Journal and Proceedings

of the

Royal Society of New South Wales

2016

Volume 149 Parts 1 &2

Numbers 459 to 462

"... for the encouragement of studies and investigations in Science Art Literature and Philosophy ..."

The Royal Society of New South Wales

Office Bearers for 2016

Patron	His Excellency General The Honourable David Hurley AC DSC (Ret'd) Governor of New South Wales
President	Em. Prof. David Brynn Hibbert BSc PhD CChem FRSC FRACI FRSN
Vice Presidents	Mr John Hardie BSc (Syd), FGS, MACE FRSN
	Dr Donald Hector BE(Chem) PhD (Syd) FIChemE FIEAust FAICD FRSN
	Ms Judith Wheeldon AM, BS (Wis) MEd (Syd) FACE FRSN
Hon. Secretary (Ed.)	Em. Prof. Robert Marks, BE, MEngSci, ResCert, MS, PhD (Stan.) FRSN
Hon. Secretary (Gen.)	Dr Herma Buttner PhD
Hon. Treasurer	Mr Richard Wilmott
Hon. Librarian	Dr Ragbir Bhathal PhD FSAAS
Councillors	Dr Erik W. Aslaksen MSc (ETH) PhD FRSN
	Dr Mohammad Choucair PhD
	Prof. Max Crossley PhD FAA FRAC FRSN
	Dr Desmond Griffin PhD AM FRSN
	Prof. Stephen Hill PhD AM FTSE FRSN
	Em. Prof. Heinrich Hora DipPhys Dr.rer.nat DSc FAIP FInstP CPhys FRSN
	Prof. E James Kehoe PhD FRSN
	Em. Prof Roy MacLeod AB (Harv) PhD, LittD (Cantab) FSA FAHA FASSA FRHistS FRSN
	Prof. Bruce Milthorpe PhD FRSN
	Prof. Ian Sloan AO PhD FAA FRSN
	Hon. Prof. Ian Wilkinson FRSN
Web Master	A/Prof. Chris Bertram PhD FRSN (by invitation)
Southern Highlands Branch Representative	Mr Hubert Regtop
Executive Office	The Association Specialists

Editorial Board

Website: http://www.royalsoc.org.au

The Society traces its origin to the *Philosophical Society of Australasia* founded in Sydney in 1821. The Society exists for "*the encouragement of studies and investigations in Science Art Literature and Philosophy*": publishing results of scientific investigations in its Journal and Proceedings; conducting monthly meetings; awarding prizes and medals; and by liaising with other learned societies within Australia and internationally. Membership is open to any person whose application is acceptable to the Society. Subscriptions for the Journal are also accepted. The Society welcomes, from members and non-members, manuscripts of research and review articles in all branches of science, art, literature and philosophy for publication in the Journal and Proceedings.

Journal & Proceedings of the Royal Society of New South Wales, vol. 149, parts 1 & 2, 2016, pp. 1–4. ISSN 0035-9173/16/010001–04

Editorial

Robert E. Marks

Finally, the first issue of the *JProcRSNSW* under the new editorship. Several papers: the outgoing president's address by Don Hector, the W. B. Clarke Memorial Lecture by Griffin et al., the Liversidge Lecture by Banwell et al., a paper by the late Commonwealth Statistician, Ian Castle, on one of the most illustrious members of the Royal Society and its forerunner, the Philosophical Society of N.S.W., the forgotten polymath, William Stanley Jevons, scientist and economist, followed by a paper of mine which puts Jevons' activities in the Society into context and updates Castle's article with some recent debates about the implications of Jevons' work for energy policy. The last paper is by Foster, a Royal Society Scholarship winner There are also 16 abstracts of recent doctoral dissertations from several N.S.W. universities.

The delay in publishing this issue is due to two things. First, the handover took place in May, with few accepted papers. Second, I threw myself into indexing the contents of past issues back to 1866 and before, making the index accessible to Google's indexing robots (which has now happened), and making the contents of past articles readily accessible to anyone on the Internet.

This process would not have been feasible without the work done by past editors and librarians of the Society, the Biodiversity Heritage Library (the host on the on-line repository of the *Journal*), the Smithsonian Libraries, the Missouri Botanical Garden Peter H. Raven Library, the Harvard University Museum of Comparative Zoology Ernst Mayr Library, the University of California Libraries, the Leland Stanford Jr. University Library, the Wayback Machine's Internet Archive, and the National Library of Australia's incomparable, but threatened, Trove on-line archive of Australian material back to first European settlement. For the on-line repositories of the *Journal*, past issues were scanned to PDF and placed on-line in large files, one per issue or volume. These were embedded in a viewing platform which includes Optical Character Recognition output.

Readers can see the format of the main repository by going to the Journal Archive page of the *Journal's* contents, at the Society's web pages.

Clicking on a volume and then a paper reveals a PDF of each page with a plain-text OCR on the right (when clicked on). Although the files are large, each page (corresponding to a page published in the hard-copy version of the *Journal*) has a unique URL, which allows us to link the initial page of the 3,110 articles in the *Journal* since 1867. I used plaintext versions of each issue's contents to derive the pages of the contents of each volume. These contents pages, roughly one a year, enable an on-line index for the *Journal's* contents, with the URLs providing the links to each paper.

The index of articles and papers starts in 1822, forty years before the Royal Society was granted its letters patent, when the first forerunner of the Society, the Philosophical Society of Australia, was active, under the patronage of the Governor, Sir Thomas Brisbane. At that time there was no dedicated publication for the Society's papers (that

would have to wait for over thirty years), but some papers presented to the Society were published as chapters in a book published in London in 1825, edited by a former member of the Society, Barron Field, a lawyer. This book is now in the public domain and its contents have been made available on-line as part of the Gutenberg Project.[1]

After thirty years of little if any activity, the Philosophical Society of New South Wales began in 1856, under the patronage of the new governor, Sir William Denison, an engineer. Some papers were published in the Sydney newspapers, especially Henry Parkes' *The Empire*, and are now available on Trove. There were two other outlets for papers in the 1850s and early 1860s: a commercial monthly, *The Sydney Magazine of Science and Art*, published papers from the Society and other learned groups for the two years it was in existence. It too is freely available on-line. The Philosophical Society of N.S.W. also published the *Transactions of the Philosophical Society* from 1862 to 1865, and this too is available on-line. In 1867 the *Journal of the Royal Society* first appeared, and has done so ever since. Perhaps someone will use this newly accessible resource to write a paper analysing how the contents, authorship (numbers, sexes), etc of papers have changed over the past 110+ years.

In 1955, the president of the Society, Ronald Nyholm, mused about the three phases of the Society, as reflected in submissions to the *Journal*:

> "Broadly speaking, the history of the Society falls into three periods. Before the first world war the Royal Society of New South Wales was the main scientific society in Sydney, at least so far as the physical sciences were concerned. The Society was, for scientific people, an important means of mutual contact, discussion and the *Journal* received many of their original researches. Between the two world wars there were founded in Sydney many specialist scientific bodies or branches of older ones, such as the Institute of Physics and the Royal Australian Chemical Institute, the meetings of which catered for discussions of specialist subjects. Nevertheless, many of the original papers of these specialist still found their way to our *Journal*. Thus, the 1940 *Journal* was one of the largest ever, and in it were 38 research papers. There were 23 chemistry papers, 4 in mathematics and 9 in geology. After the Second World War we enter the third phase — the development in Australia of new specialist journals to cater for the needs of scientists. Examples of these are the *Australian Journal of Chemistry* and the *Australian Journal of Physics*. Furthermore, overseas societies publishing specialist journals, e.g. the Chemical Society of London, speeded up the rate of handling of papers and went out of their way to provide air-mail facilities in order to assist folk submitting papers from Australia."

The decline in the number of research papers received (as distinct from the Presidential Address, Clarke and Liversidge Lectures) is shown in Figure 2 of Nyholm's paper. In 1952 the *Journal* was the smallest since 1929.

Nyholm argued that this had at least two effects: the mix of disciplines in the *Journal* had become unbalanced, which would even-

[1] The Gutenberg Project's copy appears to come from the Stanford library, although Stanford University was only founded in the 1890s. It turns out at that Thomas Welton Stanford, brother of Leland Stanford, the railroad baron who founded Stanford, lived in Australia for many years and amassed a library of Australiana, which he bequeathed to the University. (I thank Jessica Milner Davis for this sleuthing.)

tually affect journal exchanges with other institutions; and Society members would lose interest in the Journal and perhaps in the Society. Sixty years ago, Nyholm quoted a previous president, Richard Bosworth, who argued for a policy of encouraging researchers to write reports on their research worded so as to be intelligible to a novice in the field, rather than to the expert readers the specialist journals assume.

What was true sixty years ago still holds today, although the pressure to publish in A-rated journals means that fewer such accessible papers will be submitted. And the fourth phase of the *Journal*—the age of the Internet—means that the *Journal*, at least in its hard-copy form, is increasingly an anachronism. The other side of that coin is the ability to make over 160 years of articles accessible to anyone with a browser. The *Journal* still publishes the Clarke and Liversidge lectures and now also a garland of papers from the annual forum. We also publish short abstracts from recent Ph.D. dissertations. But the flow of first-rate, cutting-edge research papers has stopped long since.

What is happening at our sister societies? *The Transactions of the Royal Society of South Australia* is the result of an amalgamation (in 2004) with the *Records of the South Australian Museum* and is published by Taylor & Francis in both hard and soft copies. Its 2015 impact factor was 0.484. Contents of the *Transactions* are not freely available. Subscriptions to the two annual issues of the *Transactions* are included in members' dues, but non-members and institutions pay up to $285 a year for hard and soft copies.

The Proceedings of the Royal Society of Victoria is published by CSIRO Publishing. Current issues are freely available. The *Proceedings* are only available in soft copy. Articles back to 1855 are available on-line.

The *Papers & Proceedings of the Royal Society of Tasmania* are freely available on- line, but not for the last two years. There are, apparently, no hard copies printed. Only members of the Society who pay to do so have access to the last two years of the *Papers*.

The Proceedings of the Royal Society of Queensland are apparently freely available on-line. The *Proceedings* publishes only a single issue a year, and then only in soft copy.

The Journal of the Royal Society of Western Australia is (since December 2015) no longer printed, but is available only on-line to fully paid members of the Society and approved exchange partners and educational institutions.

The Journal of the Royal Society of New Zealand is published quarterly in soft and hard issues by Taylor & Francis. It has a 5-year impact factor of 0.918. The current issue is available on-line, but archive (permanent) access to soft and hard copy costs AU$640 a year. Earlier issues (1868 to 1961) are freely available on-line.

What is to be done? Sixty years ago Ronald Nyholm's suggestion was not particularly effective. And today it is even less likely to succeed. I encourage review articles and articles taking an historical approach to the development of science and social phenomena. I also urge readers to consider writing longer book reviews of recent books that raise issues of interest, particularly of science policy and history. This fits, I hope, with the Society's push to widen its membership from the hard sciences to the social sciences and to the arts and humanities. Please consider the *Journal* for your next such paper.

Finally, I'd like to thank Ed Hibbert, Don Hector, and Jason Antony for their assistance in processing the *Journal*'s text.

30 November 2016

References

Nyholm, Ronald S. Presidential Address, JProcRSNSW 89: 1–29, 1955. http://biodiversitylibrary.org/page/46193345

Journal & Proceedings of the Royal Society of New South Wales, vol. 149, parts 1 & 2, 2016, pp. 5–16. ISSN 0035-9173/16/010005–12

Presidential Address

Donald C.A. Hector

The Royal Society of NSW

Email: dchector@royalsoc.org.au

Abstract

Donald Hector AM was President of the Royal Society of NSW from 2012 to 2016. In an address marking the conclusion of his presidency, immediately following the annual general meeting of the Society on Wednesday, 6 April 2016, he considered the nature of the complex problems that face 21st-century Australia, the way in which people tend to approach these highly-complex socio-techno problems and the cognitive and cultural limitations they have in identifying solutions. In particular, he considered the role that the Royal Society of NSW might play as it is re-established as a leader in the intellectual life of NSW and of the country.

For many years, it was a practice of the Society for the President to deliver an address at the conclusion of the presidential term. This custom fell into disuse in recent years but with the change to the rules and bylaws last year, it was decided to reintroduce it.

My aim tonight is not to reflect on the activities of the Society in the last four years, other than in passing—rather, it is to attempt to chart a way for the Society as it re-establishes itself as an intellectual force in New South Wales and the country. So I shall limit my comments on the recent history to these.

By far the most successful development in the last several years has been the establishment of the category of Fellow and the elevation of the former Fellows to Distinguished Fellowship. This raised considerable interest in the activities of the Society and we were fortunate that very capable people indeed have accepted the invitation to Fellowship and that some of them have become involved in the activities of the Society and its governance. We expect that this will continue and that we will see sustained growth in all membership categories. But this will only be the case if the activities of the Society are considered to be making a valuable contribution to the public discourse. How might we do this?

In September last year, for the first time, the Society organised a forum with the four Australian learned Academies. One of the outcomes of the meeting was a list of major challenges and issues where the Society could contribute, taking a transdisciplinary approach across art, science, literature and philosophy. Of the issues identified at the forum, one common characteristic they shared was that they are all highly-complex, socio-techno-economic problems. Most of these are not limited to NSW nor to Australia—in many cases, they are global issues. I would like to spend the remainder of my address exploring how these complex problems have come to be, why we see them in the way we do and what we can do to contribute to a solution. I will take a historical perspective and consider some issues around philosophy and cognitive psychology that I believe are important in framing these problems and identifying solutions.

The way in which all animals interact and survive in their environment is through solv-

ing problems. Humans have developed a remarkable capacity for intellectualising problems and solving them in the abstract. Some of these problems can be simply stated and have simple solutions—for example, will I catch the bus to work this morning or will I ride a bicycle? At the other end of the spectrum, there are many problems that can be both difficult to articulate and to resolve. Contemporary examples of these are: what are we to do about climate change? or how can we provide a cost-effective health system? I would like to briefly explore the nature of problems and why some of them are so difficult to understand and to solve.

The way in which we define and attempt to solve problems today has its origins in the philosophy of ancient Greece. Indeed, the rediscovery of classical philosophy in the 13th and 14th centuries was a major influence on the Renaissance. Let me refer to an example. Many of you will have seen this painting or be familiar with it. It was painted by Raphael in 1509 and is a fresco in the Apostolic Palace in the Vatican. It is widely considered as one of the finest pieces of art from the Renaissance. It is usually referred to as *The School of Athens* (although its formal name is *Knowledge of Causes*).

The School of Athens

The two central figures are Plato and Aristotle but other Greek philosophers (Socrates and Diogenes) are also represented, as are other philosophical influences from the pre-Christian era. I will refer to this painting again later to make some other points but what the painting shows is the influence of philosophy in Renaissance thinking. It is intended to represent natural truth as acquired through reason, arithmetic, geometry, astronomy, rhetoric and dialectic and also represents art, music and poetry.

On the opposing wall is a second painting, also by Raphael, called *Disputation over*

the Most Holy Sacrament. It was painted the following year and shows God the Father looking down on the resurrected Christ who is flanked by the Virgin Mary and John the Baptist and prophets and saints of the old and new Testaments. Beneath are Popes, saints and the faithful masses and with Aristotle, head slightly bowed and his books on the ground.

Disputation over the Most Holy Sacrament

On the one side of the chamber, is a representation of knowledge and reason; on the other, the realm of God. In many respects, these two juxtaposed paintings represent the thinking and belief-system of that era and upon which the Renaissance developed. Art can give great insight into human thought—let us explore this notion a little further.

Consider this example of ancient Greek art. It is from a piece of pottery of an uncertain date and is thought to represent Euripides' *Medea.* Its composition is what Paul

A piece of Greek pottery of an uncertain date and is thought to represent Euripides' Medea.

Feyerabend (1975) refers to as a "paratactic aggregate" — a specially-structured group of individual elements. Feyerabend suggested that this shows that Greek thought was elemental in nature — they believed that that everything in the world consisted of atoms that were aggregated into bigger and bigger things.

The story is told by the relationship of the elements in the artwork. Another characteristic of Greek art was that it had no perspective. Together, this suggests that Greek thought was not developed into an integrative, representation of the world and that the sense of perspective that is important in modern representations simply had not yet developed. This notion is reinforced by the nature of the ancient Greek language. It is also paratactic — it depends heavily on structure. Their thinking — the paradigms they used — were, perhaps, elemental, mechanistic and lacking in perceptual depth.

Now let us move to the very early Renaissance — about 1350. Consider the fresco in Campo Santo, Pisa, by Francesco Traini, called *Triumph of Death.*

Fresco in Campo Santo, Pisa, by Francesco Traini, Triumph of Death.

There is much similarity between the style of Greek art and this painting: there is no perspective and the story is told by structure of the elements represented in the painting. Let us now go forward about 100 years to 1430 — this is a scene painted by Paolo Uccello representing Mary approaching a temple. In the space of 100 years or so, perspective has started to emerge, giving a sense of depth and three-dimensionality. The style is more integrative, with the characters becoming part of the scene, rather than simply arranged in it.

A scene by Paolo Uccello representing Mary approaching a temple.

Now let us return to our painting by Raphael, *The School of Athens*. Painted 70 years later, in 1509, and at the height of the Renaissance, the style is entirely different. It is much more fully developed: perspective is clear—it is a representation of a three-dimensional scene that truly appears to be in three dimensions. Everything is integrated: the various philosophers and thinkers are engaged in conversation with each other (even though some are from different eras). It tells a story.

What I have tried to show here are some of the foundational influences on the Western way of thought, as represented through its art. Whether or not Feyerabend's theory is correct is open to discussion but it is hard to accept as coincidental the extraordinary development in the sophistication of artistic representation that happened at the same time as the development of philosophical thought in centres such as Florence and Padua. As the influence of the Renaissance moved from Italy across Europe, the centre of intellectual thought gravitated towards Holland, to (what is now) Germany and to England. The discoveries and thinking of Copernicus, Galileo, Bacon, Locke and Newton, based on Greek philosophy, continued to develop within the mechanistic Greek paradigm—the universe was like a great machine overseen by God. This thinking prevailed until the 18th century when philosophers such as Kant and Hegel brought different perspectives to our interpretation of reality and the "interconnectedness" of everything in the universe. Nonetheless, the mechanistic paradigm persisted until the late 19th century. At about this time, biology and ecology began to develop and the mechanistic paradigm was insufficient to explain many of the phenomena that were now being observed. A new model emerged for explaining these—systems theory.

Mechanisms, like clocks, behave linearly—a disturbance to the mechanism produces an effect in proportion to the disturbance. The analytical technique developed in Padua in the mid-Renaissance works very well. If you have a problem, disassemble it into its component parts, solve the component problems and synthesise a solution to the original problem from these. But systems do not work this way. They are non-linear—a tiny disturbance in one part of the system can result in a surprisingly large disturbance in another. Systems can appear to be stable but a small disturbance can introduce major instability—they can flip. They are characterised by subsystems whose behaviour interacts with other subsystems to influence the behaviour of the whole—you cannot predict the outcome by simply adding the subsystem responses together. At the heart of systems theory is that everything in the universe influences everything else. Systems theory and its underlying philosophy of interconnectedness and uncertainty was remarkably successful as a means to understand an enormous array of phenomena from the behaviour of ecosystems, to quantum mechanics, to biological systems to the behaviour of high-speed aircraft and the control of equipment

in power stations and other industrial processes.

After the Second World War, there was massive rebuilding and restructuring of society. New problems started to emerge: how to provide healthcare, establishing effective educational systems, trying to make sense of economics to avoid catastrophes such as the Great Depression and deal with ever-increasing environmental damage. Advanced mathematical techniques such as linear programming, game theory, queueing theory, marginal analysis and information theory were developed as a consequence of militarisation, in particular strategic analysis as the Cold War deepened. But these were generally unsuccessful in solving this new class of problem. They were variously described as "messes" and "wicked problems". Generally, there was no shortage of data to draw upon to characterise the problem. But the systems nature of these problems were surprisingly resistant to analytical approaches. Typically, these problems had social dimensions that were difficult model.

Summarising, over the last 500–600 years the way in which problems are identified in characterised has evolved substantially. We now think of problems in three broad types:

But there is another dimension to problem-solving: the "domain of interests": that is, the people or stakeholder groups involved in either the problem itself or any solution that might be identified. The domain of interests can range from a single individual trying to solve a simple problem up to highly complex, global problems whose domain of interest extends across species and ecosystems. One might conceive of three broad domains of interest: unitary; pluralist; and disparate.

Problem type	Characteristics
Simple Problems (or mechanistic or scientific problem)	Problems that can be represented using a mechanistic model and resolved using the reductionist approach.
Single-Dimensional Complex Problems (or technical or systems problem)	Problems — often of a technological nature — that can be represented on one problem dimension.
Multi-Dimensional Techno-Societal Problems	Problems that can only be represented on multiple dimensions, considering issues such as moral status, intrinsic character, value, beliefs, aesthetics etc.

Table 1: Increasing problem complexity

A unitary domain exists where there is a single decision-maker or, if there is more than one individual, where the decision-makers have a shared worldview and an agreed determination in resolving the problem. A pluralist domain is one where there is a shared determination to problem resolution but there are differing worldviews among the stakeholders. Issues of power and coercion are either explicitly or implicitly set aside. And a disparate domain of interests is where there are major differences in underlying beliefs and values among the stakeholders. The worldviews represented in the domain may be in open conflict. There may not even be agreement that a problem exists or that action needs to be taken. There may be distrust among stakeholders

and there may be deliberate use of power to coerce or frustrate problem definition and decision-making. These three domains are represented in table 2.

Domain of interests	Characteristics
Unitary	A single decision-maker or a group of decision-makers and other stakeholders which have the same interests and similar worldviews.
Pluralist	Decision-making interests are largely aligned but there may be many different worldviews among stakeholders. However, they share the same determination or interest in arriving at a satisfactory problem resolution. Power is equally shared among constituents or, because of the shared determination to resolve the problem, issues of power are set aside.
Disparate	There are major differences in underlying beliefs and values and the interests of stakeholders may differ widely. There may be a lack of shared determination to resolve the problem, distrust of the motives and intentions of other interests, and even specific intention not to see the situation resolved and to derail attempts to agree upon the problem definition or efforts to proceed. There may also be significant power imbalances among the constituents and these are used coercively.

Table 2: A further dimension of problem complexity—the Domain of Interests

of problem can be identified as shown in diagram 1:

Type 1: these are problems which normally yield to reductionist or systems-analysis problem-solving approach. Traditional scientific and engineering methodologies can be applied such as mathematical modelling and computer simulation.

Type 2: these problems which due to their complexity and systems nature require a combination of reductionist, analytical and hard- and soft-systems analysis approaches.

Type 3: these problems are often unique and always highly complex—this precludes or severely limits the use of traditional scientific, engineering and systems analysis approaches. Human stakeholders hold apparently irreconcilable differences in beliefs and values and are more than willing to exploit power imbalances coercively to achieve their own ends. Moral status of stakeholders and their interests may be difficult to identify and some (for example, non-human species) may not be formally represented in the decision-making domain.

Taking these two dimensions of problem structure together, three fundamental types

This characterisation of Type 3 problems that has emerged over the last half century or so is not unique nor is it particularly new. These "wicked problems" or "messes" and have occupied the thoughts of operational researchers for many years but with only limited success. But what is different here is the representation of these problems on two dimensions—recognising that the influence of differing worldviews and the

coercive use of power has enormous influence both on characterising the problem and moving towards some resolution. An important point to note is that describing or structuring the problem is fundamentally a human, social construct. Worldviews and belief-systems are at the heart of both defining and solving problems.

Let me summarise my argument so far.

As the humans have evolved, so too has the way in which we conceive of and attempt to solve problems. The worldview of the

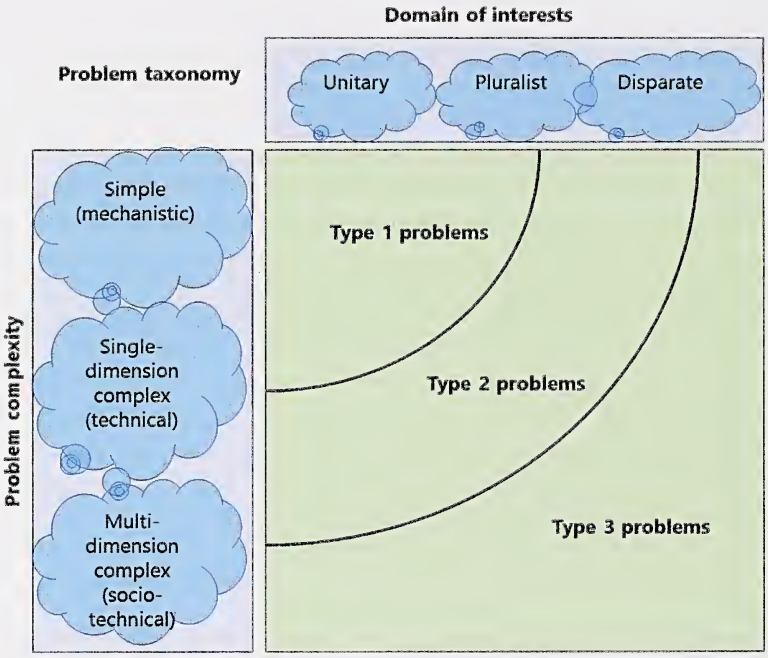


Diagram 1—problem taxonomy.

ancient Greeks persisted for well over a millennium. But in just a couple of hundred years, the Renaissance brought a dramatic change in the Western world—there was a flourishing of thought and a number of different philosophical approaches emerged. But as population and social complexity increased, so too did the complexity of the problems that confront us. Not only are the technical aspects of the problems challenging but they are further complicated by the divergence in worldviews that occurred. In the last century or so, social and cultural influences in an increasingly liberal society have added another dimension to the way in which we need to consider complex problems. The second dimension of problem structure that I have proposed here is predominantly about influence and power and is a major obstacle in solving the highly complex socio-economic problems.

Before exploring how these types of problems might be addressed, I would like to take a brief diversion to outline the philosophical framework upon which Anglo-American society (by which I mean the various countries around the world that emerged from or were strongly influenced by Britain) has developed in the period since the late 16th century. I confine my remarks to the Anglo-American philosophical framework because Royal Societies around the world are crea-

tures of this. It has also been very influential in the development of the modern era. Time does not permit a detailed examination of these, so I will just outline them briefly.

What was originally called "philosophy" and has evolved into scientific enquiry is dependent on the scientific method of conjecture and refutation. It is founded on a rationalist philosophy and traces its origins to thinkers such as Bacon, Locke and Newton. One of the principles of rationalism is that we can acquire knowledge in two ways: one is empiricist (interpreting knowledge that we acquire through our senses); and the other is intuitive and deductive (there is some knowledge that we can acquire through thought and deduction alone—mathematics being an example). It is oversimplifying somewhat to say that scientific enquiry is entirely rationalist—there are many factors that influence it, including sociological ones. But its intention is to converge upon some notion of truth through rigorous, intellectual enquiry.

Political and social institutions are generally framed on different philosophical principles—they are utilitarian. Utilitarianism originates with Bentham and Mill and has been developed by many others. Its original concept was that a "good" act is one that maximises pleasure. Unlike rationalism, it is less concerned about finding truth; rather it is a normative ethical system—it attempts to define a set of rules for society to live by. Over the last couple of hundred years, "pleasure" has been replaced with "benefit" or, more recently, "happiness". Most economic analysis is utilitarian in its nature: what will deliver the maximum benefit for the minimum cost? Similarly, our political systems attempt to arrive at maximising public good (or happiness) with minimum interference with individual liberty—they are fundamentally utilitarian, liberal frameworks.

Legal institutions are different again. They are also based on normative philosophical principles but are framed around deontological or duty-based ethics. One particularly influential philosopher in this area was Kant who argued that a "good" act is one in which one does one's duty. Duty can be defined in terms of a legal code or duties that emanate from moral good. Kantian ethics is controversial but nonetheless the British legal system is largely duty-based system. (For example, sections 180 to 183 of the Corporations Act defines duties that must be observed by company directors.)

So, the society in which we find ourselves today is largely the product of three philosophical systems that are becoming evermore influential and, in many aspects, are replacing the influence of religion that until relatively recently dominated our value-systems. The extent to which belief (whether religious or humanist or some other value-based system) influences decision-making is of critical importance in solving the highly-complex Type 3 problems that prove so challenging.

I will now briefly explore some cognitive psychology in an attempt to identify the way in which these Type 3 problems might be addressed. There is a large body of literature in cognitive psychology relating to problem-solving originating, in the 1920s and 1930s. I will confine myself just to drawing a few points from this literature.

One of the key researchers in this area was Hammond (1955) who integrated the work of a number of eminent psychologists relating to the way in which people respond to cues that they receive. Researchers found that people form judgements and make inferences based on observations that are weighted according to their experience and other subjective influences. The analogy of the "lens model" was created—just as light

is distorted by an optical lens, giving different images to different observers depending on their position, so too do individuals involved in a complex situation form different perceptions of the problem and the path forward. Hence, there can be no objectively-determined understanding of complex problems.

In a ground-breaking piece of work in the 1950s, Miller (1955) found that people have a very limited capacity to retain pieces of information in their minds (somewhere between five and eight pieces of information at any one time) but an extraordinary capacity to recall information to mind to process it. Another related body of research by Boulding found that people form "images" or mental representations of situations that are important in the way in which they reach decisions. They imagine what the future might be and then strategise to achieve it. These images are not simply mental pictures, rather they are complex mental representations of situations that we are attempting to understand. An interesting example of this is the "cognitive map" that we form to help us relate to our situation in the physical world—not only is it a locational map, it is a representation of self and our relationship with the physical world. This fundamental cognitive process probably underlies the human penchant for representing complex information in a wide range of graphical and visual formats, such as maps.

Many of these mental phenomena are not specific to humans—all cognisant animals seem to utilise them. It is how cognisant beings deal with the enormous complexity of the world in which they find themselves. The complexity is too great to comprehend, so a form of thinking—intuitive thought—evolved to make sense of it. At some point our evolution, humans developed the capacity for rational thinking. It is the capacity for rational thought that makes humans sapient (some other animals appear to possess limited capacity for rational thought but there is none that comes close to humans). But the capacity for rational thought is bounded—the world is far too complex for the human mind to comprehend it completely.

On one hand, intuitive thought is used by all cognisant animals. It is instinctive and quick and the main mechanism by which we survive. On the other, rational thought is largely peculiar to humans. It is slow, deliberate and it is learnt. In the 1970s and 1980s, work by Tversky and Kahneman (1974) and others found that intuitive thought is subject to a range of biases and that these have a significant impact on the success of decision-making. Rational thought (or least some of the means to it) can be taught and improved but it is error-prone. Whereas intuition is subject to bias, rational thought is subject to error.

But we need to put these mental representations and processes into a both a chronological and cultural context. This requires another cognitive device—the narrative.

Narrative and story-telling is as old as humanity itself. It predates writing and occurs in every human society and culture. Throughout most of history, story-telling has been the principal means by which knowledge is transferred from one generation to the next. There are various theories of narrative but they share some common characteristics. They are always about people or things and a group of characters forms part of the thread that holds the narrative together. They are developed against an explicit set of values or a moral standard against which the actions in the narrative can be evaluated. Until the 1970s, narrative was thought to be simply a cultural artefact, but now it is considered to be a fundamen-

tal cognitive process. While cognitive maps provide the three-dimensional framework that we use to relate to the real world, narrative adds the fourth dimension — time. It also provides the means to fill in the gaps in our understanding and to make our mental representation coherent with our experience and our worldview. In other words, we make things up — we confabulate — to fill in the gaps in our knowledge and most importantly, in order to make our representation of the problem conform with our belief-system.

So, let me summarise these few fragments of psychology. No two individuals see a problem in exactly the same way — we are all looking at things through "lenses" that distort our view of reality according to our perceptions and experience. We form images of problem situations that are heavily influenced by our philosophical framework and belief-system. Our immediate response to problems is intuitive but this is subject to bias. A more measured analytical approach — rational thought — can be learnt but we must remain aware that we can make mistakes. These two thought processes have been described as two different systems but that misunderstands the fundamental nature of cognition — they are a single system responding to different stimuli and this system exhibits all the nonlinear and unexpected characteristics that one would expect. In order to make sense of the enormous complexity we encounter, we confabulate to make sense of things that we do not understand to make them conform to our notions of reality.

So how might we move forward?

Recognising the enormous human creativity available to us through combining our capacity for intuitive and rational thought, we can use the enormous body of knowledge (that continues to grow at an exponentially rate) and our capacity for rational analysis to gain much greater insight into problems that were previously unassailable. We can imagine what futures might look like. If we remain conscious of the bias associated with intuition and alert to the ever-present chance of error with rational thought, we can reduce the chance of serious mistakes. Recognising the systems nature of cognition, we can harness both intuitive and rational thought to bring great creativity. Because we can recognise that various stakeholders in situations will approach the problem from different perspectives, we can accept this as fundamental to the human condition and that should facilitate understanding. The big challenge is to embrace the complexity of the problem — particularly the sociological dimensions — to overcome the inherent bias that we all hold to find common ground, rather than focus on the differences.

Most importantly, we can write narratives. Drawing upon our diverse experience, these narratives can engage people with a wide range of worldviews and draw them along with us.

And now I come to my final point. The Royal Society of NSW is uniquely placed to provide leadership in this type of complex analysis. The wisdom of the founders in defining such a broad remit of human knowledge — science, art, literature and philosophy — was truly prescient and recognised the ever-increasing complexity of modern life. But we need to change if we are to maximise our impact. Historically, the Society has focused on the sciences: in its early days, the physical sciences — physics, chemistry and geology — and, later, zoology, botany and biology. Only recently, have we extended into the other areas of human knowledge encompassed by our charter. We need to attract Fellows and Members from all fields of human knowledge, if we are to engage in the representation and solution

of Type 3 problems. We need more writers, artists, sociologists, musicians and historians. Only then, will we be able to completely engage with the community. That is not to say that we should abandon our scientific heritage — quite the opposite, most of the problems that the world faces today have enormous technological challenges. But these solutions will not be found in science and technology alone — they will require the engagement of non-scientists in terms they can understand.

References

Feyerabend, P. (1975), *Against Method*, (3rd edn., 1993), Verso, London, pp 170-187.

Hammond, K.R., (1955), Probabilistic Functioning and the Clinical Method, Psychological Review, vol. 61, no. 4, 1955, pp 255-262.

Miller, G.A., (1956), The magical number seven, plus or minus two: some limits on our capacity for processing information, *The Psychological Review*, 63, 2, pp 81-97.

Tversky, A., Kahneman, D. (1974), Judgment under uncertainty: heuristics and biases, *Science*, New Series, 185, 4157, pp 1124-1131.

General bibliography

Ackoff, R.L., (1979), The future of operational research is past, *Journal of the Operational Research Society*, 30, 2, pp 93-104.

Gabriel, Y, (1991), Turning facts into stories and stories into facts: hermeneutic exploration of organisational folklore, *Human Relations*, 44, 8, pp 711-724.

Hammond, K.R. (2007), *Beyond rationality: the search for wisdom in a troubled time*, Oxford University Press, New York, USA

Hector, D.C., Petrie, J. *et al.*, (2009), A problem-structuring method for complex societal decisions: its philosophical and psychological dimensions, *European Journal of Operational Research*, 193, 3, pp 693-708, doi:10.1016/j.ejor.2007.06.058.

Kintsch, W., van Dijk, T.A. (1978), Toward a model of text comprehension and production, *Psychological Review*, 85, 5, pp 363-394.

Kubovy, M. (1986) The psychology of perspective and Renaissance art. Cambridge University Press, Cambridge, UK.

Miller, K.D., Waller, H.G. (2003), Scenarios, real options and integrated risk management, *Long Range Planning*,. 36, pp 93–107.

Pentland, B.T., (1999), Building Process Theory with Narrative: From Description to Explanation, *Academy of Management Review*, 24, 4, pp 711-724.

Randall, J.H., (1940), The development of scientific method in the School of Padua, *Journal of the History of Ideas*, 1, 2, pp 177-206.

Rosenhead, J. (ed.), (1989), *Rational analysis for a problematic world: problem structuring methods for complexity, uncertainty and conflict*, John Wiley & Sons, Chichester, UK

Russell, B. (1946), *History of Western Philosophy: and its connection with political and social circumstances from the earliest times the present-day*, (2nd edn., 1961), Routledge, London.

Tolman, E.C., (1948), Cognitive maps in rats and men, *Psychological Review*, 55, 4, pp 189-208.

von Bertalanffy, L., (1950), An outline of General System Theory, *British Journal for the Philosophy of Science*, 1, 2, pp 134-165.

Donald Hector AM was President of the Society from 2012 to 2016.

Journal & Proceedings of the Royal Society of New South Wales, vol. 149, parts 1 & 2, 2016, pp. 17–33. ISSN 0035-9173/16/010017–17

Deep-earth methane and mantle dynamics: insights from northern Israel, southern Tibet and Kamchatka

William L. Griffin[1*], Sarah E.M. Gain[1], David T. Adams[1], Vered Toledo[2], Norman J. Pearson[1] and Suzanne Y. O'Reilly[1]

[1] ARC Centre of Excellence for Core to Crust Fluid Systems, EPS, Macquarie University, NSW 2109, Australia

[2] Shefa Yamim (A.T.M.) Ltd., Akko, Israel

* Corresponding author.
Email: bill.griffin@mq.edu.au

Abstract

The oxidation state of fluids in Earth's mantle affects processes ranging from volcanism and the formation of the crust, to the generation of many types of ore deposits. In general, the lowest oxidation state of the mantle (and hence its fluids) is defined by the buffer reaction $2FeO \rightarrow 2Fe + O2$. However, unusual mineral assemblages that require far more reducing conditions are found in volcanic rocks from a variety of geotectonic settings, raising questions about how such conditions can be generated in the mantle. Examples from northern Israel, Tibet and Kamchatka suggest that interaction between magmas and methane-hydrogen fluids derived from the deep Earth have generated highly reducing conditions within some volcanic plumbing systems. Such systems appear to be related to the margins of tectonic plates, including zones of continent-continent collision and/or deep oceanic subduction, and transform faults extending deep (up to 200 km) into the Earth's mantle. This represents an important but previously unrecognized fluid-transfer process within the mantle.

Foreword

This paper is both a condensation and an expansion of the 2015 Clarke Memorial Lecture, given by WLG at Macquarie University in August 2015, which summarized recent work by the ARC Centre of Excellence for Core to Crust Fluid Systems (CCFS). We hope to provide both geologists and non-specialists with a glimpse into some recent exciting developments in Earth Science, and to show how the integration of observations at scales from microns to mountain ranges can give us a new picture of how Earth works. We are trying to understand processes not previously recognized, and the paper therefore contains some "interesting" speculations, which we hope can generate (polite) discussion.

Introduction

The nature of the rocks in Earth's deep mantle (from the base of the crust to the top of the core; Fig. 1), and clues to their formation, are generally hidden beneath our feet in the vast space of inner Earth. However, small samples of the mantle are brought to the surface by some volcanic eruptions in which the magmas originated at depths of 250–100 km. Such magmas can rise to the surface at speeds of 1–4 km/hour, entraining fragments of deep-seated rocks and minerals (xenoliths and xenocrysts; O'Reilly and Griffin, 2010). Larger samples of mantle rocks, tens to thousands of cubic km in volume, can be brought to the surface by geodynamic forces in regions where tectonic plates collide (e.g., Tibet, the Andes, New Guinea).

