

Geochemical Perspectives

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LAWRENCE D. MEINERT

Geology, Policy, and Wine – The Intersection of Science and Life



Each issue of *Geochemical Perspectives* presents a single article with an in-depth view on the past, present and future of a field of geochemistry, seen through the eyes of highly respected members of our community. The articles combine research and history of the field's development and the scientist's opinions about future directions. We welcome personal glimpses into the author's scientific life, how ideas were generated and pitfalls along the way. *Perspectives* articles are intended to appeal to the entire geochemical community, not only to experts. They are not reviews or monographs; they go beyond the current state of the art, providing opinions about future directions and impact in the field.

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About the cover

The cover is a montage of two photographs, both by Larry Meinert. The lower one is of a partly skeletal, but euhedral, galena crystal (about 4 by 2 cm) on a bed of red-brown garnet from the San Juan chimney in the El Mochito mine, Honduras. The upper photograph shows a small chapel in a vineyard in the Tokaji region of Hungary.

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PREFACE

I am not sure exactly when I first met Larry Meinert. I certainly knew of him long before I met him; as a stalwart of the Society of Economic Geologists and later, as the Editor of their flagship journal *Economic Geology*. It is likely that I met him as a post-doc at one of the “Hydrothermal Fluid Society” (HFS) events that Larry organises at various conferences around the globe. To gain access to one of these meetings, one must buy a bottle of wine and send the details to Larry in advance. He then sends you an address, where you spend the evening with a room full of Economic Geologists “tasting” the wine. Although the HFS meetings are great fun, they also give early career researchers an opportunity to interact with senior figures in the field in an informal setting away from the conference and I, certainly, benefited from this personally.

I approached Larry to write this *Geochemical Perspectives*, not because of his contributions to understanding skarn deposits, which are significant, but because of the diversity of his career. Initially, his academic career developed like many others, with graduate work and post-docs leading to a tenured position at Washington State University. However, I was surprised to learn that Larry gave up that permanent position to move to the eastern U.S. to facilitate a career move for his wife, and did it again, when she got a job in Washington D.C. In doing so, he took a leap into the unknown and changed his career path, which resulted in a stint as a Congressional Fellow in the U.S. Government and later as the Deputy Associate Director for Energy and Mineral Resources at the U.S. Geological Survey. This led to a very different use of the research and communication skills he had acquired as an academic; influencing science policy.



I am writing this preface at home in week 8 of the COVID-19 lockdown in Germany. Having lived in 4 countries, I am monitoring the way the different governments respond to the scientific advice, how effective the experts are in communicating their science, but also how effective the governments are in communicating facts to the public. In academia, I think sometimes we forget that citations and H indices are just a measurement of how successful we are at communicating to other scientists. In this “post-truth” world, in light of the challenges ahead in developing a sustainable future for the planet (and the human race), science will be important, but the effective communication and practical application of that science will be paramount. I hope in reading this *Geochemical Perspectives*, Larry’s story will inspire some of you to become involved in the shaping of science policy for future generations; we need our best and brightest to lead the way.

Sarah A. Gleeson

May 2020 (with a glass of Reisling from the Rhinegau in hand!)
German Research Centre for Geosciences, Potsdam, Germany
Geochemical Perspectives Handling Editor of this issue



ACKNOWLEDGEMENTS

This issue of *Geochemical Perspectives* started with an invitation by editorial board member Sarah Gleeson, to go beyond reflection on a scientific career and describe a journey through life (luckily not ended yet, since this issue was written during the early stages of the COVID-19 pandemic). This was a daunting task because my path has not been typical and several parts of the journey epitomise what the poet Robert Frost described as “the road not taken”, at least not by most scientists. This *Geochemical Perspectives* issue would not have been possible without, and certainly was greatly improved by, the careful review of individual chapters by knowledgeable experts. They include: Angel Abbud-Madrid, Shaun Barker, Maeve Boland, Alan Busacca, Zhaoshan Chang, Dave Cooke, Rich Goldfarb, Jeff Hedenquist, Murray Hitzman, Samantha Noble, and Mary Savina. In addition, Sarah Gleeson and two anonymous reviewers examined the entire issue. Each person is thanked for their careful consideration and everyone is absolved for any remaining errors, which fall solely to me. Finally, I would like to thank Marie-Aude Hulshoff for her gracious handling of the publication production process, Rob Raiswell for his fastidious copyediting, and Juan Diego Rodriguez Blanco for his technical artistry with the figures.

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GEOLOGY, POLICY, AND WINE – THE INTERSECTION OF SCIENCE AND LIFE

ABSTRACT

A full life can encompass many things including education, teaching, editing, research, government service, policy, and wine. Such a life may not even be restricted to Earth but may extend to investigations of asteroids, the Moon, and other planets, such as Mars. Underlying this broad range of interests, mineral resources are the building blocks of civilisation. Geochemistry helps us understand mineral resources in a fundamental way, ranging from origin, through discovery and utilisation, to disposal and consequences of use. Geochemistry is particularly important in the study of skarn deposits because they are a natural geochemical laboratory for mineral reactions involving hot silicate magmas with cooler carbonate-bearing wall rocks. Skarn deposits can also concentrate gold, a metal that has fascinated humans throughout history. Pre-dating even this, is the human interest in wine, as evidenced by archaeological finds in China, Georgia, Greece, Iran, and Turkey dating back some 9,000 years and by a fully functioning winery established in Armenia more than 6,000 years ago. All of the above are explored in this *Geochemical Perspectives* issue with an eye towards young scientists who are fashioning their own paths through a world made more chaotic by pandemics and changing social and political attitudes towards truth, facts, and evidence.



Previous *Geochemical Perspectives* on scientific careers have been deserved celebrations of distinguished scientists, their work, and their science. They range from very large publications (259 pages!) covering the broad field of Mineral-Aqueous Solution Interfaces (Brown and Calas, 2012) to trailblazing applications of isotope geochemistry like Fogel (2019), the first woman to be featured in this series. In general, the focus has been on the science and the contributions of the featured authors to that science. The present paper will be somewhat different. Although there will be a review of the science of skarn deposits and the geochemistry, mineralogy, and petrology relevant to understanding these natural geochemical laboratories, there will also be discussion of a broad career covering a range of topics including public policy, space resources, teaching, the scientific publication process, wine, and the resources needed for modern civilisation. This totality is being presented in *Geochemical Perspectives* to illustrate for young scientists that there is not just one scientific path to success. When I talk to young scientists today, I increasingly hear questions of “Do I belong?”, “How do I balance career and family?”, “Is there room for women, minorities, LGBTQ, or people interested in policy, societal issues, or leading a balanced, meaningful life?”. I cannot address all of these issues in detail but I think that my career path differs enough from that of a traditional lab scientist to offer some insight into the range of possibilities that a young scientist might explore during their lifetime.

Although I am now a geologist and to some degree a geochemist, I did not grow up thinking that an earth science career lay ahead. I did not know any geologists, I did not have a rock collection, nor did I have any particular fascination with dinosaurs. In fact, like many young people I did not know anything about geology and precious little about planet Earth. It really was serendipity that led to my first exposure to geology in college and subsequent good fortune (luck is not too strong a word) to encounter professors and fellow graduate students that turned me into an economic geologist who uses geochemistry as a primary tool.

The first step on my path was attending Carleton College, a small liberal arts institution in rural Minnesota. Unbeknownst to me Carleton was and is a geological legend, having turned out more students *per capita* who went on to become PhD geologists and university professors than perhaps any such college on Earth. I will elaborate on that in the section on Education but suffice it to say that out of the students in my cohort at Carleton four of us went on to become professors of economic geology at major universities (University of Alberta, University of Oregon, University of Wisconsin, and Washington State University) and several others became professors in other geological and geochemical fields. Serendipity continued at Stanford University where I had the good fortune to enroll in the same year that Professor Marco Einaudi began his academic career, which fostered dozens of economic geologists, although few if any of us knew anything about economic geology when we came to Stanford. Fellow graduate



students who came with strong chemistry backgrounds from institutions such as MIT and Cal. Tech. taught me more about geochemistry than I would ever have learned in the classroom. Once again, my cohort of about two dozen graduate students produced multiple professors (7) of economic geology and about half of the graduate students in my cohort became professors in other geological and geochemical fields. To summarise, I did not grow up thinking I would be an economic geologist or a university professor but that is where my winding educational path led.

Following my PhD and then throughout my 30 year academic career, first at Washington State University and later at Smith College, I worked closely with private industry exploring the far corners of the earth for mineral resources. I found it very satisfying to be able to apply the basic science of geology and geochemistry in the search for economic concentrations of metals such as copper, gold, tungsten, and zinc that are the building blocks of modern civilisation. Although much of my basic science research was funded by the National Science Foundation and other governmental agencies, it is the application of that science to discovery that I found most satisfying. My main contribution was the development of the first model for the occurrence of gold in skarns (Meinert, 1986, 1988, 1989, 1998, 2000). This model was built on a detailed understanding of geochemistry, mineralogy, and petrology such that for the first time it was possible to do predictive exploration on the occurrence of such deposits. Prior to this groundbreaking work, little was known about gold skarns, as evidenced by zero mention of them in the classic skarn review paper in the *75th Anniversary Volume of Economic Geology* (Einaudi *et al.*, 1981). Fast forward to the present and there are now dozens of skarn deposits that produce gold and there is an entire section on gold skarns in the *100th Anniversary Volume of Economic Geology* (Meinert *et al.*, 2005). If I live long enough I might be able to contribute to the *125th Anniversary Volume of Economic Geology* and thus become the first person to publish review articles in three successive Anniversary Volumes.

As a professor at a major research institution my primary responsibility was maintaining an externally funded research programme to advance knowledge and train the next generation of researchers. My students and I have published more than 200 peer reviewed papers on various ore deposits and several of my former PhD students and post-docs now have academic positions of their own at universities around the world including Dr. Zhaoshan Chang who is now the Charles Fogarty Endowed Chair and Professor in Economic Geology at the Colorado School of Mines, one of the top positions in this field in the world.

Another role of my university career was as teacher, instructing students ranging from undergraduates to PhD candidates and post-docs. I enjoy and take great pride in my teaching. If I had to choose one course to illustrate my teaching it would be a course I created called “Sherlock Holmes and the Scientific Method”. The course’s premise is that Sherlock was a master of observation, a skill that field geologists rely on in their daily work. The final assignment for the course is to



write an original Sherlock Holmes story, in dialogue, whose central plot element involves geology, geochemistry, and geologic observation. I will elaborate on that in the section on Teaching.

A third duty of a university professor is public service. This can take many forms but one that contributed to my later activities in the public policy sector is that I was elected and served two terms as the Chair of the ~1,500 Faculty at Washington State University. As such I served on the university governing Board of Regents, represented the University to the State Legislature, and presided over monthly meetings of the Faculty Senate that were televised statewide to a potential audience of more than 5 million people. I assumed that such academic proceedings would have little interest to the general populace but learned otherwise when more than once on airline flights or even on the Alaska state ferry system I would have people start talking to me, as if we were close personal acquaintances, about various subjects that I had led the discussion of in the Faculty Senate. Although I have never been and never will be a celebrity or movie star, this gave me some insight into what it must be like when people feel that they know you because they have seen you on television.

In 2003 I left Washington State University to follow my wife, Georgia Yuan, who had accepted a position as General Counsel at Smith College on the other side of the country in Massachusetts. This was somewhat unusual in several regards. First it meant walking away from a tenured Full Professor position to an uncertain future where I would have to reinvent my life in a new setting. Second it meant subordinating my career to my spouse's because at this stage of our lives it was the right thing to do (some might invoke the phrase "payback time"). Neither of these actions will be foreign to the experience of generations of women who have done similar things in the patriarchal societies of many countries around the world. And I claim no special credit or application for sainthood in so doing; as I previously stated it was simply the right thing to do. But for all those early career and dual career scientists who might be reading this paper, I hope this serves as encouragement that society is changing, albeit too slowly, and that there is hope for people who have not always been privileged by the society in which they live.

Smith College was in some ways a return to my roots because, like Carleton, Smith is a liberal arts college. But it is greatly different in that it is a women's college with its own history and culture that are unlike anything I had ever experienced. I was fortunate to occupy a Professor in Residence position which allowed me to continue to participate in academic life. In addition to teaching the previously mentioned Sherlock Holmes and the Scientific Method course I also taught economic geology. Such a course is not unusual at major research universities but it is rare to non-existent at liberal arts colleges in general and women's colleges in particular. Much to everybody's surprise, including my own, the course was very popular and successful. Since economic geology had ceased to be taught at other prestigious Universities in the northeastern United States, such as Dartmouth, Harvard, and Yale to name but a few, it was heartwarming that students from other universities enrolled as well. In response to those schools



that view economic geology as a dying subject, including my *alma mater* Stanford University, the success of this course should serve as a bellwether. Equally surprising that Smith College students would sign up for such a course is the fact that the majority of the students who took the course during my years at Smith went on to graduate school in economic geology and several have already earned PhDs in economic geology or related disciplines.

My life took another unexpected turn in 2010 when my wife was recruited to join the Obama administration in Washington, DC, first in the Department of Education's General Counsel Office and then as the Deputy Under Secretary of Education for the United States. Once again, I was the trailing spouse but now I was leaving the academic world entirely. I took the opportunity to apply for, and was accepted, as a Congressional Fellow. The Congressional Fellowship programme is administered by the American Association for the Advancement of Science (AAAS) and the approximately 30 Fellows are selected and funded by individual scientific societies such as the American Chemical Society, the American Mathematical Society, and in my case the Geological Society of America and the United States Geological Survey (USGS). The aim of the Congressional Fellowships is to inculcate scientific expertise and to some extent, culture, into the United States Congress. After intense training on the legislative process each Fellow serves a year in a Congressional office or committee, such as the Senate Energy and Natural Resources Committee. In my case I first served in the office of Representative Gabrielle Giffords (8th district of Arizona) and was there at the time of the tumultuous shooting that resulted in her being unable to continue in public office. I then served in the office of Senator Chris Coons (Delaware). In both cases I helped staff the respective House and Senate committees dealing with energy, resources, and environmental policy. Learning the internal workings of government was invaluable for my later involvement with the USGS where I would testify before the very same committees that I used to staff. Needless to say, this provided invaluable insight that could not have been gained by any amount of study or mentoring.

After the Congressional Fellowship I joined the Mineral Resources Program at the United States Geological Survey. This was an important transition time because the Program's budget had been in steep decline for several years and two successive studies by the National Academy of Science (National Research Council, 1996, 2003) indicated that only a radical change in leadership could save it. I was brought in to provide that leadership to help rebuild the budget, integrity, and scientific focus of the Mineral Resources Program. I subsequently became Deputy Associate Director for Energy and Mineral Resources (adding Energy to my portfolio) where I was partly responsible for the activities of approximately 500 scientists across the country and a budget of \$100 M.

Since the budget for the USGS and the Energy and Mineral Resources Program is set each year by the United States Congress, it was important to build or rebuild the relationship with Congress. This was accomplished by briefings for individual Representatives, Senators, and Congressional staff to help them



better understand the importance of mineral resources to the people of the United States. I also became involved with policy at the Executive Branch level including co-chairing the White House National Science and Technology Council: Subcommittee on Critical and Strategic Mineral Supply Chains (Nassar *et al.*, 2015). This included work on the policy implications of potential scarcity (Nickless *et al.*, 2015; Meinert *et al.*, 2016) and supply disruptions (Ali *et al.*, 2017) of critical mineral commodities such as rare earth elements (Eggert *et al.*, 2016). I testified on this subject before Congress and also spearheaded U.S. Geological Survey activities that led directly to recent Executive (Presidential Order 13817) and Secretarial (Department of Interior – S.O. 3359) orders. I also represented the United States in meetings at the European Union (EU), the European Commission (EC), the Organisation for Economic Cooperation and Development (OECD), and China and Japan.

More recently I have engaged in the field of space resources (Meinert, 2019). NASA and the space community recognise that human travel to, and future habitation of, celestial bodies such as the Moon and Mars will require utilisation of resources found in space, particularly water, as it is not economically feasible to transport the needed quantities from Earth. I have published research on the types and availability of resources on asteroids, the Moon, and Mars that might be used in the future (Meinert and Williams, 2018; Keszthelyi *et al.*, 2017, 2019). I am also working with individuals in the private sector who are leading this innovation.

A personal passion is the application of geological science to viticulture and wine. I have published numerous scientific papers on specific appellations (Meinert and Busacca, 2000, 2002; Busacca and Meinert, 2003; Costantini and Meinert, 2003; Meinert and Curtin, 2005; Meinert and Nelson, 2006), general reviews of the field (Macqueen and Meinert, 2006), and most recently a special issue of the journal *Elements* on “*Terroir: Science Related to Grape and Wine Quality*” (Meinert, 2018a,b). In addition to research, I also operate a small home winery specialising in a barrel-fermented Bordeaux-style blend of Cabernet Sauvignon, Carmenere, and Malbec. Periodic sampling is required.

I have been heavily involved in the field of scientific publication. Starting in 2003 I was co-editor of *Mineralium Deposita*, a scientific journal published by Springer Verlag based in Heidelberg, Germany. Twice a year I attended meetings at their offices in Germany to discuss not only the journal but the entire business model of the academic press. *Mineralium Deposita* was increasingly successful and in 2008 I was recruited to become the sixth Editor in Chief in the 113 year history of the journal *Economic Geology*, the premier scientific journal in the field of mineral resources, a position that I have now held for more than 10 years. I am responsible for helping to guide the science of an essential discipline related to global mineral resources and also manage an editorial board of 25 top scientists around the world. At the policy level I have participated in ongoing global discussions about Open Access to publications and scientific protocols. I lecture widely on the scientific publication process, both in the U.S. and abroad (e.g., in



China, where there is a different view on this process), including how to write, review, and edit quality papers. For students and faculty who want to publish in top tier journals it is essential to understand how to convey the results of research in publications, and I can provide an insider's view of that topic.

