at the surface reflect the nature of their deeper source materials, so that they can be used as probes of the deeper crust. As a pioneer in using X-ray spectrometry for trace element analysis of rocks, he has made important contributions in other geological fields, most notably in the analysis of lunar samples.

He was awarded the Centenary Medal 'for service to Australian society in Earth and planetary science' in 2003, and in 2007 was elected a Fellow of the Geological Society of Australia. He was posthumously awarded the Keith Norrish AXAA Award for Excellence in X-Ray Fluorescence Analysis in 2014.

Academic Appointments

Chappell was appointed Professor of Geology at the ANU in 1992, a position that he held until his retirement in 1997 when the position was declared redundant as a result of the ANU Restructuring and Retirement Scheme. For the following two years, as Emeritus Professor, he worked at the university as a Visiting Fellow. In 2000 he was appointed an Honorary Professor of the University of St Andrews and an Adjunct Professor at Macquarie University. In 2001 he was the Leverhulme Fellow and Visiting Professor at the University of Bristol, and in 2006 was appointed Professor of Earth Sciences at the University of Wollongong.

A Man of Contradictions

On a personal level, Bruce Chappell was a person of extreme complexity—a private man full of contradictions whose compartmentalized life revolved around his work, a select group of colleagues, his close family and relatives, and a few true friends. He did not marry, but instead immersed himself in the upbringing of his nieces and nephews, challenging their young minds and bringing a sense of irreverent fun, spontaneity and excitement into their lives. Bruce was a hard man to know, demanding unswerving loyalty from those who worked with him and generous in his support in return. He could be stubborn and bloody minded, but also charming and entertaining. He had a prodigious memory for facts and figures that he applied with equal facility to analytical data, 'party tricks' and sports statistics. He could be intimidating and scathingly forthright, but also exceedingly kind and gentle, loved by people of all ages, from young children to the elderly.

Although never too far removed from his work, Bruce had a diverse range of outside interests. He adored the music of Mozart, especially the piano concertos and operas, and particularly when played rather loudly. He had multiple performances of many works with half a dozen each of The Magic Flute and Don Giovanni, and treasured his copy of the Philips Complete Mozart Edition. His tastes also extended to a very select number of popular artists, and when riding in his Mercedes Benz during the 1970s and 80s one had a choice of either The Beatles' Abbey Road or Hey Jude, the only two 8-track cassettes he appeared to own. Bruce read widely across a range of books on scientific non-fiction and politics and was always on the lookout for a debate on a broad range of topics. A keen golfer himself, he also enjoyed cricket and Australian Rules football, and was Manager of the ANU Australian Rules Team Perth Inter-Varsity in 1964.

Figure 4. Collecting granite at Moonbi in 1975. Rocks too large to be broken with a sledge hammer were drilled, then split with feathers and wedge. Samples for whole rock geochemistry commonly weighed in excess of 20 kg.

Bruce's work ethic is legendary, and he expected those working with him to share his dedication. In the early days of XRF everything was labour intensive, requiring long hours in the laboratory. Changing samples, collimators, crystals, detectors and the goniometer was all done by hand. Even when in routine operation the XRF required regular attention, which for a period of time Bruce provided, returning to the laboratory every 4 h day and night. Prior to the development of an automatic sample changer, initially a Heath Robinson device constructed from a Lazy Susan and components from an old washing machine, everyone vaguely close to Bruce was enlisted to help with sample changes, be they students past and present, young nieces and nephews, friends (and their children) and even the Geology Department's night cleaner.

Bruce was obsessed with quality, and this applied to his analytical data more than anything else. In his work on granites, this started with the sample collection. Although XRF analysis required only a few grams of material, every granite sample that he collected weighed 10 kg or more, his argument being that analyses accurate to 0.1% required the sampling of at least 1 million crystals. The bigger the grain size, the bigger the rock collected. When on a sampling trip, the word 'overloaded' appeared to vanish from his lexicon. A petrol-driven Cobra or Pionjär percussion rock drill, feathers, splitting wedges and a ten-pound sledge were his stock in trade (Fig. 4)—that is unless he happened to have some dynamite to hand. Back in the laboratory each whole rock sample was crushed to sand size, then the sand quartered, quartered and quartered again until reduced to a perfectly representative sample ready to be powdered for analysis. Over 6000 samples of eastern Australian granites were collected by Bruce, his students, post-docs and colleagues (many of those from New England and Queensland by one of the few who could match him with a sledge, Bob Bultitude), and prepared for analysis in this way.