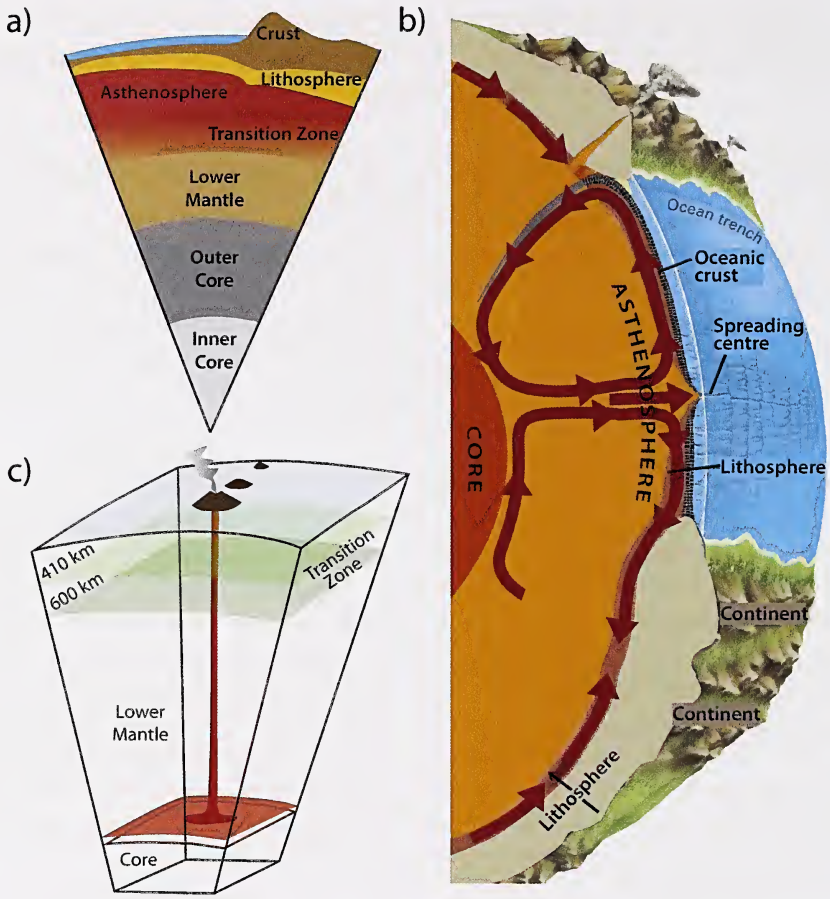


Figure 1. (a) Cross-section of Earth's interior, showing the divisions defined by mineralogy; (b) Cross-section emphasizing the convection of the mantle, driven by the heat in the core; (c) cartoon of deep-seated mantle plumes, in this case producing oceanic islands like Hawaii; smaller upper-mantle plumes may rise from the Transition Zone and produce much less magma.

This report focuses on three locations that have yielded surprising discoveries about the nature of some mantle rocks and minerals and their conditions of formation deep in the mantle. Material from two of these areas (S. Tibet, N. Israel) is being studied by the CCFS team, while recent discoveries in the Kamchatka Peninsula of NE Siberia provide important comparisons.

The Deep Earth and the Importance of Fluids

The large-scale structure and composition of Earth's convecting mantle (the asthenosphere), extending from 100–200 km below Earth's surface to the outer edge of the core at ~2,900 km, are generally understood (Fig. 1). The uppermost (lithospheric) mantle is relatively cool and coupled to the crust; (10 to 40 km thick in oceanic and old continental regions respectively); these make up

the lithosphere, and Earth's tectonic plates. The mantle is made up largely of ultramafic rocks — high in MgO and low in SiO_2. At depths between 410–660 km, in the Transition Zone, the dominant minerals (olivine, pyroxenes, garnet) go through a series of changes (phase transitions) to denser, higher-pressure forms, which dominate the mineralogy of the lower mantle (>660 km). The convection of the asthenosphere drives (or responds to) the movement of the tectonic plates that make up Earth's crust (Fig. 1b). In the upwelling parts of the convection system, decompression induces melting, with the production of a range of magma types, at relatively shallow levels of the asthenosphere. Where plates descend into the mantle at subduction zones, the introduction of water helps to cause large-scale melting, producing volcanic arcs — ranges of volcanoes like the Andes. Whether the whole mantle convects in the same way is still debated, but it is clear that material does emerge from the Transition Zone or even the core-mantle boundary, in the form of plumes, which bring hot mantle to near the surface. The results are visible in chains of volcanoes such as Hawaii; these "hotspot trails" reflect the movement of an oceanic plate over a stationary plume (Fig. 1c).

The role of fluids in all of these mantle processes is a major focus of the research program in the ARC Centre of Excellence for Core to Crust Fluid Systems (CCFS). The presence of fluids helps to determine the viscosity of the convecting mantle, the temperatures at which it melts to produce magmas (which also are fluids), the nature of volcanic eruptions (explosive *vs* quiescent) and the compositions of the magmatic products. We need to know the nature and distribution of different types of fluids in the mantle if we are to understand these processes.

Oxidation-reduction (redox) reactions, in which oxygen is transferred from one mineral to another, or from a fluid to a rock or vice versa, play a vital role in many Earth processes, especially in the genesis of igneous rocks, and the movement and reaction of fluids at all levels of Earth's internal architecture. Redox reactions, as well as pressure (P) and temperature (T), can control which minerals are stable in rocks, and the distribution of water, carbon dioxide (CO_2), methane (CH_4), hydrogen and other components in fluids moving through the mantle and crust. Via such fluids, redox reactions also are very important in the formation of many types of ore deposits.

The "redox state" of a chemical system can be expressed in terms of the oxygen fugacity ($fO2$), which is simply the partial pressure of oxygen in an ideal gas of a given composition. It commonly is expressed as values relative to the $fO2$ of a known reaction (a "buffer"; Fig. 2). For example, a relatively high oxygen fugacity ("oxidizing" conditions) would be defined by the reaction:

Fayalite (Fe-olivine) + O_2 → magnetite + qtz

$Fe_2SiO_4 + O_2 \rightarrow Fe_3O_4 + SiO_2$ (1)

the ***"FMQ"*** buffer

A much lower fO_2 (more "reducing" conditions) would be defined by a reaction such as:

Iron + oxygen → wustite

$2Fe + O_2 \rightarrow 2FeO$ (2)

the ***"IW"*** buffer.

Most magmatic rocks in Earth's crust record fO_2 around the FMQ buffer; the upper mantle tends to have lower fO_2, and to become generally more reducing (lower

fO_2) with depth (Fig. 2). The IW buffer is thought to represent a lower limit for fO_2 in the mantle, simply because mantle rocks contain so much FeO that it would be hard to reduce it all to Fe.

However, we do know that conditions more reducing than the IW buffer must occur locally in the mantle, partly because the mineral moissanite (silicon carbide, SiC) is found in some mantle-derived magmatic rocks such as kimberlites (the host rock of most diamonds) and even as rare inclusions in diamonds. The stability of moissanite is controlled by reactions such as:

Enstatite + carbon → moissanite + forsterite

$$MgSiO_3 + C \rightarrow SiC + Mg_2SiO_4 \quad (3)$$

As we study other mantle-derived rocks, we are finding that moissanite is unexpectedly common in the mantle, and can be accompanied by a wide range of other "super-reduced" minerals (e.g., metallic elements, carbides, nitrides) that require even more reducing conditions than moissanite itself. These occurrences raise two important questions: (1) what sort of processes can generate such conditions in Earth's mantle? and (2) why didn't these minerals react with the more oxidized mantle in which they are embedded?

Recent studies also have shown that remarkably similar super-reduced mineral assemblages can be found in mantle-derived rocks from completely different tectonic settings. This suggests the widespread operation of poorly-understood processes, not previously recognized in the mantle. Can the similarities and differences between some of these occurrences provide clues to the nature of those processes?

Here we will give brief descriptions of three such occurrences, in southern Tibet, northern Israel and the Kamchatka volcanoes of NE Russia; by examining their simi-

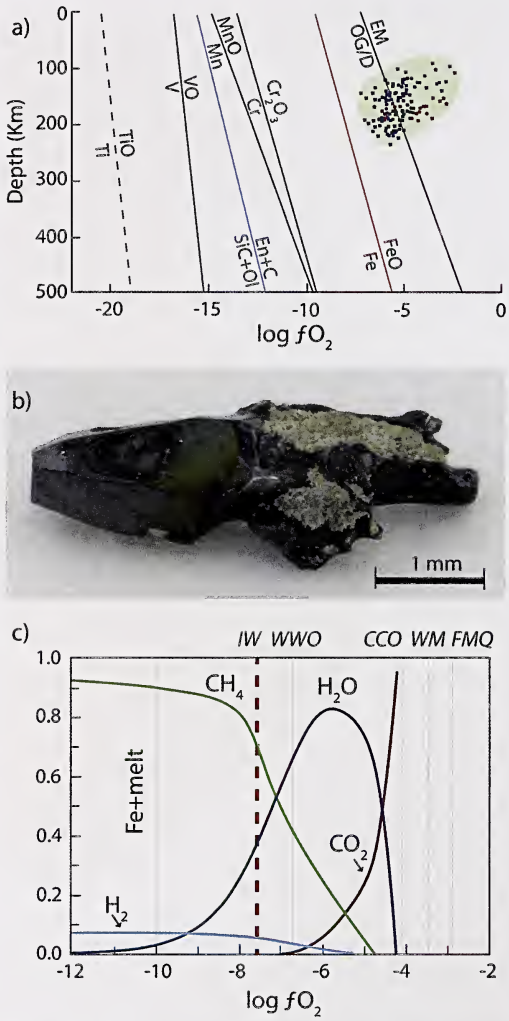


Figure 2. Oxidation-reduction (redox) reactions and their control on fluid compositions. (a) Oxygen fugacity vs depth (at 1500 °C) for some redox buffers; shaded field shows the range of fO_2 measured in rock samples from the upper (lithospheric) mantle, all above the Iron-Wustite (Fe-FeO) buffer; (b) a crystal (4.1 mm long) of moissanite from the Mt. Carmel area, Israel; (c) relative abundances of different species in C-O-H fluids as a function of fO_2 (after Kadik, 1997). Below the Iron-Wustite buffer the fluids are completely dominated by CH_4 and H_2. EMOG/D, the buffer reaction Enstatite + magnesite = olivine + graphite/diamond.

larities and differences, we can speculate on a common process.

Study Areas

Tibet

In southern Tibet, the Yarlung-Zangbo suture zone (Fig. 3) marks the great continental collision between India and Asia, which began ca 55 million years ago and continues today, pushing up the Himalayan Mountains. Scattered along this suture zone is a line of peridotite massifs — fragments of Earth's mantle, up to 1000 cubic kilometers in volume. Some of these contain minable bodies of chromite ore, which formed at shallow depths (5–15 km) ca 325 million years ago, when the peridotites were part of the mantle above a subduction zone. However, structures and relict minerals in the chromite ores and the peridotites indicate that these rocks were later subducted down as far as the Transition Zone (≥410 km), where they remained for about 200 million years (McGowan et al., 2015). During their residence in the Transition Zone, the peridotites probably heated up to 1400–1500 °C; this heating, and their composition, would result in them becoming buoyant relative to the surrounding mantle.

The excavation of these peridotite bodies from the Transition Zone back to the surface can be attributed to the forces exerted by a later slab, subducting during a plate collision event and penetrating into the Transition Zone. As the slab stalled, it began to roll

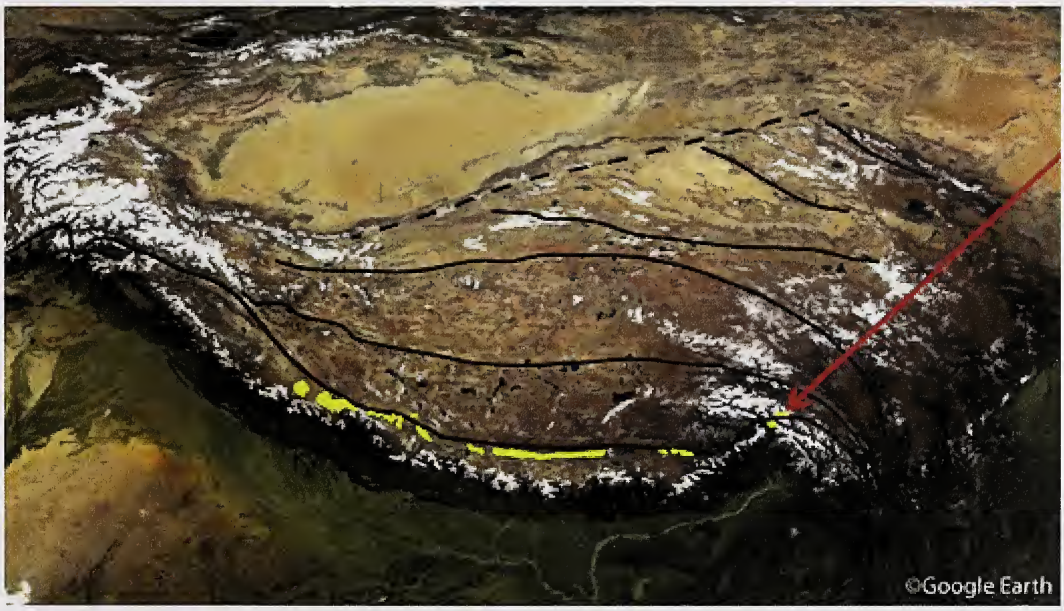


Figure 3. Bird's-eye view (looking north) of the Tibetan Plateau, bounded in the south by the Himalayas. Black lines show sutures between crustal blocks that have drifted together to form the region. The southernmost line marks the Yarlung-Zangbo suture zone, where numerous bodies of mantle peridotite (yellow) were emplaced 60-70 million years before the collision of the Indian plate with Asia initiated the rise of the Himalayas. Many of these bodies contain diamonds, super-reduced mineral associations and evidence of derivation from the Transition Zone; the red arrow indicates the famous Luobusa peridotite. Map courtesy of Google Earth.

back, causing the mobile asthenospheric mantle (Fig. 1, Fig. 4) to flow in to fill the "gap". Dynamic modeling (Afonso and Zlotnik, 2011; McGowan et al., 2015) has shown that this can create a broad upwelling in the deep mantle, near the top of the Transition Zone. As slab rollback continues, this broad upwelling rapidly develops into a narrower channel of upward-flowing asthenosphere; this upwelling combined with the compositional buoyancy of the peridotite bodies to bring them rapidly (in 6–8 million years) from the Transition Zone to crustal levels, where at least some became the seafloor in small ocean basins (Liu et al., 2015).

Small diamonds were first recovered from some of the chromite ores in the peridotites more than 40 years ago (Fig. 5; Bai et al., 1993). Since then diamonds have been extracted from both the ores and the peridotites in at least seven tectonically emplaced mantle-derived bodies along the Yarlung-Zangbo suture zone, in peridotites on older sutures in farther north in Tibet (Fig. 3), and in similar bodies in the Polar Ural Mountains of northern Russia (Yang et al., 2014, 2015). These diamonds have created both interest and disbelief, because they differ in many respects from "normal" diamonds with which most geologists are familiar.

"Normal" diamonds come from magmatic bodies of kimberlite (an alkaline igneous rock) that typically occur in the stable cratonic areas of continents. Most diamonds in the kimberlites are fragments from the continental roots, and some may have resided there for billions of years; they usually form octahedral crystals, which may be rounded by chemical resorption.

The Tibetan diamonds, in contrast, strongly resemble synthetic diamonds that are produced industrially in America, Russia and China. They have smooth cubic faces, which are rarely seen on kimberlitic dia-

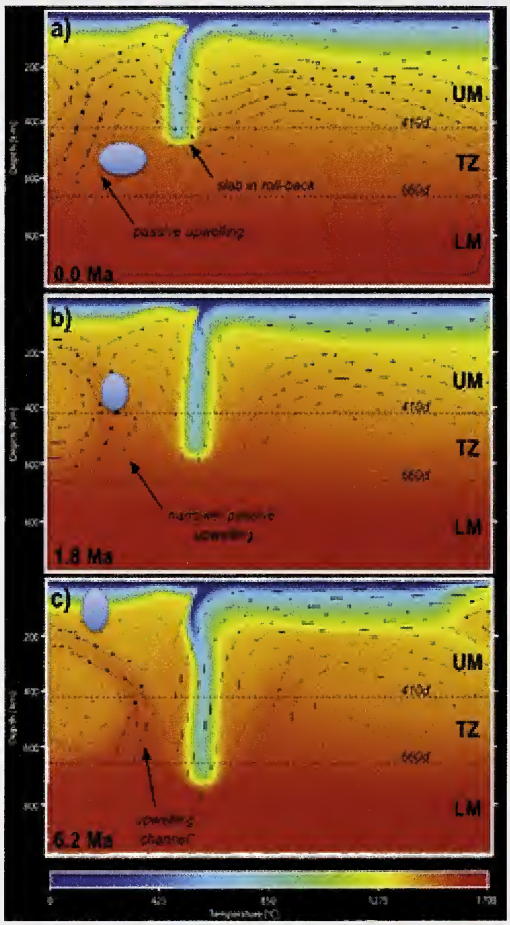


Figure 4. A thermo-mechanical model (Afonso and Zlotnik, 2011) showing how the rollback of a subducting slab sets up forces that lead to rapid upwelling of the mantle from the Transition Zone. The blue marker represents a mass of much older, more depleted peridotite rising from the Transition Zone to the ocean floor. (After McGowan et al., 2015).

monds (Fig. 5); they contain inclusions of metallic alloys (Ni-Mn-Co); their carbon is isotopically very light; they contain nitrogen as single atoms, whereas nitrogen in kimberlitic diamonds is largely recombined into N-N pairs or N4 tetrahedra. However, several diamonds have been found *in situ* in the chromites (Yang et al., 2007, 2014) where they are surrounded by zones of amorphous carbon. Detailed studies (Howell et al., 2015) strongly suggest that the diamonds in the peridotites and chromite ores are in fact natural and represent a new environment for diamond formation in the mantle—but one that is not well-understood.

Diamonds do not require strongly reducing conditions to form in the mantle (EMOD buffer, Fig. 2). However, the diamonds in the peridotites of Tibet and the Polar Urals are accompanied by a great variety of "super-reduced" minerals (Yang et al., 2007, 2014, 2015). These include moissanite (silicon carbide), native elements (Fe, Ni, Ti, Si, Cr, Al), carbides of titanium and other elements, silicides of iron and titanium, and titanium nitrides. Many of the more unusual minerals occur as inclusions in crystals of corundum (aluminium oxide, Al_2O_3) with unusually high contents of titanium (Xu et al., 2015).

Aside from the very low fO_2 required by many of these minerals, it is difficult to precisely define the conditions of their formation. Many of the minerals imply high temperatures (1200–1500 °C), and the inferred presence of stishovite (a high-pressure form of quartz) around some super-reduced phases suggests depths >300 km (Dobrzhinetskaya et al., 2009).

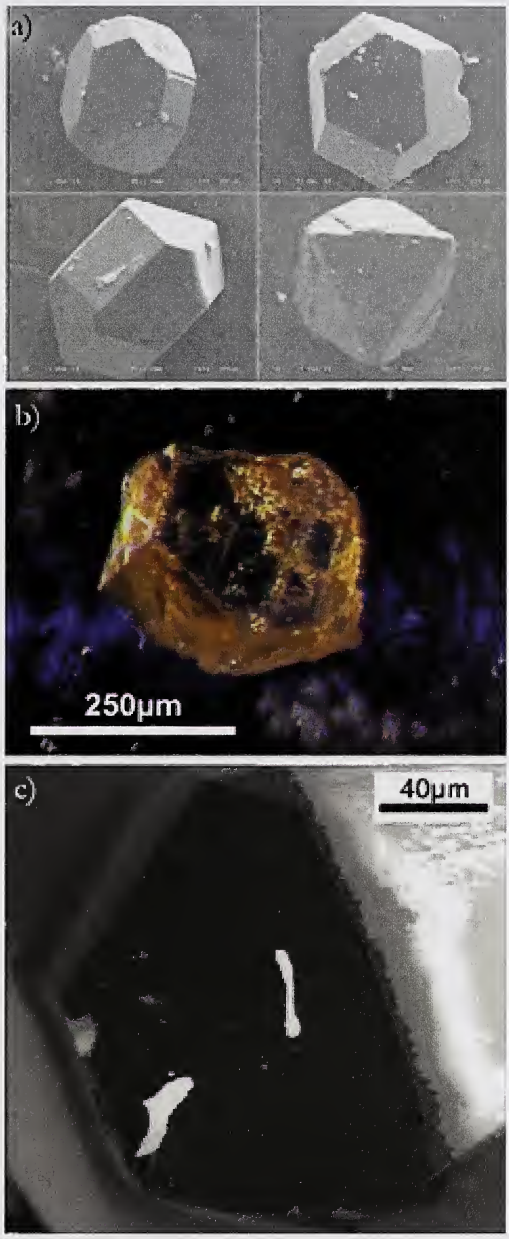


Figure 5. Microdiamonds from Tibetan peridotites (a) SEM images of diamonds, with octahedral and cubic faces; (b) diamond separated in CCFS labs, showing yellow colour and smooth faces; (c) polished section showing melt inclusions of Ni-Mn-Co alloy. Reproduced from Griffin et al. (2016) by permission of Oxford University Press.

Northern Israel

In the Mount Carmel area of northern Israel (Fig. 6), exploration for gemstones by Shefa Yamim Ltd. has discovered a remarkable assemblage of super-reduced minerals,

comparable in many ways to the Tibetan assemblage (Table 1). These occur especially in Cretaceous (ca 99–94 million year-old) volcanic rocks on Mount Carmel, and in alluvial deposits derived from them. The volcanism occurs near the Dead Sea Transform Fault, which represents the boundary between the Arabian plate and the northern (Mediterranean) edge of the African plate.

However, the Cretaceous eruptions predate the first known movements (Miocene) on the fault by about 70 million years (Sass, 1980; Garfunkel, 1989). Gas-rich explosive eruptions produced thick pyroclastic deposits (Fig. 6b) and some flows of frothy, glassy lavas (Sass, 1980). The primary magmas are mildly alkaline basalts. The presence of fragments of dense mantle rocks (garnet pyroxenites and websterites; Mittlefehldt, 1986; Kaminchik, 2014; this work) shows that the magmas erupted very rapidly once they had risen to depths of around 80 km.

In addition to gem-quality sapphires, rubies and "normal" diamonds, the Shefa Yamim exploration program has produced unusually large crystals of moissanite (Fig. 2) and large grains (up to 2.5 cm across)

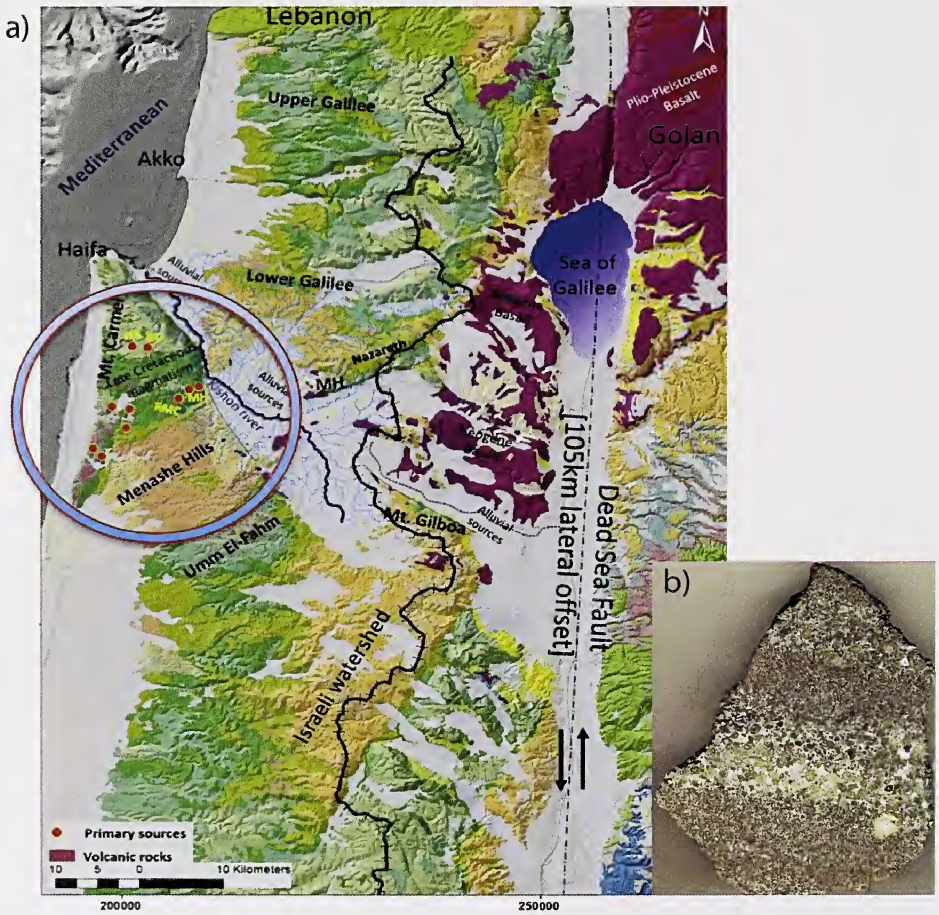


Figure 6. (a) Geological map of northern Israel; Mt Carmel area is circled, and volcanic centres are marked by red dots; (b) sawn section, ca 30 cm high, of volcanic tuff from Mt Carmel.

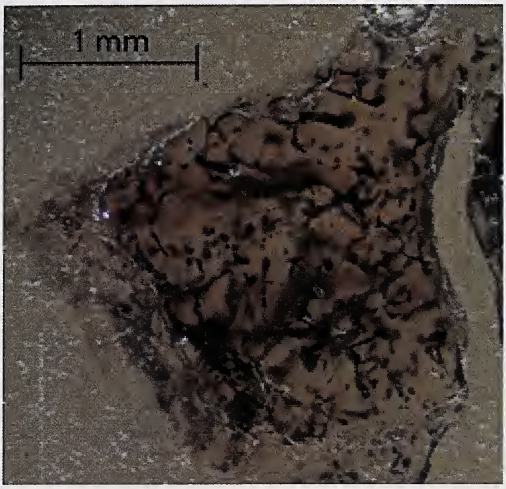


Figure 7. Fragment of non-gem corundum from Mt. Carmel; dark irregular blobs are pockets of melt trapped within and between grains of transparent corundum. (After Griffin et al., 2016b).

of "non-gem corundum" (Fig.7). The latter has proved to be a *Rosetta Stone* for understanding the development of highly reducing conditions in Earth's mantle.

Irradiation of the non-gem corundum with electrons produces a bright pink fluorescence (cathodoluminescence, or CL; Fig. 8), which shows remarkable patterns that outline the growth of the crystals. Microchemical analysis shows that variations in the CL response correlate with differences in the Ti content of the corundum — light areas fluoresce brightly, while high Ti contents induce darker shades. The patterns show that individual samples of the corundum typically consist of many smaller crystals, with pockets of melt trapped along the grain boundaries and within the crystals (Fig. 7, 8). These melt pockets now consist of calcium-aluminium-magnesium silicate glass and minerals that crystallized from it before the volcanic eruption carried the corundum

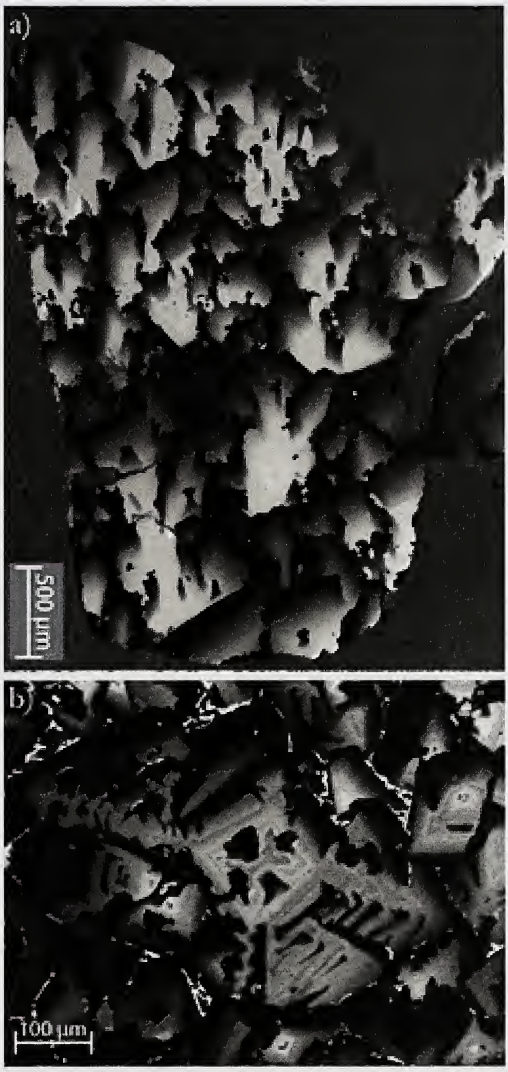


Figure 8. Cathodoluminescence images of polished fragments of non-gem corundum. Real colours range from light to dark pink to nearly black. Light areas have low concentrations of Ti; dark areas are zoned toward melt pockets and have up to 2.6 at.% Ti. (a) multiple "stacked" crystals of corundum outlined by high-Ti zones; (b) detail of crystal showing growth zoning that outlines hollow ("hopper") faces and internal cavities filled with glass (dark CL; frozen melts). (After Griffin et al., 2016b).

fragments to the surface — so these minerals were crystallizing in (or somewhere above) the magmatic plumbing system.

The corundum and its trapped minerals record very reducing conditions. Microchemical analysis shows that the Ti substituting in the corundum is the highly reduced

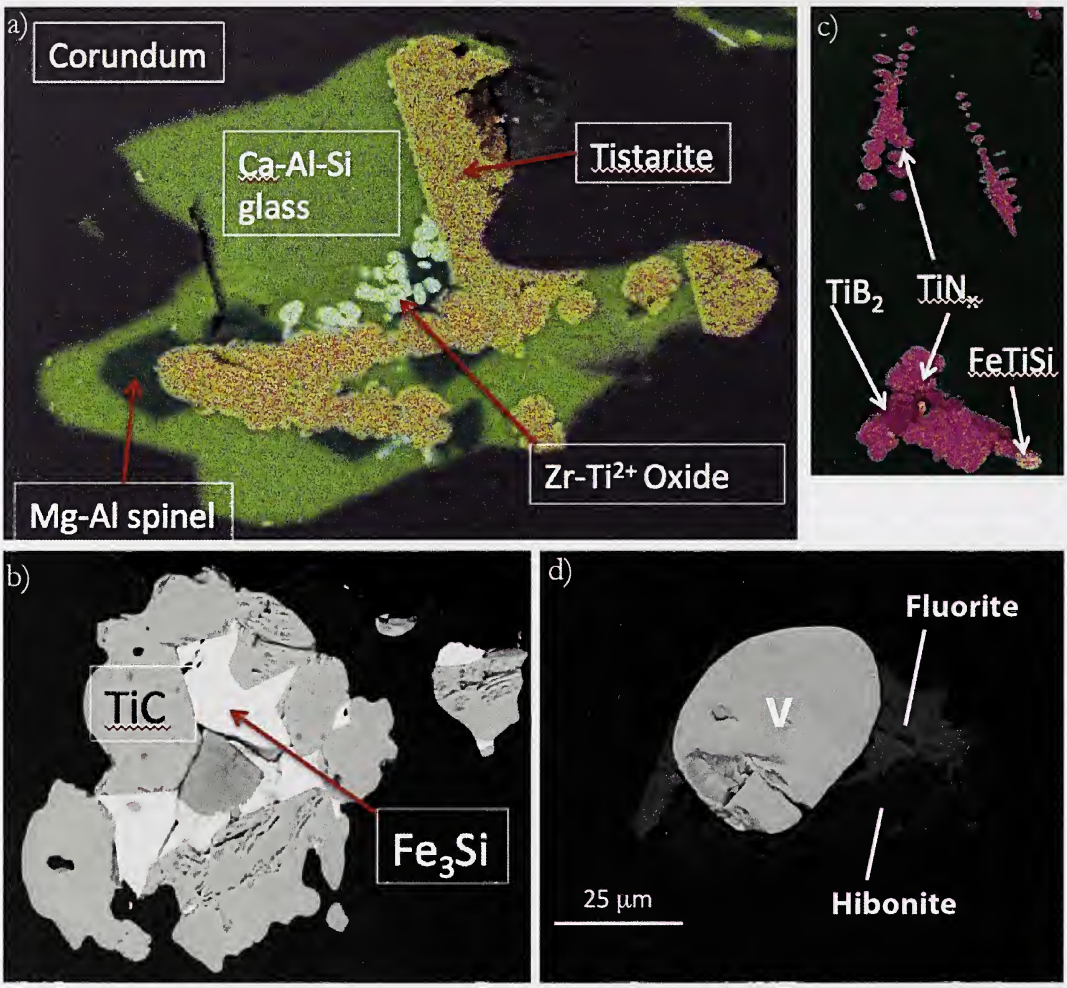


Figure 9. Four types of melt pocket in non-gem corundum from Mt. Carmel, illustrating some of the unusual, highly-reduced mineral associations. (a) SEM false-colour phase map showing minerals and glass in a typical silicate melt pocket in corundum; (b) Ti map showing nitrides, borides and silicides filling internal cavities in hopper crystal of corundum; (c) back-scattered electron (BSE) image of TiC crystallized from an Fe-silicide melt, enclosed in corundum; (d) BSE image of composite pocket of native vanadium, fluorite (CaF_2) and hibonite (a Ca-Al oxide) enclosed in corundum.

form Ti^{3+} (most Ti minerals contain the more oxidized Ti^{4+}), and one of the most common minerals in the melt pockets is *tistarite* (Ti_2O_3; Fig. 9a). Reduction of TiO_2 (Ti^{4+}) to Ti_2O_3 (Ti^{3+}) requires fO_2 6–8 orders of magnitude below the IW buffer; these are seriously reducing conditions. However, *even lower* fO_2 is required by the presence of TiO (with Ti^{2+}) as a separate mineral, and as a component in other oxides (Fig. 2). Other low-fO_2 minerals in the melt pockets include kharambaevite (titanium carbide, TiC), iron silicide (Fe_3Si), titanium nitrides, native iron and native vanadium (Fig. 9b-d). The crystallization sequence of minerals in the melt pockets suggests a continuous decrease in fO_2 during their formation.

Moissanite has been found included in the corundum, suggesting that both were part of the same magmatic system. The CL patterns of the corundum show that it grew as "hopper crystals" (Fig. 9), with hollow faces and branching internal cavities. This type of growth is characteristic of rapid crystallization from fluids that are supersaturated in a component, in this case Al_2O_3. There is no obvious genetic link between the diamonds and the corundum, although exploration has recovered a few microdiamonds similar to those found in Tibet. However, the abundance of carbide minerals, and breccia veins full of amorphous carbon cutting the grains of corundum, imply the presence of fluid(s) very rich in carbon. These two observations may be the key to the origin of this bizarre mineral system (see below).

It is difficult to constrain the temperature and depth of the fluid plumbing system. As in the Tibetan example, some of the minerals present (and the presence of glass) suggest temperatures in the range 1200–1500 °C. The presence of the feldspar anorthite ($CaAl_2Si_2O_8$) in some melt pockets suggests the reaction corundum + melt → anorthite, which would constrain the depth to between 30 and 100 km. Fragments of mantle rocks found in the volcanic ashes suggest that the lithospheric mantle (Fig. 1) beneath the area at the time of eruption was less than 100 km thick.

Kamchatka Peninsula, NE Russia

The Kamchatka peninsula (Fig. 10) hosts many large, active stratovolcanoes, reflecting the ongoing subduction of the Pacific plate beneath NE Asia. From November 2012–September 2013, fissure eruptions occurred on the flank of the Plosky Tolbachik volcano. The first eruptions, especially at the site known as Proryv Naboko, were voluminous and highly explosive, with gas jets erupting >250 m in the air (Gordeev et al., 2013); later stages produced huge emissions of sulfur dioxide (SO_2), with lava fountains and pyroclastic deposits. Much of the early-erupted material consisted of extremely frothy, glassy lavas and pyroclastic material. The lavas are silica-rich basalts, and can be divided into a low-Fe group and a high-Fe group.

Two samples of the frothy lavas from the first eruptions yielded abundant diamonds (>700 grains); most were of a "yellowish-greenish" colour, and occur in gas cavities in the lava. Individual grains of moissanite, corundum (red, blue and Ti-bearing) and native elements (Fe, Cu, Al) were found in the same samples, also within gas cavities. Similar reduced minerals also have been reported from the lavas of several other volcanos on Kamchatka (Gordeev et al., 2013), and both moissanite and Ti-bearing corundum are common associates of "diamond-bearing ores of unconventional types" related to explosive volcanism in Russia (Karpov et al., 2014).

The diamonds from Tolbachik (Karpov et al., 2014) are typically 250–700 μm in size, and show many remarkable similarities with those from the peridotites of Tibet and the Polar Urals. They have the same distinctive colour and the same cubo-octahedral habit, with smooth cubic faces (Fig. 10); they contain nitrogen almost entirely as single nitrogen atoms; they have similar isotopically-light carbon ($\delta^{13}C$ = -27 to -23, compared to -28 to -24 in the Tibetan diamonds). Some crystals show hollows on the cubic faces, suggestive of hopper growth ("diffusion hunger"; Karpov et al. 2014). Unfortunately, no information is available so far on the nature of inclusions in the Tolbachik diamonds.