In summary, I have had a full career that along with raising a family has allowed me to engage in a diverse range of topics. I suspect that more lies ahead as I have always been curious about things that I have not yet been exposed to or understood. There is an excitement in the new and the unexplored. It is somewhat like my work as an exploration geologist; we go to places that have not yet been fully tested to see if there is something new or unnoticed by others. It keeps life exciting. In my spare time I am a published photographer, avid cook, and run marathons. Starting about 10 years ago I started running to stay in shape and clear my head. I have qualified for and run the Boston Marathon twice, in addition to most of the military (Air Force, Army, Marine Corps, and Navy) and scenic (Big Sur and St. George, Utah) marathons in the United States. I do not have the build of a runner but I enjoy training and am persistent. In the race between the tortoise and the hare, I am definitely the turtle.

The remaining sections of this *Geochemical Perspectives* publication will explore in more depth each of the subjects mentioned above. As previously stated, the audience for this publication is not just scientists who may have a detailed interest in a particular field but also young scientists who have broad interests that include policy and societal issues that are not the strict domain of science. It is my belief that science can contribute to many aspects of a well-lived life and that even the best scientists do not need to be restricted to a life of only science. Let art, music, policy, and yes, a nice glass of wine, bring pleasure to your scientific career.



2.1 Early Days

One purpose of the *Geochemical Perspectives* series on scientific careers is to explore how one became involved with geochemistry in the first place since very few people are aware of this scientific discipline in their early days and unless one's parents were geochemists it would be easy to sail through one's primary education without any knowledge or awareness of geochemistry. In my case I was not only unaware of geochemistry but I literally did not know about the science of geology or even the broader field of earth science.

For my European and Asian colleagues who tend to have much stronger pre-university science training than Americans let me explain a bit about the American educational system. Elementary and Secondary education, *i.e.* pre-university, is nearly universal in the United States. For example, enrollment of 7 to 13 year old children has been 98-99 % across the country for the past several decades, but not everyone who attends high school (grades 9-12), graduates. About 88 % of people living in the United States obtain a high school degree (U.S. Department of Education, 2019).

In addition, the quality and required subject matter varies substantially from state to state (which control pre-university education) and from locality to locality within the United States. Because of this local control, the wealth of the community correlates with the amount of money available for education, since most public schools are supported by property taxes. In addition, there is a significant difference between public (~90 %) and private schools (~10 %), again with a strong link to economic status since public school is free and private schools cost money, in some cases as much as the cost of going to university (U.S. Department of Education, 2019).

I grew up in Cincinnati, Ohio and went to public schools throughout my pre-university education of 12 years. During this time, I had one general biology course and one general chemistry course. There was no geology or earth science, and as a result, I was unaware of these disciplines. Physics was optional and approximately 30 of us out of my high school graduating class of ~1,500 took physics. Mathematics was more available and most students took at least some math through high school. Sixty of us (out of 1,500) enrolled in calculus. I liked math and science and did well in these subjects, although I certainly did not think of myself as a scientist. I preferred history and literature and took what are called advanced placement courses (those with high scores on the end-of-year nationwide tests, earn college credit) in them as well as calculus. Thus, my background entering university was uneven – an unformed ball of clay that could end up as



fine pottery or an adobe brick. In addition, I had no models of a scientific career. My parents were not scientists, my mother did not go beyond high school, and neither my older sister nor younger brother had any graduate education.

2.2 Carleton College

As stated in the Introduction I did not grow up thinking that a geological career lay ahead. The first step on my path was attending Carleton College, a small liberal arts institution in rural Minnesota. It was a fortuitous choice based on a weekend high school road trip with a friend to visit a mutual friend who was a first year student at Carleton. Without this trip I would not have known that Carleton existed. During my first years I was a classic liberal arts student taking a wide range of courses out of interest rather than a clearly defined plan. For reasons I cannot explain I liked taking courses that others viewed as difficult and from professors who were known to be, shall we say, stern taskmasters. Thus, I took a senior level English Literature course from a bear of a man whom even English majors tried to avoid and a political philosophy course from a professor who did his PhD at the University of Chicago on the authors we read, and whom I suspect did not think that there were any other thinkers worth our time.

Text Box 2.1 – U.S. Higher Education and Liberal Arts Colleges

There are many different types of higher education institutions (post-high school) in the United States. The standard university offers a 4 year course of study leading to a bachelor's degree, obtained by about a third of Americans (U.S. Department of Education, 2019). This contrasts with many universities around the world in which a 3 year programme is standard, with the option of a fourth "honors" year that typically includes an integrative thesis of some sort. In the United States there also are numerous 2 year post-secondary programmes, called community colleges because they typically serve a fairly local student population. They offer introductory courses in most subjects and some students take these and then transfer to a 4 year college or university to complete a bachelor's degree. Community colleges tend to be more applied, with specialised courses that teach a trade.

In the United States there is not a consistent distinction between the terms "college" and "university". Universities tend to be larger (>10,000 and in some cases more than 100,000 students) and consist of many different colleges. Most universities also have extensive graduate programmes leading to Master's and Doctorate degrees in dozens to hundreds of different fields, as well as professional schools like Dentistry, Law, and Medicine. University courses can be taught by graduate students and part-time teachers, as well as professors. In contrast, colleges typically have fewer than 10,000 and sometimes less than 1,000 students, they typically do not have graduate programmes, and most classes are taught by professors. A subset of colleges are referred to as liberal arts colleges. These are not common outside of the United States.

Liberal arts colleges offer a broad course of study across the arts, humanities, and sciences, with a focus on critical thinking, writing, and interdisciplinary study. They typically are residential (students live in college-provided housing) and have fewer than 3,000 students. To ensure that students are broadly educated most liberal arts



colleges require students to take courses in different general subject areas like art, language, and physical science. Although students can major in a particular subject, such as history, philosophy, or physics, all students get the same bachelor's degree. The thinking is that the liberal arts education prepares one for life rather than a specific profession. Many liberal arts students go onto graduate school for more specialised education leading to a Masters, PhD, or professional degree.

At Carleton, I took more math, physics, and chemistry because I knew there was more to learn than I had been exposed to in high school. I even took the entire sequence in accounting because I liked the financial rigour in that part of the “dismal science” of economics and because it was taught by Ada Mae Harrison, the only woman in the United States to be awarded a National Research Professorship in Economics in 1957 (I was four years old at that time). I was completely unaware of her achievements when I signed up for her course, but I was aware that there were few female professors in economics, much less in science. In her 1999 obituary she was described by then Carleton President Stephen R. Lewis, Jr. as, *“A diminutive but demanding teacher of accounting and microeconomics, she expected analytical rigor and high standards of precision. With a quick mind and sharp wit, she often struck fear in the hearts of hundreds of future business leaders, who testify abundantly to her lasting effect on their lives.”* Maybe that is why I did not become a business leader, I had no fear, just respect.

Notice that none of the preceding paragraphs make any mention of geology and the simple reason is that I did not know when I entered college that it existed, other than from the basic Latin etymology roots, in that it translates simply as the study of the Earth. So how did I encounter geology? Truth be told it was a simple schedule conflict. I could not take a class that I had signed up for and the only other course in the entire catalogue that met during that time slot was Introductory Geology. I am pretty sure that I did not know what was the subject matter that I had just signed up for. And I wish I could say that the light bulb went on and I immediately knew that geology was my life. But that is not the case. The class was at best moderately interesting, the professor slightly boring, and at the end of the school year I boarded an airplane to fly back home to Cincinnati, a flight that I had done several times previously with no special effect. But as I looked out the airplane window at the same landscape that I had seen many times before, suddenly I started seeing folds in the Precambrian bedrock and dendritic erosional patterns in the younger cover rocks, things that I had looked at many times before but now, with my almost subliminal geological knowledge, I saw and understood for the first time what had always been there. This was transformative for me because even though I could do reasonably well in almost any subject matter, now through the power of geology I could make sense of an entirely new world. I gobbled up what remaining geology courses I could take before I graduated, and knew that my life was changed even though I didn't fully comprehend what that path might be like and how lucky I was to start it at Carleton.



During my senior (fourth and final) year I took off the autumn semester for a 3 month shipboard academic programme called World Campus Afloat that travelled from Los Angeles around the tip of South America, across the Atlantic to Africa and around the Mediterranean, with stops at ports along the way before returning to the U.S.. I realised that some of this itinerary retraced some of Charles Darwin's travel that led to his ideas about evolution, including an important stop in the Galapagos Islands, so I brought a copy of Darwin's *The Voyage of the Beagle* to read *en route*. This led indirectly to my senior honors thesis that I will describe later.

I had signed up for two advanced courses in marine biology and oceanography onboard the ship because they sounded like interesting things to do while travelling. I had no background in these subjects so during the summer beforehand I took a condensed year long biology course at the University of Cincinnati while working full time to earn money for college. This introduction to biology included components of evolution and genetics, which proved useful for better understanding my developing fascination with Darwin. For my marine biology course, I focused on the changes in morphology of chitons, a mollusk that lives in the intertidal zone and is somewhat like a cross between a modern abalone and an ancient trilobite. Due to nutrients in the upwelling Antarctic current, chitons ranged from several centimetres to several decimetres from north to south along the South American coast. I documented this change photographically, not imagining that this would be useful for my senior honors thesis back at Carleton.

Upon returning to Carleton I faced the prospect of producing a thesis, a requirement for graduation. I decided to do it on my travels retracing Darwin's voyage on the Beagle and specifically the rocks and wildlife of the Galapagos Islands. It was not a standard geologic research project with thin sections and chemical analyses but rather an audiovisual tour of the places that both Darwin and I had visited. I paired photographs with music, ranging from classical to modern, to create a sense of discovery that I felt was akin to what Darwin might have experienced more than a century ago. It was performed in an auditorium before a small but mostly enthusiastic audience of students and professors. The most difficult part of the thesis was figuring out how to make the required "copy" for the library.

As stated in the introduction, unbeknownst to me Carleton was and is a geological legend, having turned out more students *per capita* who went on to become geologists, many with PhDs, and university professors than perhaps any such college on Earth. Since every university and its graduates will have pride of place, let me elaborate on that a bit because it is fundamental for my development as a geologist and scientist.

The modern Carleton Geology Department was founded in 1932 by Drs. George Gibson and Laurence M. Gould. Dr. Gould was the chief scientist of the first Byrd Expedition to Antarctica to explore scientifically the Antarctic interior (<https://www.carleton.edu/geology/about/facts/>). The Carleton alumni directory states that there have been about 1,200 geology majors in total, 5-10 annually



when I was there in 1971-1975, and about 20-30 annually since 1980. When normalised by enrollment Carleton ranks first in the United States in the number of students who go on to earn geoscience doctorates (Table 2.1).

Table 2.1 Total number of undergraduates going on to earn geoscience PhD degrees during the years 1966–2011 normalised by undergraduate enrollment (Renshaw, 2014).		
Rank	Institution	Doctorates/Year/1000 Undergraduates
1	Carleton College	2.05
2	California Institute of Technology	1.51
3	Franklin and Marshall College	1.31
4	Amherst College	1.12
5	Pomona College	0.97
6	Beloit College	0.90
7	Colorado College	0.85
8	New Mexico Tech	0.80
9	Colgate University	0.74
10	University of Montana	0.74

In addition, the Carleton Geology Department was ahead of the curve in fostering female scientists. According to American Geological Institute information summarised by Williams (1994), the national average percentage of women receiving bachelor’s degrees in geology between the years 1973 and 1982 was 20 %. Carleton averaged 46 % during that time period. Between the years 1979-1988, female Carleton alumni went on to earn more earth science PhD degrees than any other undergraduate college, including Wellesley and Smith (both highly ranked all female colleges).

Thus, during my initial exposure to geology at Carleton there was roughly an equal split between male and female, between male and female who went on to earn PhD. degrees, and between male and female who became university professors. I assumed that this was normal. When I arrived at Stanford in 1975 to start a PhD programme my first reaction was, “Where did all the women go?” as less than 5 % of the graduate students were female.

Another unusual aspect of the Carleton Geology Department, at the time, is that out of the students in my cohort at Carleton four of us went on to become professors of economic geology at major universities (at the universities of Alberta, Oregon, Wisconsin, and Washington State) and several others became professors in other geological and geochemical fields. This is surprising

in that economic geology is not taught at Carleton and we all went to different graduate institutions, so the focus on economic geology is difficult to explain. It is not that we all had the same academic themes within economic geology, as we each studied different types of ore deposits and used different geochemical techniques. The common denominator is simply that we all were undergraduates at Carleton College and thus overlapped to some extent in professors, classes, and the cold Minnesota climate.

2.3 [Stanford University](#)

My decision to go to graduate school in geology was rather late as I had initially planned to go to law school and had done well enough on the appropriate tests to get admitted. But the Darwin experience during my final year and my honors thesis had strengthened my interest in science. This is somewhat ironic because Darwin is better known for biology than for geology and my thesis was more art than science. But that was my path. Because I was applying after the normal application deadlines, my options were somewhat limited and Stanford University had a rolling admissions process such that I could still apply. They offered me a scholarship to attend and I was thrilled to accept. I was so naïve that I had no idea that in the sciences it is fairly common to be supported to go to graduate study in the U.S.

In between Carleton and Stanford, I attended geology field camp in the Wind River Mountains in Wyoming. This was my introduction to classic geology with real outcrops. Growing up in the flat Midwest and learning geology in equally flat and glaciated Minnesota I had not actually seen glorious rock exposures like I was now experiencing in Wyoming. I knew then I had made the right choice.

After field camp I had a few weeks before beginning the Stanford graduate programme so I detoured north through the Canadian Rockies, exploring the beauties surrounding Banff and Jasper. I had a tarp and sleeping bag with a full view of the stars and Milky Way at night. Some mornings I awoke to find myself covered beneath a blanket of new snow. My journey south was interrupted by a mountain climbing accident that resulted in a broken jaw and other body parts such that when I arrived at Stanford my jaw was wired shut. Perhaps this was a good thing since it prevented me from saying stupid things for a few months.

In the American graduate education system, one typically takes general courses before deciding on a research focus. I initially thought that I wanted to be an igneous petrologist. However, after a few uninspiring courses, serendipity again came into play as it turned out that I had the good fortune to enroll at Stanford in the same year that Professor Marco Einaudi arrived from industry and began an academic career. Dr. Einaudi fostered dozens of economic geologists, although few if any of us knew anything about economic geology when we came to Stanford. He came from a background in private industry, mostly



with a company called Anaconda that was in the forefront of applying basic science to exploration. Anaconda worked closely with Professor Charles Meyer at the University of California, Berkeley and Professors Ulrich Peterson and J.B. Thompson, Jr. at Harvard University, applying the latest techniques in geochemistry and mineralogy to the understanding of ore deposits. Not surprisingly, many of Anaconda's geologists at the time came from those two institutions (Einaudi's PhD was from Harvard). Dr. Einaudi's specialty was skarn and porphyry copper deposits, and not surprisingly that became my research focus as well. Perhaps also not surprising, my PhD dissertation was on a former Anaconda porphyry-skarn deposit at Cananea in Sonora, Mexico (Meinert, 1982) and my first job after graduation was as an exploration geologist in Alaska with Anaconda.

Text Box 2.2 – Skarns and Skarn Deposits

Skarn is a type of rock that consists of calc-silicate minerals, such as garnet and pyroxene, that typically form at the contact of an intrusion and limestone. Because of the strong compositional and thermal gradients between the hot magma and cooler carbonate rocks, this is a zone of intense reactions that form new, commonly coarse grained minerals and precipitate economically important elements such as copper, gold, and tungsten. The galena-garnet sample on the cover of this *Geochemical Perspectives* issue is an example. These mineralised occurrences are called skarn deposits and constitute some of the largest and most abundant ore deposits on Earth. They are described in more detail in the next section.

In addition to being introduced to economic geology, mineral exploration, and porphyry-skarn deposits by Dr. Einaudi my graduate education was strongly influenced by professors Konrad Krauskopf in geochemistry, George Parks in metallurgical thermodynamics, Bill Dickinson in sedimentology and tectonics, and George Thompson in geophysics. Also, graduate students who came with strong chemistry backgrounds from institutions such as MIT and Cal. Tech. taught me more about geochemistry than I learned in the classroom. I am especially grateful to Rainer Newberry and John Dilles, both of whom later went off to their own careers as professors of economic geology. Rainer Newberry was particularly influential as he not only helped me with geochemical conundrums during my PhD research but following graduation, we continued with Dr. Einaudi as post-docs exploring the wonders of skarn mineralogy and geochemistry (Fig. 2.1). We eventually collaborated to write the skarn review paper for the *75th Anniversary Volume of Economic Geology*, a seminal work that was the standard in the field for 25 years and remains a classic reference (Einaudi *et al.*, 1981).

As with my experience at Carleton, my cohort of about two dozen graduate students at Stanford produced several professors of economic geology and about half of the graduate students in my cohort became professors in other geological and geochemical fields. To summarise, I did not grow up thinking I would be an economic geologist or a university professor but that is where my winding educational path led. That path started with a schedule conflict leading to my first geology course at an institution that just so happened to be incredibly strong





Figure 2.1

Professor Marco Einaudi (in the middle), Rainer Newberry (on the right), and the mine geologist examining skarn mineralogy in the Chino open pit of the Santa Rita porphyry Cu skarn deposit, New Mexico (photo by Larry Meinert, 1979). Light coloured material in background is the mineralising granodiorite porphyry and dark material is garnet-pyroxene skarn.



in the education of geologists. It continued with being in the right place at the right time to get a solid education in geochemistry and economic geology that then led to a career in those fields, with a focus on skarn deposits and the natural geochemical laboratory of reactions that they represent. And the beginning of my research career on skarn deposits coincided with a time of rapidly increasing gold prices following de-coupling of gold from the U.S. dollar. The price of gold rose from \$ 38/ounce in 1971 to about \$ 800/ounce in 1980. This price increase along with the novel application of processing technology, allowed much lower gold grades to be mined economically. This stimulated exploration and led to new deposit models, such as for Au skarns, to help guide geological targeting and assessment. So due to that economic transformation I was once again in the right place (subject) and at the right time to make significant scientific advances. That scientific journey will be outlined in the next section.



3.1 Introduction

Most of my career has been concerned with mineral resources in one form or another. This general subject was covered in a previous issue of *Geochemical Perspectives* (Arndt *et al.*, 2017) so I will not repeat that overview treatment here. Instead I focus on my experience with a particular type of ore deposit, skarn deposits, and the unique geochemical laboratory that they represent. In simplest terms, a skarn deposit forms at the contact between an igneous intrusion and reactive wall rocks, commonly limestone. The strong temperature and compositional gradients between the hot magma and the cooler wall rocks lead to a series of geochemical reactions resulting in the formation of calc-silicate minerals, including garnet and pyroxene, as well as the deposition of numerous elements of economic importance such as Au, Cu, Fe, Sn, W, and Zn. Skarn is a relatively simple alteration type defined by its calc-silicate mineralogy, and skarns that contain economic concentrations of metals are called skarn deposits.