Bruce's obsession with quality extended to the analyses themselves. Prior to his work, the common practice in XRF analysis was to develop separate calibration curves relating X-ray intensities to concentrations for similar rock types, ignoring inter-element interferences and assuming matrix effects to be similar. The Norrish and Chappell approach[52] was based on X-ray physics. Background and inter-element corrections were determined empirically and matrix corrections were measured directly or calculated. Matrix-matched standards were no longer required, and synthetic standards provided accurate calibrations across the entire spectrum of rock compositions, a factor that became critical when analyses of Lunar rocks were required.

The obsession with analytical quality put Bruce under enormous pressure. Some samples were analysed many times over many years to ensure consistent accuracy as instrumentation and analytical techniques were refined. Although students were engaged to assist with sample preparation, Bruce insisted on doing all analyses and data processing himself, refusing students and even staff of the Geology Department direct access to the XRF. He would only analyse samples for those projects that met his own high standards. This ensured quality control, but the consequent long delays also led to great frustration on the part of those waiting for data. It caused tensions within the Geology Department, some senior staff with geochemistry research projects of their own that were of no interest to Bruce having no or limited access to the XRF. In the case of two staff members these tensions escalated to the stage where Bruce refused to work with them and they had to arrange to have their samples analysed elsewhere.

Some staff also voiced concern that students working with geochemistry were getting no experience in using the analytical equipment. Bruce was asked to run a lecture course in which students could learn the theory and practice of XRF analysis. He declined, arguing that giving a group of students access to the XRF would stop him doing essential analytical work, that there were no staff who could re-optimize the XRF after their students had been using it, and that students did not have sufficient knowledge or skill in mathematics to do the calculations necessary to process the X-ray data. The Department conceded, largely because so many people had become dependent on the flow of data from the XRF laboratory at the time.

In a way Bruce became a victim of his own success. As his reputation as an analyst grew, the demand for him to provide analytical services increased. Not only were former students who had found employment requesting analyses, but he was in demand to analyse returned Lunar samples, including providing critical measurements of Rb and Sr concentrations in support of the Rb-Sr isotopic dating of Lunar rocks being carried out at the ANU Research School of Earth Sciences by Bill Compston.[53] Some of the greatest demand came from industry, but that at least provided significant funding for the laboratory. The pressure of work, long hours and poor diet began to impact on Bruce's health. The superb quality of the data that he produced over many years, however, is a permanent testament to his refusal to compromise.

Bruce put enormous effort into developing his analytical techniques. He was scrupulous about calibrations and correction factors and took great pride in the quality of the data that he produced. He had zero tolerance for people who produced sloppy work or reasoning. One of his guiding principles was that correct conclusions fall out of quality data. Consequently he did not take kindly to criticism, direct or implied, of his analytical results. At the start of his major project on the granites of the US Cordillera with Leon T. Silver, a senior Caltech professor, he analysed the first batch of powders, only to find that Silver had included powders of several international standard rocks as a blind test. Bruce told Silver in no uncertain terms to stop wasting his time.

Bruce was a competitor, intellectually and physically. Once challenged by an American colleague to name all the states on the US mainland, he thought for a moment, then named them all in sequence such that he moved from one to the next across their common borders without break or repetition. On one occasion Bruce sent two students to the New England region ahead of him to start sampling granites. Reporting back by phone, they commented proudly on the impressive number of samples that they had collected in the first several days. Bruce later joined them, arriving from Canberra looking tired and worn—on the way north he had detoured and filled his VW Kombi van with the same number of samples, collected alone in a fraction of the time. His point was made!

Bruce had a dry, acerbic, sometimes impish, sense of humour. He would provide an explanation or recount a story, then with a slight smirk and twinkle in the eye, wait to see how long it took the listener to realize that their leg had been pulled. He loved word play and was a master of the intentional 'non sequitur'. At times he took perverse enjoyment in the harmless discomfort of others, a classic example being his pleasure in calculating the range of his vehicle while on joint field work and running the fuel tank virtually to dryness before refuelling. On one occasion, driving an unfamiliar minibus laden with field trippers in the Sierra Nevada, California, he miscalculated. Unfazed he put the automatic transmission into neutral and coasted over 10 km down the mountain road without power assist for the steering or brakes. The passengers heaved a sigh of relief when a gas station eventually came into view, only to have Bruce sail past it saying 'The road is still downhill, we'll go on to the next one'.