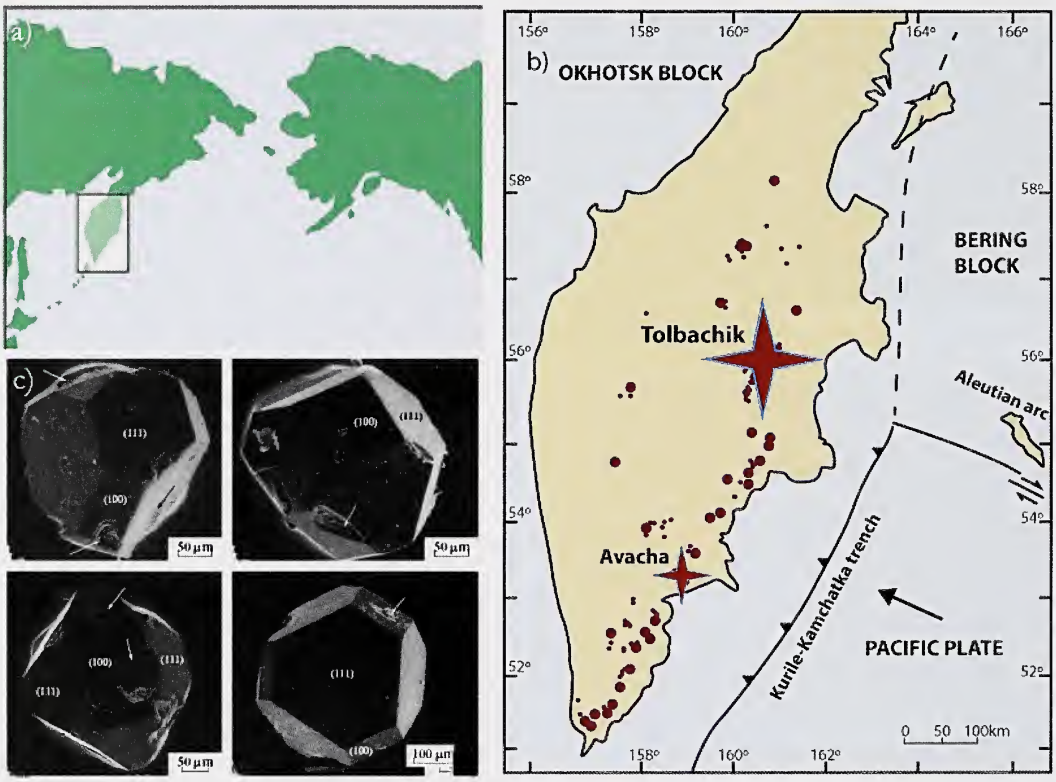


Figure 10. (a) location of the Kamchatka Peninsula (box) in Far Eastern Russia; (b) map of the Kamchatka Peninsula showing lines of volcanoes (red dots) related to subduction of the Pacific Plate beneath the continental margin (Okhotsk Block); red stars mark sites of Avacha volcano, and the 2012-2014 Tolbachik eruption; (c) SEM images of diamonds from lavas of the Tolbachik eruption of 2012, showing mixtures of octahedral (111) and cubic faces (cf. Fig. 5a); arrows point to hollow faces that may indicate either hopper growth or later dissolution (After Karpov et al., 2014).

Discussion

Similarities and Differences

(1) Tectonic environment: The three localities discussed here lie in three distinct tectonic environments, but there may be common factors. The Kamkatcha peninsula lies above a major ocean-continent collision, with ongoing subduction and large active volcanoes. The Tibetan peridotites are in a major continental- collision zone (India-Asia), as are the Polar Urals occurrences (Asia-Europe), and there is only limited evidence of volcanism related to their emplacement. However, the continent-continent collisions in both cases were preceded by the subduction of oceanic plates, which may have brought up the peridotite bodies. The Cretaceous volcanism in the Mt Carmel area also lies along a plate boundary, but in this case it is the Dead Sea Transform Fault (Fig. 6), along which the plates grind past one another rather than subducting. In this case the movement on the fault accommodates the opening of the Red Sea to the south, transferring the movement to another major fault in southern Turkey. This plate boundary (1000 km long) thus must extend well down into the mantle, and could provide a conduit for deep-seated magmas and fluids similar to those generated by deep subduction.

(2) Associated magmas: The composition of the lavas that carry the Kamchatka and Mt Carmel low-fO_2 mineral assemblages lie in the broad spectrum of basaltic compositions associated with shallow melting of the mantle below the lithosphere. The Kamchatka lavas are characteristic of the volcanic rocks of magmatic arcs above continental-margin subduction zones. The basalts of northern Israel are more similar to "intraplate" basalts, and have been described as the products of a deep-seated mantle plume, with most of the melting occurring just below the base of the lithosphere (Fig. 1c; Stein and Hofmann, 1992). The only magmas contemporaneous with the Tibetan peridotites are similar to the basalts erupted at mid-ocean ridges (Liu et al, 2015; Zhang et al., 2015); there is no evidence to link these magmas to the super-reduced mineral suite. These differences suggest that the composition of the magmas is not a critical factor in generating the low-fO_2 assemblages.

(3) Super-reduced mineral assemblages: The major minerals of the low-fO_2 assemblages are similar in all three occurrences (Table 1). The investigations of the Kamchatka lavas have only begun, so relatively few phases have been identified. The Tibetan minerals, which have been studied by many Chinese scientists for more than 30 years, include more than 80 different species, many known only as single grains (Yang et al., 2014). The assemblage from northern Israel has been under detailed study for only a year or two; it contains >65 identified compounds, many not previously known as naturally occurring minerals, but it also lacks many of those identified in Tibet. This may reflect the vagaries of observation, but may also indicate subtle differences between the conditions of crystallization in different localities. For example, diamonds are relatively abundant in the Tibetan and Siberian localities, but very rare in the Mt. Carmel volcanics (one microdiamond in a 252 kg sample); this might reflect differences in the depth of their respective volcanic systems. It is important to recognize the unique nature of the diamonds found in both Tibet/Polar Urals and Kamchatka, which appears to require processes different from those that generate the "normal" kimberlitic diamonds formed in old continental roots (Howell et al., 2015).

Generating super-reducing conditions — some evidence, some speculation

As noted in the Introduction, there are two problems — how to generate super-reducing conditions in the upper mantle, and how to stop the products from reacting with the surrounding oxidized mantle. A key to the first question may lie in the mineral tistarite (Ti_2O_3; Fig. 9). The N. Israel samples represent the first known terrestrial occurrence of this mineral; its "type locality" (Fig. 11) is a single tiny grain in the Allende meteorite, where it occurs together with TiC and corundum, as in the N. Israel samples. Allende is a carbonaceous chondrite — one of the most primitive types of meteorite, and one of the oldest objects in the Solar System. The tistarite-TiC-corundum association in Allende represents early condensates from the solar nebula, in regions near the Sun; they reflect conditions of low pressure, but high temperature (>1400 °C) and a very low fO_2 (Fig. 2) related to the streaming of the hydrogen-dominated solar wind through the nebular cloud. How could we generate such "nebular" conditions on Earth?

One possibility is illustrated by Figure 2c; in the deep Earth, at fO_2 below the IW buffer, mantle fluids are dominated by methane (CH_4) and hydrogen (H_2). If we can bring large amounts of such fluids to shallow depths, and keep them from equilibrating with the mantle on the way up, they would have a strongly reducing effect on their environment when they reached the upper mantle, as shown by reactions such as (4):

$$2CH_4 + O_2 \rightarrow 2H_2 + 2C + 2H_2O \quad (4)$$

where C is diamond or graphite, depending on pressure.

In addition, reaction (5) can occur at shallow depths (<3 km), and carbon monoxide

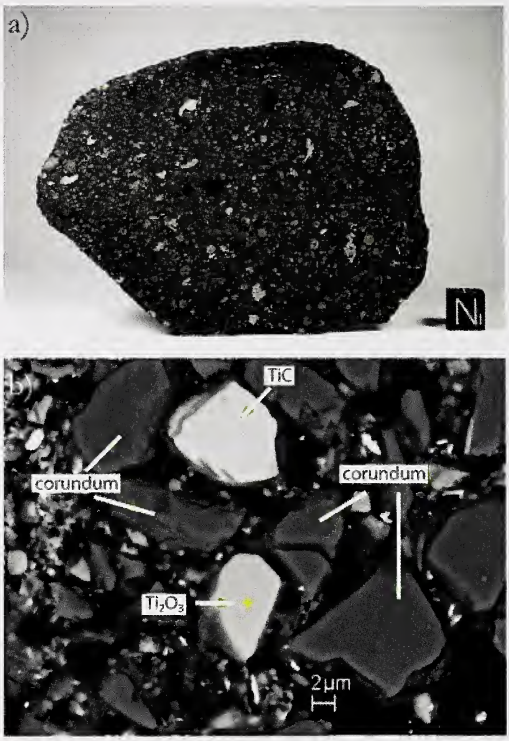


Figure 11. (a) Slice of the Allende meteorite, showing pea-sized chondrules and irregular light-coloured Calcium-Aluminium Inclusions, containing refractory phases condensed from the early Solar nebula; (b) the association of tistarite (Ti_2O_3), khamrabaevite (TiC) and corundum in the Allende meteorite (After Ma and Rossman, 2009). This is the type material of tistarite, and was the only known occurrence before the discovery of this mineral association in the corundum from the Mt Carmel area (cf. Fig.9).

is a very powerful reducing agent in its own right:

$$2CH_4 + O_2 \rightarrow 4H_2 + 2CO;$$
$$2CO \rightarrow C + H_2O \quad (5)$$

Note that these reactions also can liberate and deposit large proportions of carbon, which is consistent with the abundance of diamonds and/or carbide minerals in these deposits.

Rapid crystallization of corundum, SiC and other minerals

The second problem noted above is in keeping the newly-formed low-fO_2 minerals from reacting with the surrounding mantle; the available observations offer a few suggestions. Where the Tibetan moissanite (and diamond) have been seen *in situ*, the grains are surrounded by mantles of amorphous carbon. The nature and origin of this material is not clear from the available research, but it could at least provide a protective coating. Perhaps more important is the presence in all three localities of a Ti-rich corundum; our work suggests that this is itself an indicator of low fO_2. The hopper growth of the corundum in the Mt Carmel localities is an important clue. The rapid growth of a large, porous network of corundum crystals in a magmatic (or hydrothermal) conduit could provide a low-fO_2 "sheltered environment" that would be isolated from the surrounding mantle, while reducing fluids could continue to flow through the network. This process could be the key link among the localities.

But what processes can produce a melt or fluid that is so super-saturated in Al that it can rapidly crystallize large volumes of corundum, apparently unaccompanied by any of the minerals common in mafic magmas? One possibility is suggested by the crystallization of anorthite (a feldspar mineral; $CaAl_2Si_2O_8$) in the melt pockets of the Shefa Yamim corundum. Anorthite melts directly to liquid, or crystallizes directly from melts, at low pressure, but at depths of 10 km-30 km, corundum crystallizes first from Al-rich melts (Goldsmith, 1980), and anorthite only begins to crystallize at lower temperatures. Anorthite is unstable deeper than about 30 km, but corundum can crystallize from melts to much greater depths. The simplest way to make a basaltic magma "dump" corundum is to remove silica (SiO_2). If this occurs at 10–30 km depths, this desilication can move the magma into a compositional space rich in Ca and Al (the anorthite component); at depths >30 km, corundum will be the first phase to crystallize, and will continue to be the only crystallizing phase over a wide span of temperature as the magma cools. The reducing processes discussed above provide a way to desilicate the magma, for example by reactions like (3) and (6):

$$SiO_2 \text{ (in silicates)} + CH_4 \rightarrow SiC + 2\ H_2O;$$
$$H_2O + 2CH_4 \rightarrow C + CO_2 + 4H_2 \quad (6)$$

Thus the streaming of CH_4-rich fluids through the large "plumbing systems" associated with deep-seated volcanism at plate boundaries could be the process that results in the crystallization of both corundum and moissanite, and their associated low-fO_2 minerals, within the upper mantle. In the case of the Tibetan peridotites, these plumbing systems have not been recognized; they may have been obscured by the post-emplacement deformation and recrystallization of the peridotites and many of the chromite ores.

Conclusions: Relationships to tectonics

It appears that the common factor in the three localities described here may be the streaming of CH_4 from deep inside Earth's mantle, related to deep-seated volcanism at plate boundaries. In Tibet, geodynamic models suggest that the peridotites were exhumed from the Transition Zone (>400 km) at rates of 6–8 cm/year (McGowan et al., 2015)—very rapid in geological terms. We expect that this upwelling process also would generate large fluxes of deep-mantle fluids, helping to produce the basaltic magmas. Kamchatka lies above a major

subduction zone, and the rollback of this slab would produce similar upwellings from the deep mantle. In both cases, fluids rich in CH_4 and H_2 might also be supplied by the "dewatering" of carbon-rich marine sediments attached to the subducting slab that triggered the rise of the peridotites.

There was no obvious subduction system active beneath northern Israel in Cretaceous time; the magmatism has been ascribed to the activity of a deep-seated mantle plume, and it seems likely that such plumes also would carry deep-mantle, CH_4-rich fluids. However, seismic tomography shows that the whole Eastern Mediterranean region is underlain by a network of ancient subducted slabs, from which buoyant material could rise, if triggered by tectonic activity or slab rollback, as in the Tibetan situation. In either case, local plume-like upwellings could be focused into the major plate boundary that became the Dead Sea Transform Fault, providing a tectonic environment where both magmas and deep-mantle fluids could rise to shallow levels.

We therefore suggest that such "jets" of $CH_4 \pm H_2$ may commonly accompany certain types of mafic volcanism, especially along plate boundaries, driven by deep tectonics. We expect that in the future, the unusual low-fO_2 mineral assemblages described here will be recognised in many types of volcanic settings. However, they will only be discovered when researchers begin to look more carefully at the minute trace minerals in volcanic ejecta; future studies will reveal if our speculations are correct.

Acknowledgements

We thank Shefa Yamim Ltd., Dave Apter and John Ward for their enthusiastic collaboration on the Mt Carmel material referred to in this study. Steve Craven gave invaluable assistance with the mineral separation work. Shi Rendeng, Qing Xiong and Jonathon Aitchison are thanked for helpful discussions on Tibetan geology, and Jingsui Yang and Paul Robinson for provision of samples and published figures relating to the Tibetan diamond problem. This work was funded by the ARC Centre of Excellence for Core to Crust Fluid Systems (CCFS), with additional support from the Institute of Tibetan Plateau Research, Chinese Academy of Sciences (Beijing). Analytical data were obtained using instrumentation funded by DEST Systemic Infrastructure Grants, ARC LIEF, NCRIS, industry partners and Macquarie University. This is publication 876 from the ARC Centre of Excellence for Core to Crust Fluid Systems (http://www.ccfs.mq.edu.au), and 1126 from the GEMOC ARC National Key Centre (http://www.gemoc.mq.edu.au).

References

Afonso, J.C. and Zlotnik, S. 2011. The subductibility of continental lithosphere. In Brown, D. & Ryan, P.D. (Eds), *Arc - Continent Collision*. Frontiers in Earth Sciences, Springer-Verlag, 53-86.

Bai, W-J., Zhou, M-F. and Robinson, P-T. 1993. Possibly diamond-bearing mantle peridotites and podiform chromites in the Luobusa and Donqiao ophiolites, Tibet. *Canadian Journal Earth Science* 30, 1650-1659.

Dobrzhinetskaya, L.F., Wirth, R., Yang, J-S., Ian, D., Hutcheon, P.K. and Green, H.W. 2009. High-pressure highly reduced nitrides and oxides from chromitite of a Tibetan ophiolite. *Proceedings of the National Academy of Sciences* 106, 19233-19238.

Garfunkel, Z. 1989. Tectonic setting of Phanerozoic magmatism in Israel. *Israel J. Earth Science* 38, 51-74.

Goldsmith, J.R. 1980. The melting and breakdown reactions of anorthite at high pressures and temperatures. *American Mineralogist* 65, 272-284.

Gordeev, E.I., Muravyov, Y.D., Samoylenko, S.B., Volynets, A.O., Melnikov, D.V., Dvigalo, V.N. and Melekestsev, I.V. 2013. First results from the 2012-2013 Tolbachik Fissure Eruption *Bull. Volcanological Society of Japan* 58, 1-8.

Griffin, W.L., Afonso, J.C., Belousova, E.A., Gain, S.E.M., Gong, X-H., González-Jiménez, J.M., Howell, D., Huang, J-X., McGowan, N., Pearson, N.J., Satsukawa, T., Shi, R., Williams, P., Xiong, Q., Yang, J-S., Zhang, M. and O'Reilly, S. Y. 2016a. Mantle Recycling: Transition-Zone metamorphism of Tibetan ophiolitic peridotites and its tectonic implications. *Journal of Petrology* 57, 655-684.

Griffin, W.L., Gain, S.E.M., Adams, D.T., Huang, J-X., Saunders, M., Toledo, V., Pearson, N.J. and O'Reilly, S.Y. 2016b. First terrestrial occurrence of tistarite (Ti_2O_3): Ultra-low oxygen fugacity in the upper mantle beneath Mt Carmel, Israel. *Geology* 44, 815-818.

Howell, D., Griffin, W.L., Gain, S., Stern, R.A., Huang, J-X., Yang, J., Pearson, N.J. and O'Reilly, S.Y. 2015. Diamonds in ophiolites: Contamination or a new diamond growth environment? *Earth and Planetary Science Letters* 430, 284-295.

Kaminchik, J. 2014. The origin of intraplate alkaline mafic magmatism in continental shelves: lavas and xenoliths from the Upper Cretaceous volcanoes of Mt Carmel, Israel. Unpublished MSc thesis, Beer Sheva University, Israel.

Karpov, G.A., Silev, V.I., Anikin, L.P., Rakin, V.I., Vasil'ev, E.A., Filatov, S.K., Petrovskii, V.A. and Flerov, G.B. 2014. Diamonds and accessory minerals in products of the 2012-2013 Tolbachik fissure eruption. *Journal of Volcanology and Seismology* 8, 323-339.

Liu, F., Yang, J-S., Dilek, Y., Xu, Z-Q., Xu, X-Z., Liang, F-H., Chen, S-Y. and Lian, D-Y. 2015. Geochronology and geochemistry of basaltic lavas in the Dongbo and Purang opniolites of the Yarlung-Zangbo suture zone: Plume-influenced continental-margin-type oceanic lithosphere in southern Tibet. *Gondwana Research* 27, 701-718.

Ma, C. and Rossman, G.R. 2009. Tistarite, Ti_2O_3, a new refractory mineral from the Allende meteorite. *American Mineralogist* 94, 841-844.

McGowan, N.M., Griffin, W.L., González-Jiménez, J.M., Belousova, E., Afonso., J.C., Shi, R., McCammon, C.A., Pearson, N.J. and O'Reilly, S.Y. 2015. Tibetan chromitites: excavating the slab graveyard. *Geology* 43, 179-182.

Mittlefehldt, D.W. 1986. Petrology of high pressure clinopyroxenite series xenoliths, Mount Carmel, Israel. *Contributions to Mineralogy and Petrology* 94, 245-252

O'Reilly, S.Y. and Griffin, W.L. 2010. Rates of magma ascent: Constraints from mantle-derived xenoliths. In Dosseto, A., Turner, S.P. and Van Orman, J.A. (eds) *Timescales of Magmatic Processes: From Core to Atmosphere.* Blackwell Publishing Ltd. Pp. 116-124.

Sass, E. 1980. Late Cretaceous volcanism in Mount Carmel, Israel. *Israel Journal of Earth Sciences* 29, 8-24.

Stein, M., and Hofmann, A.W. 1992. Fossil plume head beneath the Arabian lithosphere? *Earth and Planetary Science Letters* 114, 193-209.

Xu, X., Yang, J., Robinson, P.T., Xiong, F., Ba, D. and Guo, G. 2015. Origin of ultrahigh pressure and highly reduced minerals in podiform chromitites and associated mantle peridotites of the Luobusa ophiolite, Tibet. *Gondwana Research* 27, 686-700.

Yang, J.S., Dobrzhinetskaya, L., Bai, W-J., Fang, Q-S., Robinson, P.T., Zhang, J. and Green, H.W. II 2007. Diamond- and coesite-bearing chromitites from the Luobusa ophiolite, Tibet. *Geology* 35, 875-878.

Yang, J.S., Robinson, P.T. and Dilek, Y. 2014. Diamonds in ophiolites. *Elements* 10 127-130.

Yang, J.S., Meng,. F., Xu, S., Robinson, P.T., Dilek, Y., Makeyev, A.B., Wirth, R., Wiedenbeck, M. and Cliff, J. 2015. Diamonds, native elements and metal alloys from chromitites of the Ray-Iz ophiolite of the Polar Urals. *Gondwana Research* 27, 459-485.

Zhang, C., Liu, C-Z., Wu, F-Y., Zhang, L-L. and Ji, W-Q. 2015. Geochemistry and geochronology of mafic rocks from the Luobusa Ophiolite, South Tibet. *Lithos* 245, 93-108.

Journal & Proceedings of the Royal Society of New South Wales, vol. 149, parts 1 & 2, 2016, pp. 34–50. ISSN 0035-9173/16/010034–17

Chemoenzymatic pathways for the synthesis of biologically active natural products

Martin G. Banwell*, Benoit Bolte, Joshua N. Buckler, Ee Ling Chang, Ping Lan, Ehab S. Taher, Lorenzo V. White and Anthony C. Willis

Research School of Chemistry, Institute of Advanced Studies,
The Australian National University, Canberra, ACT 2601, Australia

* Corresponding author.
Email: Martin.Banwell@anu.edu.au

Abstract

The whole-cell biotransformation of mono-nuclear aromatic compounds using certain genetically-engineered micro-organisms that over-express the enzyme toluene dioxygenase (TDO) allows for the large scale production of compounds known as *cis*-1,2-dihydrocatechols. These metabolites, which are normally obtained in enantiomerically pure form, can be manipulated, by chemical means, in a range of distinct (and predictable) ways with the result that they have proven to be especially versatile starting materials for the assembly of a range of structurally diverse and biologically active systems. Herein we describe, on a case-by-case basis, the recent applications of various combinations of TDO-mediated and chemical steps in so-called chemoenzymatic total syntheses of a range of organic compounds with therapeutic potential.

Introduction

Chemical space (*viz.* the space spanned by all possible small molecules and chemical compounds) is essentially infinite.[1] The challenge, then, has been to access the most meaningful or useful parts of it. Nature has provided critical inspirations. So, 3.8 billion years of evolution has produced a global molecular library of unsurpassed size, structural diversity and functional value – our planet's chemome.[2,3,4] Humankind has sought to "mine" this bioactive molecule resource for its benefit and such endeavors have been spectacularly successful as evidenced by the existence of the remarkable array of medicines, materials and agrochemicals that underpin society as we know it today. As a result the world we live in has been transformed. This is evidenced by our exploitation of drugs with household names such as penicillin, morphine and Taxol®. There are many additional but perhaps less well-known examples. For instance, organ transplant surgery would fail completely without the post-operative application of the chemome-derived anti-rejection drugs such FK506 and cyclosporin A.[5] Similarly, a significant number of agents that control agricultural pests, and so helping to ensure both the security and efficiency of world food production, have also come from Nature/the global chemome.[6]

Despite such successes, enormous challenges remain. So-called unmet scientific and societal needs include those arising from the development of resistance to current therapies (perhaps seen most prominently in the area of antibiotics[7]) and, in the

agrochemical sector, pest-control agents.[8] In addition, there is a desperate need for small molecule entities that provide, *inter alia*, effective control of neurodegenerative diseases and diabetes in a globally aging population, for ones that treat certain types of refractory cancers and for others that effectively modulate mammalian and other immune systems.

After forays into areas such as combinatorial chemistry,[9] major players in the pharmaceutical industry, sometimes in partnerships with Government-funded agencies, are returning to interrogation of the chemome (or at least portions thereof) as a means for productively probing chemical and thence biological space.[10] There are a number of reasons for such moves[10] including the recognition that, for example, the current pharmaceutical industry is built on <10% of the biosynthetic capacity of the microbial world, one that continues to show a remarkable ability to deliver biologically relevant small molecules.[11]

Occurring in tandem with these trends is the emergence of a plethora of new techniques and concepts concerned with the generation of biologically relevant molecular diversity involving the use of, *inter alia*, techniques of *de novo* biosynthesis for producing functionally annotated chemome components,[12] the creation of new metabolic pathways,[12] synthetic fermentation,[13] and activity-directed synthesis.[14] Simultaneously, new synergies are being recognized between *in vitro*, *in vivo* and *in silico* studies of drug metabolism [15] and thus allowing for much more efficient/rapid assessments of the utility of certain compounds as molecular probes, drugs and/or agrochemicals.

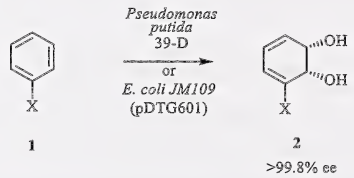
The development of new methods and protocols for effecting the chemical synthesis of biologically active natural products and various analogues remain important parts of the range of activities concerned with exploiting components of the global chemome for therapeutic and other purposes. At least two motivations drive such efforts, the first being the need to address issues of supply. Thus, it is often the case that secondary metabolites[2] are only available in miniscule amounts from their natural source with the result that insufficient material is available for development purposes. Chemical synthesis is often the best method for addressing such issues. Secondly, truly useful chemical syntheses offer the capacity to generate analogues of the natural product that would not normally be available through manipulation of the natural product itself.

This article, which is based on a lecture presented by the senior author at the University of Sydney as part of the RSNSW's 2014 Liversidge Award, details work being undertaken at the Australian National University on the exploitation of certain chemoenzymatic methods for the synthesis of biologically active natural products and their analogues. The work is presented according to the class of natural product being targeted as well as the structural and chemical relationships between them.

Results and discussion

The term chemoenzymatic synthesis used in this article, and elsewhere,[16] refers to the assembly of target compounds using a combination of chemical and enzymatic techniques. While there are many variations on this theme that reflect the extraordinarily diverse range of chemical and enzymatic transformations available these days, the specific form of the latter that applies here involves the whole-cell biotransformation of a range of simple and readily available aromatic compounds of the general form **1** (**Scheme 1**) into the corresponding *cis*-1,2-dihydrocatechols (**2**).[16] When genetically engineered micro-organisms such as *E. coli* JM109 (pDTG601)[17] are used for such

purposes, these metabolites can be readily produced at kilogram scales and are often obtained in >99.95 enantiomeric excess (ee). In the illustrated cases the enzyme responsible for these conversions is toluene dioxygenase (TDO) but a number of related ones are known including biphenyl dioxygenase, naphthalene dioxygenase and toluate dioxygenase. The end result is that a remarkable suite of *cis*-1,2-dihydrocatechols and related metabolites is known - these number in the many hundreds at the present time.[16c] Given the capacities to produce numerous mutants, and thus expand the range of substrates that can be biotransformed, the possible extensions of such processes would appear to be vast. A further fascinating aspect of them is the "chemoselectivities" they can display. So, for example, styrene (**1**, X = $CH{=}CH_2$) is converted into the triene **2** (X = $CH{=}CH_2$), a process wherein the aromatic ring is oxidised in preference to the exocyclic olefin, a functional group selectivity that cannot be achieved by any of the strictly chemical methods known at the present time.[18]



Scheme 1

The utility of the *cis*-1,2-dihydrocatechols (**2**) as starting materials in chemical synthesis has taken some time to be recognised in a broader sense. Various groups, especially those led by Ley in the UK[19] and Hudlicky in North America,[16a,d] have carried out the pioneering work in the area. Such studies established the reactivity "patterns" shown in **Figure 1** as well as attendant hazards arising from the dehydrative re-aromatisation of these substrates[20] and the propensity of certain derivatives, most notably the corresponding acetonides, to engage in normally unproductive Diels-Alder (DA) dimerization reactions.[21]

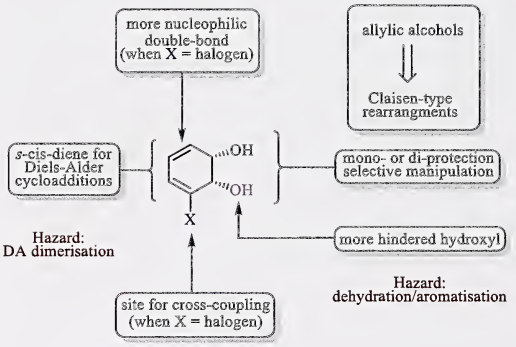


Figure 1

Our own contributions in the area began in the late 1980s[22] and in the intervening period we have been able to establish a series of total syntheses (**Figure 2**) that emphasise the extraordinary range of natural product targets available through manipulation of these metabolites. Some specific examples arising from our recent research are discussed on a case-by-case basis in the following sections.

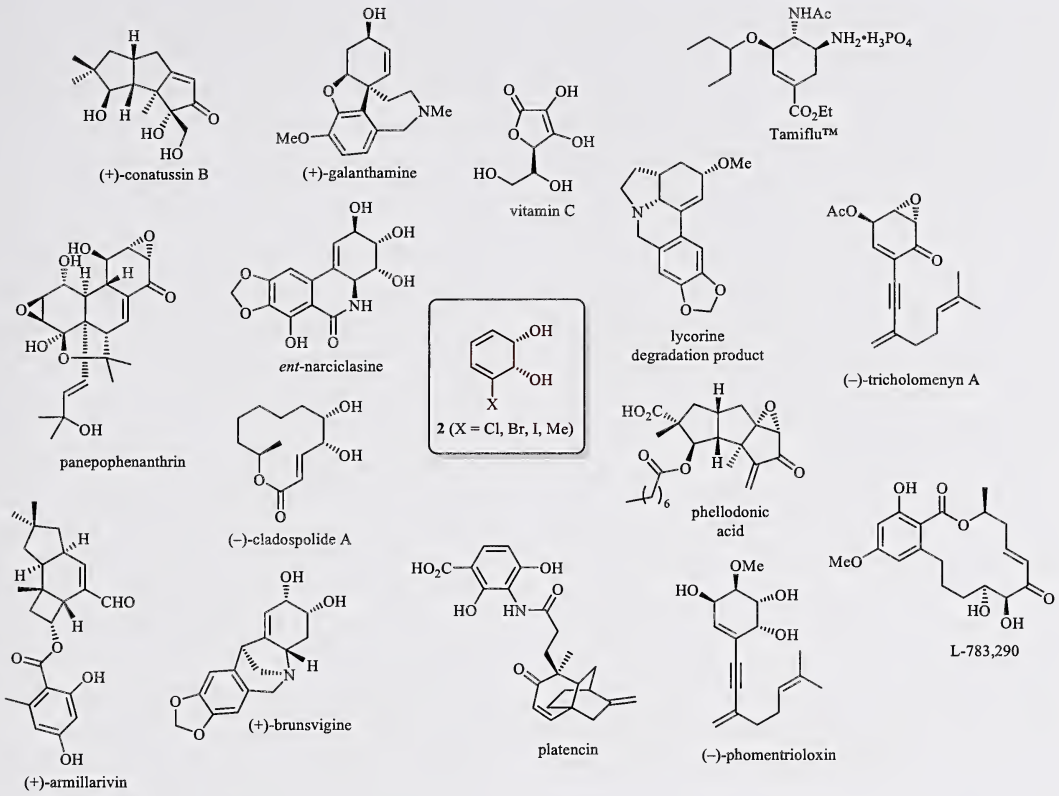


Figure 2

The Ribisins

Ribisins A-D were isolated by Fukuyama and co-workers from *Phellinus ribis* (Schmach.) Quél (Hymenochaetaceae),[23] a fungus used in traditional medicine for various purposes. Using a range of spectroscopic methods they were assigned structures **3**-**6** (**Figure 3**), respectively, and shown to enhance neurite outgrowth in PC12 cells at *ca.* 1 μM concentrations. As such they have potential for development as agents for the treatment of certain neurological disorders.

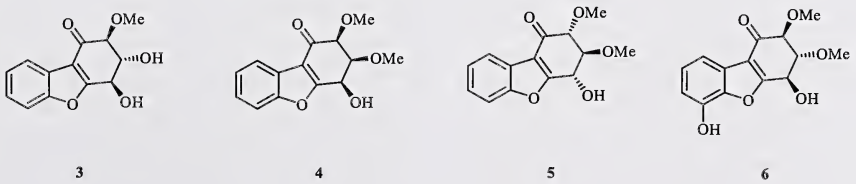
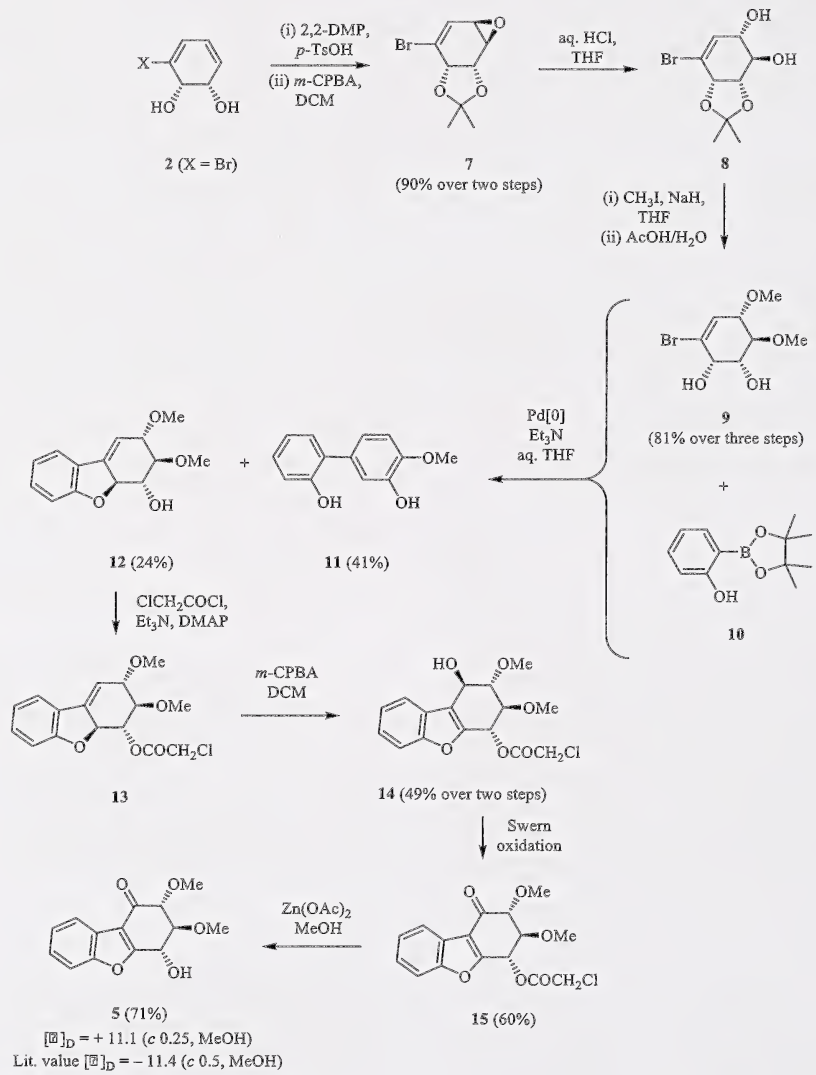


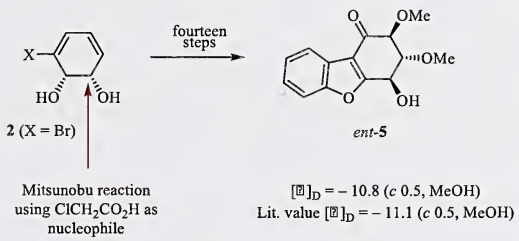
Figure 3

Given the structural resemblance of the polyoxygenated cyclohexane ring of these natural products to the *cis*-1,2-dihydrocatechols **2** (X = Br) we sought a means for effecting the relevant chemical conversions. The route used for establishing a synthesis of compound **5**, the structure assigned to ribisin C and the most active compound in the series, is shown in **Scheme 2**.[24]



Scheme 2

The opening stages of this reaction sequence are typical of the manner in which the *cis*-1,2-dihydrocatechols can be manipulated and involve the initial conversion of compound **2** (X = Br) into the corresponding acetonide and the regio- and stereo-selective epoxidation of the latter to give the oxirane **7**. Treatment of compound **7** with aqueous mineral acid resulted in a regioselective ring-opening reaction to afford the *trans*-diol **8** that could be bis-*O*-methylated under conventional conditions and the resulting acetonide was then cleaved, again under conventional conditions, to give the *cis*-diol **9** that embodies most of the key elements of the Eastern hemisphere of target **3**. Compound **9** could be engaged in a Suzuki-Miyaura cross-coupling reaction with the commercially available boronate ester **10** and two products thereby formed, namely the bis-phenol **11** and the dihydrobenzofuran **12**. Product **12** is presumably formed through cyclisation of the initially produced cross-coupling product while congener **11** arises from successive loss of the elements of water and methanol (no particular order implied) from the same intermediate. The lone hydroxyl group within compound **11** could be protected as the corresponding α-chloro-acetate **13**, a necessary step because of the looming introduction of a second hydroxyl group as the precursor to the ketone moiety. The use of the α-chloroacetate as a protecting group proved essential as in the final step of the reaction sequence attempts to remove the less labile parent acetate resulted in decomposition of the substrate. Epoxidation of compound **13** using *m*-chloroperbenzoic acid (*m*-CPBA) led, presumably *via* spontaneous rearrangement of the initially formed oxirane, to the benzofuran alcohol **14** that could be oxidised to the corresponding ketone **15** under Swern conditions. Cleavage of the α-chloroacetate residue within this last compound was accomplished using zinc acetate in methanol and thus forming the target compound **5**. While all the usual spectroscopic data acquired on compound **5** matched those reported for ribisin C, the specific rotation derived from the synthetic material was of the same magnitude but the opposite sign to that reported for the natural product. The implications are clear – the structure of ribisin C is represented by structure *ent*-**5** rather than **5**. Since we required an authentic sample of ribisin C (*ent*-**5**) for biological testing, a synthesis of it was pursued. This could be achieved (**Scheme 3**) using the same starting material and many of the same transformations as employed in generating its enantiomer (**5**). A key step of the fourteen-stage reaction sequence involved the inversion of configuration at C3 within a derivative of compound **2** (X = Br) using Mitsunobu chemistry. As a result ribisin C was obtained and all of the derived data, including the specific rotation, matched those reported for the natural product.



Scheme 3

Extensions of this sort of chemistry enabled the synthesis of all of the structures originally assigned to the ribisins and thus revealed that while ribisins A and D are constituted as originally described[23] that attributed to congener B is, like C, incorrect.[25] The true structures of all the ribisins are shown in **Figure 4** with the corrected stereocentres within compounds B (**16**) and C (*ent*-**5**) highlighted in red. Extensive biological evaluations of the ribisins and the range of

congeners prepared during the course of our synthetic studies are now underway.

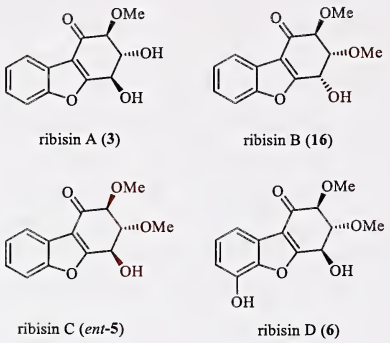


Figure 4

Analogues of Galanthamine

Ribisin D (**6**) bears a "provocative" structural resemblance to the ABC ring-system of the alkaloid galanthamine (**17**) that is used in many countries for the symptomatic treatment of Alzheimer's disease (**Figure 5**).[26] As such we were prompted to explore means by which the chemistry described above could be adapted so as to produce compounds bearing greater similarities to galanthamine (or, in the first instance at least, the enantiomer thereof).