Just as mineralogy is the key to recognising and defining skarns, it is also critical in understanding their origin and in distinguishing economically important deposits from interesting but uneconomic mineral localities. Skarn mineralogy can be mapped in the field, providing a broader “alteration envelope” around a potential orebody. Because most skarn deposits are zoned, recognition of distal alteration features can be critically important in the early exploration stages. Details of skarn mineralogy and zonation can be used to construct deposit specific exploration models as well as more general models useful in developing grass roots exploration programmes or regional syntheses. Most skarn deposits that are economic to mine are related to magmatism, meaning that investigation of igneous petrogenesis and tectonic setting forms a framework for regional exploration or classification.

Mining of skarn deposits dates back at least 4,000 years and evidence of the mining of skarns can be found in the ancient Chinese, Greek, and Roman empires (Nicolescu and Mârza, 1989; Gilg, 1993; Chang *et al.*, 2019). Although there are earlier descriptions of skarn-forming processes and deposits now known to contain skarn, such as Peters (1861), the first published use of the term “skarn” is by Alfred Elis Törnebohm (1875), an early director of the Geological Survey of Sweden. The history of skarn studies up to my first involvement was summarised by Burt (1982). A rough chronology starts in Europe during the 19th century (von Cotta, 1864; Goldschmidt, 1911), shifts to the United States in the early 20th Century (Lindgren, 1902, 1924; Barrell, 1907; Umpleby, 1913; Knopf, 1918), progresses in the middle of the 20th century to Russia (Korzhinsky, 1946, 1950; Zharikov, 1959, 1970; Smirnov, 1976) and Japan (Watanabe, 1960; Shimazaki, 1980), and returns to the United States towards the end of the 20th century



(Einaudi *et al.*, 1981). My own involvement started during the transition between the Russian-Japanese epochs and the American resurgence, partly driven by the utilisation of the electron microprobe to explore the details of skarn mineralogy. This led to a transformation in the understanding of skarn formation processes that previous workers, giants though they were, did not unravel in the absence of quantified mineralogy and geochemistry.

Both Goldschmidt and Lindgren had strong ties to Scandinavia, the type locality of skarns. After his university education at Freiberg, Lindgren made his career in America, where he conducted definitive studies of many important skarn deposits and processes (Lindgren, 1902, 1905, 1914, 1924, 1925), helped found the journal *Economic Geology* in 1905, and served as the Chief Geologist of the U.S. Geological Survey (1911). He also literally “wrote the book” on mineral deposits, simply called *Mineral Deposits* (Lindgren, first published in 1913, with subsequent editions in 1919, 1928 and 1933). In 2013, on the centenary of the first publication of *Mineral Deposits*, I had the opportunity to participate in a small field excursion to visit Lindgren’s birthplace at Vassmolösa and some of the skarns that he had visited in southern Sweden (Fig. 3.1).



Figure 3.1

(a) The author, Larry Meinert, holding a copy of Waldemar Lindgren’s seminal textbook *Mineral Deposits* (1933 edition), while standing in front of the Vassmolösa house where Lindgren grew up in southern Sweden. (b) Field trip participants at the Falun copper mine entrance. The alchemical symbols (over entrance, left to right) are iron sulphate, sulphur, zinc, iron, copper, gold, silver, lead, steel, copper sulphate, red paint. Front row, from left: Göran Fredrikson (Lindgren’s great grandnephew, also a geologist), Araceli Fredrikson, Jeffrey Hedenquist; back row: Krister Sundblad (trip leader), James Saunders, Richard Sillitoe, Jeannie Billington, Juhani Ojala, and Larry Meinert.



When I next encountered skarn it was in Professor Marco Einaudi's introductory ore deposits class at Stanford University, and instead of big beautiful crystals it was through Schreinemaker's graphical analysis and phase diagrams (Fig. 3.2). Even on trips to observe skarns in the field, we would sketch P-T- X_{CO_2} diagrams on large pieces of paper taped on rock exposures to understand why a particular mineral assemblage was stable, and why the replacement of pyroxene by actinolite and garnet by epidote represented a retrograde path in geochemical space. Even though I came to understand much more about mineralogy and geochemistry, I still didn't really understand the complexities of skarn development. Indeed, it would take me several more years, if not decades, to begin to understand how little I understood and, more importantly, how much the giants such as Goldschmidt and Lindgren had gleaned from their careful field observations, without the benefit of modern analytical techniques. That path will be discussed in the following sections.

3.2 General Processes of Skarn Formation

3.2.1 Stages of skarn formation

Although the formation of a large skarn deposit is clearly metasomatic, *i.e.* the introduction of large amounts of ore elements into the local geological environment, the earliest stages of alteration are largely metamorphic, driven simply by changes in temperature, pressure, grain-scale diffusion and fluid flow. The driving heat can be from deep burial or by the intrusion of magma into the earth's crust. Since these are the rocks that will later be overprinted by large scale metasomatism and hydrothermal fluids, it is important to understand in some detail these early, largely metamorphic processes. Figure 3.3 illustrates the main types of mostly metamorphic reactions (Fig. 3.3a-c) that typically occur prior to the all important hydrothermal stage illustrated in Figure 3.3d. It is worthwhile to step through these metamorphic events one at a time, even though the fundamental processes individually are relatively straightforward.

The first step is simple heating of the rocks such that isochemical metamorphism of the rocks on the left side of Figure 3.3a results in the metamorphic equivalents on the right side of Figure 3.3a. Thus, limestone is metamorphosed to marble, sandstone to quartzite, and shale to hornfels. This is mainly a change in texture without any new minerals being formed. The situation becomes slightly more complicated with a silty limestone that is metamorphosed to a wollastonite marble or a calcareous shale that is metamorphosed to a calc-silicate hornfels. In these cases, there not only is a textural change but also the development of new calc-silicate minerals that were not previously present. There is no change in bulk composition, simply a change in the stable mineral assemblage, confirming the largely isochemical nature of this process.



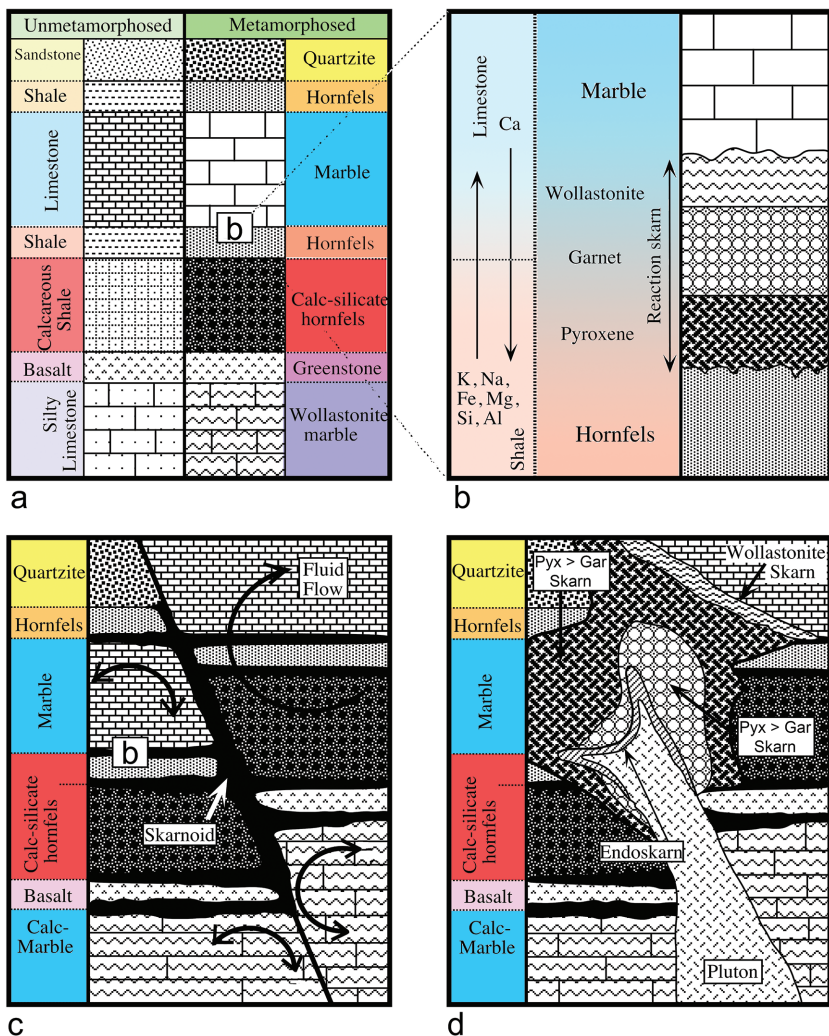


Figure 3.3

Types of skarn formation (modified from Meinert, 1983). **(a)** Isochemical metamorphism involves recrystallisation and changes in mineral stability without significant mass transfer beyond the grain scale. **(b)** Reaction skarn results from metamorphism of interlayered lithologies, such as shale and limestone, with mass transfer between layers on a local scale (bimetasomatism). **(c)** Skarnoid results from metamorphism of impure lithologies with some local mass transfer by small scale fluid movement. **(d)** Fluid-dominated metasomatic skarn is typically coarse grained and largely does not closely reflect the composition or texture of the protolith.

Things are more complicated at the contact between different lithologies, such as limestone and shale, as illustrated in Figure 3.3b. Here, there is movement of Ca from the carbonate lithology into the adjacent shale and movement of elements such as K, Na, Fe, Mg, Si, and Al from the shale towards the adjacent limestone. This results in monomineralic bands of calc-silicate minerals such as wollastonite, garnet and pyroxene that collectively are called “reaction skarn”, also termed bimetasomatism (Zarayskiy *et al.*, 1987) or calc-silicate bands (Vidale, 1969). Of diagnostic importance, the most Ca-rich phase, wollastonite, is next to the most Ca-rich lithology, marble; and the most Si-rich phase, pyroxene; is next to the most Si-rich lithology, shale; garnet, being intermediate in both Ca and Si, is in the middle. Thus, there is a mineralogical zonation that can be mapped in the field to demonstrate the host rock compositional control and the process that has occurred (Vidale, 1969). There is no scale on this diagram, since reaction skarns can occur on the scale of microns (seen in thin section), centimetres (hand specimens), and tens to thousands of metres at the regional scale, as in the type locality of skarn, in the Bergslagen region of central Sweden (Törnebohm, 1875).

The terms metamorphic and metasomatic are scale-dependent (Putnis and Austrheim, 2010). The reaction skarn (Fig. 3.3b) is metasomatic relative to the garnet layer which has replaced what used to be limestone, but in the larger context (Fig. 3-3a), nothing has moved into or out of the zone of the reaction skarn; in total, however, this is largely an isochemical metamorphic process. The primary drivers are heat and time. The largest reaction skarns occur proximal to large, deeply emplaced plutons, or during high grade regional metamorphism over a protracted period of time, as much as 10s to 100s Myr.

Things become more complicated where fluids circulate through the rock column (Fig. 3.3c), augmented by channelised flow along fault or stratigraphic contacts, enabling reactions to occur that are facilitated at a given P-T-X by the presence of an aqueous fluid. Calc-silicate mineral-forming reaction, such as isochemical metamorphism (Fig. 3.3a) or reaction skarn (Fig. 3.3b) will proceed more quickly and/or at lower temperature in the presence of water (lower X_{CO_2}) than under anhydrous conditions (see below). Thus, calc-silicate minerals will form within impure carbonate lithologies such as a silty limestone (Fig. 3.3a) or reaction skarns between unlike lithologies (Fig. 3.3b), as well as along stratigraphic and fault fluid flow paths whereby elements such as Ca are transported from one site to another. Such calc-silicate mineral occurrences are called “skar-noid”, a term from the Russian literature (Korzhinsky, 1946, 1950, 1970; Zharikov, 1970), because such rocks have skarn mineralogy, *i.e.* calc-silicate minerals, but demonstrably are controlled by, and reflect the compositions of, the host rock lithologies.

This again raises the question of metamorphism *versus* metasomatism (Putnis and Austrheim, 2010) and, as with the case of the reaction skarn (Fig. 3.3b), it is a matter of scale. At the scale of the system of Figure 3.3c, little moves into or out of the rock column, although elements move around at the local



scale, inside the system. The essential feature of reaction skarns, and to a lesser extent for skarnoid, is that it is possible to reconstruct the observed calc-silicate mineralogy in terms of the adjacent or nearby rocks without calling on an external magmatic hydrothermal source.

Although calc-silicate mineral reactions (illustrated in Fig. 3.3a-c) do not require an igneous intrusion and could result from simple regional metamorphism, it also is possible that the heat driving the reactions is from an underlying intrusion. Such a pluton may not only metamorphose the surrounding rocks in the classic sense of contact metamorphism, it may also exsolve a hydrothermal fluid that creates a purely metasomatic skarn that will overprint the previously formed metamorphic aureole and be zoned relative to the causative pluton. Figure 3.3d illustrates such a superposition of a pluton-associated skarn upon the previously metamorphosed rocks of Figure 3.3a-c. Note that the skarn is zoned around the pluton with a proximal garnet > pyroxene zone, a more distal pyroxene > garnet zone, and wollastonite at the skarn-marble contact. The contacts of metasomatic skarn zones cut across stratigraphy and are not strictly controlled by host rock composition. Thus, the hydrothermal fluid controls the skarn mineralogy whereas in the mostly metamorphic case (Fig 3.3a-c), the protolith composition determines the calc-silicate mineralogy.

There is both a spatial (Fig. 3.3d) and temporal (Fig. 3.3a-d) zonation within essentially all skarn deposits. This can be mapped in the field at the scale of a deposit, down to the scale of outcrops or hand specimens. It can also be seen at the scale of individual mineral grains (Fig. 3.4). In Figure 3.4b, isolated, poikilitic, Fe-poor garnets reflect compositional irregularities in the original metamorphosed rock unit. In Figure 3.4c the early metamorphic garnets are overgrown by relatively inclusion-free garnet rims that reflect influx of skarnoid fluids from the surrounding rocks or even the initial stages of metasomatism of magmatic hydrothermal fluids. Figure 3.4d illustrates complexly zoned, birefringent, and Fe-rich garnet formed by a magmatic metasomatic fluid that has replaced unaltered carbonate rock as well as overprinted previously formed metamorphic garnets.

The complexity of skarn overprinting and replacement is reflected in the detail that can be preserved, such as fossils that are replaced molecule for molecule with razor sharp boundaries and no distortion (Fig. 3.5). Following the development of the electron microprobe (and later instruments such as LA-ICPMS), skarn mineralogy could be analysed at the scale necessary to unravel the complex zonation and replacement textures common in skarn deposits. Even some recent studies are hampered by not fully understanding, and thus not appropriately sampling, the complexity of skarn deposits (Gevedon *et al.*, 2018; Ramos *et al.*, 2018; Ryan-Davis *et al.*, 2019).



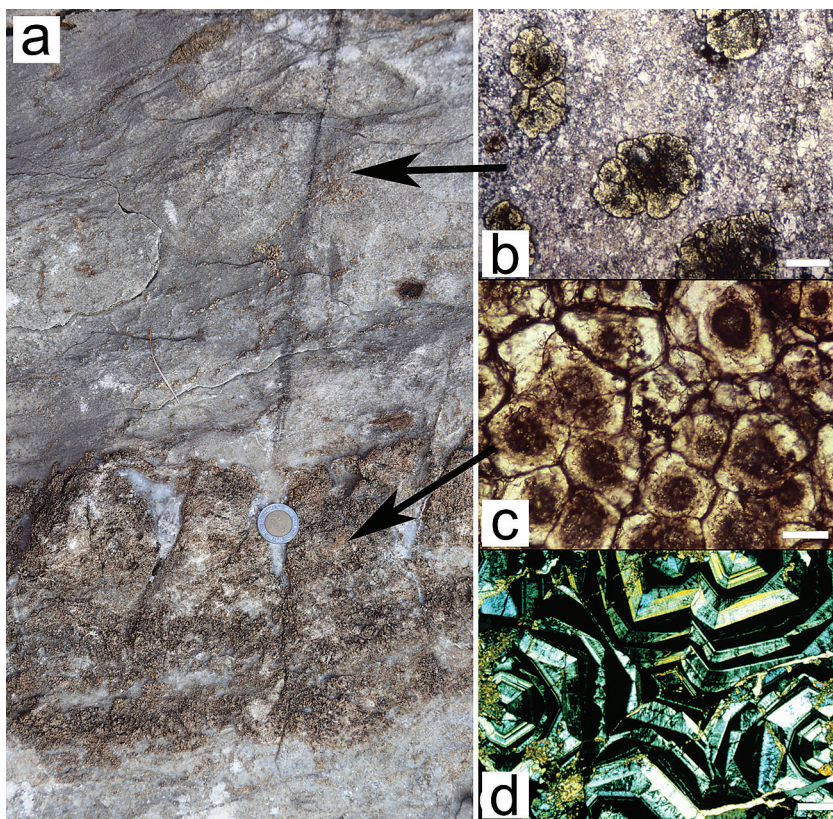


Figure 3.4 Textures of garnets representative of the different skarn types shown in Figure 3.3. **(a)** Skarnoid layer in marble with both isolated garnet crystals and stratigraphic layer replacement (Aranazura, Mexico; Meinert photo). **(b)** Lobate, poikilitic metamorphic garnet (Ad20–50) in marble typical of metamorphic or skarnoid growth (Cananea, Mexico; Meinert, 1982). **(c)** Overgrowth of inclusion-free garnet rims on murky metamorphic/skarnoid garnet cores (Cananea, Mexico; Meinert, 1982). **(d)** Complex zoning, both sector and oscillatory, of metasomatic garnet typical of growth from hydrothermal fluid (Big Gossan, Irian Jaya; Meinert *et al.*, 1997). Isotropic bands Ad90–100 and birefringent bands Ad50–80, crossed nicols. Scale bars 1 mm.