Bruce loved Scotland and had a deep interest in the history of ideas about granite genesis. While spending a year at Cambridge University he took the opportunity to visit and sample all the granites in the Scottish Highlands that he had read about as a student. In later years he was a regular visitor to St Andrews University, taking the opportunity to think and write, and watch the Open Golf Championship being played on the town's famous Old Course. These visits included long discussions with geologist Edrid Stephens, comparing and contrasting the Scottish granites with the remarkably similar, broadly contemporaneous, granites of the Lachlan Fold Belt. One such visit included an excursion to the famous outcrops in Glen Tilt where, in 1785, James Hutton was able to demonstrate the magmatic and intrusive nature of granite.[54] This led Bruce and Ed to propose a conference to mark the bicentenary of the discovery. The Hutton Conference on the Origin of Granites and Related Rocks, sponsored jointly by the Royal Society (London) and the Royal Society of Edinburgh, was held in Edinburgh in 1987, the first of a highly successful series of conferences since reconvened about every four years in different parts of the world. The 1991 Hutton Conference was held in Canberra, and like several other international conferences in which Bruce participated, included an extended field trip to introduce the delegates to his concepts about granite petrogenesis and the rocks of south-eastern Australia on which those concepts

Figure 5. The International Geological Congress in 1976 provided an opportunity to showcase the granites of eastern Australia to geologists from around the world. The front of a VW Kombi van provides an ideal surface on which to explain the geochemistry of the Moruya Batholith and the Mount Dromedary alkaline complex.

were based (Fig. 5). Field guides from those trips remain basic references about the granites of the region, and where to find the best outcrops.

Bruce classified his peers in much the same way that he classified rocks. A rare few were his heroes, people that he looked up to as the best in their field. He was prepared to do almost anything for someone that he respected. He would go to extraordinary lengths to arrange for colleagues to visit Australia, and once they were there would treat them as the most honoured of guests, looking after them in every possible way and taking them on private trips to anywhere that he thought they should see or might enjoy. Most trips, of course, revolved around his beloved granites of eastern Australia. On some trips he would include a student or two that he thought would benefit from close interaction with the visitor.

He could be a little inflexible in his plans, however. When Professor Hugh Taylor (Caltech) visited Australia, Bruce met him at Sydney airport with plans to take him to performances at the Sydney Opera House. Unfortunately Taylor fell at the airport, sustaining a deep gash to his forehead. Concerned that they would miss the performance, Bruce refused to allow him to go to hospital for treatment, and dragged him off to the Opera House with his bloody head roughly bandaged by an airport paramedic. The bandage was still prominent when Taylor presented the prestigious Jaeger-Hales lecture at the ANU later in the week.

Bruce went out of his way to identify, nurture and reward talent. He was constantly on the lookout for the best students and worked hard to convince them of the need to work on a geological problem that was of global importance, namely granite petrogenesis. He regarded the mentoring of students and post-docs, past and present, as a personal and professional responsibility. He knew that if talent was to survive, it needed to be guided and nurtured, and he did his best to do so, even if that guidance did not always accord with the mentee's own perception of their research interests. Unobtrusively he took a particular interest in advancing the careers of young women whom he considered to have potential, and believed individuals should be promoted on merit rather than physical attributes. He was exceptionally generous, helping his 'adoptees' in many ways—running field trips for them, guiding their research, providing one-on-one tutoring, helping with analyses or analytical data, helping to establish academic contacts and helping with finding jobs. His expectations of dedication to the task, and personal and intellectual loyalty were high, but if they were met, the time and effort he was prepared to invest were almost unlimited. Many are the students who learned the intricacies of granites at home with Bruce as Mozart played in the background.

Bruce Chappell DSc FAA FAGS FMSA died in Canberra on 22 April 2012. His support of students continues, however, in the form of an endowment from his estate of over one million dollars, the income from which provides scholarships for the best ANU PhD students doing field-based research in petrology. A full list of Chappell's publications can be found in the Supplementary Material.

Acknowledgements

We thank the many colleagues, former students and post-doctoral fellows who worked with Bruce who have contributed to this memoir. We thank in particular members of Bruce's close family, Andrew, Cliff and Lynne Treloar, for sharing their memories with us.

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