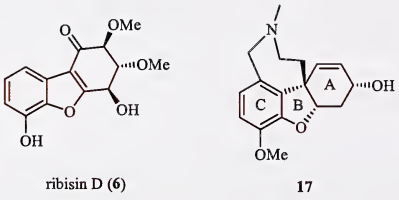
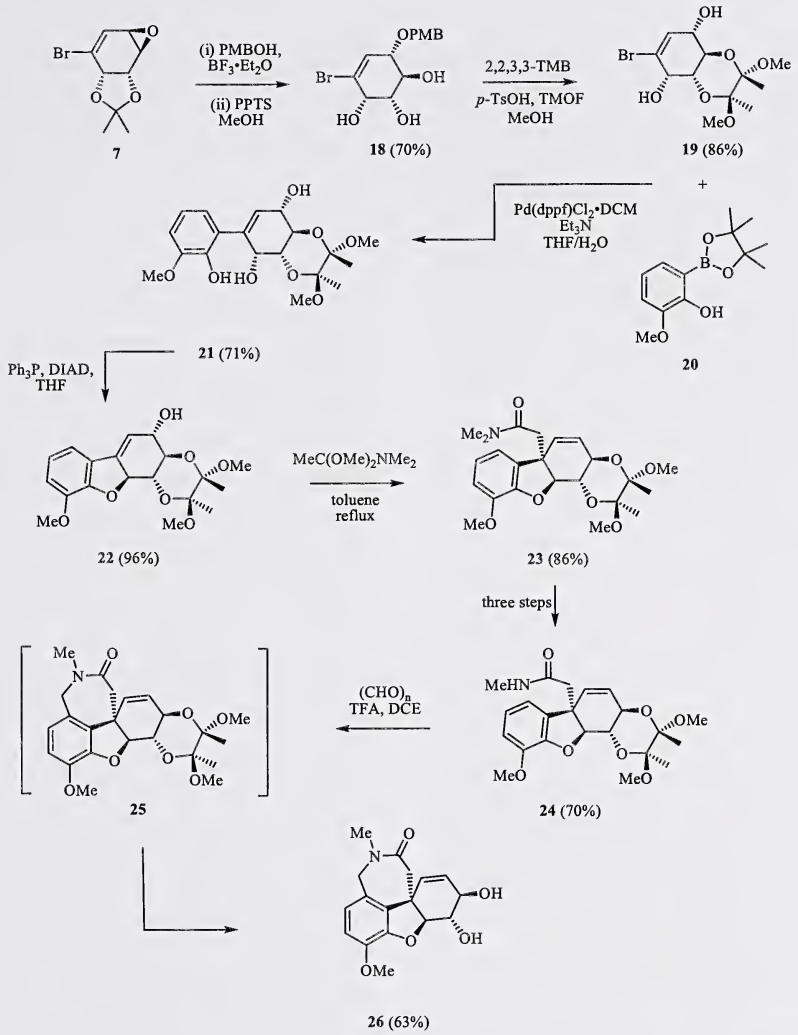


Figure 5

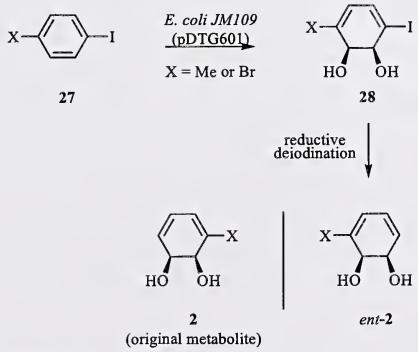
An efficient reaction sequence leading to a dioxygenated derivative of *ent*-galanthamine is shown in **Scheme 4**[27] and involves an initial reaction of the abovementioned oxirane **7** with *p*-methoxybenzyl alcohol (*p*-MBOH) in the presence of boron trifluoride diethyl etherate to generate the anticipated addition product that upon treatment, in a second step, with methanol containing pyridinium *p*-toluenesulfonate (PPTS) affords triol **18**. This last compound could be converted into the corresponding Ley ketal **19**[28] through treatment with 2,2,3,3-tetramethoxybutane (2,2,3,3-TMB) in the presence of *p*-toluenesulfonic acid (*p*-TsOH)/trimethyl orthoformate (TMOF) and Suzuki-Miyaura cross-coupling of this with the boronate ester **20** (produced directly from *o*-methoxyphenol using a C-H functionalization protocol) afforded the arylated cyclohexene **21**. This last compound that was itself engaged in an intramolecular Mitsunobu reaction using di-*iso*-propyl azodicarboxylate (DIAD) to afford the dihydrobenzofuran **22**.

Despite the potential for aromatisation (through simple double-bond migration), compound **22** could be engaged in an Eschenmoser-variant of the Claisen rearrangement reaction using the dimethyl acetal of *N*,*N*-dimethylacetamide[29] and thus affording the angularly substituted ABC-ring analogue **23** of *ent*-galanthamine. Over three conventional steps compound **23** could be converted into its mono-methylated counterpart **24**. The last compound participated in a Pictet-Spengler cyclisation reaction on exposure to a mixture of paraformaldehyde and trifluoroacetic acid (TFA) and the presumably first-formed product **25** underwent cleavage of the Ley acetal residue to give diol **26** as the only isolable product of reaction. Compound **26**, representing a dioxygenated derivative of *ent*-galanthamine (*ent*-**17**), and various congeners that have been prepared using related reaction sequences are currently being subjected to evaluation as inhibitors of the neurologically significant enzyme acetylcholine esterase (AChE).



Scheme 4

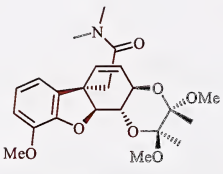
It is worth noting, at this point, that the enantiomer of certain of the *cis*-1,2-dihydrocatechols described above are also available.[30] So, for example, biotransformation of *p*-iodotoluene or *p*-iodobromobenzene [**27a** (X = Me) and **27b** (X = Br), respectively] (**Scheme 5**) using *E. coli* JM109 (pDTG601) affords metabolite **28** that upon exposure to dihydrogen in the presence of palladium on carbon undergoes hydrogenolytic cleavage of the associated C-I bond and thus delivering either *cis*-1,2-dihydrocatechol *ent*-**2** (X = Me) or *ent*-**2** (X = Br).



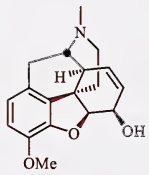
Scheme 5

The Opiates

Morphine and its congener codeine are members of opiate family. They are used extensively for the management of pain and represent the most widely applied and highest grossing medicines in the world today.[31] Their structural complexity means that for the moment, at least, opiates such as morphine are obtained from natural sources and then derivatized by simple chemical means so as to produce related drugs. Nevertheless, much progress has been made in terms of developing commercially viable total syntheses of these systems. Hudlicky and co-workers have defined the current "gold standard" in the area.[32] Given the tantalising structural resemblance between the readily available compound **23** and *ent*-codeine (**29**) (**Figure 6**) we are now attempting to modify the synthesis of the former so as to access the latter. This will likely involve introducing the necessary additional two-carbon unit by using a variant of boronate ester **20** and completing the synthesis of the less functionalised cyclohexane ring within target **29** using an intramolecular S_N' reaction that simultaneously cleaves the Ley acetal subunit.



23



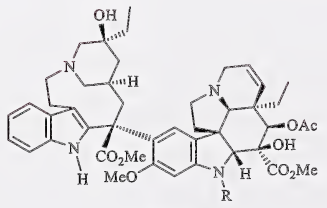
29
(*ent*-codeine)

Figure 6

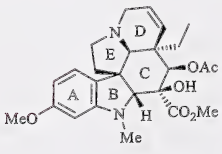
Vinblastine, Vincristine and Vindoline

Vinblastine (**30**) and vincristine (**31**) (**Figure 7**) are indole-indoline-based alkaloids derived from various plant sources, perhaps most notably the Madagascan rosy periwinkle.[33] They are used in the clinical treatment of non-Hodgkin's lymphomas as well as testicular, breast and lung cancers. These compounds are derived *in vivo* from the significantly more abundant and co-occurring alkaloid vindoline (**32**). Given the development of direct, chemically based and "bio-inspired" methods for effecting the conversion of this simpler compound into alkaloids **30** and **31**, vindoline has become the focus of considerable attention as a synthetic target.[34]

Our own efforts in this area have been inspired by the observation (**Figure 8**)[35] that the mutant organism *P. putida* BGXM1 can effect, in an enantioselective fashion, the whole-cell biotransformation of abundant *m*-ethyltoluene (**33**) into the carboxylic acid diol **34** that bears a striking resemblance to the highly functionalised C-ring of vindoline. Accordingly, a recent focus of some of our work in the area of chemoenzymatic synthesis has been on identifying methods for converting this metabolite into vindoline (**32**) and thence into vinblastine (**30**) and vincristine (**31**).



30 (R=Me)
31 (R=CHO)



32

Madagascan rosy periwinkle

Figure 7

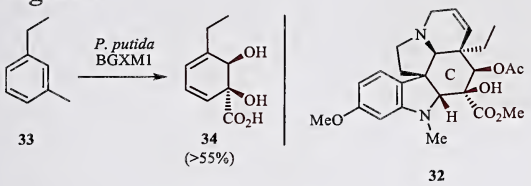
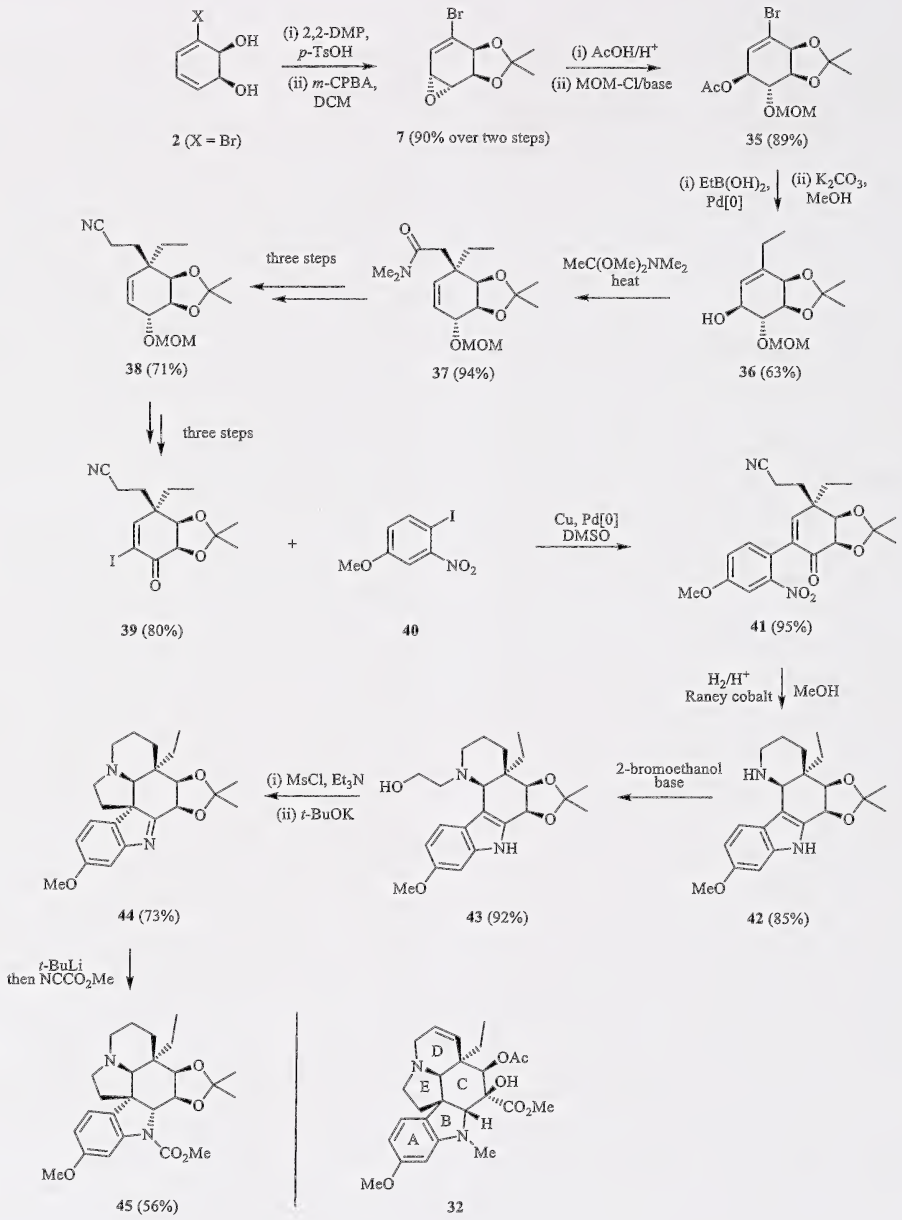


Figure 8

The model study outlined in **Scheme 6** has provided encouragement.[36] Thus, the *cis*-1,2-dihydrocatechol **2** (X = Br), representing a model for congener **34**, was converted, by the means described earlier, into the oxirane **7**. Treatment of this last compound with acetic acid in the presence of mineral acid afforded a *trans*-diol mono-ester that was protected under standard conditions as the corresponding MOM-ether and thus affording compound **35** that could be cross-coupled with ethyl boronic acid in the presence of a Pd[0] catalyst to give, after completing cleavage of the acetate residue using methanolic potassium carbonate, the allylic alcohol **36**. This last compound was engaged in a sluggish Eschenmoser-Claisen rearrangement reaction to give amide **37**, the side-chain of which could be elaborated, over three steps, into the nitrile **38**. Over a further three conventional steps this was converted into the α-iodocyclohexenone **39** that itself served as a substrate for a palladium-catalysed Ullmann cross-coupling reaction[37] with *o*-iodonitroarene **40** and so delivering the α-arylated cyclohexenone **41**. On exposure to dihydrogen in the presence of Raney cobalt[38] and a proton source compound **41** engaged in a series of chemoselective reductions and two cyclisation reactions with the result that the tetracyclic compound **42** was formed. The completion of the synthesis of the pentacyclic framework of vindoline proved straightforward and involved reaction of the last compound with 2-bromoethanol in the presence of base, mesylation of the resulting alcohol **43** and treatment of the sulfonate ester so formed with potassium *tert*-butoxide to generate the isoindole **44**.

In an effort to introduce the carbomethoxy group associated with alkaloid **32**, compound **44** was subjected to successive treatment with *tert*-butyllithium then Mander's reagent ($NCCO_2Me$).[39] However, rather than obtaining the hoped-for *C*-carbomethoxylated imine, carbamate **45** was produced, presumably by a pathway whereby the *tert*-butyllithium acts as a hydride source[40] with the resulting indoline anion then reacting (at nitrogen) with the added electrophile. Efforts are now underway to adapt these chemistries so as to convert metabolite **34** into vindoline. The most challenging issue associated with doing so will be finding a means for introducing the C-C double bond incorporated within the D-ring of target **32**.



Scheme 6

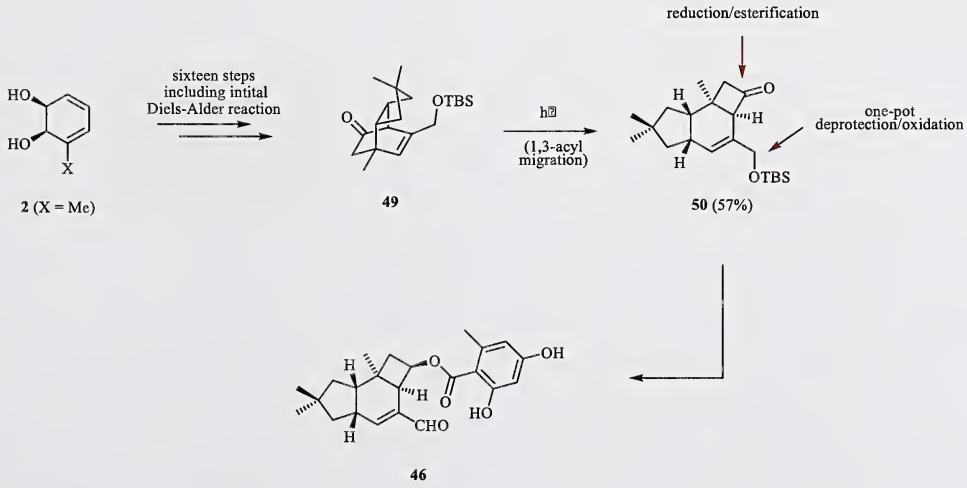
The Protoilludanes

The title sesquiterpenes embody a distinctive tricyclic framework wherein a central cyclohexane ring is annulated, in an angular arrangement, to both a four- and a five-membered ring.[41] The protoilludane aryl ester (+)-armillarivin (**46**) (**Figure 9**) has been found in the edible sugar mushroom *Armillaria mellea*[42] while representative additional natural products in this family include **47**[43] and **48**[44] that are derived from the saprotrophic wood decomposing fungus *Granulobasidium vellereum* (Ellis & Cragin) Ju□lich.

Figure 9

In 2013 we described the first and thus far only total synthesis of (+)-armillarivin.[45] A key element of our approach (**Scheme 7**) was an initial high-pressure promoted and completely regio- and stereo-selective Diels-Alder reaction between the *cis*-1,2-dihydrocatechol **2** (X = Me) and cyclopentenone.[46] Relatively conventional but rather extensive manipulations of the resulting adduct lead to the cyclopentannulated bicyclo[2.2.2]octenone **49** that engaged, as a second pivotal step of the synthesis, in a photochemically-promoted 1,3-acyl migration reaction (Givens rearrangement)[47] to afford the tricyclic isomer **50**. This last compound, which embodies the tricyclic protoilludane framework, was readily manipulated over just three steps to deliver (+)-armillarivin. The structure of this synthetically produced material was confirmed by single-crystal X-ray analysis and all the derived spectroscopic data, including specific rotation, matched those reported for the natural product.

Subjection of the acetonide derivative of compound **2** (X = Me) to a Diels-Alder reaction with cyclopentenone affords, *via* addition of the dienophile to the face of the diene opposite to that "occupied" by the hydroxyl groups, cyclopentannulated bicyclo-[2.2.2]octenones that are enantiomerically related to those obtained by the pathway described immediately above. In essence, then, by controlling the facial selectivity of such cycloaddition reactions either enantiomeric form of the relevant Diels-Alder adduct can be obtained.



Scheme 7

By such means we have recently been able to complete total syntheses of the enantiomeric forms of the protoilludanes **47** and **48**[48] and thus confirming, for the first time, the structures assigned to them.

Platencin

The Diels-Alder cycloaddition chemistry involving *cis*-1,2-dihydrocatechols as the 4π-component can be effectively extended to intramolecular variants. This is perhaps best exemplified in our recently completed first- and second-generation chemoenzymatic syntheses of platencin (**51**),[49,50] a compound isolated from *Streptomyces platensis* MA7327 that acts as a potent and dual inhibitor of FabH and FabF, key enzymes associated with fatty acid biosynthesis in bacteria (**Figure 10**).[51] By virtue of its novel structure and modes of action, platencin is regarded as an important new lead in the development of urgently needed, next-generation anti-bacterial agents.[52]

In our first generation synthesis of compound **51** (**Scheme 8**),[49] the acetonide derivative, **52**, of the *cis*-1,2-dihydrocatechol **2** (X = I) was engaged in a Stille cross-coupling reaction with the *Z*-configured alkenylstannane **53** to give the tetra-ene **54**. Substrate **53** was prepared in a straightforward manner with the stereochemistry at the quaternary carbon centre being controlled through the agency of a chiral auxiliary.

While compound **54** failed to engage in an intramolecular Diels-Alder (IMDA) reaction, the readily derived ketone **55** did so when heated in refluxing toluene and thus affording, in stereochemically pure form, adduct **56** embodying the tricarbocyclic core of platencin. Over a further thirteen steps compound **56** could be converted into (–)-platencin (**51**).

Some of these steps were needed to deal with functional group incompatibilities, an issue that has been addressed, albeit in a modest way, through our recently disclosed second-generation synthesis.[50] In a developing collaboration with the Hudlicky group at Brock University (Canada), efforts are now focussed on a third-generation approach.

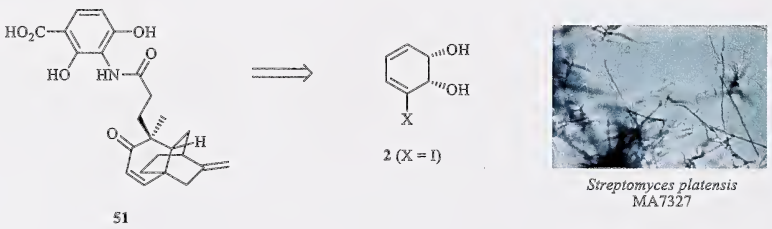
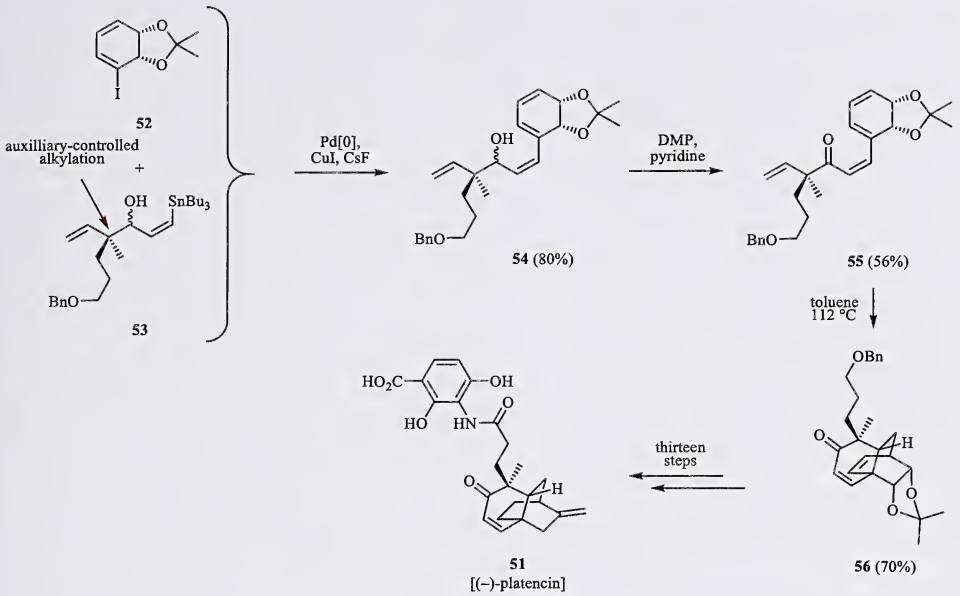


Figure 10



Scheme 8

Conclusions

Enzymes have an almost unparalleled capacity to transform simple organic substrates into synthetically more valuable ones, especially enantiomerically pure compounds (EPCs). Through the use of various genetic engineering, gene shuffling and directed evolution techniques the opportunities to expand upon the existing "library" of metabolites seem almost infinite. Furthermore, pathway-engineering techniques provide a capacity to produce (mutant) organisms that effect, through the orchestrated action of a series of enzymes, multistep transformations. The conversion of *m*-ethyltoluene (**33**) into compound **34**[35] is a case in point and wherein both mono-oxygenases and dioxygenases act in concert to produce a potentially high-value metabolite. When combined with the power of chemical synthesis (as manifest in the techniques of chemoenzymatic synthesis), such bio-transformations provide a powerful tool kit for preparing a wide range of compounds of biological relevance. Ironically, perhaps, while microbiologists have a remarkable capacity to generate a diversity of low molecular weight metabolites (and often at multi-kilogram or larger scale) and synthesis chemists have an almost insatiable appetite for new synthons, the often siloed nature of academic research activities results in less than desirable overlap of the relevant sets of expertise. Changing this situation can only benefit both disciplines.

Acknowledgements

We thank the Australian Research Council and the Institute of Advanced Studies at the Australian National University for ongoing support. The contributions of our colleagues who co-authored the publications referenced below are also gratefully acknowledged, as are the useful comments of Rob Capon and Craig Williams (University of Queensland), Ron Quinn (Griffith University) and Peter Karuso (Macquarie University).

References and notes

1. J. L. Reymond, *Acc. Chem. Res.*, 2015, **48**, 722.
2. The term chemome is used here in the sense defined by Wender (see ref. 3) and taken to mean that vast collection of secondary metabolites produced by the planet's flora and fauna.
3. P. A. Wender, *Nat. Prod. Rep.*, 2014, **31**, 433.
4. The term "terpenome" has been introduced to define that subset of the chemome that is terpenoid in origin: M. B. Quin, C. M. Flynn and C. Schmidt-Dannert, *Nat. Prod. Rep.*, 2014, **31**, 1449.
5. See, for example, H. van Hattum and H. Waldmann, *J. Am. Chem. Soc.*, 2014, **136**, 11853; (b) S. Rizzo and H. Waldmann, *Chem. Rev.*, 2014, **114**, 4621; (c) M. E. Maier, *Org. Biomol. Chem.*, 2015, **13**, 5302.
6. B. C. Gerwick and T. C. Sparks, *Pest Manag. Sci.*, 2014, **70**, 1169.
7. M. A. T. Blaskovich, J. Zuegg, A. G. Elliot and M. A. Cooper, *ACS Infect. Dis.*, 2015, **1**, 285.
8. R. F. Service, *Science*, 2013, **341**, 1329.
9. A very limited number of drugs has thus far emerged from the *de novo* applications of combinatorial chemistry techniques: D. J. Newman and G. M. Cragg, *J. Nat. Prod.*, 2012, **75**, 311.
10. (a) E. Kellenberger, A. Hofmann and R. J. Quinn, *Nat. Prod. Rep.*, 2011, **28**, 1483; (b) J. L. Fox, *Nat. Biotech.*, 2014, **32**, 305; (c) A. L. Harvey, R. Edrada-Ebel and R. J. Quinn, *Nat. Rev. Drug Discov.*, 2015, **14**, 111; (d) M. Pascolutti, M. Campitelli, B. Nguyen, N. Pham, A.-D. Gorse and R. J. Quinn, *PLoS ONE*, 2015, **10**, e0120942.
11. J. R. Doroghazi, J. C. Albright, A. W. Goering, K.-S. Ju, R. R. Haines, K. A. Tchalukov, D. P. Labeda, N. L. Kelleher and W. W. Metcalf, *Nature Chem. Biol.*, 2014, **10**, 963.
12. X. Zhu, J. Liu and W. Zhang, *Nat. Chem. Biol.*, 2015, **11**, 115.
13. Y. Huang and J. W. Bode, *Nat. Chem.*, 2014, **6**, 877.
14. G. Karageorgis, S. Warriner and A. Nelson, *Nat. Chem.*, 2014, **6**, 872.
15. J. Kirchmair, A. H. Göller, D. Lang, J. Kunze, B. Testa, I. D. Wilson, R. C. Glen and G. Schneider, *Nat. Rev. Drug Discov.*, 2015, **14**, 387.
16. For reviews on methods for generating *cis*-1,2-dihydrocatechols by microbial dihydroxylation of the corresponding aromatics, as well as the synthetic applications of these metabolites, see: (a) T. Hudlicky, D. Gonzalez and D. T. Gibson, *Aldrichimica Acta*, 1999, **32**, 35; (b) M. G. Banwell, A. J. Edwards, G. J. Harfoot, K. A. Jolliffe, M. D. McLeod, K. J. McRae, S. G. Stewart and M. Voegtle, *Pure Appl. Chem.*, 2003, **75**, 223; (c) R. A. Johnson, *Org. React.*, 2004, **63**, 117; (d) T. Hudlicky and J. W. Reed, *Synlett*, 2009, 685; (e) D. J.-Y. D. Bon, B. Lee, M. G. Banwell and I. A. Cade, *Chimica Oggi*, 2012, **30**, No. 5, (Chiral Technologies Supplement), 22; (f) U. Rinner, Chiral Pool Synthesis: Chiral Pool Syntheses from *cis*-Cyclohexadiene Diols In: E. M. Carreira and H. Yamamoto, (Eds) *Comprehensive Chirality*, 2012, **2**, 240.
17. G. J. Zylstra and D. T. Gibson, *J. Biol. Chem.*, 1989, **264**, 14940.
18. The chemical dihydroxylation of benzene has been reported as a means of preparing the cyclitol (±)-pinitol: P. M. J. Jung, W. B. Motherwell and A. S. Williams, *Chem. Commun.*, 1997, 1283.
19. See, for example, S. V. Ley, F. Sternfeld and S. Taylor, *Tetrahedron Lett.*, 1987, **28**, 225.
20. (a) S. M. Brown and T. Hudlicky, in Organic Synthesis: Theory and Applications, 1992, JAI Press Inc., Greenwich, Connecticut, 1992, vol. II, 113; (b) D. R. Boyd, J. Blacker, B. Bryne, H. Dalton, M. V. Hand, S. C. Kelly, R. A. More O'Ferrall, S. N. Rao, N. D. Sharma and G. N. Sheldrake, *J. Chem. Soc., Chem. Commun.*, 1994, 313.
21. These types of acetonides are prone to dimerization: (a) S. V. Ley, A. J. Redgrave, S. C. Taylor, S. Ahmed and D. W. Ribbons, *Synlett*, 1991, 741; (b) T. Hudlicky, E. E. Boros, H. F. Olivo and J. S. Merola, *J. Org. Chem.*, 1992, **57**, 1026.
22. M. G. Banwell, *Org. Prep. Proced. Int.*, 1989, **21**, 255.
23. Y. Liu, M. Kubo and Y. Fukuyama, *J. Nat. Prod.*, 2012, **75**, 2152.
24. P. Lan, M. G. Banwell, J. S. Ward and A. C. Willis, *Org. Lett.*, 2014, **16**, 228.
25. P. Lan, M. G. Banwell and A. C. Willis, *J. Org. Chem.*, 2014, **79**, 2829.
26. For points-of-entry into the relevant literature

see: (a) J. Nugent, E. Matoušová and M. G. Banwell, *Eur. J. Org. Chem.*, 2015, 3771; (b) M. G. Banwell, J. Buckler, C. J. Jackson, P. Lan, X. Ma, E. Matoušová and J. Nugent J. – Devising New Syntheses of the Alkaloid Galanthamine, a Potent and Clinically Deployed Inhibitor of Acetylcholine Esterase in *Strategies and Tactics in Organic Synthesis* (Ed. M. Harmarta), 2015 **11**, 29.

27. J. N. Buckler, E. S. Taher and M. G. Banwell, unpublished observations.
28. S. V. Ley, D. K. Baeschlin, D. J. Dixon, A. C. Foster, S. J. Ince, H. W. M. Priepke and D. J. Reynolds, *Chem. Rev.*, 2001, **101**, 53.
29. For a relevant application of this process see M. G. Banwell, X. Ma, O. P. Karunaratne and A. C. Willis, *Aust. J. Chem.*, 2010, **63**, 1437.
30. (a) D. R. Boyd, N. D. Sharma, S. A. Barr, H. Dalton, J. Chima, G. Whited, R. Seemayer, *J. Am. Chem. Soc.*, 1994, **116**, 1147; (b) C. C. R. Allen, D. R. Boyd, H. Dalton, N. D. Sharma, I. Brannigan, N. A. Kerley, G. N. Sheldrake, S. C. Taylor, *J. Chem. Soc., Chem. Commun.*, 1995, 117.
31. For relevant background accounts see: (a) L. D. Kapoor, *Opium Poppy: Botany, Chemistry, and Pharmacology*, Food Products Press, New York, 1997; (b) M. Booth, *Opium: A History*, St. Martin's Press, New York, 1998.
32. J. W. Reed and T. Hudlicky, *Acc. Chem. Res.*, 2015, **48**, 674 and references cited therein.
33. (a) M. E. Kuehne and I. Marko, *The Alkaloids*, 1990, **37**, 77; (b) H. L. Pearce, *The Alkaloids*, 1990; **37**, 145; (c) N. Neuss and M. N. Neuss, *The Alkaloids*, 1990, **37**, 229.
34. J. E. Sears and D. L. Boger, *Acc. Chem. Res.*, 2015, **48**, 653.
35. M. G. Banwell, A. J. Edwards, D. W. Lupton and G. Whited, *Aust. J. Chem.*, 2005, **58**, 14.
36. L. V. White and M. G. Banwell, *J. Org. Chem.*, 2016, **81**, 1617.
37. M. G. Banwell, M. T. Jones and T. A. Reekie, *Chem. N. Z.*, 2011, **75**, 122.
38. M. G. Banwell, M. T. Jones, T. A. Reekie, B. D. Schwartz, S. H. Tan and L. V. White, *Org. Biomol. Chem.*, 2014, **12**, 7433.
39. S. R. Crabtree, W. L. A. Chu and L. N. Mander, *Synlett*, 1990, 169.
40. G. B. Bennett, W. J. Houlihan and R. B. Mason, *J. Organomet. Chem.*, 1975, **99**, 185.
41. For a recent and comprehensive review of the area, see P. Siengalewicz, J. Mulzer and U. Rinner, *Eur. J. Org. Chem.*, 2011, 7041.
42. (a) J. S. Yang, Y. L. Su, Y. L. Wang, X. Z. Feng, D. Q. Yu, and X. T. Liang, *Yaoxue Xuebao (Acta Phamaceutica Sinica)*, 1991, **26**, 117; (b) P. Cremin, D. M. X. Donnelly, J.-L. Wolfender and K. Hostettmann, *J. Chromatogr. A*, 1995, **710**, 273; (c) D. M. X. Donnelly, T. Konishi, O. Dunne and P. Cremin, *Phytochem.*, 1997, **44**, 1473.
43. C. L. Nord, A. Menkis, R. Vasaitis and A. Broberg, *Phytochem.*, 2013, **90**, 128.
44. C. L. Nord, A. Menkis, C. Lendel, R. Vasaitis and A. Broberg, *Phytochem.*, 2014, **102**, 197.
45. B. D. Schwartz, E. Matoušová, R. White, M. G. Banwell and A. C. Willis, *Org. Lett.*, 2013, **15**, 1934.
46. See, for example, M. G. Banwell, K. A. B. Austin and A. C. Willis, *Tetrahedron*, 2007, **63**, 6388.
47. For a review of this and related photochemically-promoted rearrangements see M. G. Banwell and D. J.-Y. D Bon, Applications of the Di-π-Methane and Related Rearrangement Reactions in Chemical Synthesis in *Molecular Rearrangements in Organic Synthesis* (Ed. C. M. Rojas), 2015, 261.
48. E. L. Chang, B. Bolte, P. Lan, A. C. Willis and M. G. Banwell, J. Org. Chem., 2016, **81**, 2078.
49. E. L. Chang, B. D. Schwartz, A. G. Draffan, M. G. Banwell and A. C. Willis, *Chem. Asian J.*, 2015, **10**, 427.
50. R. N. Muhammad, A. G. Draffan, M. G. Banwell, M. G. and A. C. Willis, *Synlett*, 2016, **27**, 61.
51. For useful reviews of this topic see (a) K. Tiefenbacher and J. Mulzer, *Angew. Chem. Int. Ed.*, 2008, **47**, 2548; (b) K. Palanichamy and K. P. Kaliappan, *Chem. Asian J.*, 2010, **5**, 668; (c) E. Martens and A. L. Deamin, *J. Antibiot.*, 2011, **64**, 705; (d) M. Saleem, H. Hussain, I. Ahmed, T. van Ree, and K. Krohn, *Nat. Prod. Rep.*, 2011, **28**, 1534; (e) A. M. Allahverdiyev, M. Bagirova, E. S. Abamor, S. C. Ates, R. C. Koc, M. Miralogu, S. Elcicek, S. Yaman and G. Unal, *Infect. Drug. Resist.* 2013, **6**, 99.
52. (a) R. E. W. Hancock, *Nat. Rev. Drug Discov.*, 2007, **6**, 28; (b) P. C. Appelbaum, *J. Antimicrob. Chemother.*, 2012, **67**, 2062; (c) S. Shapiro, *J. Antibiot.*, 2013, **66**, 371; (d) R. Tommasi, D. G.

Brown, G. K. Walkup, J. I. Manchester and A. A. Miller, *Nat. Rev. Drug Discov.*, 2015, **14**, 529.

Martin Banwell is a Professor of Chemistry in the Research School of Chemistry at the Australian National University. His research focus is on the total synthesis of biologically active natural products and his contributions in this area have formed the basis of his award of the 2014 Liversidge Lectureship and Medal.

Journal & Proceedings of the Royal Society of New South Wales, vol. 149, parts 1 & 2, 2016, pp. 51–58. ISSN 0035-9173/16/010051–08

The curious economist: William Stanley Jevons in Sydney

Address at the Dinner to Mark the Opening of the Exhibition at the Powerhouse Museum[1]

The late Ian Castles[2]

Former Australian Statistician, 28 October 2004

Abstract

In 2004, which marked the 150th anniversary of William Stanley Jevons' arrival in Sydney, the Powerhouse Museum mounted an exhibition on "Jevons: The Curious Economist." Jevons was born in Liverpool, in England. He studied chemistry in London, and came to New South Wales at the age of 19 to work at the Sydney Mint. The Gold Rush was in full swing, and his job was to assess the quality and purity of the precious metal from the diggings. This work put him in a unique position, at the intersection of geology, chemistry, economics and industry. Wanting to document as many aspects of life in Australia as he could, Jevons also took up photography, even taking his camera equipment to the goldfields. After five years in Sydney, Jevons returned to England, where he eventually became the first Professor of Economics at University College in London. He became a member of the N.S.W. Philosophical Society on 13 June 1856. He left Australia in April 1859. He drowned in 1882, aged 46.

At a dinner to celebrate the opening of the Exhibition, the late Ian Castles gave this address. Ian Castles (1935-2010) was an accomplished statistician and civil servant. He was Secretary of the Commonwealth Department of Finance (1979-1986), the Australian Statistician (1986-1994), and Visiting Fellow at A.N.U. between 1995 and 2000. He was Executive Director and Vice President of the Academy of the Social Sciences in Australia. His family has given permission for the *Journal* to publish the address, lightly edited by Robert Marks.

Introduction

I begin by congratulating the Powerhouse Museum and especially the exhibition curators — Matthew Connell and Lindsay Barrett — on the splendid exhibition we've had the privilege of viewing this evening. I'm sure that the curators would agree that they had in "the curious economist" an extraordinary subject upon which to focus.

My job tonight is to try and give some added context to the amazing story that began just 150 years ago when the teenage Stanley Jevons landed in this city. I'm

[1] http://www.powerhousemuseum.com/exhibitions/jevons.php

[2] Lightly edited, with references, by Robert Marks, 2016.

honoured that the Powerhouse has invited me to perform this task, and especially grateful in that, ten or twelve years ago, the Museum could only have seen me as a nagger and a nuisance.

My interest in persuading the Powerhouse to mount an exhibition on Jevons' years in Sydney dates back to a conference that I attended at the Reserve Bank in the early 1990s. I can't remember the subject of the conference, but I remember well that, during the luncheon break, I strolled southward along Macquarie Street with a visiting British economist. I pointed across the street to the fine building that formerly housed the Sydney branch of the Royal Mint, and remarked that that was where Jevons had spent the first four or five years of his working life.

My companion's initial reaction was one of disbelief. So we crossed the road and spent a few minutes in the building known as the Mint Museum, which at that time was part of the Powerhouse Museum. To my satisfaction, we were able to confirm immediately that Jevons had indeed worked at the Mint.

But to my consternation, and that of my economist colleague, the captions to the display revealed nothing about who Jevons was or what he had done. Let me quote:

> This room ... focuses on the lives of two Mint employees and social aspects of the gold rush era. [It] focuses on contrasting experiences of those years: life on the diggings and the experiences of two gentlemen who worked at the Mint, William Jevons and Robert Hunt...

This was true as far as it went, but my companion and I thought that visitors to the Mint Museum should have been told that "William Jevons" was later to become one of the founders of modern economics. And perhaps also that he pursued a remarkable range of interests in his Sydney years.