3.2.2 Decarbonation reactions

Skarns are defined by their mineralogy, with a variety of mineral reactions describing the formation of calc-silicate minerals. Most are decarbonation



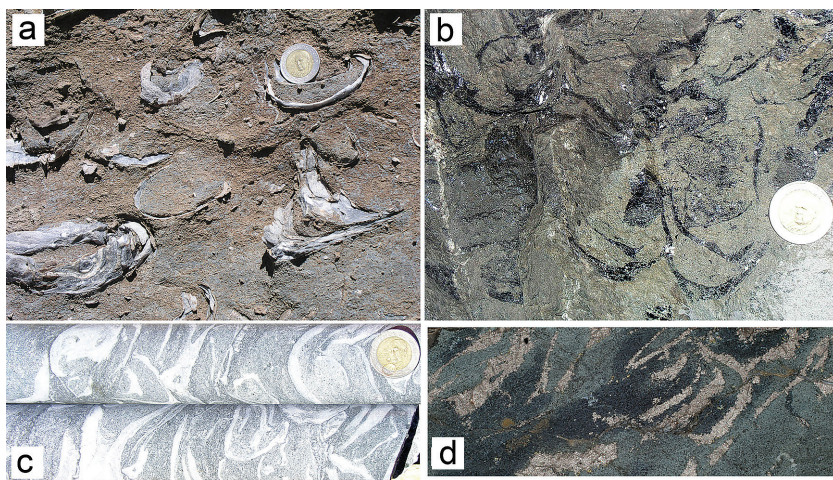
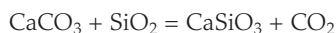


Figure 3.5

Skarn replacement textures. (a) Outcrop of unaltered *Gryphaea* (oyster) fossil shells in the Cretaceous Toqui Formation, Chile. (b) Sphalerite replacement of *Gryphaea* (oyster) fossil shells and green garnet-pyroxene skarn replacement of carbonate in between shells. (c) Drill core of unaltered *Gryphaea* (oyster) fossil shells in the Cretaceous Toqui Formation. (d) Pyrrhotite replacement of *Gryphaea* (oyster) fossil shells and dark green pyroxene skarn replacement of carbonate between shells (El Toqui Zn-Au skarn deposit, Chile, Bussey *et al.*, 2010). All photographs by Larry Meinert.

reactions and the simplest being the development of wollastonite at the contact between calcite and quartz:



Since all decarbonation reactions generate CO_2 , it is necessary to lower the CO_2 concentration for a reaction to proceed, since the buildup of CO_2 , as expressed by Le Chatelier's principle, will prevent the reaction from proceeding very far. Either the generated CO_2 is flushed from the system or the temperature needs to increase to continue the reaction. This is easiest to visualise in a simple phase diagram of temperature of basic skarn-forming reactions *versus* CO_2 in the fluid phase, termed X_{CO_2} . This visualisation helps us understand how these reactions can create rock textures and mineralogy that may be misinterpreted in the field (Fig. 3.6).

A simple fracture in a carbonate rock (Fig. 3.3a), with both rock and fluid at 540 °C and a X_{CO_2} of 0.3, is at calcite + quartz stability (Fig. 3.6a), below wollastonite stability, and there is no reaction. If CO_2 is removed at constant temperature along the fracture (*e.g.*, Fig. 3.3c), a vein of wollastonite-anorthite will form in the carbonate rock, since the fluid composition crosses into

wollastonite stability (towards point B). Further complicating the situation is that the temperature and X_{CO_2} are lower in Figure 3.6c than at the start (point A; Fig. 3.6a), thus resulting in the formation of a garnet-wollastonite vein cutting the carbonate rock (point C, Fig. 3.6c), a type of skarnoid reaction (Fig. 3.3c). If metals from an external source are introduced (e.g., in a magmatic hydrothermal fluid), the composition of mineral phases (such as garnet), may be affected (Fig. 3.3d). Comparison of an impure limestone (Fig. 3.6a) to a similar rock cut by a garnet-chalcocopyrite vein (Fig. 3.6d) may lead some to conclude that the garnet-veined specimen experienced higher temperature fluids than the unreacted limestone, but this is not correct. The take home message is that textures are easily misinterpreted and that mineralogy and mineral compositions are necessary to accurately interpret the skarn environment.

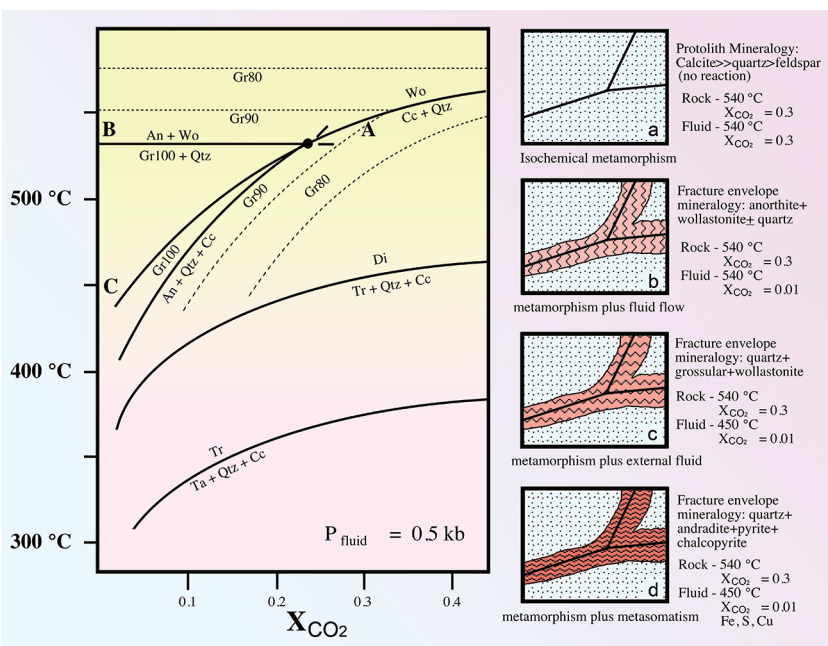


Figure 3.6

Illustration of metamorphic phase equilibria for selected reactions in the system Ca-Mg-Al-Si-H₂O-CO₂. Modified from Greenwood (1967) and Kerrick (1974). Examples of four fracture-controlled alteration events. (a) Fluid in fracture is same temperature and composition as surrounding rocks at high X_{CO_2} . (b) Fluid in fracture is the same temperature as surrounding rocks but some CO₂ was lost from the system. (c) Fluid in fracture is cooler than surrounding rocks, and has lost some CO₂. (d) A concentrated metasomatic fluid with magmatic components, including Fe, Cu, and S.



3.3 Skarn Mineralogy

Mineralogy not only defines a rock as skarn, it also is the key to understanding genesis and zonation, with the latter being critical to exploration success for skarn deposits that may be economic to mine. As previously mentioned, my love affair with skarn mineralogy began in an introductory geology class but deepened considerably in graduate school as I came to realise that each skarn mineral had a story to tell. Some minerals, such as pyroxene, are like a novel with individual chapters named diopside and hedenbergite, sub-plots like johannsenite, and oddball characters like the Tschermak substitution of aluminum into the pyroxene structure with the theoretical end members of fassaite ($\text{Ca}(\text{Mg}, \text{Fe}^{3+}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$) and esseneite ($\text{CaFe}^{3+}\text{AlSiO}_6$), having their own quirky stories to tell.

But first, the basics. Although there are hundreds of minerals that occur in skarn deposits, the two most important and abundant are garnet and pyroxene. Each has a general formula and various groups and end members that occur in skarn deposits (Table 3.1). The details can get quite complicated, but are necessary as they are informative. Some mineral compositions occur only in certain skarn types; for example, johannsenite only occurs in Zn skarns and this skarn type typically occurs distal to the magmatic source of the hydrothermal fluids, commonly along stratigraphic or fault contacts. Thus, the occurrence and abundance of the johannsenite component in pyroxene tells a lot about the nature of the skarn, if one knows how to read the significance. Similarly, the Tschermak substitution of aluminum into pyroxene occurs in many Au skarns, with up to 10 % fassaite component.

Because of the importance of skarn mineralogy in understanding and exploring these complex systems, it is essential to use mineral names correctly. For example, all diopside is pyroxene whereas all pyroxene is not diopside. Unfortunately, it is quite common in the scientific literature (even by people who should know better) for a mineral to be called diopside when all that is known is that it probably is pyroxene. This is particularly problematic when there is a picture, or sometimes even a chemical analysis, that clearly indicates the pyroxene is Fe and/or Mn-rich, yet it is called diopside.

The compositional variation of garnets can be even more extreme than for pyroxene. Not only is garnet composition useful for understanding skarns, I also have used it in the qualifying examinations of potential PhD candidates. Such examinations typically are held in a university classroom and most such rooms have a periodic table of the elements hanging on the wall. As the examination proceeds, I hand the candidate a dart, such as would be used in most pubs with a dartboard, and ask them to aim it at the periodic table. Then, depending on what element has been struck by the dart, I ask them to discuss where that element would fit in the garnet structure and what type of skarn deposit such a garnet might be found in. Some students wished they had practiced more with their dart skills in the pub so that they could hit a relatively common element like Fe or Mg, rather than a head-scratcher like Neodymium or Technetium.



Table 3.1

General formulas, end members, and compositions of the two main skarn-forming minerals, garnet and pyroxene.

Mineral	End Members	Abbrev.	Composition	Related Names
Garnet	General formula:	$A_3^{2+}B_2^{3+}C_3^{4+}O_{12}$		
	grossularite andradite	Gr Ad	$Ca_3Al_2Si_3O_{12}$ $Ca_3Fe_2Si_3O_{12}$	} grandite
	spessartine almandine	Sp Al	$Mn_3Al_2Si_3O_{12}$ $Fe_3Al_2Si_3O_{12}$	
	pyrope	Py	$Mg_3Al_2Si_3O_{12}$	
Pyroxene	General formula:	$A_1^{2+}B_1^{2+}C_2^{4+}O_6$		
	diopside	Di	$CaMgSi_2O_6$	salite
	hedenbergite	Hd	$CaFeSi_2O_6$	
	johannsenite	Jo	$CaMnSi_2O_6$	

In most skarn deposits there is a general pattern of proximal garnet and distal pyroxene. In addition, the colour of garnet changes from proximal dark red-brown, to brown, to green to distal pale green and yellow, whereas pyroxene is generally the opposite, changing from proximal tan or pale green to increasingly darker green in distal locations. For garnet, the colours do not correspond to major element composition, in that andraditic or grossularitic garnet can be almost any colour, whereas pyroxene becomes progressively darker green with increasing Fe content and more brown ± pink with increasing Mn.

This zonation in garnet:pyroxene ratio and colour is mappable in the field. Having worked all over the world on numerous skarn projects, ranging from grass roots exploration to near-mine brownfields development, my experience has been that it is common to encounter geologic maps, if maps exist at all, that simply show intrusion, skarn, and limestone as rock units, without any attempt to map skarn mineralogy. This invariably leads me to ask a series of questions: *"Is there any place with lots of garnet? How about pyroxene? Do you see any dark red-brown garnet? Do you see any pale green garnet? Do you see any dark green pyroxene?"* Sometimes I can revise the maps even before going into the field to make my own observations.

There are many variations, such as oxidation state and wall rock composition, that affect these general mineralogical patterns. To greatly simplify, most skarn deposits can be thought of as a three part system: intrusion, wall rocks, and the reaction zone between intrusion and wall rocks, *i.e.* skarn. Each of these three parts will have an overall oxidation state ranging from oxidised to reduced.



For example, a reduced magma will crystallise ilmenite as the main Fe-Ti phase whereas more oxidised magmas will contain magnetite, and more oxidised still will contain hematite. Similarly, reduced wall rocks will be dark, carbonaceous, and may contain graphite, whereas more oxidised wall rocks will be lighter in colour and may contain Fe^{3+} , such as a red bed sandstone.

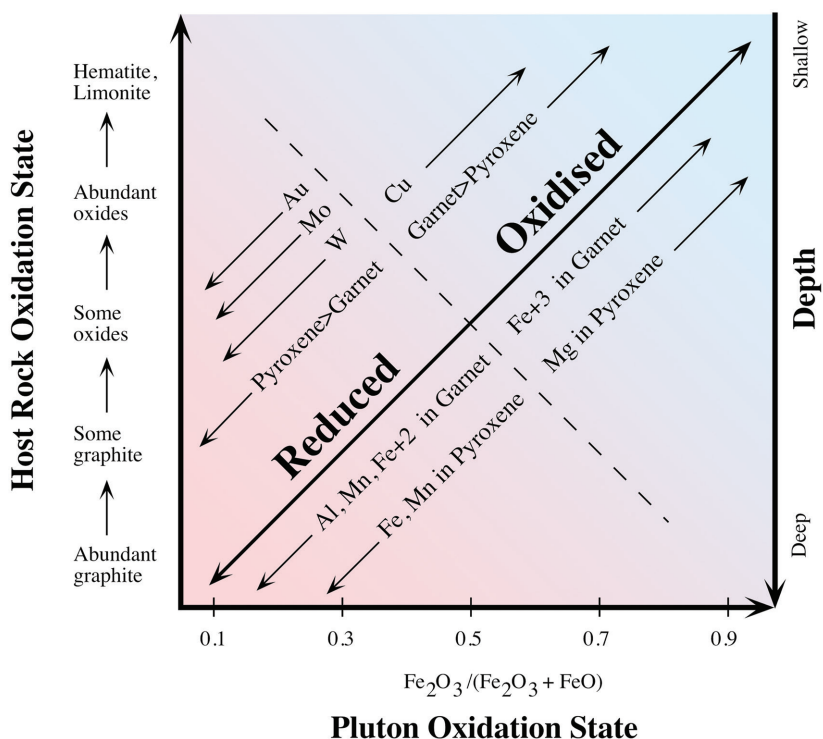


Figure 3.7

Variations in skarn deposits based on oxidation state of plutonic and host rock characteristics (modified from Newberry, 1991). The oxidation state of plutonic rocks is measured by the whole rock $\text{Fe}_2\text{O}_3/(\text{Fe}_2\text{O}_3 + \text{FeO})$ ratio. Alternative indicators of oxidation state include oxide mineralogy (e.g., ilmenite, magnetite, hematite) and Fe content of mafic minerals such as pyroxene, amphibole, and biotite. The oxidation state of host rocks is measured by the abundance of carbon (e.g., graphite, carbon, hydrocarbon), sulphides (pyrrhotite, pyrite), and oxides (ilmenite, magnetite, hematite). Depth of formation is a rough estimate, with shallow rocks (<5 km) being in contact with the atmosphere and meteoric water near the surface, whereas deep rocks (>10 km) will be completely buffered by the contained minerals.



The oxidation state of the system will affect the total amount of skarn formed as well as its mineralogy. Because of decarbonation reactions (Section 3.2), metamorphism or metasomatism of carbonaceous or graphitic wall rocks will generate excess CO_2 that will inhibit calc-silicate mineral formation until CO_2 is flushed from the system. Since skarn garnets mainly contain Fe^{3+} and skarn pyroxenes mainly contain Fe^{2+} , the amount of garnet *versus* pyroxene will reflect the oxidation state of the system. This in turn shifts the boundary between garnet-dominant and pyroxene-dominant parts of the skarn system. Thus, a reduced system that has both a reduced intrusion and reduced wall rocks will consist mostly of pyroxene, whereas an oxidised system will consist dominantly of garnet (Fig. 3.7). Oxidation state combined with mineral compositions forms a framework for better understanding and classifying different types of skarns (Meinert, 1998).

3.4 The Rise of Gold Skarns

Although I have studied and visited almost every type of skarn on Earth, most of my early work was on the Cu, Fe, W, and Zn skarns that are very common along continental margins. I gave many talks at scientific conferences on this research and in the early to mid-1980s I started receiving questions along the lines of “*that was all very interesting but is there any potential for GOLD in skarns?*” This was at the same time that the price of gold was sharply increasing (discussed in Section 2.3) and driving a lot of exploration budgets. I didn’t really have an answer to the question as there was only one mine in the world that had produced gold from skarn as the primary commodity, the Nickel Plate mine in the Hedley district of British Columbia (Camsell, 1910; Billingsly and Hume, 1941); the mine had closed in 1955, only to reopen in the late 1980s as the price of gold increased (Ettlinger *et al.*, 1992). It is hard to build a model based upon a sample size of one.

So, I did what any young professor would do: I started including gold in analyses that I was doing on other skarn deposits to see what I could learn (Meinert, 1986). I also initiated a graduate seminar at WSU to investigate the occurrence of gold in skarns. This entailed detailed library research and data compilation that established a framework for the occurrence of gold in skarns. In particular, the identification of oxidation state as a key variable was instrumental to subsequent research. Field trips to various skarn deposits that fit the emerging trend resulted in a preliminary model (Meinert, 1988) that was gradually fleshed out by investigating the mineralogy and geochemistry of identified and newly discovered deposits (Meinert, 1989, 1990). This was followed by a series of eight MSc and PhD projects by students (Table 3.2) on individual deposits that greatly improved our understanding of the range of characteristics of gold skarn deposits (Meinert, 1998, 2000; Meinert *et al.*, 2005). Many of these student projects were directly funded by exploration and mining companies that could see the direct utility of the research. Not surprisingly, most of the students were immediately hired upon graduation by exploration companies and one became a university professor, to continue spreading the gospel of skarn.



Table 3.2 MSc and PhD studies at Washington State University on Au skarn deposits.

Date	Degree	Student	Title
1990	MSc	Robert Hickey	The geology of the Buckhorn Mountain gold skarn, Okanagon County, Washington
1990	PhD	Art Ettlinger	A geological analysis of gold skarns and precious metal enriched iron and copper skarns in British Columbia, Canada
1991	MSc	Todd Johnson	Geology, hydrothermal alteration, and Cu-Ag-Au skarn mineralization in the New World District, Park County, Montana
1994	PhD	Greg Myers	Geology of the Copper Canyon-Fortitude skarn system, Battle Mountain District, Nevada
1994	PhD	Jeff Brooks	Petrology and geochemistry of the McCoy gold skarn, Lander County, Nevada
1996	PhD	Kurt Wilkie	Geology and hydrothermal evolution of the Beal Mountain gold deposit, Silver Bow County, Montana
2001	MSc	Chris Smith	Geology of the South Redline Au skarn deposit, Humboldt County, Nevada
2005	PhD	Miguel Gaspar	Geology and geochronology of gold skarn mineralisation, Crown Jewel deposit, Washington

Gold skarns are similar to other skarn deposits in that there is an intrusion, carbonate-bearing wall rocks, and the reaction zone between them, *i.e.* the skarn. However, the differences are important. The intrusions tend to be reduced, usually ilmenite-series diorite-granodiorite, with $\text{Fe}_2\text{O}_3/(\text{Fe}_2\text{O}_3 + \text{FeO}) < 0.40$ (Meinert, 1993, 1995). Sills are unusually common but it is not clear why that might be. Tectonically, they tend to form in back arc basins with clastic-rich protoliths that are carbonaceous and hence reduced (Meinert, 1992). The clastic-rich nature of the protolith leads to abundant hornfels in the metamorphic aureole, biotite hornfels in particular (Fig. 3.8a,b). This is then overprinted by skarn as the alteration system expands (Fig. 8c). The skarn mineralogy reflects the reduced nature of the plutons and wall rocks, since pyroxene can be more abundant than garnet, and the pyroxene is Fe-rich; as previously mentioned some of the pyroxene contains more Al than in other skarn types, and epidote locally contains high concentrations of Rare Earth Elements (REE), particularly the light REE (Meinert, 1990). The reduced nature also results in a higher abundance of pyrrhotite relative to pyrite, the presence of major arsenopyrite and loellingite, and the absence of oxidised species such as hematite (Fig. 3.9).

Geochemically, Au skarns are anomalously rich in a suite of elements that includes As, Au, Bi, Co, and Te (Meinert, 1998, 2000). This association is not entirely understood but may be related to the speciation of sulphur; the reduced environment allows these metals to be transported as bisulphide complexes.



Bismuth and Te in particular are significant; several workers proposed a “liquid bismuth collector model” for Au and other elements, since Bi is a liquid at $>271^{\circ}\text{C}$, and will be transported as an immiscible liquid in, and scavenge Au from, hydrothermal fluids (Okamoto and Massalski, 1983; Douglas *et al.*, 2000; Tooth *et al.*, 2008; Cockerton and Tomkins, 2012). On cooling below the eutectic of the melt, Bi minerals, Au, and other miscible elements such as Te will be deposited, mainly as native Au but also minor Au-Bi tellurides such as hedleyite (Bi_7Te_3 , whose type locality is the Hedley gold skarn). Gold is in close physical association with Bi minerals such as bismuthinite and native bismuth, as is observed in all Au skarn deposits (Fig. 3.9; Meinert, 1998). For any given deposit, the Au-rich zones tend to be in the distal, *i.e.* cooler parts of the system (Meinert, 1997).

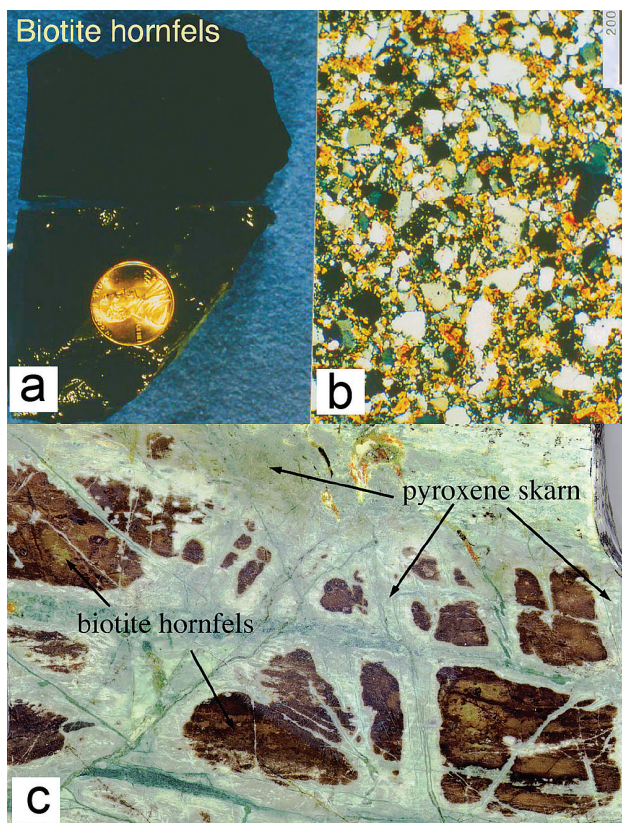


Figure 3.8

(a) Fine grained, dark brown to black biotite hornfels, Hedley District, British Columbia. (b) Biotite hornfels with 10-20 % brown biotite replacement of argillaceous material between quartz grains (photomicrograph crossed nicols, scale bar 200 microns). (c) Pyroxene veins that overprinted brown biotite hornfels at the edge of a Au skarn system, McCoy, Nevada (sample ~10 cm wide).



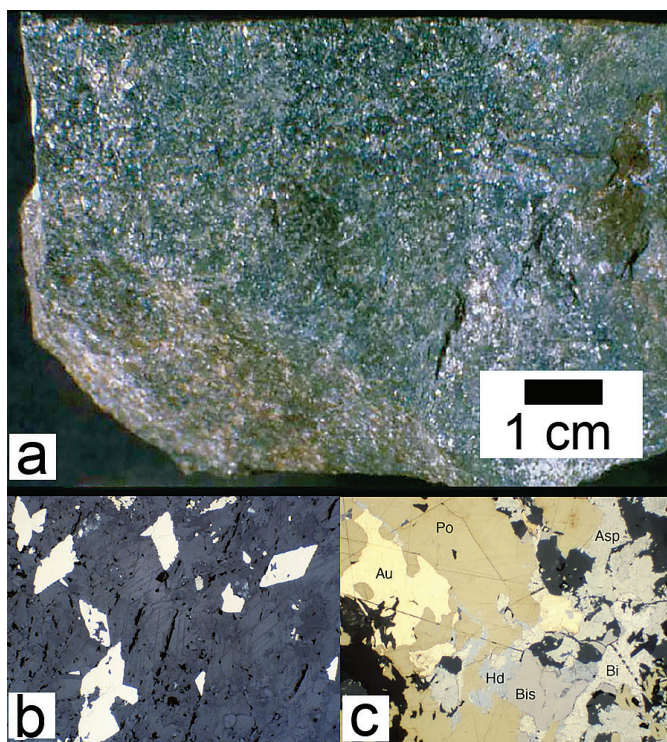


Figure 3.9

(a) Typical dark green hedenbergitic pyroxene skarn from Hedley District, British Columbia with ~7 % disseminated arsenopyrite >> pyrrhotite. (b) Polished slab of Hedley pyroxene skarn with euhedral diamond shapes of arsenopyrite (sample ~3 cm wide). (c) Photomicrograph of gold ore in Hedley pyroxene skarn with native gold (Au), native bismuth (Bi), bismuthinite (Bis), hedenlite (Hd), and pyrrhotite (Po) (field of view 1 mm).

All of these features now constitute an occurrence model for Au skarns, which now includes several sub-types (as reviewed by Meinert *et al.*, 2005). Although skarns have been mined for millennia, the understanding of Au in skarns progressed rapidly since the previous review in 1981, in which they were not even mentioned (Einaudi *et al.*, 1981). Again, this is mainly due to the sharp increase in the price of gold, which enabled the mining of new types of gold deposits at lower grade. I was fortunate to begin my academic career during this time, as well as to be asked by curious audiences about Au in skarns.

The rising price of gold also substantially increased the exploration budgets of mining companies worldwide and this in turn helped support many of the research projects listed in Table 3.2. An additional benefit is that I was called to

consult on new exploration projects and discoveries, allowing me to observe and learn from the many different styles of skarn deposits with new exposures from drilling and mining.

Text Box 3.1 – Work of a Consulting Economic Geologist

Because skarns occur on every continent and in most countries, I travel a bit. I am the sort of person who has to have more pages sewn into their passport because it gets filled up with all the entry and exit stamps before it expires. I stopped counting at 50 different countries, some of which no longer exist or have changed names since I was first there. Throughout my career, in addition to my “day job” I have worked as a consulting geologist. When there is a new skarn discovery somewhere on the planet, or a known deposit is confusing as to whether it actually is a skarn deposit, I sometimes will get a call to come take a look. This is rewarding in multiple respects: 1) I get to see many new deposits, meaning that I may have seen more skarn deposits than anyone else (there is a saying in geological circles that *“the best geologist is the one who has seen the most geology”*), 2) I enjoy the challenge of going to a deposit that is totally new to me and trying to understand it, and 3) The work is fun and I get paid for it.

Typically, the visit is a day or two, and rarely more than a week. One needs to be a quick learner because the geologists on site will have spent months, years, or their entire careers working on these rocks. When I step off the plane, helicopter, pickup truck, or horse I need to be conversant with the local stratigraphy, geochronology, and mining history (if any). Every consultant has their own way of doing this but here is what I do. In my trusty field book, I write down all the important information: the names of everyone I will interact with, the rock names and ages, important mineralogy, and sketch maps of the stratigraphic column and whatever geologic maps are available. People always say, *“you didn’t need to do that, we will give you paper or digital copies of all the maps, drill logs, etc.”* That may be useful for writing the final report but the physical act of sketching a geologic map, no matter how crude (and trust me, I am no artist) forces me to understand the geological relations. It probably is not necessary for everyone to do this but that is how my brain works. Until I write or draw it myself, with my own hand, I haven’t grappled with and started to understand the geology.

Next, I silently say to myself a mantra, *“I know nothing. I am here to observe. Understanding will come later.”* Commonly, my hosts will start asking from the first hour and the first outcrop, *“What do you think? How did this form? etc.”* I learned early on from Dick Sillitoe, the most experienced and arguably the best consulting economic geologist in the world, to avoid those questions and wait until one is halfway wading across a river or part way up a mountain before entertaining those discussions. The physical difficulty will minimise such premature speculation and is much more effective than the truth, which is *“I don’t know (yet)”*.

Every consulting job starts off the same, sheer terror. Will I understand this deposit? Will it be different than anything I have ever seen before? Will I be exposed as a fraud who really doesn’t know much about anything? Here I rely upon another lesson I learned early on, from the instructor on the first day at the geology field camp I attended before starting graduate school. He said, *“the most important step in field geology is picking up your pencil, putting it on the paper, and starting to draw a line. You may have no idea what you are going to draw but unless you start you will never finish.”*



With that in mind, I move past the apprehension and carefully observe the rocks in front of me and take lots of photographs to document what I am seeing. A better artist would make sketches.

At the end of every day, I jot down my evolving impressions and it never fails that I know a lot more than I did at the start of the day. That is what gets me through. I have the advantage of having seen hundreds if not thousands of other examples. Some things are similar and some things are different; both are worthwhile and can be learned from. At the end of the job I take a day or two to write up my report while everything is fresh in my mind. I never go onto another job without writing up the previous one. This is good training and discipline for a scientific career – do not put off writing up (and publishing) your results. It never gets easier with time.

The reports all have a common format after a brief introduction about the purpose: this is what I have observed (descriptions, amply illustrated by photographs so that staff geologists can revisit outcrops and drill core to correlate what I have seen with their observations of the rocks), this is how it compares to other things I have seen, and here is what I think it means. Most importantly, I always conclude with clear and definite recommendations about what to do next. This might include things like map the rocks and alteration in this area, sample these rocks, and perhaps even “drill here”. Every report is the most important one I have ever written because it forms the foundation for the next consulting job and the next one after that. Almost all my consulting jobs come through word of mouth, based upon previous performance. I don’t advertise and in fact I don’t even have a company. It is just me and my experience of having seen a lot of skarns in my life. I also teach skarn short courses at numerous scientific meetings, as well as in house courses for individual companies that wish to train their staff.

3.5 Skarn Geochemistry, Zonation Models, and New Discoveries

All of my research on skarn deposits has been built on a foundation of detailed mineralogy and geochemistry. In this regard, characterising mineralogy and fluid compositions through the application of phase equilibria and analysis of fluid inclusions has been a mainstay of skarn geochemistry for decades (Kwak, 1978, 1986; Bowman and Essene, 1982; Bowman, 1998a), leading to overall models of skarn zonation. Some more detailed studies have documented the evolution of skarn-forming hydrothermal fluids, in terms of temperature and salinity gradients, over distances of kilometres from the causative intrusion (Meinert, 1987). To conduct such studies, it is necessary to map skarn mineralogy as well as to understand fluid flow paths, such as along igneous and stratigraphic contacts, and towards the marble front (contact of skarn with marble). Because of the mineralogical complexity of skarn deposits, there must be a detailed geological context for the samples collected and studied. This is difficult to do without proper mapping; analytical work conducted on samples that have been “grabbed from a mine” over a day or two are unlikely to yield maximum benefit.



Standard stable isotopic analyses indicated a magmatic origin of most prograde skarn-forming fluids (Taylor and O'Neil, 1977; Bowman, 1998b). The hydrous minerals that form retrograde alteration are now known to be caused largely by later stage magmatic fluids rather than, as previously thought, the result of incursion of meteoric water (Fig. 3.10; Meinert *et al.*, 2003). New tools such as LA-ICPMS and PIXE have led to a more detailed understanding of skarn-forming fluids (Baker *et al.*, 2004; Gaspar *et al.*, 2008; Samson *et al.*, 2008; Shu *et al.*, 2017). These tools enable measurement of not just the composition of major daughter minerals in fluid inclusions, but also the metal content of the fluid phase itself (Fig. 3.11). This confirms that the magmatic fluid provided most of the metals that are present in most skarn deposits.

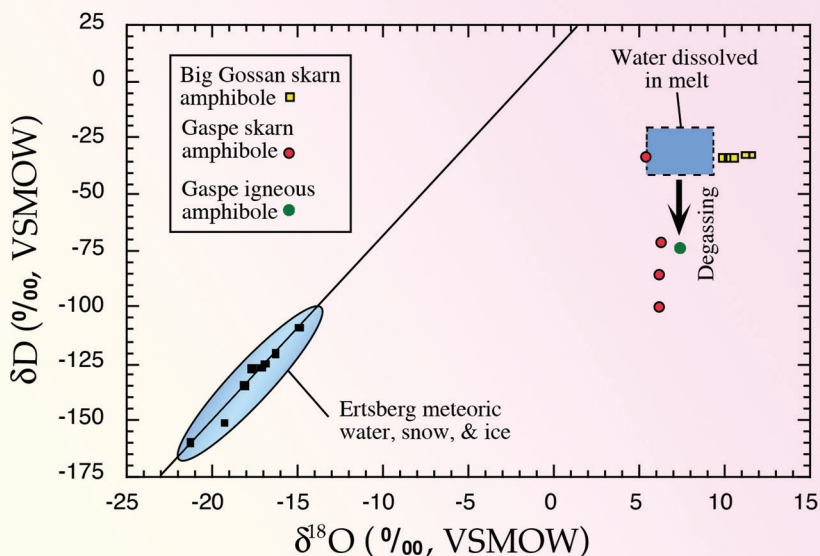
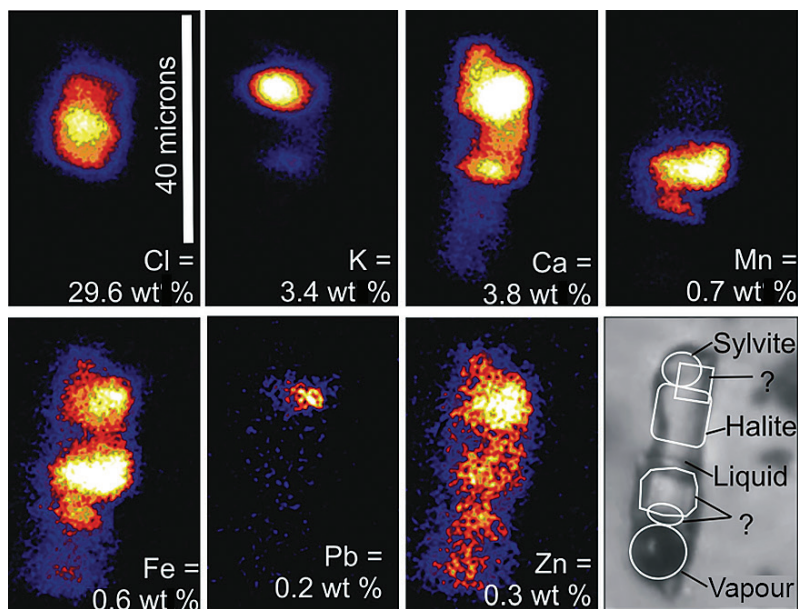


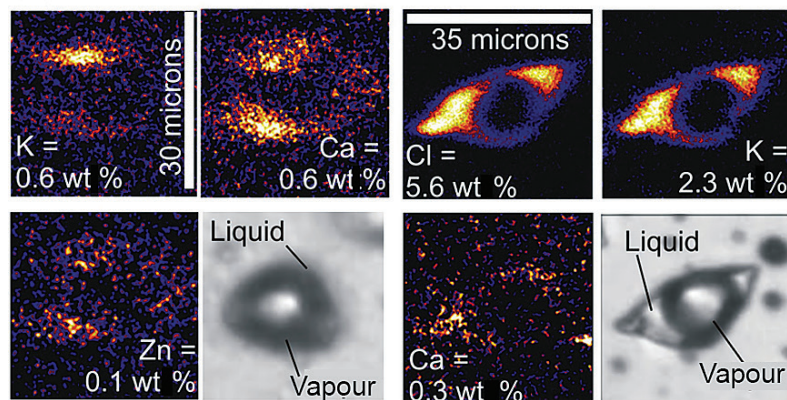
Figure 3.10

Calculated $\delta^{18}\text{O}$ versus δD values of fluids in equilibrium with amphibole from the Big Gossan and Mines Gaspé skarn deposits. The field for water initially dissolved in felsic melt is from Taylor (1992). As water exsolves from magma, the δD value of residual water remaining in the melt decreases (Suzuoki and Epstein, 1976). Therefore, the δD values of late exsolved water is lower (Taylor, 1986; Hedenquist and Richards, 1998). Values for present day meteoric waters from the young (~3 Ma) Ertzberg district are from Harrison *et al.* (1999). Mineral data from Meinert *et al.* (2003).