So strongly did I believe this that I wrote to the director of the Powerhouse Museum to suggest that the a museum of applied arts and sciences was missing an opportunity by not making a good deal more of the young Jevons' association with Sydney — and his contribution to the applied arts and sciences during his five years in this city. I had a polite response, and one or two useful meetings with people at the Powerhouse.

But, just at this stage, the Powerhouse Museum announced a major acquisition: the famous difference engine invented by Charles Babbage, commonly recognised as the forerunner to the modern computer. In discussions at the Powerhouse, I said that this was all very well, and that the engine was indeed an eminently appropriate artefact for a museum of applied arts and sciences. But Babbage had had no connection with Australia.

I argued that the Museum should take an interest in the fact that Jevons too had built a proto-computer. Moreover, unlike Babbage, the former resident of Sydney had done the whole thing at his own expense. And Jevons' machine was the first machine that could solve a complex logical problem faster than that problem could be solved without using the machine.

Then there was a further development. The Powerhouse Museum acquired Jevons' telescope — not just a telescope like the one Jevons used, but the instrument that he actually used. I was told, and of course I agreed, that one object directly relating to Jevons was not enough to build an exhibition around. The inscription on the telescope reveals that, not long after leaving Sydney, Jevons gave it to his cousin who was then in Penang in what is now Malaysia. It is not clear how or why this telescope found its way back to Australia.

The instrument is, I suggest, a deeply symbolic artefact. It encapsulates Jevons' passionate interest in the means and meaning of observation and measurement of the natural and the social world. It was through this telescope that the young Jevons --- whom we now know to have been Australia's first urban sociologist — first viewed an Australian city. The city was Melbourne, not Sydney. In a ship anchored off the port of Melbourne on 24 September 1854, Jevons confided to his journal that:

> the town is very curious; it looks like a crowd of ugly buildings of every size chiefly iron and wood arranged as if no two houses were in one street. There seem to be very few large buildings and these are as ugly as the rest, but we can make out by the telescope an Exhibition building, 2 or 3 churches ... [and] a railway station on the other side of the bay. (Black & Könekamp 1972, p. 109)

This would have been the just-completed collection of weatherboard train sheds on the site now occupied by Flinders Street station.

In Sydney, Jevons used the same little telescope to observe two eclipses of the sun in 1857. In an extended report written after the second of these events, he told the readers of Henry Parkes' newspaper, *The Empire*, that

> The first contact of the moon with the lower limb of the sun could be easily observed with the aid of an ordinary telescope, and seemed to take place within a few seconds after the time ... calculated by Mr. Tebbutt, of Windsor, my watch being regulated by the noon gun at Fort Philip. The coincidence would, no doubt, have been the more complete the more accurate the means of observation. (The Empire, 19 Sept. 1857, p.4)

"Mr. Tebbutt[3], of Windsor" was later to become the world-famous amateur astronomer who formerly appeared on the Australian $100 banknote. At this time, he was 23 years of age, one year older than Jevons. The report of the eclipse in *The Empire* on the day after the eclipse is quite an extended one, and Jevons' diary on the day that he wrote this report survives in the John Rylands library in Manchester.

Let me quote the entry for this day in the life of W. S. Jevons, a 22-year-old public servant:

> After sleepless night got up about 3.30 and started to Bellevue Hill in dark. About 5 a.m. commenced observations concerning eclipse. Returned to Mint [this was presumably where he wrote the report that was published on the following day]. Tea at Mr. Newton's [Mr.Newton was Chief Engineer at the Mint] and then to Victoria Theatre. Brooke and Mrs. Heir very good in Much Ado About Nothing.
> Nature books for Willy Newton 8/6 [presumably his host's son]. Whewell's Lect. on Political Economy 11/-.

On the facing page of the diary, the entry for the succeeding day (28 March 1857) reads:

> Played much music in evening [this would have been on the harmonium that appears in the photograph of his study at Double Bay, which appears in the exhibition]. Meteorological work, etc. Wrote and sent letter to Empire with aim

[3] Like Jevons, John Tebbutt Jr. was also a member of the Philosophical Society of N.S.W.

of shutting up writers about "Protective humbug"[4].

Jevons was a strong free-trader.

During Jevons' stay in Sydney, *The Empire* published many reports and letters authored by him, on subjects as diverse as meteorology; the land and railway policy of New South Wales; the resolutions passed at the protection meeting; "A Cure for the Revenue"; lead poison in the Sydney water; the danger from lightning strikes on the ammunition stores on Goat Island; a new sun-gauge[5]; the royal prerogative of mercy; the conflict between the archaelogical and Biblical accounts of the length of human existence on earth; and "New Facts Concerning the Interior of Australia".[6]

Many of Jevons' pieces in *The Empire* were quite combative. He acknowledged this in a letter to his cousin toward the end of his sojourn in Sydney (9 October 1858):

> I am becoming quite accustomed to the pen as a weapon of offence & defence, indeed I suffer under such a rage for writing that I am scarcely to be trusted with a pen in my hand. I often write a newspaper article and am then on thorns for ever so long after for fear of a libel action. But alas! my organ the 'Empire' has passed away in bankruptcy and I am now reduced to that milk & water affair the "Herald" which too has not yet learned to appreciate me, and sticks to small type, on the backpages, whereas Parkes always gave me large type next after the leading article, & usually reprinted me for the monthly summary. I send you the monthly summary of the Herald which is certainly a wonderful publication for a single day; the number of copies sold too is something enormous. You will find in it every scrap of colonial news... (Black 1973-1981, 2, pp. 345-346).

Some of these comments are somewhat unfair to the Herald, which had done Jevons proud by publishing his long and fascinating review of the first consolidated volume of the monthly Sydney Magazine of Science and Art, to which Jevons himself had made significant contributions.[7]

In the event, it has turned out to be for the best that the plans for an exhibition on Jevons in Sydney, including especially the Symposium, have come to fruition in 2004 rather than in 1994. Because, in the intervening ten years, Jevons' life and work in Sydney and afterwards has attracted unprecedented attention from researchers in a wide range of disciplines, both in Australia and overseas. At least a dozen peer-reviewed journals have published papers focusing solely or mainly on aspects of Jevons' work. The list of the names of the journals in which these studies have appeared testifies to the diversity of Jevons' interests, and of the continuing scholarly interest in Jevons:[8]

The History of Political Economy,
The History of Economics Review,
The Journal of the History of Economic Thought,
European Journal of the History of Economic Thought,
Economic Inquiry,

[4] See his letter to *The Empire* of March 30, 1857, listed below.

[5] Jevons' paper, "On a sun-gauge, or new actinometer," was presented at the Philosophical Society of N.S.W. on 8 July 1857.

[6] See the Reference list below for many of these, with links.

[7] *Sydney Morning Herald*, 27 Sept. 1858, p.8.

[8] Ian Castles did not specify which papers the following list refers to, but in the References below I have included possible papers — Ed.

Measurement in Physics and Economics Discussion Papers at the London School of Economics,
The History and Philosophy of Logic,
Australasian Music Research,
The Australian Meteorological Magazine,
The Journal of Physical Oceanography,
and
Scientific American.

I would like to be able to talk about the significance of some of this work, much of which has been produced by one or other of the distinguished scholars who are with us this evening and will be presenting papers at tomorrow's symposium.[9] But it would be beyond my capacity to do these scholars justice, and I can only urge those who may be able to come to the symposium to do so.

The primary source material for those who are engaged in research on Jevons consists, of course, of his own writings, published and unpublished. Only a small fraction of his writings in Australia appeared in print during his lifetime. In a volume published soon after his death, Jevons' widow published edited extracts from his personal journal and from many of the surviving letters (Jevons 1886). Much more extensive extracts of his papers and correspondence have been published in subsequent years.

Yet much of Jevons' Australian work remains unpublished. In a paper published as recently as 1999, the leading Jevons scholar Bert Mosselmans and a Belgian colleague (Mosselmans & Mathijs 1999) published extracts from a manuscript by Jevons – uncompleted but running to 50 pages – entitled "On the Science and Art of Music" which is located at the John Rylands Library at Manchester University. The work was written in Sydney and sent to Jevons' sister in London as each chapter was completed. The John Rylands Library[10] and the Public Library of New South Wales hold many letters and other manuscripts relating to Jevons' Australian years which have never been published.

It is a pity that much of Jevons' writings in Australia — whether published in contemporary journals and newspapers, intended for publication in Sydney or in Britain, or never intended for publication at all — is not now readily available. They are of value not only as a record of several formative years in Jevons' own development, but to those interested in the history of Sydney and of Australia at this time.

It is now possible for manuscript material to be "digitised", enabling it to be disseminated freely. This has the further advantage, by comparison with publication in hard copy, of providing the user access to interactive facilities for selective searching and retrieval of the contents.

So I am led to conclude with a suggestion. I'll introduce it by pointing out that, some thirty years ago, the Royal Economic Society felt justified in publishing hundreds of pages of letters and papers written by Jevons while in Australia, in the handsome seven-volume set edited by Professor Collison Black. It is fair to say that much of this material is of interest to Australian social historians but sheds little light upon the history of economic thought: this is true, for example, of the accounts of Jevons' journeys to the Hunter Valley and Maitland, [11] the Macquarie towns [12], the

[9] Mike White, Monash; Harro Maas, University of Amsterdam; Lindsay Barrett, University of Western Sydney; Geoff Barker, University of Sydney; Megan Martin, Historic Houses Trust NSW; Neville Nicholls, Bureau of Meteorology; Matthew Connell, Powerhouse Museum; Jamie Kassler, Australian Academy of Humanities; Ian Castles, A. N. U.

[10] http://www.library.manchester.ac.uk/search-resources/guide-to-special-collections/atoz/jevons-family-papers/

[11] Black & Könekamp 1972, pp. 123-130, 23 May 1856.

Illawarra district[13], Bathurst and Sofala[14], Braidwood and Araluen and the Victorian gold fields[15]. Ironically, this wealth of material is little known in Australia except among those who have been led to it by their interest in the life and work, especially the economic work, of Stanley Jevons.

With the advances of technology that have now occurred, the opportunity now arises to link all of the Australian-related Jevons material that is readily available in published sources with the as-yet unpublished letters, papers and photographs that are held in research libraries. The result would be an interactive product of considerable potential interest and value, and not only to scientists of all colours. The cost would not be small, but nor need it necessarily be prohibitive. If the exhibition that opens tomorrow stimulates as much interest in "the curious economist" in Sydney as I hope that it will, I believe that the publication of a consolidated archive in digitised form of the surviving record of Jevons' years in Sydney, published and unpublished, would be a worthy and imaginative project. It is something that the Powerhouse Museum and its supporters might wish to consider.

I am confident that such a project would attract international interest — and not only among research scholars but among people in many walks of life who find fascination in the development of an extraordinary mind — one of the minds of the century, as John Maynard Keynes wrote to Lytton Strachey in 1905, when Keynes was 22.

In the Preface to her book *A World Ruled by Number*, the first full-length study of the life and work of William Stanley Jevons, Dr. Margaret Schabas, now Professor of Philosophy at the University of British Columbia, wrote that she "had found, over the course of six or seven years, that my views on these subjects have changed considerably and that Jevons had an even richer set of insights than I had initially suspected... That the world is ruled by number may still be subject to dispute, but not the element of simplicity and beauty in Jevons's vision of mind and matter."

Thank you again for inviting me to speak this evening. I wish the Exhibition and the accompanying Symposium every success.

Primary Writings

Black, R. D. C. and Könekamp R. (ed.), (1972). *Papers and Correspondence of William Stanley Jevons. Volume I. Biography and Personal Journal.* London: Macmillan in association with the Royal Economic Society.

Black, R. D. C. (ed.), (1973-1981). *Papers and Correspondence of William Stanley Jevons.* Volumes 2□ 7. London: Macmillan in association with the Royal Economic Society.

Jevons, H. A. (ed.), (1886). *Letters and Journal of W. Stanley Jevons.* London: Macmillan.

Jevons, W. S. Protection, [a letter], *The Empire*, Sydney, 30 March, 1857, p.3 http://trove.nla.gov.au/newspaper/article/60273487

Jevons, W. S. Comparison of the land and railway policy of New South Wales, *The Empire*, Sydney, 8 April 1857, p.6 http://trove.nla.gov.au/newspaper/article/60276432

Jevons, W. S. On the resolutions passed at the Protection Meeting, [a letter]. *The Empire*, Sydney, 4 May 1857, p.3. http://trove.nla.gov.au/newspaper/article/60274810

Jevons, W. S. The public lands of New South Wales. *The Empire*, Sydney, 24 June 1857, p.4

[12] Black & Könekamp 1972, pp. 134-154, 24-28 December 1856.

[13] Black & Könekamp 1972, pp. 159-178, 9-13 April 1856.

[14] Black & Könekamp 1972, pp. 213-238, 9 March 1856.

[15] Three letters to his sister, Lucy Jevons, 13 and 16 March 1859 and 9 April 1859, reprinted in Black 1973-1981, 2, pp. 366-373.

http://trove.nla.gov.au/newspaper/article/64984880

Jevons, W. S. On a sun-gauge, or new actinometer. *The Empire*, Sydney, 14 July 1857, p.3 http://trove.nla.gov.au/newspaper/article/64985980

Jevons, W. S. The eclipse, *The Empire*, Sydney, 19 September 1857, p.4. http://trove.nla.gov.au/newspaper/article/60263467

Jevons, W. S. Lead poison in the Sydney water. [a letter]. *The Empire*, Sydney, 5 October 1857, p.5. http://trove.nla.gov.au/newspaper/article/60266124

Jevons, W. S. Gunpowder and lightning. [a letter]. *The Empire*, Sydney, 14 November 1857, p.3. http://trove.nla.gov.au/newspaper/article/60261514

Jevons, W. S. A cure for the Revenue. *The Empire*, Sydney, 14 April 1858, p.4. http://trove.nla.gov.au/newspaper/article/60427881

Jevons, W. S. The royal prerogative of mercy. *The Empire*, Sydney, 10 June 1858, p.3. http://trove.nla.gov.au/newspaper/article/60425807

Jevons, W. S. New facts concerning the interior of Australia. *The Empire*, Sydney, 10 August 1858, p.3. http://trove.nla.gov.au/newspaper/article/60424807

Jevons, W. S. Review of *The Sydney Magazine of Science and Art. Vol. I.* Sydney: James W. Waugh, 1858. *The Sydney Morining Herald*, 27 September 1858, p.8. http://trove.nla.gov.au/newspaper/article/13020816

Day & Day 1984 record that Jevons was admitted as a member of the Philosophical Society of N.S.W. at its second meeting, 13 June 1856.[16] He remained a member until he left the colony for England, in March, 1859.

[16] See also *The Empire* of 14 June 1856, p.3. http://trove.nla.gov.au/newspaper/article/60249242

References.

Bowman, Rhead S. (1997) Policy implications of W. S. Jevons's economic theory, *Journal of the History of Economic Thought*, 19, 02, 196-221. Day,

A. A. and Day, J. A. F. (1984). A biographical register of members of the Australian Philosophical Society (1850-55) and the Philosophical Society of New South Wales (1856-66). Part I. *Journal and Proceedings of the Royal Society of New South Wales*, 117: 119-127. http://biodiversitylibrary.org/page/46349357

Flatau, Paul (2004) Jevon's one great disciple: Wicksteed and the Jevonian revolution in the second generation, *History of Economics Review*, 40: 69-107, Summer.

Kassler, Jamie C. (1996) William Stanley Jevons: music and the mechanisation of logic. *Australasian Music Research*, 1.

Maas, Harro (1999) Mechanical rationality: Jevons and the making of economic man, *Studies in History and Philosophy of Science, Part A* 30 (4): 587-619.

McChesney, Fred S., Shughart, William F. II, and Haddock, David D. (2004) On the internal contradictions of the law of one price, *Economic Inquiry*, 42.4: 706-716.

Mosselmans, Bert (1998) William Stanley Jevons and the extent of meaning in logic and economics, *History and Philosophy of Logic*, 19, 2, 83-99, January.

Mosselmans, Bert and Mathijs, Ernest (1999) Jevon's music manuscript and the political economy of music, *History of Political Economy, suppl. Economic Engagements with Art*, 31: 121-156.

Nicholls, N (1998) William Stanley Jevons and the climate of Australia, *Australian Meteorological Magazine*, 47, pp. 285-93.

Owen, David (2010) The efficiency dilemma, *The New Yorker*, Dec. 20 & 27. http://www.newyorker.com/magazine/2010/12/20/the-efficiency-dilemma

Schabas, Margaret (1990) *A World Ruled by Number: William Stanley Jevons and the Rise of Mathematical Economics*, Princeton University Press.

Schabas, Margaret (1999) The economics of W. S. Jevons, *History of Political Economy*, 31.3: 604-605.

Schmitt, Raymond W. (1995) The salt finger experiments of Jevons (1857) and Rayleigh (1880), *The Journal of Physical Oceanography*, 25: 8-17, January 1995.

Steedman, Ian (1997) Jevon's Theory of Political Economy and the 'Marginalist Revolution,' *European Journal of the History of Economic Thought*, 4, 1, 43-65, Spring.

White, Michael V. (2006) Cultivated circles of the Empire: Bibliographical notes on W.S. Jevons's antipodean interlude (1854-1859), *History of Economics Review*, 43: 101-122.

Journal & Proceedings of the Royal Society of New South Wales, vol. 149, parts 1 & 2, 2016, pp. 59–64. ISSN 0035-9173/16/010059–06

William Stanley Jevons, Fellow of the Philosophical Society of New South Wales, 1856–1859

Robert E. Marks
Economics, University of N.S.W.
Email: robert.marks@gmail.com

Abstract

This paper attempts to accomplish three things: to report on Jevons' activities while in Sydney, specifically with the Philosophical Society; to argue that his activities in Sydney led directly to his work in economic theory and application on his return to England; and to underline Jevons' achievements in independently pioneering what is now known as "neo-classical" microeconomics, along with writers in France and Austria. It complements Castles' 2004 address (Castles, 2016).

Introduction

William Stanley Jevons was born in Liverpool on September 1, 1835. His father, Thomas Jevons, was an iron merchant and engineer who constructed one of the first iron boats. His maternal grandfather was the historian William Roscoe. Aged 16, he entered University College, London, and studied chemistry and botany. In 1853, before graduating, he accepted a well-paid post as assayer at the new Sydney Mint on Macquarie Street, possibly as a consequence of his father's business having collapsed. He arrived in Melbourne on September 24, 1854, and in Sydney soon after.

He threw himself into the intellectual life of the colony: he collected and studied local plants; he documented the geology of the Hawkesbury basin; he wrote the first study of Australasian weather patterns; he researched the formation of clouds; he made pioneering "social surveys" of Sydney and Goulburn; he debated the economics of railway construction and land allocation in the pages of the newspapers.[1]

It is recorded that Jevons attended meetings of the Philosophical Society on the following dates: 13 June 1856, 8 July 1857, and 9 December 1857, and later in the monthly *Sydney Magazine of Science and Arts*; photographs of his were included in a Photographic Exhibition of the Philosophical Society at the Australian Library on 19 December 1859, although he had left Australia months previously, returning to England via North America.

While in Sydney Jevons kept a detailed journal and diaries, and sent regular letters to his cousin, his sisters, his brother, and his father, describing the environment, his activities, his ideas, and innermost thoughts. These have since been published, first, by his widow, in 1886, and, then, in several volumes, by the Royal Economic Society, in 1973–81.

[1] He was not above sending the odd riddle to the papers: "Why ought the officers of the Mint to be prosecuted for treason? Because they are constantly engaged in carrying out a design upon the sovereign. — J. Jevons, Royal Mint." *Sydney Morning Herald*, 20 Jan. 1859, p. 5.

Consequently, we have a reasonable idea of the development of his intellectual life during his Sydney sojourn.

So what influence did his time in Sydney have on Jevons' thinking, and what role did it play in bringing his ideas to fruition? In fact, Jevons said later that nearly all his ideas came to him during the period he spent in Sydney. The new colonial city certainly gave him the time, the money and the intellectual freedom to undertake work in a wide range of areas: meteorology, photography, geography, geology, botany and natural science and a social survey of the city itself.

From Black (1973), we know that on June 25, 1854, he writes, "... though I have got a pretty complete set of common chemical Apparatus and chemicals, I feel as if I should take more to Geology & botany, though I don't at all intend to stick to Science above everything else all my life" (Black, p. 78). On October 31, 1855, he talks of intending to compile and send "Meteorological Reports to some paper" (Black, p. 198); the first such published report appeared in the *Empire* on 3 September 1856.

On July 19, 1856, the *Sydney Morning Herald* published his first letter on "the science of economy," about the need for profitability in railway construction (Black, pp. 235). This was in reaction to the Governor's declaration "that a railway need not necessarily be capable of paying any profits, since indirect benefits to the population may repay its costs." (Black, p. 265). Sir William Denison had been an officer in the Royal Engineers.

On October 21, 1856, Jevons writes that "a Scientific education is one of the best things possible ... It tends to give your opinions and thoughts a sort of *certainty*, *force*, and *clearness* which forms an excellent foundation for other sorts of knowledge less precisely determined and established" (Black, p. 244). Apart from his meteorological work, he was very interested in botany, music, and the theatre.

On April 4, 1857, Jevons writes "I have been much occupied lately with a new Subject viz, Political Economy, which seems to mostly suit my exact method of thought." (Black, p. 280). He had read Smith's *Wealth of Nations*, as well as more recent books, and had just published a letter in the *Empire* "on some questions of Economy here" (against protection) and followed that with a letter on the need for "wise regulations on the sale or distribution of unoccupied lands of the colony, and of a right policy in the formation of railways" (Black, pp. 282). On June 17, he writes "the subject I have been most of all concerned in for the last six months is Political Economy," having read books by Smith, Chambers, Martineau, Mill, Whately, and Chaning. (Black, p. 292).[2]

In a letter of February 28, 1858, Jevons expounds to his sister: "*Economy*, scientifically speaking, is a very contracted science; it is in fact a sort of vague mathematics which calculates the causes and effects of man's industry, and shows how it may best be applied. ... I have an idea ... that my insight into the foundations and nature of the knowledge of man is deeper than that of most men or writers ... To extend and perfect the abstract or the detailed and practical knowledge of man and society is perhaps the most useful and necessary work in which any one can now engage. There are plenty of people engaged with physical science, and practical science and arts may be left to look after themselves, but thoroughly to understand the principles of society appears to me now to be the most cogent business." (Black, pp. 321).

On June 9, 1858, he says: "Social science is the wide subject before me, and I have

[2] See also the Extracts from the Personal Diaries, R. D. C. Black (ed.), *Vol. VII*, 1981, pp. 115.

even had for many years the idea of a work on 'Towns & Cities,' to analyse their constitution, and causes, the relative character of their parts, & the relative character of particular cities & thus eventually lead to such knowledge of their nature & shall ensure their improvement, as any Scientific knowledge is eventually reduced to practice." (Black, pp. 327).

On August 4, 1858, Jevons says, "It seems to me that *Man* is a subject as little understood now as the Heavens (Astronomy) were by the Ancients. Within the last hundred years, sciences almost innumerable have sprung up, but mostly devoted to physical Nature. Comparatively few have perceived that Human Nature may also be the subject of a science. It is indeed a many-sided subject. Religion, metaphysics, ethics, jurisprudence, political economy, politics, & even, medicine, art, poetry and many other studies all have man for the subject. But the social condition of man as influenced by the many internal & external circumstances is perhaps an indefinite but a wide & rich field for future research." (Black, pp. 335).

In his penultimate letter from Sydney, on January 30, 1859, Jevons asks his sister, " ... does it not strike you that just as in Physical Science there are general & profound principles deducible from a great number of physical phenomena, so in treating of Man or Society there must also be general principles and laws which underlie all the present discussions & partial arguments? ... Man is said to possess *free* will but however this may be, he is at least a phenomenon in which effect is always connected with *cause*. All the investigations of Social Science must proceed on the assumption that there are causes as make people good & bad, happy & miserable, rich & poor, as well as strong & feeble. It follows that each individual man must be a creature of *cause & effect*. ... To attempt to define the foundations of our knowledge of man, is surely a work worth a lifetime ..."

He socialised with members of the Philosophical Society: on 13 July 1857 he spent the day "taking a bush walk with the old Rev. Mr. Clarke, the geologist, afterwards dining with him, & Mrs. Clarke, and the two Miss Clarkes." (Black, p. 298). It was, ironically, W. B. Clarke, who, as president of the Society, urged it in a direction away from Jevons' emerging interests: for the next century it focussed very much on the physical sciences, largely excluding economics and other social sciences.

So he returned to England, completed his B.A. and M.A. degrees, and was elected to a chair as the professor of logic and mental and moral philosophy and Cobden professor of political economy at Owens College, Manchester, in 1866. Meanwhile, in Australia he was remembered as the inventor of a sun gauge (1857), and the author of a contentious study of clouds (1857) and of The Climatology of Australasia (1859), as well as being a pioneering photographer (Bourke, 1955). Later, the newspapers reported his analysis of gold prices (1863), and his influential book on the effects of the exhaustion of British coal mines (1866). Australian newspapers were, however, almost mute on his advances in theoretical economics.

On the basis of entries in Jevons' diary for 1860, La Nauze (1953) states that "young Jevons arrived on one identifiable day, February 19, 1860, at a comprehension of the *true Theory of Economy*." This is less than twelve months after his leaving Sydney. In a letter to his brother, he says that his theory is "so thorough-going and consistent, that I cannot now read other books on the subject without indignation. ... One of the most important axioms is, that as the quantity of any commodity, for instance, plain food, which a man has to consume, increases, so the utility

or benefit derived from last portion used decreases in degree." (H. Jevons, 1886, p. 151). This is decreasing marginal utility, as we now know it.

Jevons wrote up his theory of value in a paper for the British Association for the Advancement of Science in 1862, which was printed in 1866. There was little recognition in Britain, given the sway of John Stuart Mills' ideas. In his 1871 book he described his theory in greater depth.

In establishing his utility theory, Jevons' training in science and measurement was very important. The quantities in the theory (quantities, prices) could be exactly measured, although its maximand, utility, was subjective. "A unit of pleasure or of pain is difficult even to conceive; but it is the amount of these feelings which is continually prompting us to buying and selling, borrowing and lending, labouring and resting, producing and consuming; and it is from the quantitative effects of the feelings that we must estimate their comparative amounts. We can no more know or measure gravity in its own nature than we can measure a feeling; but, just as we measure gravity by its effects in the motion of a pendulum, so we may estimate the equality or inequality of feelings by the decisions of the human mind." (Jevons, 1871, p. 11).

For Jevons, value was directly a function of utility. Perhaps I can illuminate how this notion was new in 1871 by an anecdote from 1961. I had just turned 15, the age in Victoria in those days when boys became men, at least as far as the barber was concerned: we were now, under the current price regulations, charged men's prices for our haircuts. I remember sitting in Mr. Merriman's chair and arguing with him that the prices should be reversed: cutting men's hair is easier than cutting boys' hair; men might begin to lose their hair as they age; the conversation with men is more interesting for the barber; and men sit still without wiggling. So men's haircuts should cost less, young Robert argued — in vain.

Turns out, although I didn't know it, that my argument was consistent with the classical theory of value (from before 1860), which states, roughly, that value, broadly speaking, derives from the labour used to produce the product, here the haircut: the cost to the barber of a man's haircut is less than a boy's, so the price charged should be lower.[3]

I had overlooked a development dating from Jevons' writings of the 1860s, in which he argued that the value (of the haircut) depends on the utility the customer associates with it. And men care more about their appearance than do boys, and moreover are able to pay more than boys can. So, on Jevons' theory of neoclassical value, men's haircuts should cost more than boys' do, so long as the barber is happy to cut at that price.

From his theory of utility and value, Jevons constructed a theory of exchange and a theory of labour supply and capital. Although he did not know it in 1862 or 1871, his utility theory was not the first, which he generously acknowledged in the preface to the second edition of his book (in 1879[4]). But many of his theoretical contributions, developed independently, were original, unassailable, and of great usefulness.[5]

Jevons' economic ideas continue to resonate. Two of his applied studies received much more attention at the time. His 1863

[3] My argument also echoed the "labour theory of value," used in Karl Marx's *Capital* (1867) in a misguided attempt to explain relative prices. Marx has been criticised for ignoring developments in economic theory, such as those of Jevons'.

[4] See http://oll.libertyfund.org/titles/jevons-the-theory-of-political-economy

[5] It must have been the *Zeitgeist*: two other men, Carl Menger (1840–1921), an Austrian, and Léon Walras (1834–1910), a Frenchman, published similar books in the 1870s. These three are the pioneers of the marginalist revolution of neo-classical microeconomics.

pamphlet on the price of gold made a remarkably accurate estimate of a 9 per cent fall in the value of gold between 1848 and 1860, a time when many gold mines had opened in California and Australia. In doing so, he virtually invented the technique for constructing price index numbers; John Maynard Keynes, a first-rate mathematician, stated that Jevons had "made as much progress in this brief pamphlet as has been made by all succeeding authors put together." (Keynes, 1936, p. 525.)[6]

In his influential 1865 book, *The Coal Question*, Jevons was pessimistic about Great Britain's future as its coal resources — the fuel of its industrial revolution — became economically exhausted. He argued that increased "economy" of coal use, by which he meant increased energy efficiency, would not delay this date. He concluded:

> It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth.

That is, he was arguing that increased energy efficiency "renders the employment of coal more profitable, and thus the present demand for coal is increased."

This is the so-called Jevons paradox: technological progress increases energy efficiency (reducing the amount necessary for any one use) but the rate of consumption of that fuel might rise because of the lower effective price and increased demand (the rebound effect). Which of these effects predominates continues to be a contentious issue, and the debate has even escaped from the pages of the learned journals. For instance, in 2010, an article in the *New Yorker* (Owen 2010) discussed the Jevons paradox, and there was a debate in the pages of the *New York Times* in 2012.[7] Castles (2016) overlooked this continuing influence of Jevons on economic thinking, 150 years after *Coal* was published.

In 1864 Jevons published a book based on George Boole's system of logic. In 1869 he built his "Logic Piano," a device for performing a function provided today by a truth table. He had essentially mechanized Boolean logic, a key aspect of contemporary computing; he was the first.[8] (Barrett and Connell, 2006). Later he became Professor of Economics at University College, London. In 1872 he became only the second economist to be elected as a Fellow of the Royal Society of London. His son, Herbert Stanley Jevons, published papers in this *Journal* in 1911 and 1912 on geology.

He was a true polymath. No other Fellow of our Royal Society or its antecedents (apart from Charles Darwin[9]) has had such an impact on the intellectual life of the world. Swimming in the English Channel on August 13, 1882, he drowned, aged 46. We should honour his memory.

Acknowledgements

I'd like to acknowledge assistance from Geoff Harcourt, Eve Wynhausen, Chris Adam, and Raja Junankar.

References

Anon., 2012, The siren song of energy efficiency, *The New York Times,* March 19.

[6] Indeed, according to Harrod (1951, pp. 106), the 22-year-old Keynes, on first reading Jevons' work wrote, "I am convinced that he was one of the minds of the century."

[7] Indeed, there are over 2,200 articles/books in Google Scholar that include the phrase "Jevons Paradox."

[8] The original Jevons' Logic Machine is held at the Museum for the History of Science, Oxford.

[9] Kelly (2009) includes a copy of a letter from Darwin of Oct. 28, 1879, accepting his honorary membership of the Royal Society.

Barrett, Lindsay, and Connell, Matthew, 2005, Jevons and the Logic 'Piano,' *The Rutherford Journal.* **1**, No. 1, December http://www.rutherfordjournal.org/article010103.html

Black, R. D. Collison (ed.), 1973, *Papers and Correspondence of William Stanley Jevons, Volume II, Correspondence, 1850–1862,* London: Macmillan, for the Royal Economic Society.

Bourke, Iris, 1955, Australia's first pictorialist, *Australian Photo Review,* pp. 6–23, Jan.

Castles, Ian, 2016, The curious economist: William Stanley Jevons in Sydney, *Journal and Proceedings of the Royal Society of N.S.W.*, this issue.

Harrod, Roy, *The life of John Maynard Keynes.* London: Macmillan. 1951.

Jevons, Harriet A. (ed.), 1886, *Letters and journal of W. Stanley Jevons,* London: Macmillan. https://archive.org/stream/lettersjournalof00jevoiala#page/n7/mode/2up

Jevons, William Stanley, 1859, The climatology of Australasia, nine chapters in *Waugh's Australian Almanac 1859.* Sydney: James William Waugh.

Jevons, William Stanley, 1863, *A serious fall in the value of gold ascertained, and its social effects set forth,* London: Edward Stanford. https://archive.org/stream/aseriousfallinv00jevogoog

Jevons, William Stanley, 1862, Notice of a general mathematical theory of political economy, presented to the British Association for the Advance of Science, Cambridge, October.

Jevons, William Stanley, 1866, Brief account of a general mathematical theory of political economy, *Journal of the Royal Statistical Society*, **29**: 282–87, June. http://la.utexas.edu/users/hcleaver/368/368jevonsmathecotable.pdf

Jevons, William Stanley, 1866, *The coal question: An inquiry concerning the progress of the national and the probable exhaustion of our coal-mines.* (2nd. ed.) London: Macmillan. http://www.econlib.org/library/YPDBooks/Jevons/jvnCQCover.html

Jevons, William Stanley, 1871, *The theory of political economy,* first edition, London: Macmillan.

Kelly, Jak, 2009, Editorial: A well known member, *Journal and Proceedings of the Royal Society of N.S.W.* **142**(1-2): 1–3.

Keynes, John Maynard, 1936, William Stanley Jevons, 1835–1882, a centenary allocution on his life and work as economist and statistician, *Journal of the Royal Statistical Society,* **99**: 516- 555.

La Nauze, John A., 1953, The concept of Jevons' utility theory, *Economica,* **20**: 356–8, Nov. Marx,

Karl, 1867, *Capital: critique of political economy, Vol. 1* (first English edition, 1886).

Owen, David, 2010, The efficiency dilemma, *The New Yorker*, Dec. 20 and 27. http://www.newyorker.com/magazine/2010/12/20/the-efficiency-dilemma

Vaughn, Kelly, 2012, Jevons paradox: the debate that just won't die, *RMI Outlet,* March 20. http://blog.rmi.org/blog_Jevons_Paradox

Journal & Proceedings of the Royal Society of New South Wales, vol. 149, parts 1 & 2, 2016, pp. 65–82. ISSN 0035-9173/16/010065–18

The evolutionary history of flowering plants

Charles S.P. Foster[1]

[1] School of Life and Environmental Sciences, University of Sydney, New South Wales 2006, Australia
This paper was an RSNSW Scholarship Winner in 2015

Email: charles.foster@sydney.edu.au

Abstract

In terms of species richness and important ecological roles, there are few biological groups that rival the success of flowering plants (Angiospermae). Angiosperm evolution has long been a topic of interest, with many attempts to clarify their phylogenetic relationships and timescale of evolution. However, despite this attention there remain many unsolved questions surrounding how and when flowers first appeared, and much of the angiosperm diversity remains to be quantified. Here, I review the evolutionary history of angiosperms, and how our understanding of this has changed over time. I begin by summarising the incredible morphological and genetic diversity of flowering plants, and the ways in which this can be studied using phylogenetic inference. I continue by discussing both the relationships between angiosperms and the other major lineages of seed plants, and the relationships between the main groups within angiosperms. In both cases, I outline how our knowledge has changed over time based on factors such as the different conclusions drawn from morphological and genetic data. I then discuss attempts to estimate the timescale of angiosperm evolution and the difficulties of doing so, including the apparent conflict between ages derived from fossil and molecular evidence. Finally, I propose future directions for angiosperm research to help clarify the evolutionary history of one of the most important groups of organisms on the planet.

Introduction

The diversity and interactions of life on Earth have long been of scientific interest. Quantifying biodiversity and the timescale over which it arose allows inferences about the biological history of the planet to be made, and can provide insight into how ecosystems might change in response to events such as climate change (Thuiller et al. 2011; Bellard et al. 2012). Flowering plants (angiosperms) have been of particular focus because of their important economic and cultural roles within society, as well as their ubiquity and importance within natural ecosystems. Specifically, angiosperms sequester large amounts of carbon from the atmosphere, and act as primary producers of food for many animal groups, with their spread and appearance shaping habitat structure globally (Brodribb and Feild 2010; Magallón 2014). In addition, angiosperms have developed important mutualistic relationships with many groups of organisms, such as pollination interactions with insects, birds, and small mammals (van der Niet and Johnson 2012; Rosas-Guerrero et al. 2014).

However, to properly quantify the extent and impact of groups such as angiosperms, biological entities must first be recognised and described into distinct groups such as species, and, ideally, placed into higher-order classifications. The goal is to

recognise groups that contain only the descendants of a common evolutionary ancestor (monophyletic groups), which represent natural evolutionary groups.

For most of history, biological groups and the relationships between them have been recognised through observations of the form and structure of organisms. When these data are shared between two or more taxa after being inherited from their most recent common ancestor, they are known as synapomorphies. In addition to aiding the classification of extant taxa, these morphological data are also able to link extant and extinct diversity through comparison with the fossil record, which can suggest a timescale of evolution. However, morphological data often cannot reliably distinguish between competing taxonomic hypotheses because of a lack of informative characters, or can be misled by the independent evolution of similar traits in organisms that are not closely related (convergent evolution). Morphological data have been supplemented by molecular data since the inception of molecular phylogenetics in the mid-20th Century.

Molecular data typically comprise sequences of the nucleotides of DNA, or the amino acids that they encode. Each nucleotide or amino acid within a sequence represents a character that can be used for phylogenetic analysis. Therefore, molecular data sets can contain millions of characters for phylogenetic reconstruction, which makes such data sets especially useful for evaluating the taxonomic hypotheses that have been suggested by morphology. Analysis of molecular data is also useful for estimating the evolutionary timescale of organisms using molecular clocks (Lee and Ho 2016), especially for groups with poor fossil records.

Both morphological and molecular data have been used extensively to evaluate the diversity of angiosperms. Angiosperms are among the most species-rich groups of organisms on the planet, and are by far the largest group of plants. The exact number of species is difficult to determine because of high amounts of taxonomic synonymy, and the fact that many species potentially remain to be discovered (Bebber et al. 2010; Pimm and Joppa 2015). Despite this, we can be fairly certain that there are at least 350,000 species of angiosperms, and probably *c.* 400,000 in total (Pimm and Joppa 2015). As expected in a group of this size, there is extreme variation in morphology, life history characteristics, and growth form. Angiosperms variously exist as herbaceous annuals, vines, lianas, shrubs or trees, and can be found growing in aquatic or terrestrial environments, or even growing on and/or parasitising other plants.

Similarly, there is large variation in genome size and content within angiosperms. For example, it is estimated that throughout their evolutionary history over 70% of angiosperms have had an increase in the number of copies of chromosomes contained within each cell (ploidy level) from the typical diploid state (Levin 2002). Most of the functions essential for growth and development are controlled by genes located within the cell nucleus, which are collectively known as the nuclear genome. *Paris japonica* Franch., a small herbaceous plant native to Japan, has the largest accurately measured genome known to science (Pellicer et al. 2010). At nearly 150 billion nucleotides, its octoploid genome is more than 50 times larger than the human genome, and nearly 2500 times larger than the smallest known plant nuclear genome of *Genlisea tuberosa* Rivadavia, Gonella & A.Fleischm., a carnivorous angiosperm from Brazil (Fleischmann et al. 2014).