(a) Brine inclusion (BISM-27)



(b) Vapour inclusion (BISM-96) (c) Critical inclusion (BISM-5)

Figure 3.11

Proton-induced X-ray emission (PIXE) images of (a) brine, (b) vapour, and (c) critical inclusions in the Bismark Zn skarn deposit, Mexico. Zones of high concentration of a particular element coincide with red, yellow, to white colours (in increasing abundance) and blue to black represent low to zero concentration, respectively. Numerical concentration in each picture is bulk element concentration in fluid inclusion (from Baker and Lang, 2003; Baker *et al.*, 2004 with permission from the Geological Society of America).



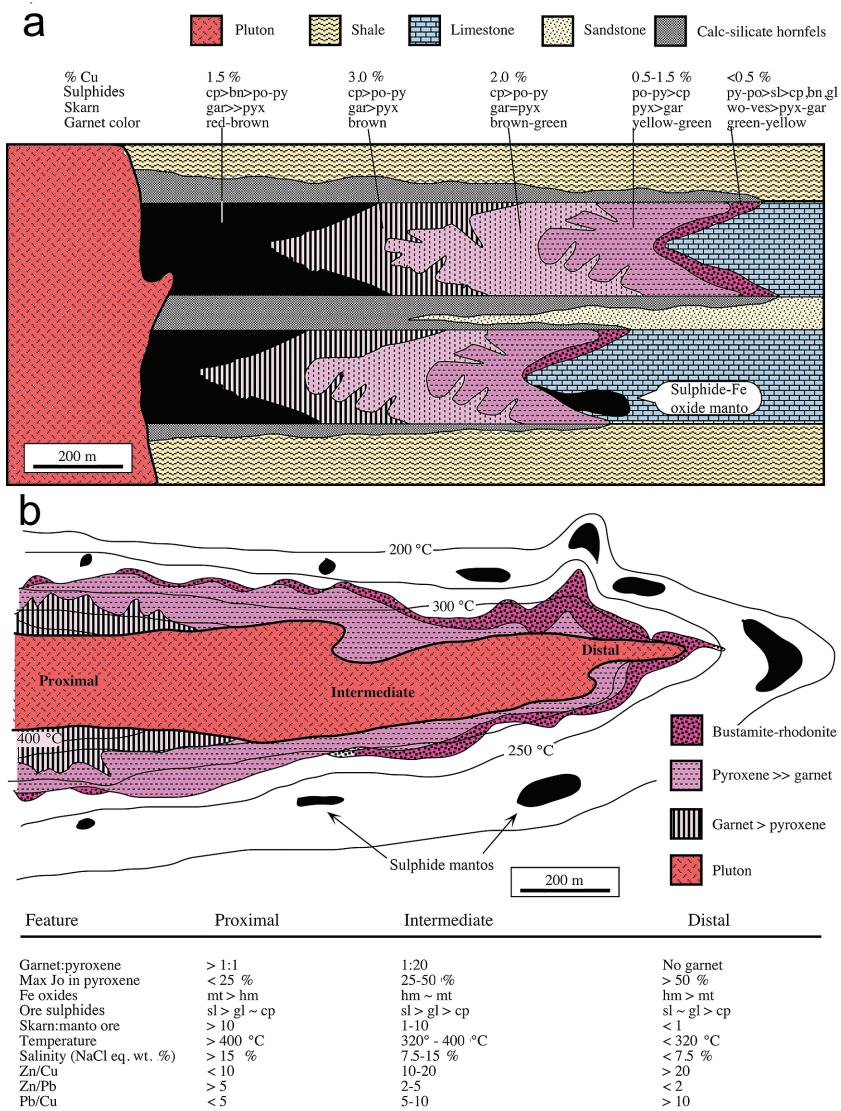


Figure 3.12 (a) Typical zonation pattern of Cu skarns (after Atkinson and Einaudi, 1978). (b) Typical zonation pattern of Zn skarns (modified from Meinert, 1987).

Skarn zonation models (Fig. 3.12) and geochemical gradients can be used in exploring skarn systems that are buried or only partly exposed. For example,



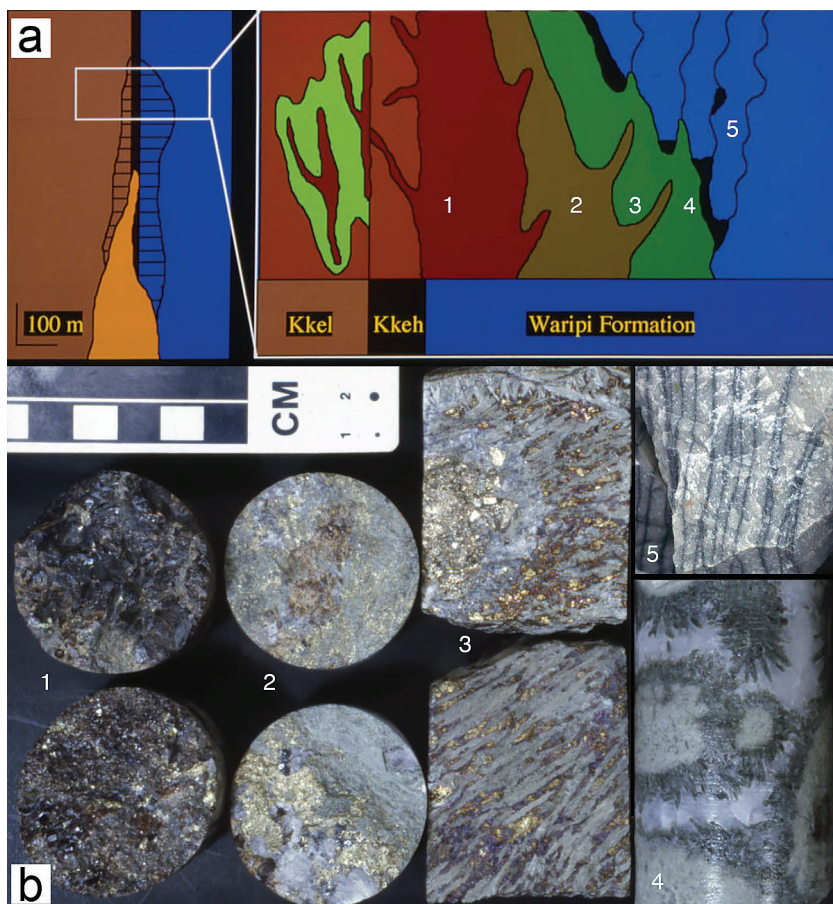


Figure 3.13 Skarn zonation in the Big Gossan Cu-Au skarn system (Meinert *et al.*, 1997). (a) Schematic cross section based on known skarn mineralogy (top and right) above a hypothetical intrusion at depth. Lithologies: Kkel = Kembelangan sandstone, Kkeh = Kembelangan hornfels, Waripi Formation limestone. (b) Skarn (in drill core) from proximal 1) red-brown garnet-chalcopyrite, 2) brown garnet-green pyroxene-chalcopyrite, 3) green pyroxene-pyrite-chalcopyrite, and 4) distal dark green Fe-rich pyroxene and 5) fluid escape structures in limestone beyond the skarn front.

the Big Gossan Cu-Au skarn in the giant Ertzberg district, Irian Jaya (5.2 Gt at 1.13 % Cu, 0.92 g/t Au, 4.38 g/t Ag) is the highest grade skarn (2.7 % Cu, 1.0 g/t Au, 16.4 g/t Ag) in the district (Leys *et al.*, 2012). However, it was unclear at the time of discovery, which of several intrusions it was related to (Meinert *et al.*, 1997). The skarn itself was classically zoned (Fig. 3.13) but the zonation did not

point towards the adjacent Ertsberg Diorite, the presumed source of the hydrothermal fluids. The skarn minerals had high temperature and high salinity fluid inclusions (Fig. 3.14) that suggested the source was not far away, so how could one analyse the skarn minerals to determine the direction and distance to the source? The key was the increasing Fe composition of the garnet and pyroxene away from the fluid source. This correctly predicted the hidden porphyry (Fig. 3.13a).

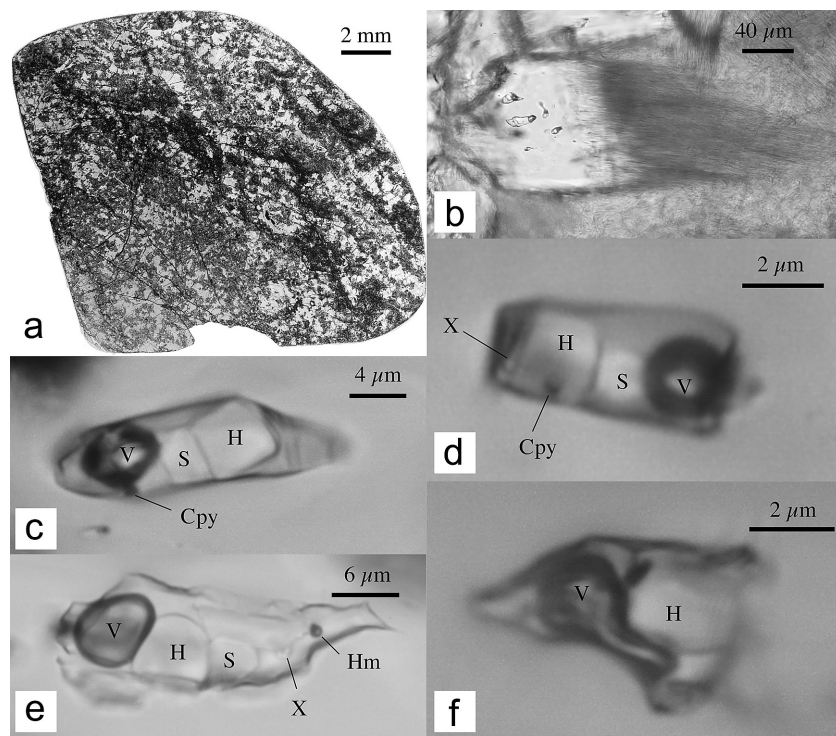


Figure 3.14

(a) Scan of pyroxene fluid inclusion plate from the Big Gossan Cu-Au skarn. (b) Pyroxene crystal with several multi-phase fluid inclusions. (c) Multiphase fluid inclusion containing vapour bubble (V), halite (H), sylvite (S), and chalcopyrite (Cpy). (d) Multiphase fluid inclusion containing vapour bubble (V), halite (H), sylvite (S), chalcopyrite (Cpy), and unknown mineral (X). (e) Multiphase fluid inclusion containing vapour bubble (V), halite (H), sylvite (S), hematite? (Hm), and unknown mineral (X). (f) Multiphase fluid inclusion with large daughter minerals that have deformed the vapour bubble (v). Such squeezing behaviour is repeated when the inclusion is cooled after homogenisation (Meinert *et al.*, 1997).



3.6 Future Skarn Studies

Further advances in geochemical understanding of skarn genesis are likely as new techniques are developed and applied. In particular, the many capabilities of LA-ICPMS are increasingly being applied to a variety of ore deposits. This has greatly increased our understanding of the metal content of hydrothermal fluids in a variety of ore systems (Pettke *et al.*, 2012; Wagner *et al.*, 2016; Audétat, 2019). There have been some applications to skarn deposits (Gaspar *et al.*, 2008; Samson *et al.*, 2008; Wang *et al.*, 2017a) but the large number of minerals that potentially could be analysed, such as olivine, ilvaite, epidote, and amphibole, suggests that there is much more to be done.

Another area of rapid advance is in the application of non-traditional isotopes such as Ag, (Argapadmi *et al.*, 2018), Cu (Larson *et al.*, 2003, Wang *et al.*, 2017b; Mathur and Wang, 2019), Fe (Wang *et al.*, 2011, 2015; Mathur and Wang, 2019), and Zn (Duan *et al.*, 2016; Mathur and Wang, 2019) as well as clumped isotopes (Mering *et al.*, 2018). These techniques may tell us about sources of metals, and for clumped isotopes, an independent measure of temperature. Since many of these isotopic techniques are new to ore deposits in general and skarn deposits in particular, it is too soon to know what insights they may reveal. But there certainly is no shortage of questions to be asked.

In addition to these emerging techniques, there are some age old questions for which we still don't have complete answers, including: *Why do we see similar patterns of skarn mineral zonation around the world when there is huge variation in the composition of igneous rocks and wall rock protoliths for individual deposits? What causes the wide range of garnet colours, and the almost universal zonation from proximal red-brown garnet to distal pale garnet and dark green pyroxene?* These and more are questions for the next generation of skarn researchers to tackle as I drive off to my retirement (Fig. 3.15).



Figure 3.15 License plate of the author's automobile.



Most university professors are also teachers. We teach in many different ways and for those in research university positions much of that teaching is in training students, from beginning graduate students to advanced post-doctoral research professionals, how to “do what we do”. Our goal is to educate the next generation of scientists on how to conduct and publish cutting edge research to advance the state of knowledge, and in parallel, their careers. That approach of learning by doing research is extremely important but is not the subject of this section. There are many other publications on that aspect of the graduate education process.

Rather, I wish to address something different and that is how one teaches and educates others to do things that no one has thought about doing before, *i.e.* the creative process itself. As someone famously said, the best education is a teacher and a student on either end of a log, deeply engaged in the process of learning. As geologists we call that log a field trip and we introduce students to field observation. That has been a primary way of teaching geology since the earliest days of the science. I tried taking that one step further in using observational field geology, not to teach geology *per se* but rather to use field observations to unlock the creative process in students who are just beginning their university education at the undergraduate level and who may have no previous interest in or knowledge of science. I will illustrate this with a course I created called “Sherlock Holmes and the Scientific Method”.

4.1 [Sherlock Holmes and the Scientific Method](#)

The impetus for this course was a conversation that I had in the early 1990s with the Dean of the Honors College at Washington State University. The Honors College offers an enriched, four year core curriculum to students of high ability and initiative. The concept is straightforward – put some of the best students from a relatively large university together with some of the best professors in relatively small classes designed especially for them. In my then role as Chairman of the Faculty Senate and without meaning to be critical of the programme, I made the observation to the Dean that Honors College students majoring in science or engineering took advantage of the opportunity to take enriched Honors courses in the humanities but that the reverse did not appear to be happening. Honors students majoring in the humanities did not take many science/engineering courses in general, and in fact there were relatively few such classes in the Honors College even if the students were so inclined. The Dean basically agreed, acknowledging that it was difficult both to get science/engineering faculty to teach courses that humanities students would want to take and if such courses existed, get the humanities students to take them. He then countered with the diabolical challenge, “If you are so full of bright ideas why don’t you create such a class?”



I thought that perhaps Sherlock Holmes could be a bridge between the worlds of science and humanities. The series of Sherlock Holmes stories created by Arthur Conan Doyle are fairly well known around the world, are often highlighted as examples of the scientific method, and would not be thought of as “science-threatening” by anyone, certainly not in the sense of calculus, thermodynamics, or microbiology. The course’s premise is that Sherlock was a master of observation and possessed encyclopaedic knowledge of such things as soil mineralogy and tobacco ashes. The course substitutes geologic observation for the ash-soil obscurata of the master, and the final assignment is to write an original Sherlock Holmes story, in dialogue, whose central plot element involves geologic observation. In order to prepare the students to “see like Sherlock” we had to go to the field so that they could develop and practice their observational skills. The texts for the course were the collected stories of Sherlock Holmes and an introductory geology textbook.

The course alternates weekly between geology field trips where students can acquire and practice their geologic observation skills (none of them had any geology or creative writing experience before taking the course so it is very much “learning on the job”) and periods where students read a dozen or more Sherlock Holmes stories and carefully dissect the reasoning and observation skills used in the plot. The students also work through a progression of increasingly complex writing assignments, with the requirement that each assignment be critiqued by an “outside voice”, *i.e.* another student, a roommate, parent, anybody - just so long as they can bring a fresh perspective to the writing. This is not unlike the scientific writing and editing process, that I will describe in more detail in a later section. Over a 30 year period of teaching this course, first at Washington State University (WSU) and later at Smith College, I never encountered a terrible final story and some of them were quite clever indeed.

Each year the students in the Honors College vote on the best professor they have experienced in Honors College classes and in 2000 I received the Honors College Faculty Medal for “Sherlock Holmes and the Scientific Method”. An even more rewarding experience was a conversation I had with a student several semesters after she had taken the course. She said something like this,

*“My roommate noticed the book on my desk called **Introduction to Geology** and knowing my aversion to science said, ‘I didn’t know that you were taking geology’. I replied that I wasn’t, it was a book for my Sherlock Holmes class. My roommate continued, ‘Well I am taking a geology course and that is the same textbook that we are using’. So, I explained to my roommate that we simply used it to understand how Sherlock made observations in the field so that we could incorporate our own observations into our final stories.”*

It is somewhat ironic that the perception of resistance to studying science persisted through the actual study of science. I didn’t feel the need to confess to the student that I also taught the Introductory Geology class in question and that not only did the two courses use the same textbook we also went on the same



field trips and basically learned the same things in the two courses. It is just that one course was called Introductory Geology and the other was called “Sherlock Holmes and the Scientific Method”.

When I taught the “Sherlock Holmes and the Scientific Method” course at Smith College this was the first (and only) course to satisfy three different graduation requirements – in literature, science, and writing. A very rewarding affirmation of this course on the non-science side came several years after one of my Sherlock students graduated as an Arts major and was applying to a competitive Master of Fine Arts (MFA) graduate writing programme. She asked me to write her a letter of recommendation to the MFA programme. I had some trepidation about how a letter from a geology professor might be received by the MFA admissions committee. I was surprised and heartened when some time later I received a note from the admissions committee thanking me for my letter and stating that they had never received one before from a scientist but that it was the tipping point in their decision to accept the student into their selective programme. She has since gone on to become a professional playwright with many fine productions to her credit.

Although I could describe in detail the weekly writing assignments and the geological field trips that were central to this course, I think it more effective to fast forward to the end result, one of the successful Sherlock Holmes stories that resulted. Although there are easily a dozen examples that I would be proud to share, the following story will illustrate the general theme. The writer is a person of tremendous potential and excellent writing ability but it needs to be stated that she is not a scientist and had no particular scientific training other than that described above. Nonetheless, her story illustrates some profound geological and geochemical insights. It is reproduced below with permission from the author so that the readers of this *Geochemical Perspectives* can see what creative excellence looks like.