Plant cells also contain specialised organelles known as chloroplasts and

mitochondria, which are responsible for the essential processes of photosynthesis and cellular respiration, respectively. Both of these organelles are predominantly uniparentally inherited and contain their own independent genomes, which is thought to be because of their origins as free-living organisms that were engulfed by early eukaryotic cells in separate endosymbiotic events (Sagan 1967; Schwartz and Dayhoff 1978). The chloroplast genome varies substantially among angiosperms, with the order of genes differing between groups, and with some genes being lost completely. For example, the chloroplast genome is drastically reduced in many parasitic plants, with many genes important for photosynthesis having been lost (Bungard 2004).

The mitochondrial genome of plants is more enigmatic, and is disproportionally less studied than the nuclear and chloroplast genomes. Plant mitochondrial genomes are large compared with animal mitochondrial genomes, and their content is highly dynamic, with many gene gains, losses, transfers, duplications and rearrangements, as well as a large proportion of repeated elements and introns (Kitazaki and Kubo 2010; Galtier 2011). Of direct importance for reconstructing the evolutionary history of plants is that the three genomes evolve at very different rates. The nuclear genome evolves at the highest rate, the chloroplast genome evolves at an intermediate rate, and, in contrast to its dynamic nature, the mitochondrial genome has by far the lowest evolutionary rate (Wolfe et al. 1987).

The global dominance of angiosperms indicates that they are ideally adapted to exist within many different habitats, and their great morphological and genomic variation suggests a history of varied selective pressures. This has long challenged those who have sought to quantify how such a diverse group arose over a supposedly short period of time. Indeed, the traditional view is that angiosperms originated in the early Cretaceous. The subsequent appearance of fossils with highly diverse morphologies, over what was apparently an extremely rapid timescale, was famously described by Darwin as an "abominable mystery" in a letter to Joseph Hooker in 1879 (first published in Darwin and Seward 1903).

To understand fully the evolutionary history of angiosperms, their diversity needs to be characterised in a phylogenetic context. This approach indicates whether key traits for success are clade-specific, or have evolved multiple times in parallel. Additionally, incorporating temporal information into these analyses can allow inferences to be made about the environmental conditions that might have driven angiosperm diversification.

In this review, I begin by discussing our understanding of the relationships among the major seed plant lineages, and the importance of this for reconstructing the origin of flowers. I then discuss the relationships of the major lineages within Angiospermae, and examine estimates of the evolutionary timescale of angiosperms. I propose a number of the future directions that are likely to improve our understanding of the evolutionary history of angiosperms.

Higher relationships of angiosperms and the origin of flowers

Angiosperms are recognised as members of the superdivision Spermatophyta along with cycads, conifers, gnetophytes, and *Ginkgo*. The last four extant cone-bearing lineages are known as acrogymnosperms, whereas extant and extinct cone-bearing lineages combined are known as gymnosperms (Cantino et al. 2007). The five extant spermatophyte lineages are linked by the production of

seeds. Estimates of the number of seed plant species vary, but are consistently in the region of many hundred thousand species (Govaerts 2001; Scotland and Wortley 2003). Among other potential factors, the success of these lineages is perhaps due to the diversification of regulatory genes important for seed and floral development following ancient whole-genome duplication events along the lineages leading to seed plants and angiosperms (Jiao et al. 2011).

Angiosperms can be readily distinguished from gymnosperms through a suite of synapomorphies. These include the presence of flowers with at least one carpel, which develop into fruit (cf. the "naked" seeds of gymnosperms); stamens with two pairs of pollen sacs (cf. the larger, heavier corresponding organs of gymnosperms); a range of features of gametophyte structure and development, including drastically reduced male and female gametophytes compared with gymnosperms; and phloem tissue with sieve tubes and companion cells (cf. sieve cells without companion cells in gymnosperms) (Doyle and Donoghue 1986; Soltis and Soltis 2004). The production of endosperm through double fertilisation was previously considered to be a further synapomorphy of angiosperms, but this phenomenon has also been observed in some gnetophyte lineages (Friedman 1992; Carmichael and Friedman 1996).

Collectively, the synapomorphies of angiosperms are thought to be responsible for providing the evolutionary advantages that led to their global dominance, which coincided with a decline in gymnosperm diversity (Bond 1989). However, to reconstruct the evolution of these characters and evaluate their importance for angiosperm evolution, it is necessary to determine which lineage of seed plants is most closely related to angiosperms. The majority of earlier studies focused on evaluating the seed plant phylogeny, including determining the sister lineage to angiosperms, using comparative morphology to assess homology of the reproductive and vegetative structures of the seed plant lineages (e.g., Doyle and Donoghue 1986).

One major hope was that determining the sister lineage to angiosperms might prove especially useful for inferring the origin and structure of the first flowers. Throughout the 20th century, the two main hypotheses for the origin of flowers were that they evolved from branched, unisexual reproductive structures found in most gymnosperms ("pseudanthial" theory, Wettstein 1907), or that flowers evolved from bisexual, flower-like structures, such as in the extinct group Bennettitales ("euanthial" theory, Arber and Parkin 1907). The inferred homology of morphological structures consistently suggested that gnetophytes were the extant sister lineage to angiosperms, with several potential close (non-angiosperm) fossil relatives. Specifically, various features of wood anatomy and flower-like structures seemed to suggest a close relationship between angiosperms, gnetophytes, and the extinct order Bennettitales, with this group being the sister lineage to the rest of the gymnosperms (Crane 1985; Doyle and Donoghue 1986). Therefore, based on the strength of morphological evidence, the euanthial theory was the most popular view in the 20th Century.

The acceptance of the euanthial theory, coupled with the predominance of Cretaceous *Magnolia*-like fossils at the time, led to suggestions that the ancestral flowers were similar to present-day magnolias. This implies that magnolias and their close relatives were some of the earliest-diverging angiosperm lineages (Endress 1987). However, most molecular phylogenetic studies from the 1990s onwards have

recovered different relationships between the extant seed plant lineages. The dominant theme in these modern studies is that all extant gymnosperm lineages form a monophyletic sister group to angiosperms (Chaw et al. 1997; Bowe et al. 2000; Chaw et al. 2000; Ruhfel et al. 2014; Wickett et al. 2014) (Figure 1). Particularly strong evidence has emerged for a close relationship between gnetophytes and conifers (Qiu et al. 1999; Winter et al. 1999). Indeed, the evidence seems to suggest that gnetophytes might even be nested within conifers and the sister group to Pinaceae (Bowe et al. 2000; Chaw et al. 2000; Zhong et al. 2010).

Overall, because none of the extant gymnosperm lineages is more closely related to angiosperms than to other gymnosperms, they cannot directly inform hypotheses on the homologies of angiosperm characters, or on the sequence of development of these characters (Doyle 2012). Therefore, while the relationships among the major seed plant lineages have been largely resolved, the structural origin of flowers, and the affinity of the earliest flowers to modern species, remains controversial. Progress in this area is likely to be achieved through improved understanding of the relationships among the major angiosperm groups.

Major relationships within Angiospermae

The major relationships within angiosperms have historically proved difficult to determine, and have long been in a state of flux. This has largely been due to differing ideas of the characters, initially morphological but later molecular, needed to reconstruct the angiosperm phylogeny. An early discovery was that flowering plants have either one or two embryonic leaves (Ray 1686–1704). While John Ray was the first to observe this dichotomy, he later followed Marcello Malpighi in referring to these leaves as 'cotyledons'. Accordingly, flowering plants with one cotyledon have subsequently been referred to as monocotyledons or 'monocots', and those with two cotyledons have been called dicotyledons or 'dicots'.

Although the most widely known early classification scheme by Linnaeus was based solely on floral reproductive characters, the division into monocots and dicots has since been recognised as an important diagnostic feature to inform classification, with varying implications for the angiosperm phylogeny. A minority of early authors argued that some key morphological differences between monocots and dicots, such as vascular bundle anatomy, were irreconcilable with a monophyletic origin of angiosperms. Instead, these authors argued that angiosperms should be recognised as a polyphyletic group (= derived from more than one common evolutionary ancestor) (e.g., Meeuse 1972; Krassilov 1977). However, the predominant view was that angiosperms are monophyletic, and the division into monocots and dicots constitutes a natural split within flowering plants. This was echoed in many angiosperm classification systems developed in the 20th century, including the highly influential Takhtajan (1980) and Cronquist (1981) systems.

To infer the evolutionary relationships within monocots and dicots, many cladistic analyses were undertaken in the latter half of the 20th century using pollen, floral, and vegetative characters. This approach led to many informal subgroups being proposed. For example, Donoghue and Doyle (1989b) recognised five major groups of angiosperms, corresponding to Magnoliales, Laurales, Winteraceae-like plants, 'paleoherbs' ('primitive' herbaceous lineages including water lilies and *Amborella*), and

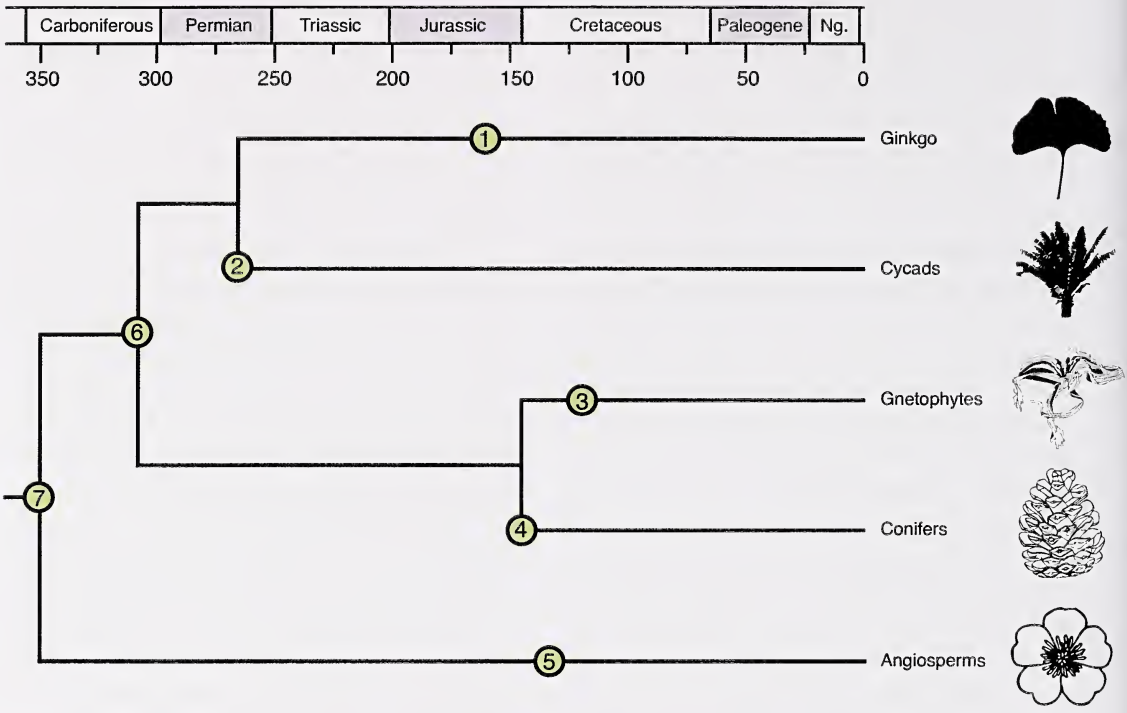


Figure 1: The relationships among seed plant lineages, scaled to geological time based on fossil ages. Numbers in green circles refer to the following: (1) oldest *Ginkgo* fossil (Yang et al. 2008); (2) oldest cycad fossil (Gao and Thomas 1989); (3) oldest gnetophyte fossil (Rydin et al. 2006); (4) oldest conifer fossils (Wieland 1935); (5) oldest angiosperm fossils (discussed in Doyle 2012); (6) oldest acrogymnosperm fossil ; (7) an estimated maximum age for crown-group seed plants (discussed in Magallón and Castillo 2009; Foster et al. 2016).

plants with tricolpate pollen. Although the constituent members of the subgroups varied across studies, the recognition of tricolpates as a monophyletic group was a consistent finding (e.g., Donoghue and Doyle 1989b; Donoghue and Doyle 1989a), leading to suggestions that dicots had multiple evolutionary origins (Endress et al. 2000; Endress 2002). Indeed, stratigraphical studies in which triaperturate pollen (tricolpate) fossils were consistently found to originate in younger sediments than both monocots and non-tricolpate dicots had already hinted that dicots did not form a monophyletic group (Doyle 1969). Consequently, Doyle and Hotton (1991) chose to recognise tricolpates as distinct from the rest of the dicots, coining the term 'eudicots' for this group.

Taxonomic concepts for the major angiosperm groups have changed over time, which makes it difficult to chronicle concisely the changing opinions about the earliest-diverging angiosperms. For example, the group Magnoliidae now has a very different circumscription compared with the past, so statements in earlier studies regarding the relationships between

magnoliids and other groups might no longer be applicable. Nevertheless, it is clear that the most common view historically was that *Magnolia*-like flowers probably occupied a position at or near the root of the angiosperm phylogeny. However, there were other suggestions for the earliest-diverging angiosperm lineages, including Piperales+Chloranthales, several of the lineages in the formerly recognised paleoherb group, or even monocots (Burger 1977, 1981).

Attempts to clarify the relationships within the angiosperm phylogeny have since been greatly strengthened by the inclusion of molecular data. Some aspects of early classification schemes based on morphology have been strongly supported by molecular data (reviewed by Endress et al. 2000; Endress 2002). For example, the key concepts of the monophyly of angiosperms, monocots and eudicots, the polyphyly of dicots, and the position of magnoliids as an early diverging angiosperm lineage, were all further supported by molecular data (Endress et al. 2000). However, many molecular estimates of angiosperm evolutionary relationships have contradicted estimates based on morphological data. For example, molecular data have firmly resolved the family Hydatellaceae within Nymphaeales, rather than within Poales as former morphology-based studies had concluded (Saarela et al. 2007). Molecular data have also helped to clarify the extent of convergent evolution within angiosperms, such as C_4 photosynthesis evolving independently at least 60 times (Sage et al. 2011).

Arguably the most important finding from analyses of molecular data has been the rooting of the angiosperm phylogeny. Success was not immediate, with disagreements being found among the results of molecular analyses, depending on the choice of molecular markers. An influential early attempt with molecular data to resolve the seed plant phylogeny and, necessarily, to determine the earliest-diverging angiosperm lineage, analysed sequences for the chloroplast *rbc*L gene from nearly 500 seed plant taxa using maximum parsimony (Chase et al. 1993). In this case, the widespread aquatic genus *Ceratophyllum* was found to be the sister lineage to all other flowering plants. However, this has subsequently been found to be an anomalous result seemingly unique to single-gene parsimony analyses of *rbc*L. A series of studies in 1999 found that the monotypic genus *Amborella* is strongly supported as being the sister lineage to all other flowering plants (Mathews and Donoghue 1999; Parkinson et al. 1999; Qiu et al. 1999; Soltis et al. 1999), and this finding has subsequently been supported by nearly all large multigene analyses (Moore et al. 2007; Soltis et al. 2011; but see Goremykin et al. 2013; Ruhfel et al. 2014; Wickett et al. 2014; Xi et al. 2014; Goremykin et al. 2015). These studies have also revealed that the base of the angiosperm phylogeny constitutes a grade of several successive lineages, originally referred to as the ANITA (*Amborella*/Nymphaeales/Illiciaceae-Trimeniaceae-*Austrobaileya*) grade, but now known as the ANA (*Amborella*/Nymphaeales/Austobaileyales) grade.

The remaining ~99.95% of angiosperms are collectively referred to as Mesangiospermae. Within this group, five major lineages are recognised: Chloranthales, Magnoliidae, Ceratophyllales, monocots, and eudicots (clade names here are standardised to Cantino et al. 2007). Unfortunately, despite large increases in the amount of available genetic data and improved analytical techniques, the relationships among these mesangiosperm groups have remained uncertain (Figure 2). When analysing

chloroplast genome sequences, the most common finding is that eudicots +*Ceratophyllum* form the sister group to monocots, with these three lineages being the sister group to magnoliids +Chloranthales. Large nuclear DNA data sets, which have only become available in recent years, tend to resolve different relationships. For example, they have supported a sister relationship between eudicots and magnoliids+Chloranthales, with monocots being the sister group to these three lineages (Wickett et al. 2014). However, the number and choice of nuclear DNA markers can affect inferred relationships within Mesangiospermae. For example, analysis of a selection of 59 low-copy nuclear genes inferred a grouping of *Ceratophyllum*+Chloranthales and eudicots, with successive sister relationships to magnoliids and monocots (Zeng et al. 2014). Additionally, the choice of phylogeny reconstruction method can lead to the estimation of different topologies (Xi et al. 2014).

Nevertheless, despite conflicting topologies sometimes being inferred, we currently have an understanding of the angiosperm phylogeny that is greater than at any other time in history. The power of molecular data to resolve the historically challenging relationships among flowering plants is now well established. In response to the rapid advances in the field, a cosmopolitan consortium of researchers regularly collaborate to release timely summaries of the state of knowledge of the angiosperm phylogeny (see Angiosperm Phylogeny Group 1998, 2003, 2009, 2016). We now have a viable framework to allow fields related to phylogenetics to flourish and provide a greater understanding of the important evolutionary steps that have contributed to the overwhelming success of angiosperms, such as through evolutionary developmental biology (evo-devo) studies (Preston and Hileman 2009). However, to gain a fuller understanding of the evolutionary history of angiosperms, it is necessary to know more than just the relationships among the major flowering plant groups; a reliable estimate of the angiosperm evolutionary timescale is also needed.

Evolutionary timescale of angiosperms

To understand how angiosperms came to dominance, including how the crucial morphological traits that led to their success first evolved, it is necessary to have some idea of the timescale of angiosperm evolution. Traditionally, the evolutionary timescale of organisms has been elucidated through study of the fossil record. In this approach, the first appearance of each taxon in the fossil record, as determined by morphology, provides an indication of when it first evolved. When considering the fossil record, it is important to distinguish between "crown" and "stem" groups. A crown group is the *least* inclusive monophyletic group that contains all extant members of a clade, as well as any extinct lineages that diverged after the most recent common ancestor of the clade (Magallón and Sanderson, 2001). In contrast, a stem group is the *most* inclusive monophyletic group that contains all extant members of a clade, as well as any extinct lineages that diverged from the lineage leading to the crown group (Magallón and Sanderson, 2001).

The fossil record of seed plants is ancient, with the oldest fossils of progymnosperms occurring in sediments from the Late Devonian, ~365 million years ago (Ma) (Fairon-Demaret and Scheckler 1987; Rothwell et al. 1989; Fairon-Demaret 1996).The fossil record of gymnosperms

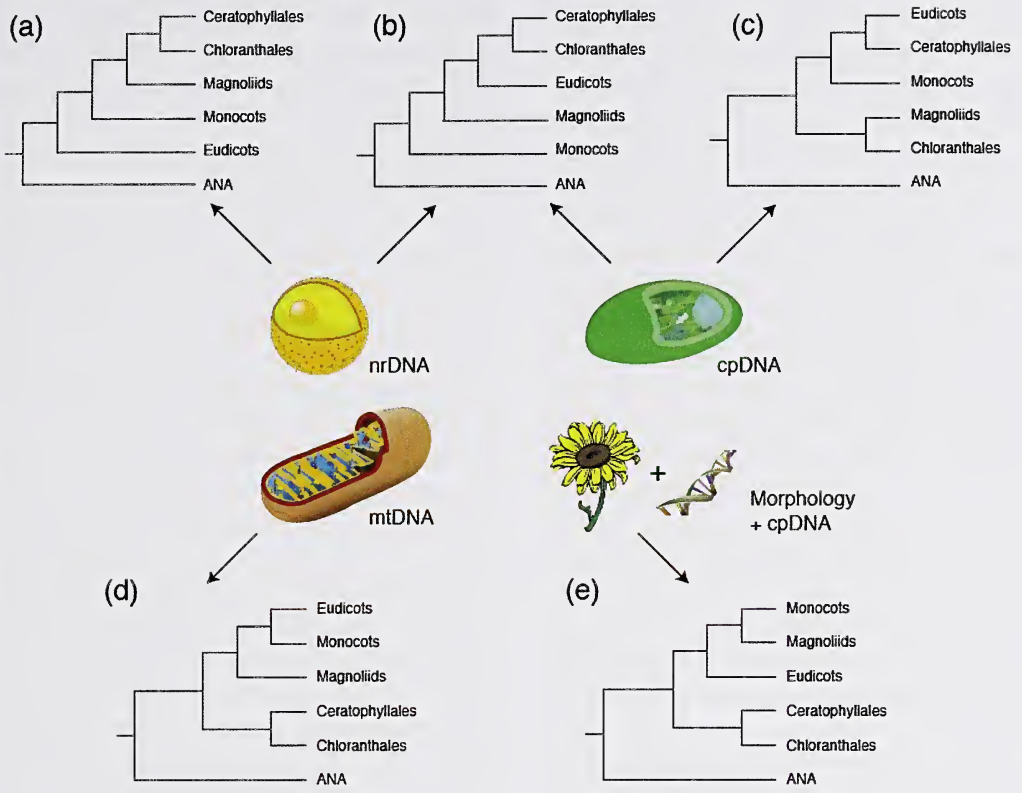


Figure 2: A comparison of several different estimates of the relationships among eudicots, magnoliids, monocots, Ceratophyllum, Chloranthales, and ANA-grade angiosperms, based on the comparison presented in Zeng et al. (2014). The different topologies represent findings from studies using nuclear DNA (nrDNA), chloroplast DNA (cpDNA), mitochondrial DNA (mtDNA), and a combination of morphological and molecular data. A sample of suitable references for the topologies are as follows: (a) Zhang et al. (2012); (b) Moore et al. (2011); Zeng et al. (2014); (c) Moore et al. (2007); Moore et al. (2010); Foster et al. (2016); (d) Qiu et al. (2010); (e) Endress and Doyle (2009).

is rich, with fossils becoming common from the Late Carboniferous to Early Triassic (Magallón 2014), and revealing an extinct diversity far greater than the extant diversity.

The oldest known fossil that can be confidently assigned to the stem group of angiosperms has suggested that angiosperms arose as early as 247.2–242.0 Ma (million years ago) (Hochuli and Feist-Burkhardt 2013). Accepted pollen fossils (microfossils) suggest that crown-group angiosperms first appeared in the Valanginian to early Hauterivian (early Cretaceous, ~139.8–129.4 Ma), albeit in sparse amounts, with vast amounts of angiospermous microfossils occurring by the Barremian (~129.4–125 Ma) (Doyle 2012). There is a noticeable disparity in the number and presence of

Unfortunately,, the fossil record of angiosperms is not as extensive or informative.

fossils between lineages, particularly at the family level and below, with many excellent fossils being present for some groups but none for others (Magallón 2014).

While fossil data have traditionally provided the only source of information about the evolutionary timescale of major groups, molecular dating techniques provide a compelling alternative, especially for groups that lack fossils. In these approaches, evolutionary timescales can be estimated using phylogenetic methods based on molecular clocks. When the concept of the molecular clock was first proposed, evolutionary change was assumed to correlate linearly with time and to remain constant across lineages ("strict" molecular clock) (Zuckerkandl and Pauling 1962). However, it has since become clear that strictly clocklike evolution is the exception, rather than the rule (Welch and Bromham 2005).

Rates of molecular evolution vary substantially across vascular plant lineages (Soltis et al. 2002), and are often strongly correlated with life history strategies. For example, substitution rates in herbaceous annual lineages of angiosperms are known to be substantially higher than in woody perennial plants (Smith and Donoghue 2008; Lanfear et al. 2013). Consequently, a variety of molecular clock models have been developed to account for evolutionary rate variation among lineages (Ho and Duchêne 2014). Fossil data are still intricately linked with these methods, because fossils are used to provide temporal information to calibrate the molecular clock, thereby providing absolute rather than relative ages of nodes. For example, in Bayesian analyses, temporal information is incorporated through calibrations priors, which can take the form of a variety of probability distributions (Ho and Phillips 2009). In the absence of fossils for a particular group being studied, biogeographic events and rate estimates from other groups can be used as calibrations, but these are subject to a wide range of errors (Ho et al. 2015).

Collectively, molecular dating studies have yielded remarkably disparate estimates for the age of crown-group angiosperms (summarised in Bell et al. 2010; Magallón 2014; Foster et al. 2016). Inferred ages have ranged from the extreme values of 86 Ma (when considering only the 3rd codon positions of *rbc*L; Sanderson and Doyle 2001) to 332.6 Ma (Soltis et al. 2002). Most age estimates fall between 140 and 240 Ma, but this still represents a substantial amount of variation. Additionally, the earliest analyses found that crown-group angiosperms were considerably older than implied by the fossil record, in some cases by more than 100 million years (e.g. Martin et al. 1989). Smaller disparities between molecular and fossil estimates were obtained in later studies (e.g. Sanderson and Doyle 2001). However, some more recent estimates have tended to support a more protracted timescale for angiosperm evolution (e.g. Smith et al. 2010), echoing the results of the earliest molecular studies.

Progress in molecular dating can be characterised in terms of increasing methodological complexity and improving sampling of taxa and genes (Ho 2014). A persistent problem, however, has been the need for a trade-off between taxon sampling and gene sampling. Low gene sampling has been typical of studies of angiosperm evolution, albeit with some other exceptions, including the 12 mitochondrial genes analysed by Laroche et al. (1995), 58 chloroplast genes analysed by Goremykin et al. (1997), 61 chloroplast genes analysed by Moore et al. (2007), and the 83 chloroplast genes analysed by Moore et al. (2010). However, most of these studies had sparse angiosperm taxon sampling. Among the few

other studies that have included more than 50 taxa, the largest number of genes sampled was five. The largest taxon samples have been those of Zanne et al. (2014), which used a staggering 32,223 species, and Magallón et al. (2015), which included 792 angiosperm taxa and one of the largest samples of fossil calibration points ever used. An exception to the above trade-off between taxon and gene sampling is the study by Foster et al. (2016), which analysed 76 chloroplast genes from 193 angiosperm taxa.

The most controversial aspect of angiosperm molecular dating studies has been an apparent incongruence between molecular estimates and those extrapolated purely from fossil occurrence data. Many modern molecular dating estimates without strongly informative temporal calibrations tend to suggest that angiosperms arose in the early to mid-Triassic (Figure 3) (Foster et al. 2016), which implies a considerable gap in the fossil record (Doyle 2012). This contradicts the claim that the evolutionary history of crown-group angiosperms is well represented in the fossil record (Magallón 2014), despite several lines of evidence supporting this suggestion: the gradual increase in abundance, diversity, and distribution of fossil angiosperms; the ordered progression of both morphological and functional diversification; and the agreement between the stratigraphic record and molecular data in the sequential appearance of angiosperm lineages.

If the fault lies instead with the molecular estimates, then it has been suggested that the substantial disparity between molecular and fossil-based estimates of the age of crown angiosperms might be a result of the choices of molecular markers, taxa, calibrations, or models of rate variation (Magallón 2014). Particular blame has been placed on the inability of molecular dating methods to account properly for non-representative sampling of angiosperms and life history-associated rate heterogeneity (Beaulieu et al. 2015). However, comprehensive investigations of the impact of models, priors, and gene sampling on Bayesian estimates of the angiosperm evolutionary timescale, using a genome-scale data set and numerous, widely distributed fossil calibrations, have still yielded remarkably robust estimates of a Triassic origin of angiosperms (Foster et al. 2016). This implies a long period of no angiosperm fossilisation, or that fossils of this age simply remain to be discovered (but see Wang et al2007; Gang et al. 2016).

Despite the disparate estimates for the origin of crown-group angiosperms, the timescale of evolution within this group is beginning to be understood with increased precision. Of particular note is that estimates for the origin of most modern angiosperm orders seem to be consistent regardless of the age inferred for the angiosperm crown group (Magallón et al. 2015; Foster et al. 2016). Ordinal diversification is most commonly estimated to have begun in the early Cretaceous, and is concentrated predominantly from this time through to the mid-Cretaceous (Magallón et al. 2015; Foster et al. 2016). Modern angiosperm families are estimated to have originated steadily from the early Cretaceous, with the peak of family genesis occurring from the late Cretaceous to the early Paleogene (Magallón et al. 2015) During this time, the supercontinent Pangaea largely completed its breakup into the continents of the present day. Concurrently, there were dramatic shifts in climate, with global temperatures and CO_2 levels far higher than in the present day (Hay and Floegel 2012). These changes, particularly in temperature, would have had significant impacts on the levels and efficiency of.

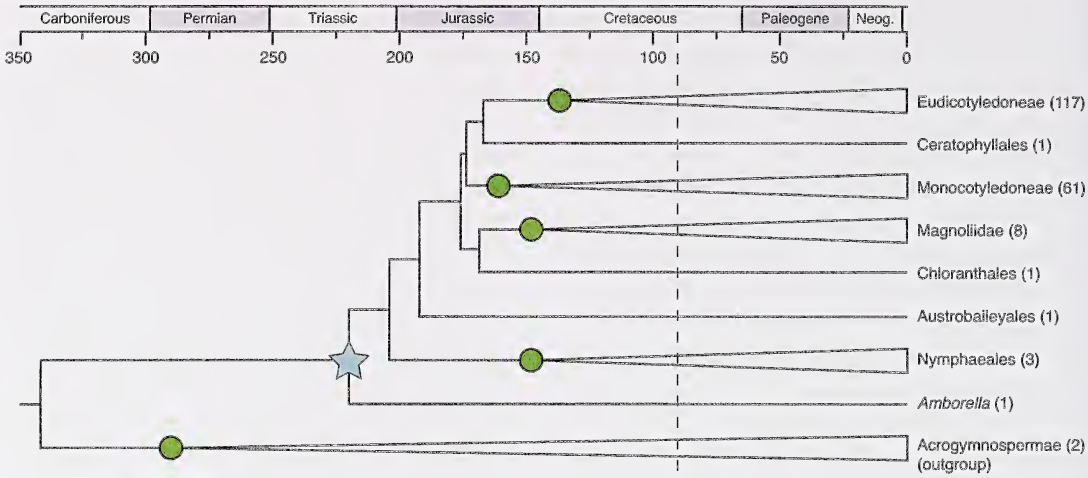


Figure 3: A recent estimate of the angiosperm evolutionary timescale, modified from Foster et al. (2016). Numbers in parentheses after taxon names refer to the number of taxa included from those groups in the study. Green circles indicate estimates of the crown age for lineages when more than one taxon has been included, and the blue star indicates the inferred age for the origin of crown-group angiosperms. The dashed line indicates the time by which all modern orders were inferred to have arisen.

photosynthesis (Ellis 2010; Hay and Floegel 2012). Selective pressures would have been high, ultimately influencing the evolution of angiosperms and, presumably, other taxa that interacted with them.

Concluding remarks and future directions

The substantial diversity and global dominance of flowering plants have puzzled and intrigued many researchers throughout history. The classification of angiosperms has long proved difficult because of the monumental size and such varied morphologies within this group. Subsequently, the key evolutionary innovations that first occurred to produce flowers, as well as the reasons for the overwhelming success of angiosperms, have historically been obscured. Therefore, it is reasonable to surmise that for most of history, the relationship of angiosperms to other seed plants, the relationships within angiosperms, the timescale of angiosperm evolution, and the reasons for the relative success of angiosperms compared to gymnosperms were all largely unknown or not understood.

Thankfully, we have now made great progress in the quest to answer these questions. Work remains to identify potential stem-group relatives of seed plants, but we now have reliable estimates of the phylogeny of extant seed plants. However, the most widely accepted seed plant phylogeny suggests that no extant gymnosperm lineage preserves the evolutionary steps that led to the origin of the first flowers. Therefore, in some respects the resolution of the seed plant phylogeny has been somewhat of a disappointment for those wanting to reconstruct the

development of the flower (Doyle 2012). While this might be considered a setback, our greatly improved knowledge of the angiosperm phylogeny, including a strongly supported position for the root, allows increasingly sophisticated questions to be asked about angiosperm macroevolution (e.g., Turcotte et al. 2014; Zanne et al. 2014). Similarly, our modern estimates for the timescale of angiosperm evolution allow us to explore further the selective pressures that might have shaped the present-day distribution and diversity of flowering plants.

Despite our significant improvements in understanding the patterns and timescale of angiosperm evolution, the field is far from settled. The celebrated consistent, strongly supported phylogeny based on chloroplast markers is increasingly being recognised as only one estimate of the angiosperm phylogeny. The alternative phylogenies inferred through analysis of nuclear markers, and through the choice of phylogeny reconstruction methods, suggests that more work is needed to reconcile potentially conflicting evolutionary histories. Additionally, the controversy surrounding the age of flowering plants shows no signs of abating. Modern knowledge of the fossil record suggests that the rapid radiation of angiosperm lineages was not quite as explosive as implied by Darwin's "abominable mystery" proclamation, yet a new mystery is why molecular date estimates still generally far pre-date the oldest angiosperm fossils. It is unlikely that increasing the amount of genetic data will solve this problem (Foster et al. 2016); instead, increased sampling from underrepresented groups and methodological improvements in incorporating fossil data appear to be the way forward. The last point appears to be an especially promising avenue of research, with new methods being developed for the simultaneous analysis of extant and extinct taxa (Ronquist et al. 2012; Gavryushkina et al. 2014; Heath et al. 2014). Overall, it is clear that our understanding of the evolutionary history of angiosperms has changed considerably over time, and we are now in an exciting new era of angiosperm research.

Acknowledgements

I would like to thank Simon Ho for helpful feedback on this manuscript.

References

Angiosperm Phylogeny Group, A. P. G. (1998) An ordinal classification for the families of flowering plants, *Annals of the Missouri Botanical Garden*, 85, 531–553.

Angiosperm Phylogeny Group, A. P. G. (2003) An update of the Angiosperm Phylogeny Group classification for the orders and families of flowering plants, *Botanical Journal of the Linnean Society*, 141, 399–436.

Angiosperm Phylogeny Group, A. P. G. (2009) An update of the Angiosperm Phylogeny Group classification for the orders and families of flowering plants: APG III, *Botanical Journal of the Linnean Society*, 165, 105–121.

Angiosperm Phylogeny Group, A. P. G. (2016) An update of the Angiosperm Phylogeny Group classification for the orders and families of flowering plants: APG IV, *Botanical Journal of the Linnean Society*, 181, 1, 1–20.

Arber, E. A. & Parkin, J. (1907) On the origin of angiosperms, *Journal of the Linnean Society of London, Botany*, 38, 263, 29–80.

Beaulieu, J. M., O'Meara, B., Crane, P. & Donoghue, M. J. (2015) Heterogeneous rates of molecular evolution and diversification could explain the Triassic age estimate for angiosperms, *Systematic Biology*, 64, 5, 869–878.

Bebber, D. P., Carine, M. A., Wood, J. R. I., Wortley, A. H., Harris, D. J., Prance, G. T., Davidse, G., Paige, J., Pennington, T. D. & Robson, N. K. B. (2010) Herbaria are a major frontier for species discovery, *Proceedings of the*

National Academy of Sciences, 107, 51, 22169–22171.

Bell, C. D., Soltis, D. E. & Soltis, P. S. (2010) The age and diversification of the angiosperms re-revisited, *American Journal of Botany*, 97, 8, 1296–1303.

Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W. & Courchamp, F. (2012) Impacts of climate change on the future of biodiversity, *Ecology Letters*, 15, 4, 365–377.

Bond, W. J. (1989) The tortoise and the hare: ecology of angiosperm dominance and gymnosperm persistence, *Biological Journal of the Linnean Society*, 36, 3, 227–249.

Bowe, L. M., Coat, G. & dePamphilis, C. W. (2000) Phylogeny of seed plants based on all three genomic compartments: Extant gymnosperms are monophyletic and Gnetales' closest relatives are conifers, *Proceedings of the National Academy of Sciences*, 97, 8, 4092–4097.

Brodribb, T. J. & Feild, T. S. (2010) Leaf hydraulic evolution led a surge in leaf photosynthetic capacity during early angiosperm diversification, *Ecology Letters*, 13, 2, 175–183.

Bungard, R. A. (2004) Photosynthetic evolution in parasitic plants: insight from the chloroplast genome, *Bioessays*, 26, 3, 235-247.

Burger, W. C. (1977) The Piperales and the monocots, *The Botanical Review*, 43, 3, 345–393.

Burger, W. C. (1981) Heresy revived: the monocot theory of angiosperm origin, *Evolutionary Theory*, 5, 40, 189-226.

Cantino, P. D., Doyle, J. A., Graham, S. W., Judd, W. S., Olmstead, R. G., Soltis, D. E., Soltis, P. S. & Donoghue, M. J. (2007) Towards a phylogenetic nomenclature of Tracheophyta, *Taxon*, 56, 3, 1E–44E.

Carmichael, J. S. & Friedman, W. E. (1996) Double fertilization in *Gnetum gnemon* (Gnetaceae): its bearing on the evolution of sexual reproduction within the Gnetales and the anthophyte clade, *American Journal of Botany*, 83, 6, 767–780.

Chase, M. W., Soltis, D. E., Olmstead, R. G., Morgan, D., Les, D. H., Mishler, B. D., Duvall, M. R., Price, R. A., Hills, H. G. & Qiu, Y.-L. (1993) Phylogenetics of seed plants: an analysis of nucleotide sequences from the plastid gene *rbc*L, *Annals of the Missouri Botanical Garden*, 80, 3, 528–580.

Chaw, S.-M., Parkinson, C. L., Cheng, Y., Vincent, T. M. & Palmer, J. D. (2000) Seed plant phylogeny inferred from all three plant genomes: monophyly of extant gymnosperms and origin of Gnetales from conifers, *Proceedings of the National Academy of Sciences*, 97, 8, 4086–4091.

Chaw, S.-M., Zharkikh, A., Sung, H.-M., Lau, T.-C. & Li, W.-H. (1997) Molecular phylogeny of extant gymnosperms and seed plant evolution: analysis of nuclear 18S rRNA sequences, *Molecular Biology and Evolution*, 14, 1, 56–68.

Crane, P. R. (1985) Phylogenetic analysis of seed plants and the origin of angiosperms, *Annals of the Missouri Botanical Garden*, 72, 4, 716–793.

Cronquist, A. (1981) *An integrated system of classification of flowering plants*, Columbia University Press, New York City, USA.

Darwin, F. & Seward, A. C. (1903) *More letters of Charles Darwin: a record of his work in a series of hitherto unpublished letters*, John Murray, London, UK.

Donoghue, M. J. & Doyle, J. A. (1989a) "Phylogenetic analysis of angiosperms and the relationships of Hamamelidae", in Crane, P. R. & Blackmore, S. (eds.) *Evolution, systematics, and fossil history of the Hamamelidae. Vol. 1. Introduction and "Lower" Hamamelidae.*, Clarendon Press, Oxford.

Donoghue, M. J. & Doyle, J. A. (1989b) "Phylogenetic studies of seed plants and angiosperms based on morphological characters", in Fernholm, B., Bremer, K. & Jörnvall, H. (eds.) *The hierarchy of life: molecules and morphology in phylogenetic analysis*, Elsevier Science, Amsterdam, 181–193.

Doyle, J. A. (1969) Cretaceous angiosperm pollen of the Atlantic Coastal Plain and its evolutionary significance, *Journal of the Arnold Arboretum*, 50, 1–35.

Doyle, J. A. (2012) Molecular and fossil evidence on the origin of angiosperms, *Annual Review of Earth and Planetary Sciences*, 40, 301–326.

Doyle, J. A. & Donoghue, M. J. (1986) Seed plant phylogeny and the origin of angiosperms: an experimental cladistic approach, *The Botanical Review*, 52, 4, 321–431.

Doyle, J. A. & Hotton, C. L. (1991) "Diversification of early angiosperm pollen in a cladistic context", in Blackmore, S. & Barnes, S. H. (eds.) *Pollen and spores: patterns of diversification*, Clarendon Press, Oxford, 169–195.

Ellis, R. J. (2010) Biochemistry: Tackling unintelligent design, *Nature*, 463, 7278, 164–165.

Endress, P. K. (1987) The early evolution of the angiosperm flower, *Trends in Ecology & Evolution*, 2, 10, 300–304.

Endress, P. K. (2002) Morphology and angiosperm systematics in the molecular era, *The Botanical Review*, 68, 4, 545–570.

Endress, P. K., Baas, P. & Gregory, M. (2000) Systematic plant morphology and anatomy: 50 Years of progress, *Taxon*, 49, 3, 401–434.

Fairon-Demaret, M. (1996) *Dorinnotheca streelii* Fairon-Demaret, *gen. et sp. nov.*, a new early seed plant from the upper Famennian of Belgium, *Review of Palaeobotany and Palynology*, 93, 1, 217-233.

Fairon-Demaret, M. & Scheckler, S. E. (1987) Typification and redescription of *Moresnetia zalesskyi* Stockmans, 1948, an early seed plant from the Upper Famennian of Belgium, *Bulletin-Institut Royal des Sciences Naturelles de Belgique. Sciences de la Terre*, 57, 183-199.

Fleischmann, A., Michael, T. P., Rivadavia, F., Sousa, A., Wang, W., Temsch, E. M., Greilhuber, J., Müller, K. F. & Heubl, G. (2014) Evolution of genome size and chromosome number in the carnivorous plant genus *Genlisea* (Lentibulariaceae), with a new estimate of the minimum genome size in angiosperms, *Annals of Botany*, 114, 8, 1651–1663.

Foster, C. S. P., Sauquet, H., van der Merwe, M., McPherson, H., Rossetto, M. & Ho, S. Y. W. (2016) Evaluating the Impact of Genomic Data and Priors on Bayesian Estimates of the Angiosperm Evolutionary Timescale, *Systematic Biology*, in press.

Friedman, W. E. (1992) Evidence of a pre-angiosperm origin of endosperm: implications for the evolution of flowering plants, *Science*, 255, 5042, 336–339.

Galtier, N. (2011) The intriguing evolutionary dynamics of plant mitochondrial DNA, *BMC Biology*, 9, 1, 61.

Gang, H. A. N., Zhongjian, L. I. U., Xueling, L. I. U., Limi, M. A. O., Jacques, F. & Xin, W. (2016) A Whole Plant Herbaceous Angiosperm from the Middle Jurassic of China, *Acta Geologica Sinica (English Edition)*, 90, 1, 19–29.

Gavryushkina, A., Welch, D., Stadler, T. & Drummond, A. J. (2014) Bayesian inference of sampled ancestor trees for epidemiology and fossil calibration, *PLoS Computational Biology*, 10, 12, e1003919.

Goremykin, V. V., Hansmann, S. & Martin, W. F. (1997) Evolutionary analysis of 58 proteins encoded in six completely sequenced chloroplast genomes: revised molecular estimates of two seed plant divergence times, *Plant Systematics and Evolution*, 206, 1–4, 337–351.

Goremykin, V. V., Nikiforova, S. V., Biggs, P. J., Zhong, B., Delange, P., Martin, W., Woetzel, S., Atherton, R. A., McLenachan, P. A. & Lockhart, P. J. (2013) The evolutionary root of flowering plants, *Systematic Biology*, 62, 1, 50–61.

Goremykin, V. V., Nikiforova, S. V., Cavalieri, D., Pindo, M. & Lockhart, P. (2015) The Root of Flowering Plants and Total Evidence, *Systematic Biology*, 64, 5, 879–891.

Govaerts, R. (2001) How many species of seed plants are there?, *Taxon*, 50, 4, 1085–1090.

Hay, W. W. & Floegel, S. (2012) New thoughts about the Cretaceous climate and oceans, *Earth-Science Reviews*, 115, 4, 262–272.

Heath, T. A., Huelsenbeck, J. P. & Stadler, T. (2014) The fossilized birth–death process for coherent calibration of divergence-time estimates, *Proceedings of the National Academy of Sciences*, 111, 29, E2957–E2966.

Ho, S. Y. W. (2014) The changing face of the molecular evolutionary clock, *Trends in Ecology & Evolution*, 29, 9, 496–503.

Ho, S. Y. W. & Duchêne, S. (2014) Molecular-clock methods for estimating evolutionary rates and timescales, *Molecular Ecology*, 23, 5947–5965.

Ho, S. Y. W. & Phillips, M. J. (2009) Accounting for calibration uncertainty in phylogenetic estimation of evolutionary divergence times, *Systematic Biology*, 58, 3, 367–380.

Ho, S. Y. W., Tong, K. J., Foster, C. S. P., Ritchie, A. M., Lo, N. & Crisp, M. D. (2015) Biogeographic calibrations for the molecular clock, *Biology Letters*, 11, 9, 20150194.

Hochuli, P. A. & Feist-Burkhardt, S. (2013) Angiosperm-like pollen and *Afropollis* from the Middle Triassic (Anisian) of the Germanic

Basin (Northern Switzerland), *Frontiers in Plant Science*, 4, 344.

Jiao, Y., Wickett, N. J., Ayyampalayam, S., Chanderbali, A. S., Landherr, L., Ralph, P. E., Tomsho, L. P., Hu, Y., Liang, H. & Soltis, P. S. (2011) Ancestral polyploidy in seed plants and angiosperms, *Nature*, 473, 7345, 97–100.

Kitazaki, K. & Kubo, T. (2010) Cost of having the largest mitochondrial genome: evolutionary mechanism of plant mitochondrial genome, *Journal of Botany*, 2010, 620137.

Krassilov, V. A. (1977) The origin of angiosperms, *The Botanical Review*, 43, 1, 143–176.

Lanfear, R., Ho, S. Y. W., Davies, T. J., Moles, A. T., Aarssen, L., Swenson, N. G., Warman, L., Zanne, A. E. & Allen, A. P. (2013) Taller plants have lower rates of molecular evolution, *Nature Communications*, 4, 1879.

Laroche, J., Li, P. & Bousquet, J. (1995) Mitochondrial DNA and monocot-dicot divergence time, *Molecular Biology and Evolution*, 12, 6, 1151–1156.

Lee, M. S. Y. & Ho, S. Y. W. (2016) Molecular clocks, *Current Biology*, 26, 10, R399–R402.

Levin, D. A. (2002) *The role of chromosomal change in plant evolution*, Oxford University Press, New York.

Magallón, S. (2014) A review of the effect of relaxed clock method, long branches, genes, and calibrations in the estimation of angiosperm age, *Botanical Sciences*, 92, 1, 1–22.

Magallón, S. & Sanderson, M. J. (2001) Absolute diversification rates in angiosperm clades, *Evolution*, 55, 9, 1762–1780.

Magallón, S., Gómez-Acevedo, S., Sánchez-Reyes, L. L. & Hernández-Hernández, T. (2015) A metacalibrated time-tree documents the early rise of flowering plant phylogenetic diversity, *New Phytologist*, 207, 2, 437–453.

Martin, W., Gierl, A. & Saedler, H. (1989) Molecular evidence for pre-Cretaceous angiosperm origins, *Nature*, 339, 46–48.

Mathews, S. & Donoghue, M. J. (1999) The root of angiosperm phylogeny inferred from duplicate phytochrome genes, *Science*, 286, 5441, 947–950.

Meeuse, A. D. J. (1972) Facts and fiction in floral morphology with special reference to the Polycarpicae 1. A general survey, *Acta Botanica Neerlandica*, 21, 2, 113–127.

Moore, M. J., Bell, C. D., Soltis, P. S. & Soltis, D. E. (2007) Using plastid genome-scale data to resolve enigmatic relationships among basal angiosperms, *Proceedings of the National Academy of Sciences*, 104, 49, 19363–19368.

Moore, M. J., Soltis, P. S., Bell, C. D., Burleigh, J. G. & Soltis, D. E. (2010) Phylogenetic analysis of 83 plastid genes further resolves the early diversification of eudicots, *Proceedings of the National Academy of Sciences*, 107, 10, 4623–4628.

Parkinson, C. L., Adams, K. L. & Palmer, J. D. (1999) Multigene analyses identify the three earliest lineages of extant flowering plants, *Current Biology*, 9, 24, 1485–1491.

Pellicer, J., Fay, M. F. & Leitch, I. J. (2010) The largest eukaryotic genome of them all?, *Botanical Journal of the Linnean Society*, 164, 1, 10–15.

Pimm, S. L. & Joppa, L. N. (2015) How many plant species are there, where are they, and at what rate are they going extinct?, *Annals of the Missouri Botanical Garden*, 100, 3, 170–176.

Preston, J. C. & Hileman, L. C. (2009) Developmental genetics of floral symmetry evolution, *Trends in Plant Science*, 14, 3, 147–154.

Qiu, Y.-L., Lee, J., Bernasconi-Quadroni, F., Soltis, D. E., Soltis, P. S., Zanis, M., Zimmer, E. A., Chen, Z., Savolainen, V. & Chase, M. W. (1999) The earliest angiosperms: evidence from mitochondrial, plastid and nuclear genomes, *Nature*, 402, 6760, 404–407.

Ray, J. (1686–1704) *Historia Plantarum*, H. Faithorne, London.

Ronquist, F., Klopfstein, S., Vilhelmsen, L., Schulmeister, S., Murray, D. L. & Rasnitsyn, A. P. (2012) A total-evidence approach to dating with fossils, applied to the early radiation of the Hymenoptera, *Systematic Biology*, 61, 6, 973–999.

Rosas-Guerrero, V., Aguilar, R., Martén-Rodríguez, S., Ashworth, L., Lopezaraiza-Mikel, M., Bastida, J. M. & Quesada, M. (2014) A quantitative review of pollination syndromes: do floral traits predict effective pollinators?, *Ecology Letters*, 17, 3, 388–400.

Rothwell, G. W., Scheckler, S. E. & Gillespie, W. H. (1989) *Elkinsia* gen. nov., a Late Devonian gymnosperm with cupulate ovules, *Botanical Gazette*, 150, 2, 170-189.

Ruhfel, B. R., Gitzendanner, M. A., Soltis, P. S., Soltis, D. E. & Burleigh, J. G. (2014) From algae to angiosperms–inferring the phylogeny of green plants (Viridiplantae) from 360 plastid genomes, *BMC Evolutionary Biology*, 14, 1, 23.

Saarela, J. M., Rai, H. S., Doyle, J. A., Endress, P. K., Mathews, S., Marchant, A. D., Briggs, B. G. & Graham, S. W. (2007) Hydatellaceae identified as a new branch near the base of the angiosperm phylogenetic tree, *Nature*, 446, 7133, 312–315.

Sagan, L. (1967) On the origin of mitosing cells, *Journal of Theoretical Biology*, 14, 3, 225–274.

Sage, R. F., Christin, P.-A. & Edwards, E. J. (2011) The C4 plant lineages of planet Earth, *Journal of Experimental Botany*, 62, 9, 3155–3169.

Sanderson, M. J. & Doyle, J. A. (2001) Sources of error and confidence intervals in estimating the age of angiosperms from *rbc*L and 18S rDNA data, *American Journal of Botany*, 88, 8, 1499–1516.

Schwartz, R. M. & Dayhoff, M. O. (1978) Origins of prokaryotes, eukaryotes, mitochondria, and chloroplasts, 199, 4327, 395–403.

Scotland, R. W. & Wortley, A. H. (2003) How many species of seed plants are there?, *Taxon*, 52, 1, 101–104.

Smith, S. A., Beaulieu, J. M. & Donoghue, M. J. (2010) An uncorrelated relaxed-clock analysis suggests an earlier origin for flowering plants, *Proceedings of the National Academy of Sciences*, 107, 13, 5897–5902.

Smith, S. A. & Donoghue, M. J. (2008) Rates of molecular evolution are linked to life history in flowering plants, *Science*, 322, 5898, 86–89.

Soltis, D. E., Smith, S. A., Cellinese, N., Wurdack, K. J., Tank, D. C., Brockington, S. F., Refulio-Rodriguez, N. F., Walker, J. B., Moore, M. J. & Carlsward, B. S. (2011) Angiosperm phylogeny: 17 genes, 640 taxa, *American Journal of Botany*, 98, 4, 704–730.

Soltis, P. S. & Soltis, D. E. (2004) The origin and diversification of angiosperms, *American Journal of Botany*, 91, 10, 1614–1626.

Soltis, P. S., Soltis, D. E. & Chase, M. W. (1999) Angiosperm phylogeny inferred from multiple genes as a tool for comparative biology, *Nature*, 402, 6760, 402–404.

Soltis, P. S., Soltis, D. E., Savolainen, V., Crane, P. R. & Barraclough, T. G. (2002) Rate heterogeneity among lineages of tracheophytes: integration of molecular and fossil data and evidence for molecular living fossils, *Proceedings of the National Academy of Sciences*, 99, 7, 4430–4435.

Takhtajan, A. L. (1980) Outline of the classification of flowering plants (Magnoliophyta), *The Botanical Review*, 46, 3, 225–359.

Thuiller, W., Lavergne, S., Roquet, C., Boulangeat, I., Lafourcade, B. & Araujo, M. B. (2011) Consequences of climate change on the tree of life in Europe, *Nature*, 470, 7335, 531–534.

Turcotte, M. M., Davies, T. J., Thomsen, C. J. M. & Johnson, M. T. J. (2014) Macroecological and macroevolutionary patterns of leaf herbivory across vascular plants, *Proceedings of the Royal Society of London B: Biological Sciences*, 281, 1787, 20140555.

van der Niet, T. & Johnson, S. D. (2012) Phylogenetic evidence for pollinator-driven diversification of angiosperms, *Trends in Ecology & Evolution*, 27, 6, 353–361.

Wang, X., Duan, S., Geng, B., Cui, J. & Yang, Y. (2007) Is Jurassic *Schmeissneria* an angiosperm?, *Acta Palaeontologica Sinica*, 46, 4, 490.

Welch, J. J. & Bromham, L. (2005) Molecular dating when rates vary, *Trends in Ecology & Evolution*, 20, 6, 320–327.

Wettstein, R. (1907) *Handbuch der systematischen Botanik*, 2 edn., Franz Deuticke, Leipzig.

Wickett, N. J., Mirarab, S., Nguyen, N., Warnow, T., Carpenter, E., Matasci, N., Ayyampalayam, S., Barker, M. S., Burleigh, J. G. & Gitzendanner, M. A. (2014) Phylotranscriptomic analysis of the origin and early diversification of land plants, *Proceedings of the National Academy of Sciences*, 111, 45, E4859–E4868.

Winter, K.-U., Becker, A., Münster, T., Kim, J. T., Saedler, H. & Theissen, G. (1999) MADS-box genes reveal that gnetophytes are more closely related to conifers than to flowering plants, *Proceedings of the National Academy of Sciences*, 96, 13, 7342–7347.

Wolfe, K. H., Li, W.-H. & Sharp, P. M. (1987) Rates of nucleotide substitution vary greatly among plant mitochondrial, chloroplast, and

nuclear DNAs, *Proceedings of the National Academy of Sciences*, 84, 24, 9054–9058.

Xi, Z., Liu, L., Rest, J. S. & Davis, C. C. (2014) Coalescent versus concatenation methods and the placement of Amborella as sister to water lilies, *Systematic Biology*, 63, 6, 919–932.

Zanne, A. E., Tank, D. C., Cornwell, W. K., Eastman, J. M., Smith, S. A., FitzJohn, R. G., McGlinn, D. J., O'Meara, B. C., Moles, A. T., Reich, P. B., Doyer, D. L., Soltis, D., Stevens, P., Westoby, M., Wright, I., Aarssen, L., Bertin, R., Calaminus, A., Govaerts, R., Hemmings, F., Leishman, J., Soltis, P. S., Swenson, N. G., Warman, L. & Beaulieu, J. M. (2014) Three keys to the radiation of angiosperms into freezing environments, *Nature*, 506, 7486, 89–92.

Zeng, L., Zhang, Q., Sun, R., Kong, H., Zhang, N. & Ma, H. (2014) Resolution of deep angiosperm phylogeny using conserved nuclear genes and estimates of early divergence times, *Nature Communications*, 5, 4956.

Zhong, B., Yonezawa, T., Zhong, Y. & Hasegawa, M. (2010) The position of Gnetales among seed plants: overcoming pitfalls of chloroplast phylogenomics, *Molecular Biology and Evolution*, 27, 12, 2855–2863.

Zuckerkandl, E. & Pauling, L. (1962) "Molecular disease, evolution and genic heterogeneity.", in Kasha, M. & Pullman, B. (eds.) *Horizons in Biochemistry.*, Academic Press., New York, 189–225.

Journal & Proceedings of the Royal Society of New South Wales, vol. 149, parts 1 & 2, 2016, p. 83. ISSN 0035-9173/16/010083–01

Thesis abstract

Adherence to self-management and psychological distress in women with breast cancer-related lymphoedema

Jessica Alcorso

Abstract of a thesis for a Doctorate of Philosophy submitted to Macquarie University, Sydney, Australia

Nonadherence to breast cancer-related lymphoedema self-management is sub-optimal. In addition, women with breast cancer-related lymphoedema experience psychological distress associated with this chronic illness. Adopting a social-cognitive theoretical framework, the aim of this thesis is to identify cognitive and affective predictors of adherence to self-management behaviours and predictors of psychological distress in women living with breast cancer-related lymphoedema. To achieve this aim, a longitudinal study was conducted that measured adherence to self-management behaviours, psychological distress, and cognitive and affective factors at baseline, 6- and 12-months. An additional cross-sectional study was conducted to identify lymphoedema therapists' and affected women's beliefs about barriers to adherence to self-management. The findings from the empirical studies on adherence suggest that cognitive and affective factors are not informative for understanding self-management behaviour in women with breast cancer-related lymphoedema. Furthermore, a disconnect between therapists' and affective women's beliefs about barriers to self-management was identified, with therapists believing more strongly than the affected women that financial cost, time, concerns about appearance, difficulty accessing treatment, insufficient knowledge, and physical limitations negatively impact adherence. In contrast, a number of cognitive and affective factors significantly predicted distress. Based on the results from the longitudinal study, an online self-compassion based writing activity was developed to minimise distress and body image disturbance in this population of lymphoedema-affected women. The online intervention received moderate to high user acceptability ratings from women affected with breast cancer-related lymphoedema suggesting the potential viability of this intervention. In sum, the findings from this thesis have important implications for researchers and health professionals. Regarding self-management, medical characteristics and knowledge were identified as important factors for identifying women at risk of non-adherence. In addition, it may be beneficial to screen women for symptoms of psychological distress and body image disturbance in order to identify who may benefit from additional psychosocial support.

Jessica Alcorso,
Department of Psychology,
Macquarie University,
Sydney NSW 2109AUSTRALIA

Email: jessica.alorso@mq.edu.au

Journal & Proceedings of the Royal Society of New South Wales, vol. 149, parts 1 & 2, 2016, p. 84. ISSN 0035-9173/16/010084–01

Thesis abstract

A social psychological examination of factors shaping career and education aspirations through childhood and adolescence

Nathan Berger

Abstract of a thesis for a Doctorate of Philosophy submitted to University of Newcastle, Newcastle, Australia

Young people often are asked what they want to be when they grow up. What factors influence their responses to this most common of questions? This study used theoretical perspectives from social and vocational psychology, including Gottfredson's (1981, 2002) career circumscription and compromise theory, to investigate the formation of career aspirations during primary and secondary schooling. A particular emphasis was the relationship between social cognition and socioeconomic status (SES) — is SES associated with young people's thinking about careers-related identity questions? The study drew on data gathered during the first three years (2012-2014) of the Aspirations Longitudinal Study (ALS) in the State of New South Wales, Australia. Students in Years 3-11 were sampled in an accelerated longitudinal design, whereby three cohorts completed a comprehensive career aspirations questionnaire for three years. The sample comprised 7,462 questionnaires from 5,304 students. In addition to the questionnaires, the ALS accessed standardised demographic and literacy/numeracy data held by the state for each student. To examine the influence of students' social-cognitive styles on their career aspirations, they also completed a modified version of Berzonsky et al.'s (2013) Identity Style Index as part of the 2014 questionnaire. The latent class mixture modelling (LCMM) technique was used to analyse the accelerated longitudinal data. LCMM identified four discrete change trajectories in the prestige of career aspirations during nine years of schooling. Students' identity styles were found to differ between SES backgrounds, with high SES students more information-oriented and less diffuse/avoidant when dealing with identity questions compared to low SES students. Identity styles also differed by SES background within the LCMM trajectories, with high aspiring low SES students more information-oriented and less diffuse/avoidant than their low aspiring peers. The implications of these findings for theory, research, and practice are discussed.

Dr Nathan Berger,
School of Education,
University of Newcastle,
Newcastle NSW 2300
AUSTRALIA

Email: n.berger@westernsydney.edu.au

Journal & Proceedings of the Royal Society of New South Wales, vol. 149, parts 1 & 2, 2016, pp. 85–86. ISSN 0035-9173/16/010085–02

Thesis abstract

The cognitive and neural mechanisms of joint attention: a second person approach

Nathan Caruana

Abstract of a thesis for a Doctorate of Philosophy submitted to Macquarie University, Sydney, Australia

This project investigated the cognitive and neural mechanisms of joint attention in typical development and in high-functioning autism. A novel gaze-contingent virtual reality tasks was developed and implemented in a number of studies using a range of techniques, including functional magnetic resonance imaging (fMRI), event-related potentials (ERP) and eye tracking.

The first aim of this project was to develop an experimental joint attention paradigm that (1) captured both the initiating and responding functions of joint attention, (2) could be applied in both behavioural and neurophysiological experiments, (3) provided full experimental control over non-social task demands, and (4) established an ecologically valid context for joint attention interactions.

Chapter 2 of this dissertation reviewed the current approaches for measuring joint attention in experimental settings and introduced a new virtual reality paradigm of joint attention that achieves both experimental control and ecological validity. Critical issues associated with the measurement of joint attention are discussed.

The second aim of this project was to use this paradigm to investigate the neural and cognitive mechanisms that support joint attention in typical development and in autism.

In **Chapter 3**, fMRI was used to investigate the neural correlates that were unique and common to initiating and responding to joint attention bids in 13 adults with typical development. A right-lateralised fronto-temporoparietal network was found to be common to both initiating and responding to joint attention bids and comprised the middle frontal gyrus (MFG), inferior frontal gyrus (IFG), middle temporal gyrus (MTG), precentral gyrus, posterior superior temporal sulcus (pSTS), temporoparietal junction (TPJ) and precuneus. Compared to responding to joint attention bids, initiating joint attention was associated with additional activation of the MFG, IFG, TPJ and precuneus.

In **Chapter 4**, eye-tracking was used to investigate joint attention performance in 17 adults with high-functioning autism and 17 adults with typical development (controls). Individuals with autism made significantly more errors than controls when initiating and responding to joint attention bids.

In **Chapter 5**, another virtual reality paradigm was developed and employed in an event-related potential study which investigated the time course of neural processes associated with evaluating self-initiated joint

attention bids. In a sample of 19 participants with typical development, centro-parietal P350 and P500 ERPs were significantly larger when gaze shifts resulted in the avoidance, rather than the achievement of joint attention. This P350 and P500 morphology was absent in a second sample of 19 participants who completed a non-social version of the same task in which arrows replaced the gaze of the virtual character.

In **Chapter 6**, the same paradigm was used to investigate whether the P350 effect observed in **Chapter 5** was influenced by participants' beliefs of their virtual partner's agency. The P350 effect was only observed in participants who believed that their partner was controlled by a human (n = 19), and not in a second group of individuals who were informed that the virtual character was controlled by a computer program (n = 19).

Nathan Caruana,
Department of Cognitive Science,
Macquarie University,
Sydney NSW 2109
Australia
Email: Nathan.caruana@mq.edu.au

Journal & Proceedings of the Royal Society of New South Wales, vol. 149, parts 1 & 2, 2016, p. 87. ISSN 0035-9173/16/010087–01

Thesis abstract

Environmental flows at work; restoring floodplain wetlands through return of historical conditions

Samantha Katherine Dawson

Abstract of a thesis for a Doctorate of Philosophy submitted to the University of New South Wales, Sydney, Australia

Wetlands are among the most degraded ecosystems worldwide, demanding effective restoration. In an effort to ameliorate ecological degradation from upstream water diversions, environmental and managed flows are increasingly used to help restore vegetation communities. Understanding of factors affecting the success and efficacy, however, remains limited and is of increasing urgency as this type of restoration becomes more widespread. I investigated the capacity of flooding, including environmental flows, to restore wetland flora across areas varying in degradation from historic land-use.

I predicted that increasing land-use history (increasing duration and decreasing time since land use) would decrease restoration effectiveness, while increased flooding frequency and duration should improve restoration outcomes. A case study was used to assess vegetation restoration: a floodplain wetland with fields representing a land-use chronosequence, flooded through environmental flows, in the Macquarie Marshes in the Murray-Darling Basin of south-eastern Australia. I examined extant vegetation, soil seedbanks, plant trait distributions and historical vegetation change through surveys of plant community composition, greenhouse seed bank germination, fourth-corner trait modelling approaches and Landsat imagery analysis.

Composition of extant herbaceous vegetation correlated with both land-use history and flooding, while extant shrub and woody species were more strongly correlated with land-use. Within seedbanks, exotic and disturbance-adapted species were associated with increased duration and decreased time since land-use and native wetland species were associated with opposite land-use practice and increased flooding. Furthermore, I found that there was capacity within the soil seed bank to engender further restoration of extant vegetation. Trait analyses showed native, woody and clonal species were taking the longest to restore, especially in high land use areas, but this may be ameliorated through increased inundation. Landsat analyses demonstrated that inundation was vital to restoration and also indicated a gradient of restoration success, with areas of less land use history (e.g. clearing and one year of cultivation) restoring more quickly than longer cultivation durations. In conclusion, flooding was critical to achieving restoration objectives, with higher frequencies increasing efficacy, but increased land-use intensity compromises restoration rates and possibly success.

Dr Samantha Dawson,
Centre for Ecosystem Science,
University of New South Wales,
Sydney NSW 2052 Australia
Email: samantha.k.dawson@gmail.com
Thesis: handle.unsw.edu.au/1959.4/56248

Journal & Proceedings of the Royal Society of New South Wales, vol. 149, parts 1 & 2, 2016, pp. 88–89. ISSN 0035-9173/16/010088–02

Thesis abstract

Quantitative proteomic analyses of isolate variation and virulence in *Giardia duodenalis*

Samantha J Emery

Abstract of a thesis for a Doctorate of Philosophy submitted to Macquarie University, Sydney, Australia

Giardia duodenalis is a parasitic protozoan with a global human infection burden of 250 million, and is therefore the largest parasitic cause of diarrheal disease worldwide. Though some cases are asymptomatic, giardiasis can be acute and chronic, with post-infection sequellae including irritable bowel syndrome, chronic fatigue, obesity and type II diabetes. Importantly, *Giardia* is problematic in children under the age of five, causing ill-thrift and failure-to-thrive. In addition, diarrheal diseases including *Giardia* constitute the second-leading cause of mortality for this age category. *Giardia* has a direct life cycle, where infective, tetranucleated cysts are transmitted via the faeco-oral route, and then excyst in the duodenum into virulent, flagellated trophozoites. The prevalence of the parasite is also due to its wide host range, with zoonotic transfer from wild, livestock and domestic animal species to humans. Efforts continue to define the mechanisms of virulence and pathophysiology, as more research is needed to elucidate the relationship between host and parasite factors.

Advances in genetic epidemiology have defined clear assemblages that segregate phylogenetically according to host range, and multiple assemblage and subassemblage genome sequences are now available. These genome sequences have provided the databases necessary for bottom-up, or shotgun, proteomics, and as such have expanded possibilities for quantitative analyses in this parasite. This thesis aimed to provide a thorough quantitative proteomic foundation to enhance the *Giardia* research field both biologically and technically. To achieve this, the thesis consists of four experimental investigations into aspects of parasite variation and virulence, all of which have generated quantitative proteomic data.

Firstly, two different protein sample preparation and fractionation methods were compared for label-free quantitative proteomics. These were applied to two *G. duodenalis* assemblage A1 isolates with different phenotypes, in order to investigate possible sources of isolate variation. The optimised protocol generated from this initial investigation was applied in later studies, which are also contained within this thesis. In addition, phenotypes associated with pathogenicity correlated with up-regulation of known virulence factors in *Giardia*.

Following this initial investigation, quantitative data was generated using the same label-free approach for eight assemblage A isolates, which constituted the first comprehensive proteomic baseline for this taxonomic group. Isolates of diverse host, geographic and sub-assemblage origins were analysed using mass spectrometry to characterise their common proteomes and isolate-specific variations. In addition, both the A1 and A2 subassemblage genome databases were evaluated for peptide

to spectrum matching, which demonstrated the importance of subassemblage databases to improve identifications from the *Giardia* variable genome.

The third study investigated isolate variation in the biological context of the process of differentiation in *G. duodenalis*. Label-free quantitative proteomics was used to analyse the proteomes of cysts and trophozoites from two genome-alternate subassemblage A1 isolates. This is the first post-genomic analysis of the life cycle beyond the genome isolate, WB. A range of isolate-independent, universal encystation markers were identified, as well as several indications of isolate-specific life-cycle adaptations which may impact reinfection success in subsequent generations.

Finally, the last experiment in this thesis investigated disease induction using in vitro host-parasite interaction models between intestinal epithelial cell (IEC) lines and trophozoites. We used isobaric Tandem Mass Tags (TMT) to sensitively quantitate changes in trophozoites which were either allowed to attach to host-cell monolayers, or were exposed to host-cell secretions alone. This is the first use of TMT label technologies for quantitative proteomics in *Giardia*. This has demonstrated that distinct protein cascades are induced by both levels of host-signals, and also that induction of virulence factors is not dependent on parasite attachment to host cells.

Through these experiments, this thesis demonstrates that a range of quantitative proteomic approaches are suitable for *G. duodenalis*, all of which are capable of providing important insight into key aspects of parasite biology. These studies provide an important proteomic complement for genomic and transcriptomic data currently available in the literature, which is necessary for undertaking a systems biology approach to understanding *Giardia*.

Dr Samantha J Emery,
Department of Chemistry and Biomolecular Sciences,
Macquarie University,
Sydney NSW 2109
AUSTRALIA

Email: emery.s@wehi.edu.au

Journal & Proceedings of the Royal Society of New South Wales, vol. 149, parts 1 & 2, 2016, pp. 90–91. ISSN 0035-9173/16/010090–02

Thesis abstract

Improving labour outcomes in the creative industries: the role of creative workers' social network structure and organisational business acumen

Benjamin Farr-Wharton

Abstract of a thesis for a Doctorate of Philosophy submitted to Southern Cross University, Lismore, Australia

Individuals who work in artistic, cultural and creative fields (henceforth creative workers) are increasingly conceptualised as a labour force. Under this conceptualisation, creative workers are seen to contribute positively to significant, national economic indicators such as Gross Domestic Product and innovation indices. However, a growing body of research indicates that, as a labour force, 'creative workers' experience particularly poor *labour outcomes*, insofar as they typically work longer hours, for relatively lower incomes, and have very little job security.

The theoretical concepts provided by the Resource-Based View (RBV) of the firm and Bourdieu's theories concerning social and cultural capital, and the field of cultural production, are used in this thesis to examine the impact of *organisational business acumen* and *social network structure* on the *labour outcomes (exploitation*, *labour precarity* and *earnings satisfaction)* of creative workers. The research adopts a mixed methods approach that encompasses an initial pilot case study using social network analysis, followed by an explanatory quantitative-qualitative design. The study is situated within an Australian context, and a total of three hundred people were involved in the data collection for the sum of these three research phases.

Results from the quantitative and qualitative research indicate that *organisational business acumen* and *social network structure* significantly reduce the *labour precarity* of creative workers. In addition, *organisational business acumen* significantly reduces perceptions of *exploitation,* as well as enhances the *earnings satisfaction* of sampled creative workers.

This research is innovative and important in a number of ways. For practitioners, results from this thesis highlight the significance of both *social network structure* and *organisational business acumen* as resources that positively impact the *labour outcomes* of creative workers. For policy makers, the research encourages the development of new policy instruments to support the diffusion of *organisational business acumen* across the creative labour force, in order to enhance the efficiency of the creative sector. For theory, the research suggests that creative workers are no longer subject to a dichotomous 'arts' or 'market' mode of production, but compromise business practices and artistic pursuit to seek sustainable outcomes. For the field of network analysis, the research offers new quantitative instru-

ments (specifically catering for the context of the network-centric creative sector) to measure the impact of network structures on performance measures.

Dr Benjamin Farr-Wharton
School of Business and Tourism
Southern Cross University
Lismore NSW 2480
AUSTRALIA
Email: 128154@uts.edu.au

Journal & Proceedings of the Royal Society of New South Wales, vol. 149, parts 1 & 2, 2016, pp. 92–93. ISSN 0035-9173/16/010092–02

Thesis abstract

Dim and dimmer: the production and diffusion of the natural sciences in Australia between the 1770s and the 2010s

Lynnette Hicks

Abstract of a thesis for a Doctorate of Philosophy submitted to Macquarie University, Sydney, Australia

Despite growing public concerns around socio-scientific problems and the significance of these problems to everyday life, there is a dearth of sociological literature addressing the production and diffusion of the natural sciences in Australia. In particular, critical analyses of scientific knowledge production and diffusion relative to the actions of the state, the market and civil society are largely absent. This thesis sets out to mitigate this situation by contributing a critical historiography of scientific knowledge production and diffusion as it relates to Australia since white settlement. It is anticipated that this work will open up the topic for further academic research and rational debate.

This thesis explores the production and diffusion of scientific knowledge through the lens of social dynamics that have emerged in Australia between the 1770s and the 2010s. The research relies primarily on the theoretical work of Max Weber in order to identify and analyse the conception of *rationality* and its application to social action that is present in the policy and praxis of the natural sciences in Australia. In particular the relationships between the state, the market and civil society are analysed using secondary data drawn from published histories, official documents and the formal policies and practices of the state and the market during this period.

A tripartite analytical model has been created specifically for this thesis and is utilised to trace scientific knowledge production and diffusion through the transformative social processes associated with *instrumentalism*, *bureaucratisation*, *developmentalism*, *environmentalism*, *postmodernism* and *neoliberalism*. Rationality is applied in three ways: as *non-instrumental* science produced to further human understandings of the natural world and to promote the development of civil society; as *pre-instrumental* science produced by the state to in order to develop markets and for other instrumental purposes such as national defence strategies; and as *instrumental* scientific knowledge produced by the participants in the market expressly to enhance their own position in the market.

The research reveals that instrumental rationality has been an enduring concept in the policy and praxis of the natural sciences in Australia. Moreover, this thesis finds that a strong tension is often present between non-instrumental notions of scientific knowledge and those practices that are predominantly instrumental. Through each of the periods studied the state and the market have been close confederates, often working together

to realize instrumental outcomes through the knowledge produced by natural science. In particular, administrative and economic ends are seen to be primary; ends associated with more normative intentions, such as the nurturing of civil society, have been regularly overlooked in favour of strictly instrumental aspirations. This continuing instrumentality has altered the relationships between the state, the market and civil society during each period studied. On the current trajectory, the policy and praxis of the natural sciences in Australia may yet begin to compromise the sovereignty of that nation state and the authority of its citizenry.

Dr Lynnette Hicks,
Department of Sociology,
Macquarie University,
Sydney NSW 2109
AUSTRALIA

Email: lyn.hicks@mq.edu.au
lyn.hicks@bigpond.com

Journal & Proceedings of the Royal Society of New South Wales, vol. 149, parts 1 & 2, 2016, p. 94. ISSN 0035-9173/16/010094–01

Thesis abstract

Pale Communion: whiteness, masculinity and nationhood in heavy metal scenes in Norway, South Africa and Australia

Catherine Hoad

Abstract of a thesis for a Doctorate of Philosophy submitted to Macquarie University, Sydney, Australia

In response to the current dynamics of the Global Metal model, this thesis draws attention to how whiteness maintains an invisibilised instrumental hegemony within heavy metal music, even as research on the genre continues to grow. I address the complex problem of how whiteness is represented in heavy metal scenes and practices, both as a site of academic inquiry and force of cultural significance. I argue that the whiteness and white heteromasculinity of heavy metal emerges in disparate locales as expressions of distinct nationalist projects. This research addresses the national specificity with which whiteness is valorised in heavy metal scenes, and how disparate national identities are tacitly and explicitly tied to white heteromasculine identity.

This thesis negotiates scholarly ways of addressing whiteness in heavy metal that move beyond discussions of demographics, virtuosity and spectacular racism. I analyse how the normalisation, construction and performance of whiteness, masculinity and nationhood within heavy metal scenes can have profound, pervasive and systematic oppressive consequences. The objective of my thesis is therefore to unveil the (in) visibility of whiteness within heavy metal scenes, and indicate how such whitenesses are deployed within particular countries, as both explicit political violence and instrumental hegemony. The quest in pointing to the fragmentation and multiplicity of whitenesses across three different countries is to deconstruct the structure of white hegemony, and call into question the strategic political position that emerges in treating white selves as a uniform category.

This research maps the matrix of whiteness, masculinity and nationhood through which heavy metal scenes across Norway, South Africa and Australia have produced and defended national identity. I distinguish three key forms of white nationalism—Norway's monstrous nationalism, in which the nation is constructed as terrifying and atavistic; South Africa's resistant nationalism, which responds to post-Apartheid claims of white victimhood; and Australia's banal nationalism, which consecrates mundanity as an authentic national condition. Such constellations of whiteness, masculinity and nationhood have enabled tacit and explicit constructions of exclusionary communities formed through collective memory and territory. These scenes are demonstrative of the ways in which white inflections inform the practices of both heavy metal scenes and the specifically local whitenesses manifest within them.