Text Box 4.1 – The Adventure of the Sleeping Dragon

An original story by Samantha Noble in fulfillment of the final writing assignment for the first year seminar at Smith College, “Sherlock Holmes and the Scientific Method”.

“I think, Watson, that it is high time we had a holiday.”

This was the unlikely declaration made to me by Sherlock Holmes over breakfast one day in the summer of 1902. I glanced up from my morning paper.

“A holiday?”

“Certainly,” Holmes smiled. “In these past few months we have succeeded in subduing the criminal population of London rather too well. The streets are silent. The populace rests easy in their beds. We have earned a moment to rest on our laurels.”

He reclined in his chair as if putting action to the word.

“And where do you suggest we go?” I asked.

He seemed to consider a moment.

“Martinique, I think. It is quite pleasant at this time of year.”



I regarded him as he spoke, and some aspect of his smile aroused my suspicion.

"You've no fondness for idle relaxation, Holmes. There's some other meaning to this sudden desire for travel."

"Am I so transparent that even you can see through my ruse?"

He drew from his pocket a letter and handed it across the table to me.

"I am, in fact, summoned to that pleasant island at the request of one Madame Blanche de Bourdeille of Fort-de-France. While she is obviously a woman of fine character and one in the midst of a most fascinating conundrum, her haste to contact me has badly reduced her penmanship. I will save you the trouble of deciphering it.

I waited as he paused, then continued.

"Madame de Bourdeille has recently had the misfortune to lose her husband."

"That is a terrible misfortune indeed," said I, "But sorry as it is I see no aspect of mystery in it."

"The mystery lies not in the event itself, but rather in the circumstances of it. Monsieur de Bourdeille had the bad luck to be visiting a colleague in the city of St. Pierre three weeks ago."

"St. Pierre?"

"The name is familiar to you?"

"Yes...." I stared at him in horrified amazement. "Then Monsieur de Bourdeille was...?"

"Indeed. One of over 500 victims killed in the outskirts of that city in what has been called one of the most terrible and bizarre events of the century."

"Over 500?"

"I believe the exact figure was 554."

"But what could possibly have killed all those people at once, in a single night?"

"Therein lies the mystery. Authorities on the island are still baffled. Not one of the victims showed signs of physical trauma, nor were there signs of a struggle. In fact, most of them died peacefully in their beds."

"Perhaps a mass poisoning...?"

"An interesting supposition; one which also crossed the mind of local authorities. From whence it would have come, however, is a distinct problem with that hypothesis. It is impossible that all of them came in contact with the same poisoned foodstuff, and when their water supply was tested, it proved to be unpolluted. Several autopsies were done, but no fatal toxins were detected."

"Some strange disease, then?"

"One with no symptoms but instant death?"

I was forced to concede that this was highly improbable.

"So Madame de Bourdeille has summoned you to find the reason for her husband's untimely demise?"

"In part. She has summoned me specifically that I might prove her innocence in it."



"She was not killed in the incident," I said. "But was she with her husband at the time of his death?"

"Very observant of you, Watson! Since she has written to us, she certainly is alive. But no, Madame de Bourdeille did not accompany her husband to St. Pierre. The lady was miles away in Fort-de-France."

"Then how could she possibly have killed him?"

"I would think that by now you would know that arranging a murder over a distance is a trivial task for a clever criminal mind, Watson. In this case, I think it would be best if the lady herself explained the events that transpired. But this requires that you accompany me to Martinique and speak with her."

Holmes raised a questioning eyebrow.

"I'll pack my things at once," I said.

It was fortunate Holmes had been correct in his supposition that I would at once agree to this venture, for he had already booked passage for us on a vessel bound for Martinique the next morning. I barely had time to place my practice in the hands of a colleague before I was whisked off to the docks.

Our journey was a pleasant one, and though Holmes's suggestion of a holiday was a mere deception, I found myself overwhelmingly drawn into a delightfully relaxed humor. The fresh sea air was so invigorating and the promise of an island paradise so pleasing that I all but forgot the true purpose of the journey. Holmes too seemed rejuvenated, though more, I suspect, by the promise of an interesting case than by the fresh air. While I strolled about the deck, lost in fond recollections of novels of high seas adventure, he followed a ways behind me, from time to time pausing to linger at the rail, gazing out across the water in the direction of our goal, his eyes alight, I fancied, with anticipation of what was to come.

After several days of amiable and uneventful travel, we arrived in Fort-de-France (Fig. 4.1). Examining our surroundings as we disembarked, I was at once charmed by their exotic beauty. All the buildings huddled near the shore, as though awaiting with great anticipation the arrival of visitors to their island. Each structure was built directly abutting its neighbor, much as in London, but the homes and shops of Fort-de-France were more brightly painted and more varied in their style. Some were painted a blinding white, while others were fantastic shades of rose or gold, and everyone seemed dazzling under blue skies and radiant sunlight.

The people were crowded together almost as closely as their residences. As I followed Holmes through the city streets, I could not help but glance at the faces of those who passed me. The majority were those of the dark-skinned natives, but here and there were interspersed pale European countenances. Some of these latter obviously were those of citizens, and others, with expressions as fascinated and delighted as my own, must surely have been those of holidaymakers. Many spoke clear French, of which I have some little knowledge, but others spoke a strange dialect I could not fully decipher. It seemed to be some odd amalgamation of French and some native tongue of the island. All the people seemed to be motivated by some great purpose of their own; moving with a controlled excitement through the narrow streets, and haggling in raised voices at market stalls. This atmosphere of intense animation was palpable and contagious, and so much did it affect my own pace that I was all but on Holmes's heels when we reached our destination.





Figure 4.1 The volcanic summit of Mt. Pelée overlooks St.-Pierre, the former capital of Martinique, which was considered the Paris of the West Indies (photo credit: AFAR <https://www.afar.com/>).

It was a blue-painted residence of very fine architecture, its many long windows shielded from view by white shutters. A small terrace fenced in with wrought iron stretched across the front of the house between the upper and lower tier of windows. Holmes knocked, and we were admitted by a servant who ushered us into a small parlour, where we found Madame de Bourdeille awaiting us.

She sat facing away from our entrance, her eyes turned instead towards the window. It was obvious that she was of tropical descent, for her skin was deeply tanned and her hair was as black as the veil of mourning that restrained it. But what truly told of her tropical nature was her expression. So consumed with emotion were her dark eyes that her feelings were almost tangible. One could, with pleasure, imagine those eyes dancing with joy, or just as easily envision those expressive features transfixed in the image of a fiery rage.

The servant who had led us in gave us introduction, and the lady at once rose to greet us.

"Mr. Holmes, Doctor Watson, I'm so glad you've arrived." She gestured to two empty chairs and we seated ourselves. "It must have been a great trouble for you to come so far, and I'm sorry to have summoned you away from London, but I am at my wit's end!"

"It is no trouble, Madame," said Holmes. "I hope I may be able to set your mind at rest. But to do so I must have the facts of your husband's death in their entirety."



"Facts? I fear there is but one, and that is that I killed my husband."

The woman's eyes filled with tears.

"It was not my intention! I thought it merely a folly, but in truth this is all my doing!"

Holmes's eyebrows arched and I felt myself puzzled as well.

"It was my understanding that you were here in Fort-de-France on the night your husband died."

"Yes, but one needn't leave one's home to do wicked deeds." She looked down at her hands folded upon her lap, and seemed to regather her wits. At length she again looked up, and forced herself to smile. "Forgive me. I have gotten ahead of myself."

"If you have indeed told me the cause of your husband's death, you have proceeded to the end of the investigation," said Holmes.

"No, no! You see I have no actual evidence of my guilt, merely a suspicion. An awful, awful suspicion."

"Tell me then from beginning to end the events surrounding your husband's death, and we shall see if your suspicion shall be confirmed or proven false."

With this, Holmes settled himself back in his chair, and Madame de Bourdeille began her story.

"My husband and I married five years ago. He was in Fort-de-France on business from Paris, and," she blushed "he found reason to stay."

"We were very happy until perhaps a year ago. But then the man I knew underwent a strange and terrible transformation. He was suddenly suspicious of everyone and everything around him. He would not suffer anyone to know his comings and goings, not even myself. My husband began to disappear for weeks at a time on journeys to I knew not where. It was one of these strange travels that took him to St. Pierre.

"You may well wonder, Mr. Holmes, where in all this I gained the impression that I was the cause of my husband's death. I am sure you will think the reason foolish, but considering the manner in which he died, I cannot help but wonder at it.

"I was born and raised in Martinique. We may seem a pleasant, quiet island, but we are not so far from legendary Haiti, and we have our own traditions. I should know little of them, were it not for a maid who worked in our home when I was a small girl. She was a wonderfully kind woman, but terribly superstitious. This maid was my especial friend and companion, for she told wonderful stories, and would often slip me sweets from the kitchens. In return for these small kindnesses, she was entirely in my confidence.

"One day I found myself in small disagreement with some of the other local children. I cannot remember the cause, but it was certainly something petty, as are many things over which children quarrel. But at the time, I was most distraught by what I thought was a terrible wrong against me. I ran at once to this maid, and tearfully told her of the children's vicious treatment of me—and I greatly exaggerated it, I am sure. She was as infuriated as I by their cruel treatment of me, for I was as much her favored companion as she was mine. It was her decision that we should have revenge upon the little monsters and, in case anything of the sort should happen again, she taught me the trick to punish wicked people.

"She instructed me to find some means of collecting hairs or nail clippings or some other such part of my enemy, which I dutifully did—I shall not tell you in what



manner—and then she sewed this into a little doll. Over this she spoke a short series of words, which she taught to me. She then presented me with the toy, and told me that I could now punish my enemies. To take my revenge, I need only do to the doll what I felt should happen to the tormentor whose hair was sewn inside.

“With all the faith of a small child, I believed her. Wrathful still, I plunged a sewing needle deep into the very head of the doll. I am certain my belief in her totem would have faded were it not for the outcome of my action. The little child against whom I directed my anger had, the very next day, an awful accident. He was playing on one of the ledges that juts over the sea and ran too close to the edge. The ledge crumbled and he fell to his death. His skull was crushed by the rocks below.

“Horried, I assumed at once that his death was my doing. Over the years, I was eventually able to convince myself that it was merely an accident, that my worry was caused only by superstition. But even yet, I never again followed the maid’s instructions or made another of those dreadful little dolls—until two weeks ago.

“I am ashamed to say that I was quite upset with my husband. His abrupt change in behavior, the long, mysterious journeys, and my suspicions, led me to believe that he had betrayed me. He even received strange letters, though he tried to hide them away before I could see them. He would rise early to collect the post before I could look through it, but on several occasions he was unsuccessful. The letters had no return addresses, and they were always very thick. I dared not open them, but I believed I knew what passionate missive was inside. By the time he embarked on his journey to St. Pierre, supposedly called away on business for the second weeklong period in a single month, I was quite convinced of this hypothesis. I was blinded by my anger and my hurt, as much as I was in my childhood. I collected a few strands of my husband’s hair from his comb and constructed a second little doll, over which I spoke the potent words. But this doll I did not pierce with a needle. I instead put my hands around its little neck and squeezed it tight as though to strangle it—”

The woman broke off, her emotion overcoming her.

“I did not intend to truly do any harm!” she cried.

“And I am sure, Madame, that you did not.” Holmes, as was his custom, had listened to the strange tale with his eyes closed, but now he opened them and regarded Madame de Bourdeille levelly.

“You say he informed you he would have to travel to St. Pierre on business,” Holmes said calmly. “What was his business?”

“He never spoke of it, so I could not say for certain, but I know he was involved with the French government.”

“That may prove to be of interest. Since his death, have you found any evidence to support your suspicions?”

The woman cast her eyes down.

“No.”

Holmes regarded her for a moment before he spoke.

“I think, Madame de Bourdeille, I can prove you entirely innocent in your husband’s unfortunate end. However, I must know more of the circumstances of his death, and the men and women he died with besides.”



"Oh thank heavens! If you could find some evidence that I was not at fault I could finally rest my troubled mind."

Holmes rose.

"The place to begin, I believe, is St. Pierre. If I am correct in my calculations, we should be able to reach that city by sundown today. If we are to arrive with time to examine the town, however, we must be quick about it. For this reason we shall take our leave of you, Madame. Come, Watson."

Bidding a hasty farewell to Madame de Bourdeille, I hurried after Holmes.

When we were again in the city, he wasted no time in engaging a carriage to take us to St. Pierre.

Once we were well on our way, Holmes fell into a silent reverie, his eyes on the scenery flying by outside the window, but his thoughts elsewhere. I, respectful of his silence, found my own thoughts returning unbidden to Madame de Bourdeille's childhood adventure. Was it possible, I wondered, that she had somehow orchestrated that child's death? If so, was it possible that she had used the same, strange tactic to murder her husband?

"Holmes..."

"As I told Madame de Bourdeille, I do not believe so, no."

I stared at him, disbelieving.

"You are reflected quite clearly in the window. I merely observed the expressions that crossed your face. At first you looked concerned, as though you mulled over some unpleasant subject. As we had just spoken of the death of a child, I could not but conjecture it was the recollection of this which so shaped your features. Then you assumed such a look of horror that I knew some even more dreadful thought had crossed your mind. Continuing on the hypothesis that you had before thought of Madame de Bourdeille's tale, I assumed you must have, for a moment, considered that her story might be true. Then, when you spoke my name, I knew you intended to gain my opinion on the matter to temper doubts of your own. Thus, I provided you with the answer you required."

"Amazing, Holmes."

"What is rather more amazing, Watson, is the question of what killed Monsieur de Bourdeille."

Holmes looked again out of the window, his brow furrowed.

"As I have said, it was not Madame de Bourdeille. If she had killed her husband as she supposed, how could one account for the deaths of all those around him? Even the ire of a woman scorned is not *that* potent. No, it was not she. But the true killer is rather obvious. It is the mastermind behind the crime to whom I cannot put a name."

"You know the killer already?! But Madame de Bourdeille told us almost nothing."

"She did not have to. One must merely observe one's surroundings to know the killer's name."

"Then who is it?"

"All in good time, Watson. All in good time. For the moment I think we should look into Monsieur de Bourdeille's employment. When we arrive in St. Pierre, I shall send



a message to France. I wish to contact certain parties who I believe will be most enlightening.”

I cannot say why, but for some reason it had been my impression that St. Pierre should be far smaller than Fort-de-France. I was much mistaken. Our carriage brought us to a city which was both larger and more crowded, but just as delightfully tropical.

“I’m hardly surprised Monsieur de Bourdeille’s business brought him here.” I remarked to Holmes as we alighted. “It seems quite the bustling metropolis.”

“And well it should, Watson. St. Pierre is the capital city of this island. It is often called Little Paris.”

We proceeded through the streets until we reached the French consulate where, Holmes insisted on sending a telegram to his contact.

Still exhilarated by the island’s atmosphere I remained outside, watching the busy street. It was much like Paris in its bustle and its appearance. One should have thought oneself in Europe were it not for one aspect of the landscape which lent to the city an inescapably exotic flavor. St. Pierre stood in the shadow of a great, verdant mountain. I had seen it at a greater distance in Fort-de-France, but that vantage point had not given me proper perspective to fully understand its magnitude. With the setting sun behind its vast expanse and casting upon it an unearthly glow, it almost resembled some strange, enormous beast at rest. I fancied that it took the shape of a reclining dragon, imagining its odd outcrops as horns and its ridges as the beast’s spiny back.

“Le dragon dort encore, mais le feu dans son estomac ne s’éteint pas.”

I jumped, and wheeled round to see who had spoken. A small, slender man was regarding me intently over his half-moon spectacles.

“I beg your pardon?”

“The dragon slumbers, but the fire in its belly is not extinguished,” the man said, this time in English.

It seemed he had also learned Holmes’s rather irritating trick of reading the face, but, impossibly, his rhetoric had even dwarfed my friend’s in its baffling nature.

“I suppose the mountain does look rather like a dragon in this light.” I attempted.

The man looked surprised, then embarrassed.

“You are not Monsieur Henri de Bourdeille?”

My heart leapt at the name. Here, by pure luck, was a man with some information regarding our case. I knew that I must hold him to that spot till Holmes returned. But now that he suspected I was not de Bourdeille, the man seemed in a great hurry to depart. Instead of making an answer, I rejoined with a question of my own.

“What interest do you have in that gentleman?”

I knew at once that I had made a grave error. The little man’s eyes flashed, and he took a step away.

“Little. I hardly know him. Forgive me for troubling you.”

He turned as if to walk away, but at that very moment Holmes emerged from the post office.



“Brûle le feu dans ses pensées?”

On hearing this, the man froze, then slowly turned back to us.

“The man you’re looking for is dead,” said Holmes, “But I would be very interested to know what he was meant to deliver to you.”

“But if you are not de Bourdeille, how did you know the signal words?” cried the man in surprise, “They are known only to the highest ranking members of French Intelligence!”

“I am Sherlock Holmes. It is my business to know things of which others are ignorant. Now, Monsieur LeCroix, what information was contained in the papers de Bourdeille was to give you?”

For a moment the man studied Holmes’s face, then seemed to come to a decision.

“He was to give me the final confirmation of the death of one Monsieur Jean Malin, but I see that luck was once again on that villain’s side.”

“Not luck, but intellect, if I am not mistaken. Tell me, in your last report to de Bourdeille, did you instruct him to seek Malin by the lake on that mountain, Mount Pelée?”

“Why yes, but how did you know?”

“It is of no matter. I have the permission of your government to instruct you, Monsieur LaCroix, and so I tell you this: go at once to the Mayor of this town and tell him to send all its inhabitants away at once.”

“Why?” His eyes narrowed.

“Because if you fail to do so hundreds, perhaps thousands of people will die. What are you waiting for? Go man, now!”

“Holmes, what on earth is going on?”

“All shall be made plain shortly. For now I suggest that we leave St. Pierre and return at once to Madame de Bourdeille.” We turned and started off quickly, leaving the stunned Frenchman where he stood.

“But who is this Monsieur Malin? What of him?”

“If he has any sense at all, he has already put as much distance between himself and St. Pierre as he can. But he cannot run for long. The French are hot on his trail.”

“But who *is* he?”

“I shall explain all on our journey,” said Holmes and, despite my questions would say no more until we were safely again in a carriage, hurtling through the night towards Fort-de-France.