Dr Catherine Hoad,
Department of Media, Music, Communications and Cultural Studies,
Macquarie University,
Sydney NSW 2109
AUSTRALIA
Email: catherine.hoad@mq.edu.au

Journal & Proceedings of the Royal Society of New South Wales, vol. 149, parts 1 & 2, 2016, p. 95. ISSN 0035-9173/16/010095–01

Thesis abstract

Interhemispheric asymmetry of global warming: the role of ocean dynamics

David Karel Hutchinson

Abstract of a thesis for a Doctorate of Philosophy submitted to the University of New South Wales, Sydney, Australia

Global surface air temperature is increasing due to rising greenhouse gases. This warming has occurred at a faster rate in the Northern Hemisphere (NH) than the Southern Hemisphere (SH) and the asymmetry of warming between hemispheres is predicted to continue throughout the 21st Century. Several factors contribute to this interhemispheric asymmetry, including the greater proportion of land in the NH and the northward transport of heat by the ocean. This thesis focuses on the role of ocean dynamics in setting the warming asymmetry, using several modelling approaches.

First, the impact of the Antarctic Circumpolar Current (ACC) on the interhemispheric warming asymmetry is investigated. The role of the ACC is isolated by comparing warming experiments in a global coupled climate model with and without a land barrier across Drake Passage (DP). With DP closed, the asymmetry in sea surface temperature (SST) warming is reduced, due to the presence of a subpolar gyre, and a lower Antarctic sea ice extent.

Second, the asymmetry of warming is examined when moving from coarse (1°) to eddy-permitting (0.25°) ocean resolution. We use an idealised coupled model with a 60° sector ocean domain, comprising one basin with Atlantic-like bathymetry and an ACC channel. A larger high latitude SST asymmetry develops in the 0.25° model than the 1° model, both in control runs and in warming scenarios. The larger warming asymmetry in the 0.25° model is caused by stronger boundary current heat transport and reduced NH sea ice. The SH warming is less sensitive to the resolution change, since eddy heat transport differences between the models are small compared with mean flow heat transport differences. When SH westerly winds are enhanced, the warming asymmetry increases, with greater upwelling of cool water in the Southern Ocean and greater warming in the NH.

Finally the impact of realistic bathymetry is explored in the sector climate model. The Atlantic-like sector model is compared with a flat bottom rectangular model in similar experiments. The Atlantic and rectangular models have similar control climates, however the rectangular models have a stronger subpolar gyre in the NH in the absence of bathymetry. In warming experiments, the rectangular models develop warming and cooling regions in the NH, while the Atlantic models have no significant cooling regions. The Atlantic models exhibit greater sensitivity of ACC transport to wind forcing.

Dr David Hutchinson,
Climate Change Research Centre,
University of New South Wales,
Sydney NSW 2052 AUSTRALIA
Email: david.hutchinson@geo.su.se
Thesis: handle.unsw.edu.au/1959.4/55380

Journal & Proceedings of the Royal Society of New South Wales, vol. 149, parts 1 & 2, 2016, p. 96. ISSN 0035-9173/16/010096–01

Thesis abstract

Conscious and not-conscious processing of visual mismatch negativity

Bradley N. Jack

Abstract of a thesis for a Doctorate of Philosophy submitted to Southern Cross University, Lismore, Australia

The general aim of my thesis is to investigate conscious and not-conscious processing of sequences of stimuli that yield visual mismatch negativity (vMMN), a well-established brain signature of prediction and prediction-error. vMMN is typically observed in the oddball paradigm: an infrequent visual stimulus—a deviant, is randomly and unpredictably presented in a sequence of more frequent visual stimuli—the standards. vMMN is a negative component of event-related potentials (ERPs), and is seen most clearly in the difference wave: the ERP for the deviant minus the ERP for the standard, between 150 and 400 ms after stimulus onset.

To investigate conscious and not-conscious processing of vMMN, I conducted four electroencephalography (EEG)/ERP experiments. In Experiment 1, I showed that it is easier to find neural correlates of visual consciousness—differences in brain activity between conscious and not-conscious visual stimuli, with cardinal gratings than with oblique gratings. In Experiment 2, I showed that a source of information about which we are not-conscious, eye-of-origin (utrocular) information, yields a reliable vMMN. In Experiment 3, I hid my deviants from visual consciousness using binocular rivalry suppression, and found that the size of vMMN is smaller to that elicited by the same stimulus when it is conscious during binocular rivalry dominance. In Experiment 4, I hid my standards and deviants from visual consciousness using continuous flash suppression (CFS), and found that the size of vMMN is bigger than that elicited by the same stimuli when they are conscious.

My results are consistent with the notions that our brains establish predictive models of visual perception about regular visual input, that our brains are constantly testing the reliability of these models, and that our brains update these models when something unexpected occurs. My results also show that these processes are independent of visual consciousness. I conclude that visual consciousness is not necessary to elicit vMMN, confirming that vMMN is an automatic brain response.

Dr Bradley N. Jack
School of Health and Human Science
Southern Cross University
Lismore NSW 2480
AUSTRALIA

Email: bradley.jack@unsw.edu.au

Journal & Proceedings of the Royal Society of New South Wales, vol. 149, parts 1 & 2, 2016, p. 97. ISSN 0035-9173/16/010097–01

Thesis abstract

White matter microstructural decline and cognitive performance in older adults: the influence of cardiovascular health

Todd Jolly

Abstract of a thesis for a Doctorate of Philosophy submitted to University of Newcastle, Newcastle, Australia

Age-related cognitive decline is well documented, especially in memory, speed of processing and executive functions. Structural brain changes are also well documented but often do not directly map onto the mild cognitive decline seen in otherwise healthy older adults. Recent work has focused on whether cognitive ageing is associated with decline in the strength of structural connectivity between neural regions, using diffusion magnetic resonance imaging (dMRI). Reduced integrity of white matter microstructure across the whole brain and in regions of interest, as measured by fractional anisotropy (FA), has been shown to be associated with cognitive decline in older adults who show no signs of dementia. This thesis uses dMRI tractography to examine the association between multiple measures of white matter microstructure across the whole brain and in 18 major white matter tracts and cognitive performance on a range of tasks that vary in process specificity. Seventy non-demented older adults (aged 43-87y) with varying degree of white matter disease completed a comprehensive cognitive and imaging assessment. Cognitive functioning was assessed at three levels: Firstly, global cognitive functioning was assessed using the Montreal Cognitive Assessment (MoCA). Then through the use of standardised neuropsychological tests, more specific cognitive domains of working memory, episodic memory, executive function and processing speed were assessed. An experimental task switching paradigm was then used to assess more specific components of executive function relating to proactive and reactive control processes. These showed that ability to detect the impact of tract-specific changes in white matter microstructure on cognitive performance was dependent on the specificity of the cognitive test. Although, irrespective of the level of cognitive assessment, the relationship between decline in white matter microstructural integrity and cognitive performance was specific only to participants with poor cardiovascular health. These findings suggest that cognitive and brain ageing profiles in older adults vary as a function of cardiovascular health and have strong implications for theories of cognitive ageing. They also emphasise the importance of cardiovascular health in prevention or delay in onset of cognitive decline in old age.

Dr Todd Jolly,
School of Psychology,
University of Newcastle,
Newcastle NSW 2300
AUSTRALIA

Email: Todd.Jolly@uon.edu.au

Journal & Proceedings of the Royal Society of New South Wales, vol. 149, parts 1 & 2, 2016, pp. 98–99. ISSN 0035-9173/16/010098–02

Thesis abstract

Achieving change in student assessment in Vietnamese teacher training institutions

Gam Thi Hong Luong

Abstract of a thesis for a Doctorate of Philosophy submitted to Southern Cross University, Lismore, Australia

The role of student assessment in shaping learning outcomes is well established. In Vietnam, there is a developing consensus at official levels that reform of student assessment practices in higher education institutions is required. In 2006 and 2007, the Ministry of Education and Training issued Decisions seeking to encourage higher education institutions to make more use of student assessment methods likely to support activity-based and self-directed approaches to learning. To date, however, Vietnamese universities and colleges have been remarkably slow to respond. They continue to rely on traditional standardised tests that promote rote learning and do little to develop critical thinking or problem-solving skills among learners.

The present investigation seeks to provide an understanding of the beliefs, values and attitudes towards student assessment of a group of lecturers and educational managers from three teacher training universities in Vietnam. Its purpose is to throw light on the conditions affecting their ability and willingness to reform student assessment practices at their institutions. Theoretical perspectives on student assessment from empirical research in developed higher education systems inform the investigation, and three theories of educational change are drawn upon in seeking to identify the factors that might impact on the student assessment reform process in higher education institutions in Vietnam.

An ethnographic approach is taken to the collection of data, and Naturalistic Inquiry (Lincoln & Guba, 1985) provides a methodological framework for the investigation. Ethnographic interviews were conducted with 24 experienced members of academic staff from across the three site institutions. These participants were selected using a 'snowball' sampling technique whereby each was recommended by a colleague as being interested in and experienced with issues in student assessment. The interview data were analysed by means of thematic analysis, with particular regard taken to ensure the trustworthiness of the findings.

Three distinct groups of participants are identified. For three of the participants, attitudes to teaching and student assessment were strongly teacher-centred, supportive of traditional standardised methods of student assessment, and shaped by beliefs that students should be obedient, passive learners. These participants had a limited understanding of the range of approaches to student assessment: they were unwilling to make any changes in terms of how they assessed student learning. For 13 of the participants, however, there was recognition of the need to reform student assessment practices:

these participants expressed a willingness to change their own assessment practices, but they felt constrained from doing so because of a perceived lack of expertise and because they saw that many more hours of work would be required to do so effectively. This group, therefore, had not implemented any significant changes. The third group of eight participants aspired to reform the ways in which students were assessed: they actively implemented measures intended to achieve effective reform. They were more inclined than any of the other participants to value their students as learners. They also claimed to be strongly supportive of the role and importance of formative assessment.

The investigation points to the importance of achieving an alignment between policy, leadership and practice in order to achieve enduring educational change. This alignment requires persistent effort to be directed at ensuring that all relevant stakeholders are properly informed about the goals and objectives of desired change. It also requires them to have the resources needed to engage meaningfully in the change process by implementing continuous assessment and formative feedback to learners about their learning progress. They must also have opportunities to converse collaboratively with their peers about why and how assessment practice needs to be improved.

Achieving a more enlightened approach to student assessment on a national scale in Vietnam's higher education system appears for the time being to remain a distant prospect. This investigation does, however, provide insights into what might need to be done to make the aspiration more achievable, more rapidly.

Dr Gam Thi Hong Luong
School of Education
Southern Cross University
Lismore NSW 2480
AUSTRALIA

Email: gamluong2012@yahoo.com

Journal & Proceedings of the Royal Society of New South Wales, vol. 149, parts 1 & 2, 2016, p. 100. ISSN 0035-9173/16/010100–01

Thesis abstract

Zone of impeachment: a post-Foucauldian analysis of controlled operations law and policy

Brendon Murphy

Abstract of a thesis for a Doctorate of Philosophy submitted to University of Newcastle, Newcastle, Australia

This thesis presents a Foucauldian analysis of Australian controlled operations law. The purpose was to extend current doctrinal scholarship by exploring the discursive forces that shape this highly invasive and controversial investigative power. This thesis contends that the present doctrinal understanding is incomplete, and largely unaware of the epistemological forces operating within law and policy. By deploying a Foucauldian analytic we can extend our understanding of the complex relationship between knowledge systems, discourse, power and law.

Through the deployment of a nomadic, grounded genealogy in the analysis of controlled operations Second Reading Speeches, this research found that the governing rationalities of controlled operations law and policy is linked to an imperative logic dominated by discourses of risk, audit and exceptions. This dynamic explains why controlled operations legal architecture and policy is in its current form. Far from being a reaction to the decision in Ridgeway, controlled operations law is part of a legal and cultural shift in law enforcement, characterised by complex relationships between risk, rights, law and citizenship. The controlled operation is revealed as a form of apparatus: a technology of truth and power, facilitated by law.

This insight allows us to re-imagine the relationship between law, rights, citizenship and sovereignty in late modernity. In this environment the investigative apparatus of the controlled operation creates a field of governance within the private space of liberal citizenship, revealing the true character of citizenship in late modernity as a zone of impeachment – a location in which rights are fragile and open to perpetual potential derogation and modification. In this zone the rights attached to liberal conceptions of citizenship are increasingly the subject of subordination to a risk imperative and a logic of exception.

Dr Brendon Murphy,
Department of Business and Law,
University of Newcastle,
Newcastle NSW 2300
Australia

Email: brendon.murphy@newcastle.edu.au

Journal & Proceedings of the Royal Society of New South Wales, vol. 149, parts 1 & 2, 2016, pp. 101–102. ISSN 0035-9173/16/010101–02

Thesis abstract

The effects and mechanisms of the therapeutic hypothermia on intracranial pressure regulation following ischaemic stroke in rats

Lucy Murtha

Abstract of a thesis for a Doctorate of Philosophy submitted to University of Newcastle, Newcastle, Australia

Background: Intracranial pressure (ICP) rises to dangerous levels 2 to 5 days after large ischaemic stroke. ICP following small stroke is not routinely monitored, although animal data suggests ICP rises 24 hours following small experimental stroke. Cerebral oedema has been thought to be the primary cause for ICP elevation. This assumption may have risen because ICP has only been monitored in patients with large infarct and oedema volumes. Since small ischaemic infarcts cause less cerebral swelling, ICP elevation may be the result of a different mechanism(s). Recent human imaging data indicates that patients deteriorating soon after minor stroke do so on the basis of cerebral collateral blood flow failure. Until now there has not been a plausible explanation for this "collateral failure". Long-duration hypothermia has been shown to lower ICP in patients. Long durations of cooling increase the risk of infection and rebound ICP during rewarming. Short-duration hypothermia has shown overwhelming efficacy in animal models of stroke but has not been tested in humans. I hypothesise: that ICP increases at 24 hours after small stroke; that this rise is not due to cerebral oedema; that ICP elevation reduces collateral blood flow; and that short-duration moderate or mild hypothermia prevents ICP elevation post-stroke. Methods: An epidural ICP monitoring technique was developed. Experimental ischaemic stroke (middle cerebral artery occlusion) was performed in Long Evans, outbred Wistar and Sprague-Dawley rats and ICP was monitored. Infarct and oedema volumes were calculated using wet-dry weight calculations, histology or in vivo magnetic resonance imaging. Collateral blood flow was visualized using fluorescent microspheres through a closed cranial window and recorded using a high-speed microscope-mounted recording camera. Short-duration moderate (32.5°C) or mild (35°C) hypothermia, or normothermia (37°C) was administered 1 hour post-stroke. Results: Mean ICP was 9.1 ± 5.2 mm Hg at baseline (pooled – all animals). ICP was significantly elevated 24 hours post-stroke in all normothermic animals (40.3 ± 16 mm Hg, pooled normothermic animals, $p < 0.0001$ vs. baseline). Mean infarct volume was 22.6 ± 17.5% of contralateral hemisphere. Oedema volumes were small and were not correlated with ICP post-stroke ($r^2 = 0.09$, $p = 0.15$). There was a strong correlation between ICP elevation and collateral blood flow decrease ($r = -0.62$, $p < 0.0001$). Early intervention of short-duration hypothermia completely prevented ICP rise post-stroke (10.3 ± 6.5 mm Hg, pooled hypothermic animals at 24 hours, $p < 0.0001$ vs. normo-

thermic animals at 24 hours). Conclusions: In this thesis, I have presented data that contradicts the accepted wisdom in several ways and has important implications for patients with stroke. It suggests that ICP could be elevated in patients with small stroke and that a factor other than oedema is the primary cause of this ICP elevation. The data also suggest that ICP elevation following stroke is the likely mechanism of collateral failure leading to neurological deterioration in stroke patients. Finally, I have demonstrated that short-duration hypothermia is an effective ICP preventative treatment following experimental stroke, and suggests that short-duration hypothermia clinical studies in humans is warranted. These findings suggest that a fundamental rethink of ICP regulation post-stroke is necessary and have potentially important and exciting implications for the future treatment of stroke and stroke-in-progression.

Dr Lucy Murtha,
School of Biomedical Sciences and Pharmacy,
University of Newcastle,
Newcastle NSW 2300
AUSTRALIA

Email: Lucy.Murtha@newcastle.edu.au

Journal & Proceedings of the Royal Society of New South Wales, vol. 149, parts 1 & 2, 2016, p. 103. ISSN 0035-9173/16/010103–01

Thesis abstract

Palaeontology, taxonomy and biostratigraphy of Cambrian assemblages from the Pertaoorrta Group, Amadeus Basin, Northern Territory

Patrick Mark Smith

Abstract of a thesis for a Doctorate of Philosophy submitted to Macquarie University, Sydney, Australia

The Amadeus Basin is a large sedimentary province in central Australia that covers an approximate area of 170,000 square kilometres. Despite the known occurrence of fossils from the majority of stratigraphic units within the Cambrian Pertaoorrta Group there is a dearth of published palaeontological data, including no comprehensive biostratigraphy.

Presented as part of this thesis is a detailed investigation into three formations spanning the Cambrian Series 2–3 units of the Pertaoorrta Group. The oldest of these, the Tempe Formation and Giles Creek Dolostone have previously been regarded as coeval. Examination of specimens from both drillcore and outcrop material from these two formations revealed a considerable diversity of new and biostratigraphically-informative fossils. The described taxa provide evidence that these two sedimentary units were deposited at different times. The Tempe Formation (in Paper 1) belongs to the Ordian, whereas the fauna from the Giles Creek Dolostone (in Papers 2–4) is distinctly younger and correlates with the overlying early Templetonian. These results suggest that the current regional stratigraphic scheme needs to be amended.

The youngest stratigraphic unit examined in this thesis is the Goyder Formation (in Paper 5). The initial age estimates for this formation were based solely on vague reports of trilobites. Our collections demonstrate that the Goyder Formation contains a highly diverse fossil fauna with at least 20 different trilobite taxa. This assemblage indicates a late Mindyallan age (equivalent to Cambrian Series 3, Guzhangian) within the Glyptagnostus solidotus Zone.

Detailed logging and sampling through formations in the Pertaoorrta Group has allowed for precise ages where little to no biostratigraphic data had previously been available. These ages have facilitated the development of a preliminary quantitative biostratigraphy of the Cambrian Series 2–3 portion of the Amadeus Basin, thus permitting more accurate intra- and interbasinal correlation.

Patrick Mark Smith,
Department of Biology,
Macquarie University,
Sydney NSW 2109
AUSTRALIA

Email: Patrick.mark.smith.1990@gmail.com

Journal & Proceedings of the Royal Society of New South Wales, vol. 149, parts 1 & 2, 2016, pp. 104–105. ISSN 0035-9173/16/010104–02

Thesis abstract

Targeted, one-to-one instruction in whole-number arithmetic: a framework of key elements

Thi Lệ Trần

Abstract of a thesis for a Doctorate of Philosophy submitted to Southern Cross University, Lismore, Australia

In Australia, although there has been strong advocacy for individualised intervention programs, there is a limited research literature available that focuses on teacher-student interactions and teaching practices related to one-to-one instruction. This investigation seeks to address that gap. Its aim is to identify and illuminate the nature of Key Elements of one-to-one instruction that expert tutors use when interacting in intensive, one-to-one instruction of whole-number arithmetic with Years 3 and 4 students. A Key Element is a micro-instructional strategy that is the smallest unit of analysis of highly interactive one-to-one instruction.

The investigation draws on data collected within the framework of the Mathematics Intervention Specialist Program (Wright, Ellemor-Collins & Lewis, 2011). From this source, approximately 33 hours of video recordings of teaching sessions involving four teachers and six students were analysed.

The theoretical perspective underpinning the investigation is interpretative. Within this perspective, a phenomenological approach was used to gain insight into the essence of the Key Elements of one-to-one intervention teaching. A standard method for analysing the data, that is, "close observation" (Van Manen, 1997, p. 68), in which the Key Elements are viewed as the central phenomenon requiring exploration and understanding, was employed. The analytical techniques described by Van Manen (1990, 1997), and further elaborated as procedures for phenomenological analysis by Hycner (1999), were applied. As well, the investigation utilised methodological approaches described by Cobb and Whitenack (1996), and by Powell, Francisco, and Maher (2003), for analysing large sets of video recordings.

Twenty-five Key Elements were identified and, for each, a deeply layered description was developed. As well, a comprehensive framework for analysing one-to-one instruction was conceptualised. The framework shows how Key Elements can be used to analyse intensive, one-to-one instruction in whole-number arithmetic.

The investigation advances understanding about teacher-student interactions and teaching practice in intensive, one-to-one interventions. Understanding the Key Elements leads to more effective ways to characterise the instructional strategies that teachers utilise in one-to-one intervention teaching. The framework developed constitutes an extension of the current body of theoretical knowledge about targeted one-to-one intensive intervention in whole-number arithmetic. It will inform teachers who are working with low-attaining students by

providing useful information about teacher-student interaction in mathematical interventions, which in turn may illuminate how particular teaching intervention practices influence student learning outcomes (Tran & Wright, 2014b).

Dr Thi Lệ Trần
School of Education
Southern Cross University
Lismore NSW 2480
AUSTRALIA
Email: tranlethicdsp@yahoo.com

Proceedings of the Royal Society of New South Wales

The 2016 programme of events – Sydney

Held at the Union, Universities and Schools Club, 25 Bent St, Sydney unless otherwise stated.

Wed 3 Feb	1240th Ordinary Meeting RSNSW Scholarship winners	Adrian Dudek Charles Forster Yevgeny Stadnik	Australian National University University of Sydney University of New South Wales
Mon 25 Feb	The Four Societies Lecture	Professor Robert Clark AO FAA Dist FRSN Chair of Energy Strategy and Policy, University of New South Wales	Australian Energy Policy
	Held in conjunction with the Nuclear Engineering Panel of the Sydney Branch of Engineers Australia, the Australian Nuclear Association and the Australian Institute of Energy. Held at Hamilton and Parkes Rooms, Level 47, MLC Centre, King and Castlereagh St.		
Wed 4 Mar	1241st Ordinary Meeting	Dr Len Fisher Visiting Fellow in Physics, University of Bristol	How to win an IgNobel Prize and other adventures in communicating science
Wed 16 Mar	Joint Lecture of the Australian Institute of Physics and the RSNSW	Professor Ron Grunstein Woolcock Institute of Medical Research, University of Sydney and Royal Prince Alfred Hospital, Head	From Snoring to Somnambulism – The Mystery of the Sleeping Brain
	Joint Meeting with the Australian Institute of Physics, held at Trinity Grammar School, Latham Theatre, 119 Prospect Road, Summer Hill		
Wed 6 April	1242nd Ordinary Meeting and 149th Annual General Meeting	Dr Donald Hector FRSN President of the Royal Society of New South Wales	Presidential address: Royal Society of NSW – relevance in the 21st century

Wed 4 May	Annual Dinner: Distinguished Fellow's Lecture and presentation of the Society's 2016 awards	Guests of honour: The Society's Vice-Regal Patron, His Excellency General The Honourable David Hurley AC DSC (Ret'd), Governor of New South Wales and Em. Professor Eugenie Lumbers AM DistFRSN	Science Policy and University Research
Wed 1 June	1243rd Ordinary Meeting	Professor Peter Hiscock Tom Austen Brown Professor of Australian Archaeology, University of Sydney	The curious case of the scientist in cinema: how Indiana Jones turns out to be the bad guy!
Wed 6 July	1244th Ordinary Meeting	Dr Bob Young Associate Professor of Geoscience (ret'd), University of Wollongong	"Royal" not "Philosophical" - W.B. Clarke's Inaugural Address to the Royal Society of NSW
Wed 3 Aug	1245th Ordinary Meeting	Dr. Barbara Briggs, Honorary Research Associate Royal Botanic Gardens	Celebrating the 200th Birthday of Royal Botanic Gardens: A Personal History of 57 years of Science
	Sydney Science Festival lunchtime science talks		
Fri 12 Aug	Sydney Science Festival	Professor Mikhail Prokopenko, University of Sydney	Complex Systems and Swarm Intelligence
Tu 16 Aug	Sydney Science Festival	Dr Brett Summerell Royal Botanic Gardens	The Royal Botanic Gardens 200th Birthday
Wed17 Aug	Sydney Science Festival	Em Professor Brynn Hibbert UNSW, President RSNSW	Courts, Criminals and Chemistry: Forensic Science in NSW
Thu 18 Aug	Sydney Science Festival	Professor Pascal Perez University of Wollongong	Community-driven Internet of Things: the new revolution?
Wed 7 Sep	1246th Ordinary Meeting	Richard Neville Mitchell Librarian and Director, Education & Scholarship State Library of NSW	A source of inspiration and delight: The Mitchell Library
Wed 5 Oct	1247th Ordinary Meeting	Professor Itai Ianev School of Engineering, University of Sydney	From sand and rice bubbles to earthquakes and volcanoes
Thu 13 Oct	2016 Dirac Lecture	Duffield Professor Kenneth Freeman Australian National University	Dark Matter in the Universe
Wed 2 Nov	1248th Ordinary Meeting	Professor E. James Kehoe Professor of Psychology, UNSW	Finding the Right Course for the Right Horse: Recent Evidence-Based Advances in Instructional Design
Tue 29 Nov	RSNSW and Four Academies Forum	Government House, Sydney; hosted by his Excellency General The Honourable David Hurley AC DSC (Ret'd) Governor of NSW and Patron of the Royal Society of NSW at Government House	Society as a complex system: Implications for Science, Practice and Policy and Celebration of the 150th Anniversary of Royal Patronage

	Held in cooperation with the Australian Academy of Science, the Australian Academy of Technological Sciences and Engineering, the Australian Academy of the Humanities and the Academy of Social Sciences in Australia.		
Wed 7 Dec	1249th Ordinary Meeting	Royal Society of NSW 2016 Jak Kelly Award: Matthew Barr School of Mathematical and Physical Science, Newcastle University	Imaging with a deft touch – The scanning helium microscope

The 2015 programme of events – Southern Highlands

Held at the Performing Arts Centre, Chevalier College, Bowral.

Thu 18 Feb	Dr Charley Lineweaver School of Astronomy & Astrophysics and Earth Sciences, Australian National University	Death and Nothingness: Why did Death Evolve? Why is there Something Rather than Nothing?
Sat 12 Mar	Dr Christian Heim and Dr Caroline Heim	Special Event: An Afternoon with Chopin and George Sand
Thu 21 Apr	Prof Gordon Parker Scientia Professor of Psychiatry, UNSW, Executive Director of the Black Dog Institute	Winston Churchill, bipolar disorder, and the Dardanelles campaign
Thu 19 May	Dr Kathleen Riley Freelance writer, theatre historian and critic	The Science of Spontaneity: Fred Astaire as the Consummate Craftsmen
Thu 16 June	Dr Ken McCracken Solar physicist, foundation director of CSIRO Office of Space Science and of CSIRO Division of Mineral Physics	The Sun, Sunspots, and Space Weather
Thu 21 July	Dr David Suhy Chief Scientific Officer, Benitec Biopharma	Silencing Genes for Life
Thu 18 Aug	Ian Skinner Neuroscience Research Australia (NeuRa)	Chronic Pain
Thu 15 Sep	Assoc Prof Tony Masters Chair of the Academic Board, University of Sydney	Sustainability – Chemical Solutions for a Tricky Problem
Thu 20 Oct	Prof Gordian Fulde Director of emergency at St Vincent's Hospital, Senior Australian of the Year 2016	Do we have a problem? – Hospital emergency, alcohol and drugs
Thu 17 Nov	Prof Gordon Wallace Director, ARC Centre of Excellence for Electromaterials Science, University of Wollongong	BioPrinting: 3D Printing Parts for Bodies

Awards for 2016

The Council of the Royal Society of New South Wales have determined to make the following awards for 2016:

1. Edgeworth David Medal.

Associate Professor Simon Ho
ARC Queen Elizabeth II Fellow, School of Biological Sciences, University of Sydney.

The Edgeworth David Medal, established in memory of Professor Sir Tannatt William Edgeworth David FRS, a past President of the Society, is awarded for distinguished contributions by a young scientist under the age of 35 years.

Associate Professor Simon Ho has made hugely important contributions and developed new methods in the field of 'molecular clocks' in biology – a way of estimating evolutionary rates and timescales from DNA sequences using statistical models. These estimates underpin a broad range of studies in conservation genetics, speciation and diversification, domestication of animals and plants, events in human prehistory, and the population dynamics of pathogens. His research focuses on understanding how evolutionary rates vary at the genomic level and estimating the timescale of the Tree of Life. These are fundamental goals of biological inquiry because they deal with the details of the evolutionary process.

Simon Ho's work has set a range of standards in the field, as well as producing methods and practises that are now widely used by researchers. His research has led to important improvements in the way that researchers estimate evolutionary timescales using genetic and genomic data, with significant consequences for our understanding of the evolutionary past.

2. History and Philosophy of Science Medal.

Professor Warwick Anderson
ARC Laureate Fellow and Professor in the Department of History and the Centre for Values, Ethics and the Law in Medicine, University of Sydney. Additionally, he has an affiliation with the Unit for History and Philosophy of Science at Sydney University.

The Royal Society of NSW History and Philosophy of Science Medal was established in 2015 to recognise outstanding achievement in the History and Philosophy of Science. The medallist will have made a significant contribution to the understanding of the history and philosophy of science, with preference being given to the study of ideas, institutions and individuals of significance to the practice of the natural sciences in Australia.

Professor Anderson is a medical doctor turned historian, who has made important contributions to the history of science, medicine, and public health; the history of racial thought and postcolonial science studies. He is a Fellow of the Academy of the Social Sciences, and won the 2014 History of Science Society's Price/Webster Prize for the article, "Hybridity, Race and Science: The Voyage of the Zaca, 1934-1935."

In 2014 Professor Anderson, with immunologist Ian Mackay, wrote a brilliant and original book, *Intolerant Bodies: A Short History of Autoimmunity*, published by Johns Hopkins University Press. The authors follow the puzzle of autoimmunity from theory to laboratory practice to individual patients' case histories. The result is a compelling study of concepts in action. This sophisticated but highly readable history helps close the gap between medical science and the general public's understanding.

3. Clarke Medal for Zoology.

Professor Christopher Dickman
University of Sydney School of Biological Sciences.

The Clarke Medal was established to acknowledge the contribution by Rev William Branwhite Clarke MA FRS FGS, Vice-President of the Royal Society of New South Wales from 1866 to 1878. The Medal is awarded

annually for distinguished work in the natural sciences of geology, botany and zoology done in Australia and its Territories.

Professor Dickman's major contributions lie in terrestrial zoology and ecology. He has long been curious about the factors that promote and maintain biodiversity, especially among land mammals and other terrestrial vertebrates. For the last 35 years he has focused in particular on understanding the forces that shape the distribution and abundance of Australia's endemic mammals and identifying the factors that are causing so many species to decline. His ground-breaking work on Australia's desert mammals and on the continent's introduced predators have gained him a formidable reputation as a leading national and international authority on mammalian ecology.

4. Royal Society of New South Wales Scholarships.

Adrian Dudek (Australian National University, School of Mathematics)
Yevgeny Stadnik (University of New South Wales, School of Physics)
Charles Foster (University of Sydney, School of Botany)

The Council of the Society funds the Royal Society of New South Wales Scholarship in order to acknowledge outstanding achievements by early-career individuals working, in a science-related field within New South Wales or the Australian Capital Territory, towards a research degree in a science related field.

Adrian Dudek is working in number theory under Dr Trudgian at the ANU. During his PhD he has published (or had accepted) eight papers in the peer reviewed literature. His application explained his research thus: "In particular, I'm interested in the elusive tale of the prime numbers. When I let this slip to most people, somewhat tepid memories of their primary school days are horrifically conjured. However, the prime numbers have been studied for thousands of years, or at least since 300BC, when the great Greek geometer Euclid proved that there are infinitely many of them. Since such ancient times, the primes have attracted the attention of curious mathematicians (and other characters) for one reason: it's extraordinarily difficult to understand the behaviour of the prime numbers. For instance, if you were to write down a list of the first 100 prime numbers (a rousing exercise for a Friday night, I'm sure!), you would not be able to find an intelligible pattern. That being said, some recent spectacular advances in number theory mean that the prime numbers are becoming less elusive and more understandable …"

Yevgeny Stadnik works with Professor Flambaum FRSN on "Manifestations of Dark Matter and Variation of Fundamental Constants in Atoms and Astrophysical Phenomena". He writes: "My project is on the investigation of new effects produced by dark matter and proposing novel ways of detecting dark matter. We have published a number of important works in this direction, including results that already improve on existing sensitivities in the detection of certain types of dark matter by up to 15 orders of magnitude. Our results have been published in leading physics journals, including three publications in Physical Review Letters (which is the most highly cited physics journal), and have contributed to the initiation of a number of new laboratory searches worldwide."

Charles Forster is a botanist working with our Edgeworth David medallist Simon Ho on a project "Using genome-scale data to untangle the evolutionary history of flowering plants". A University of Sydney medallist, Charles has been able to estimate the timescale of evolution of a range of plants using genomic data. His analyses have been careful and comprehensive, and he is on the verge of publishing his outstanding work on this topic. This is in addition to three papers from his honours research and three published or under review. This work has also led to the development of some important research collaborations with colleagues at the Royal Botanic Gardens (Sydney) and Université Paris-Sud (France). He writes: "I have provided the most comprehensive combination of analyses of the angiosperm evolutionary timescale so far. The results I have obtained reflect the increasingly common finding that molecular dating estimates predate the oldest fossils by a non-trivial amount of time, up to 70 million years when considering mean estimates."

5. *The Royal Society of New South Wales and Australian Institute of Physics Jak Kelly Award.*

James Colless
University of Sydney, School of Physics

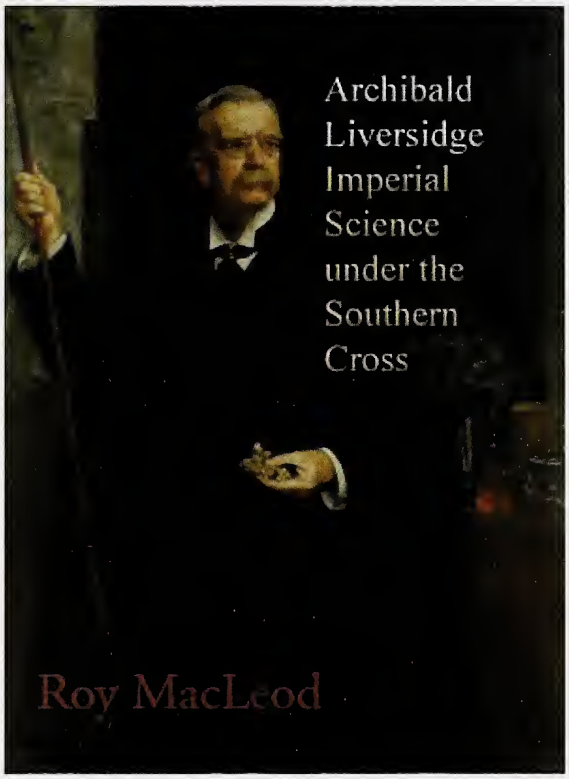
The Jak Kelly Award is awarded jointly with the Australian Institute of Physics (AIP) to the best PhD student talk, this year presented to a joint meeting with the AIP held on November 17 at Trinity Grammar School.

James Colless is a postgraduate student at the University of Sydney currently undertaking his PhD under the supervision of Professor David Reilly. His research focus is readout and control techniques for GaAs spin qubits. James hopes his research will influence the design and fabrication of reliable multiqubit gates. His talk was entitled "From Quantum Devices to Quantum Machines". It explored the complexity of scaling quantum processors and discussed new techniques and hardware developed to meet these challenges. In particular, James had developed new methods of readout that allow the dispersive sensing of single-electrons using integrated sensors and the capability to read out multiple qubits simultaneously. A scalable control scheme is also demonstrated allowing large numbers of qubits to be manipulated with a small number of input signals.

The award consists of an engraved plaque, a $500 prize and a year's membership of the Society. As the winner of the Jak Kelly award, James presented his talk to Royal Society on the 1st of November at the Union, Universities and Schools Club.

Archibald Liversidge:
Imperial Science under the Southern Cross

Roy MacLeod
Royal Society of New South Wales, in association with Sydney University Press
ISBN 9781-9208-9880-9



When Archibald Liversidge first arrived at the University of Sydney in 1872 as Reader in Geology and Assistant in the Laboratory, he had about ten students and two rooms in the main building. In 1874, he became Professor of Geology and Mineralogy and by 1879 he had persuaded the University Senate to open a Faculty of Science. He became its first Dean in 1882.

In 1880, he visited Europe as a trustee of the Australian Museum and his report helped to establish the Industrial, Technological and Sanitary Museum which formed the basis of the present Powerhouse Museum's collection. Liversidge also played a major role in establishing the *Australasian Association for the Advancement of Science* which held its first congress in 1888.

This book is essential reading for those interested in the development of science in colonial Australia, particularly the fields of crystallography, mineral chemistry, chemical geology and strategic minerals policy.

To order your copy, please complete the Liversidge Book Order Form available at: http://royalsoc.org.au/publications/books/McLeod_Liversidge_Order_Form.pdf and return it together with your payment to:

The Royal Society of NSW,
(Liversidge Book),
PO Box 576,
Crows Nest NSW 1585,
AUSTRALIA

or contact the Society:

Phone: +61 2 9431 8691
Fax: +61 2 9431 8677
Email: info@royalsoc.org.au

INFORMATION FOR AUTHORS

Details of submission guidelines can be found in the on-line Style Guide for Authors at:
http://royalsoc.org.au/publications/author_info.htm.

Manuscripts are only accepted in digital format and should be e-mailed to: editor@royalsoc.org.au

The templates available on the Journal website should be used for preparing manuscripts. Full instructions for preparing submissions are also given on the website.

If the file-size is too large to email it should be placed on a CD-ROM or other digital media and posted to:

The Honorary Secretary (Editorial),
The Royal Society of New South Wales,
PO Box 576,
Crows Nest, NSW 1585
Australia

Manuscripts will be reviewed by the Editor, in consultation with the Editorial Board, to decide whether the paper will be considered for publication in the Journal. Manuscripts are subjected to peer review by at least one independent reviewer. In the event of initial rejection, manuscripts may be sent to other reviewers.

Papers (other than those specially invited by the Editorial Board) will only be considered if the content is either substantially new material that has not been published previously, or is a review of a major research programme. Papers presenting aspects of the historical record of research carried out within Australia are particularly encouraged. In the case of papers presenting new research, the author must certify that the material has not been submitted concurrently elsewhere nor is likely to be published elsewhere in substantially the same form. In the case of papers reviewing a major research programme, the author must certify that the material has not been published substantially in the same form elsewhere and that permission for the Society to publish has been granted by all copyright holders. Letters to the Editor, Discourses, Short Notes and Abstracts of Australian PhD theses may also be submitted for publication. Please contact the Editor if you would like to discuss a possible article for inclusion in the Journal.

The Society does not require authors to transfer the copyright of their manuscript to the Society but authors are required to grant the Society an unrestricted licence to reproduce in any form manuscripts accepted for publication in the Journal and Proceedings. Enquiries relating to copyright or reproduction of an article should be directed to the Editor.

Volume 149 Parts 1 & 2 2016 Numbers 459 to 462

CONTENTS

The Royal Society of New South Wales
P.O. Box 576
Crows Nest, NSW 1585, Australia

info@royalsoc.org.au (general)
editor@royalsoc.org.au (editorial)
www.royalsoc.au
www.facebook.com/royalsoc

ISSN 0035-9173

Published December 2016