“Monsieur Malin was an agent of the French government, entrusted with some of their most secret information. He was quite talented, but also quite fond of money. Rebels within Algeria offered him a great deal of money for the information in his possession, and that amount again if he could acquire and deliver more such secrets. For some, all morality and all national pride are overwhelmed by greed. Monsieur Malin has been quietly leaking secrets to France’s enemies for close to five years.

“At first, the French government could not find the breach in their security. They were baffled. The only course of action, they decided, was to enlist the help of their most



talented agent. He had been retired for four years, and desired greatly to remain so, but, seeing that his country was in danger, he acquiesced. That agent was Monsieur Henri de Bourdeille.

"The strange missives Madame de Bourdeille believed to be love letters were in fact communications from the French government, alerting her husband to the latest developments regarding Malin. The strange journeys he embarked on were one and all attempts to track down and eliminate his quarry."

"Eliminate?"

"He was no normal agent." Holmes regarded me levelly.

My eyes widened.

"He was...?"

"Only for the good of his country, Watson. He never in his career took up arms against an innocent man."

"Two weeks ago news came to de Bourdeille that Malin had been sighted in St. Pierre. He went at once to that city, believing he finally had his man cornered. But Malin already knew of his coming, and had already designed the perfect plan to eliminate his foe.

"As many agents are, Malin had been trained in a variety of disciplines which might prove useful to one in his line of work. Principal among these had been geology. You look scornful, Watson, but were it not for Malin's geological knowledge de Bourdeille would still be alive.

"Mount Pelée, in the shadow of which St. Pierre stands, is, as you may know, volcanic. Most believe it currently to be dormant."

"The dragon slumbers," I said, remembering my puzzling conversation with LeCroix.

"But the fire in its belly is not extinguished," said Holmes. "It is ironic they should choose those words as their signal, for they are entirely true. Mount Pelée is not dormant. She is the murderess of over 500 souls and she plans to consume still more."

"How could Malin know that the volcano was active?"

"You will recall I enquired if he had been sighted near the lake?"

"Of course."

"When a volcano is active, gases build up within its inner chambers. One of these gases is carbon dioxide. In small quantities, this carbon dioxide is harmless, but in large clouds it can be deadly. The gases build up for some time within the volcano, exerting an enormous amount of pressure on its craterous mouth— incidentally, in the case of Mount Pelée, just where that lake lies—until the gas must escape or the mountain burst.

"Malin, camped by the lake, would have seen the beginnings of the gas escaping as bubbles breaking on the lake's surface. He would also have known what was to come next: a huge release of carbon dioxide gas. This gave him an idea. He devised to be seen by French agents, which he knew would draw his opponent to St. Pierre. I admit, the success of his plan rested mostly with his luck, but it just so happened that Mt. Pelée released her cloud of carbon dioxide a few days after de Bourdeille arrived. Of course, knowing the danger, Malin was long gone by then.



"So when you said you knew the murderer...."

"I meant the mountain. It was not voodoo that strangled him, Watson, but the volcano. Carbon dioxide has no smell or taste, and it would leave no discernable marks upon the bodies. Thus, the local authorities could not determine the cause of death."

"And you told that agent, LaCroix, to tell the mayor to evacuate the town as the volcano is close to eruption?"

"Exactly so."

"Speaking of LaCroix, how did you know of him and his purpose? And why was he unaware of de Bourdeille's death when the incident of the mass deaths was so widely reported?"

"I uncovered him in the course of my communications with local French officials, and gaining that his meeting place with de Bourdeille was to be the French consulate was a lucky coincidence. As to why he did not know of de Bourdeille's death; all LaCroix ever knew of his contact was his name, and the words which would entice him to speak. He was never informed of his day of arrival in St. Pierre, only that he was to meet him there on this day. Most likely, he assumed that de Bourdeille arrived at the same time that he did, this morning, and thus assumed he had escaped the incident, but that is mere conjecture."

I leaned back in my seat, somewhat overwhelmed by the enormity of the situation. Though Malin had escaped, Holmes had very likely saved the lives of an entire city, and there was also a smaller, but equally satisfying victory.

"When we return to Fort-de-France, we can finally set Madame de Bourdeille's mind at rest, both in regards to her own suspected guilt, and her husband's guilt as well. She shall see that he deceived her not to commit infidelity, but heroism."

"No Watson, she will not. She shall know that he perished in a release of volcanic gas, and that her silly conjuring is not to blame, but she shall know no more."

"But she will believe him untrue!"

"And so she must. It would only put her in danger to let her know who her husband truly was. For the sake of the French government, his heroism must, in his death, remain as secret as it was in life."

Though I felt greatly guilty at hiding the full truth from Madame de Bourdeille, the part of our tale we were allowed to share with her seemed to give her great comfort. When we left her home she seemed almost cheerful, in spite of the gravity of her loss.

Once again in the bustling streets of Fort-de-France, I glanced at Holmes. He was still animated with the recent victory.

"Well Holmes," I said "Since we are now at liberty, shall we remain a while in Martinique?"

"With its active volcano and web of bristling French intrigue? No Watson, I think not. We should leave this tropical hubbub and return at once return to the serene calm of London."

He turned to me, and smiled broadly.

"I think it is high time we had a holiday."



Epilogue

Despite my friend's finest efforts, the city of St. Pierre was doomed. LaCroix and the city's Mayor never had time to evacuate the unhappy population, for the sleeping dragon of Mt. Pelée unleashed its wrath mere hours after we had departed the island. In that rain of flame and ash more than 25,000 souls were lost, and where that proud city once stood, there is now little more than charred earth, and the echoes of awful memory (Figs. 4.2 and 4.3).



Figure 4.2 Destruction of St. Pierre in 1902, when a pyroclastic flow (*nuée ardente*) from Mount Pelée killed 28,000 people.





Figure 4.3 Similar to the lake in the Adventure of the Sleeping Dragon, in 1986 Lake Nyos in Cameroon, Africa had an outpouring CO₂, which suffocated 1,746 people and 3,500 livestock in nearby towns and villages.



5.1 The History of Scientific Publication

It goes without saying that everyone reading this paper has at least some familiarity with the scientific publishing process, if only at the level of reading articles in scientific journals such as *Geochemical Perspectives*. Most readers also will have published papers on their particular scientific expertise and thus will have experienced the review and revision process along with being the recipient of editorial judgements about the quality of their work and its ability to be published. Because of their expertise, many readers will have served as reviewers of manuscripts submitted to scientific journals and thus have direct experience with evaluating the work of others, including details of methodology, writing quality, and more difficult concepts such as originality and innovativeness. Some reviewers will have served on editorial boards where they experienced the difficult task of finding qualified reviewers *willing* to review a particular manuscript and then evaluating the sometimes conflicting reviews of various experts to make recommendations about acceptance, revision, or rejection.

With enough experience, and some would say being a glutton for punishment, a few scientists take on the daunting task of being the editor of a journal, which entails not only all of the above but selection and management of the editorial board and the mechanics of the publishing process including copy editing, proofing, and dealing with printers, online publishing, libraries, and the financial business of either profitability or for non-profits, viability. All of this exists in a changing world of open access, publishing models (corporate *versus* scientific societies), and government mandates about how, when, and where funded research can be published. I have been involved with all of the above and will describe some of the “inner workings” of the scientific publishing process based upon my experience as former co-editor of *Mineralium Deposita*, a scientific journal published by Springer Verlag based in Heidelberg, Germany, and as current editor of *Economic Geology*, published by the Society of Economic Geologists based in Littleton, Colorado in the United States.

First, a bit of history - the first scientific journal was the *Philosophical Transactions of the Royal Society of London*, Volume 1, Number 1, published in 1665 (Fig. 5.1). This journal included papers by famous scientists such as Edmund Halley and Isaac Newton. The first issue was 16 pages long and was not peer-reviewed in the modern sense; discussion or commentary occurred in print after publication of the original paper. Through the centuries that followed, pre-publication opinions (peer review) were limited and typically only sought on ideas that were likely to be controversial and even that was up to the individual discretion of editors or publishers (Baldwin, 2018). One anecdote recounted by Baldwin is about Einstein going through peer review at *The Physical Review* in 1936. Einstein



and his collaborator Nathan Rosen submitted a paper on gravitational waves that had some controversial conclusions. The editor, John Tate, sent it out for an external opinion, an action that Einstein found incredibly offensive. He told Tate that he was withdrawing the paper because he had not authorised Tate to send it to anyone else before it was published. Some authors still feel the same way!

Surprisingly, peer review did not become the standard until many years later, 1960s-1970s, and even then, it was not entirely for the presumed reason of establishing scientific legitimacy but rather to ward off United States Congressional oversight/interference with the grant funding and publication process (Baldwin, 2018). One of the leaders of this Congressional oversight movement was Senator William Proxmire, who established what were called “The Golden Fleece Awards”. These were bestowed on projects and publications, mostly funded by the National Science Foundation, that the Congressmen (and they were all men!) deemed not worthy of taxpayer dollars. In most cases they would take a topic totally out of context and recast the subject in pejorative terms aimed at garnering media headlines.

One in particular I recall from my time as a professor at Washington State University (WSU). It is widely known that ruminants (cud-chewing animals) in general and cows in particular emit methane (a potent greenhouse gas) through both belching and flatulence as part of the digestion process. It had been estimated that this contributed about 15 % of the global methane budget but there was no direct evidence to back this up. My colleagues in the Agricultural College and the Atmospheric Sciences Department received a grant to use equipment that they had designed to collect data from cows in the research herd at WSU. Even though this was legitimate scientific research (Westberg *et al.*, 2001) it was easy to characterise in the press, as Senator Proxmire did, as a total waste of taxpayer dollars (<https://lmtribune.com/>

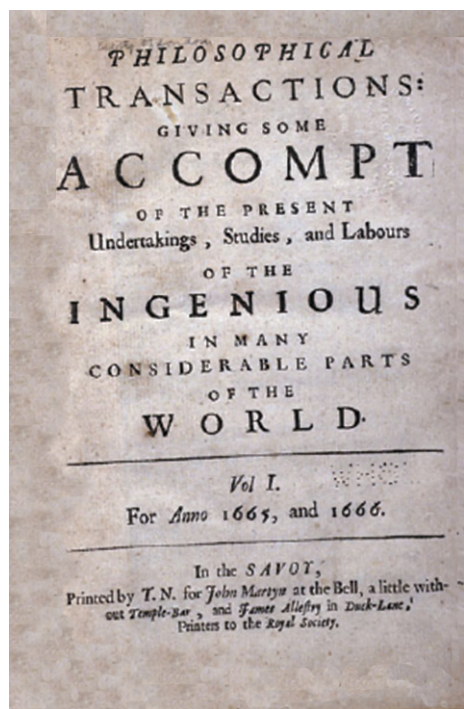


Figure 5.1 Cover of the *Philosophical Transactions of the Royal Society of London*, Volume 1, Number 1 (<https://library.si.edu/digital-library/book/philosophicaltr1roya>).



northwest/scientists-defend-cow-burp-research/article_5ec69e03-1906-5013-a476-c58ada7604b7.html). Even though my geoscience research was in a totally different field, I also received ribbing at international scientific meetings about whether I too was studying “cow farts”. From scientific colleagues this was mostly humorous but in the political realm it was more serious.

Campaigns like the Golden Fleece Awards led to increasing pressure by Congress for oversight of scientific research funding and that continues in some forms today in an increasingly partisan climate (<https://www.washingtonpost.com/news/monkey-cage/wp/2015/06/10/why-congress-should-not-cut-funding-to-the-social-sciences/>). The National Science Foundation pushed back by highlighting the need for review by experts, not politicians and this solidified the now almost universal requirement of peer review of scientific research and publication. But for the younger readers of the present article it is important to realise that it was not always so, even though many people assume that peer review has always been part of the scientific process.

5.2 The Editorial Process

The number of scientific journals has grown exponentially since 1665 and current estimates are about 30,000 scientific journals and about 2 million scientific papers published each year (<https://www.universityworldnews.com/post.php?story=20180905095203579>). Of course, not all journals are the same and reviewing standards vary widely, especially for some of the newer for-profit journals that tout their “open-access” status; more about that later. Although top tier journals are stocked by most university libraries and are well known around the world, one could argue about where the line should be drawn for what constitutes a scientific journal. Nevertheless, the editorial process is roughly the same for most top tier journals as illustrated in Figure 5.2, although the largest journals like *Nature* and *Science* that handle thousands of manuscript submissions each year, would have teams of editors instead of a single editor in chief.

When I first became co-editor of *Mineralium Deposita* in 2003 and then editor of *Economic Geology* in 2008, the previous system had been based upon submission of paper manuscripts in triplicate, with the individual paper copies being sent back and forth to editorial board members and then to reviewers and then back to authors by courier service such as FEDEX. Needless to say, this was cumbersome, time-consuming, and expensive. Like most journals, the manuscript submission for *Economic Geology* is now entirely electronic using commercial editorial software such as Editorial Manager. When a manuscript is first submitted, following the Instruction to Authors that are available on the SEG and *Economic Geology* websites, the author uploads the author information, cover letter, text, figures, tables, and appendices as separate files and editorial manager assembles them into a single pdf that can then be accessed



by editors and reviewers. Not reading and following the Instruction to Authors puts a manuscript at a serious disadvantage. It should be obvious, but “Read the Instructions”!

The typical journal process:



At *Economic Geology*:

New Submissions ~300 ms/yr

Total Traffic ~500-700 ms/year

Geochimica (600 submissions per year)
Nature (10,000 submissions per year)

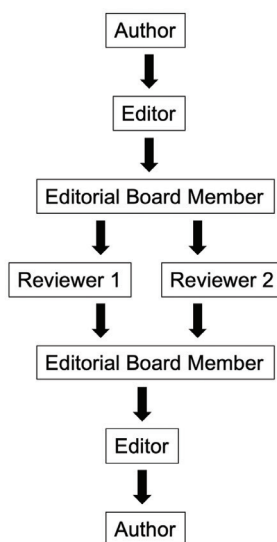


Figure 5.2 Illustration of the typical journal process for one cycle of review, and estimates of the number of manuscript submissions for a small (*Economic Geology*), medium (*Geochimica et Cosmochimica Acta*), and huge (*Nature*) journal.

Upon first receipt, my initial step is to give the manuscript a broad overview to see 1) if the topic is appropriate for the journal and 2) if the manuscript stands a reasonable chance of being ultimately publishable (after appropriate review and revision). This is not a formal review but rather a screening; it serves no purpose to occupy editors’ or reviewers’ time with manuscripts that are unlikely to make it through the review process. Approximately 50 % of manuscripts submitted to *Economic Geology* are returned to authors at this point. This is not quite the same as rejection, although it may feel like that to the authors. The decision is accompanied by a letter pointing out the main issues preventing further consideration of the manuscript. In most cases that is done within 24 hours of submission. Surprisingly I receive many more letters following such declination expressing thanks for the rapid response and feedback than complaints that an author’s manuscript was not fairly judged, although of course I receive some of those as well along with advice about which part of Dante’s Circles of Hell will be my home in the afterlife. This goes with the territory and editors should not have overly thin skins.



The next step is to select the most appropriate associate editor to handle the manuscript. The editorial board of *Economic Geology* consists of 25 associate editors, each serving a 5 year term. Thus, each year five slots open up and associate editors are chosen with an eye towards a balance of experience, subject expertise, and geography. Within the world of economic geology some topics, such as porphyry Cu deposits, receive a lot more attention than others. Thus, it is important to have the right balance of associate editors so that individuals are not overburdened. The goal is to keep the load for individual associate editors under 5 manuscripts at any one time and most associate editors have 3 or fewer assignments at present. Although some manuscripts are on geochemical techniques that are conceptual or experimental, most manuscripts concern some aspect of an ore deposit located in a specific place. Thus, a manuscript might benefit from having an editor familiar with the geology of a region like Australia or China.

A critical duty of an associate editor is selecting appropriate reviewers, two or more for each manuscript. This includes multiple factors such as subject matter expertise, geographic knowledge, and knowing the literature in a field. But most important is the ability to critically evaluate the science and make well-reasoned recommendations. This is different than being a great scientist or just rendering a decision such as publish or not. Editors refer to the latter as a non-review. A useful review critically considers the importance of the conclusions drawn and the degree to which they are supported by the evidence presented. The goal of the review process is not to look for reasons for rejection but rather to be constructive and help the author(s) improve and publish the paper. Good reviewers and good reviews make the entire editorial process work. This is why I tell the editorial board to choose their reviewers carefully and treat them well – they make your life much easier. The same is true for associate editors and I have been fortunate to be surrounded by a great editorial team throughout my career.

Once the reviews are received the associate editor's next job is to evaluate the reviews, reconcile disparate opinions, and make an informed recommendation to the editor about the fate of the manuscript. This recommendation is in the form of a draft letter outlining what needs to be done in the revision process, or why a paper is being rejected. As editor, I then read the reviews, the associate editor's draft letter, and revise the letter as needed to reflect the perspective gained from seeing every step in the evaluation chain. That letter comes from me because in general the associate editor remains anonymous so that any flak from the authors comes to me and not the associate editor handling the reviews. However, I always blind copy the associate editor on the letter so that they know their evaluation was taken seriously and in most cases is substantially the same as the final version sent to the author(s). It is then up to the authors to take the editorial comments seriously, revise, and resubmit the paper.

A general rule of thumb is that the better the original manuscript the shorter the review process, the fewer the revisions, and the quicker the resubmission. Conversely, a disproportionate share of editorial and reviewer time and energy is expended on marginal manuscripts, which is why the initial decision about a paper being ultimately publishable is so important. Moving that line



one way or the other even by 5-10 % will have a large impact upon the editorial process. And each of those decisions involves a complicated balance of scientific importance, newness of the topic, and originality of the approach. Since we all were first time authors at some point in our careers, I am particularly sympathetic towards first time authors and those who may not have benefitted from a culture of strong scientific support and training. Also, for authors for whom English is not their native language, poor English does not stop the publication of good science (although if there is a native English-speaking co-author then it is mandatory that they have done everything possible to improve the writing, and more generally, it is the responsibility of all co-authors to have read and contributed to the final submitted manuscript (and not just early drafts). The ultimate goal of scientific quality in these cases does not change, but the degree of helping the author to get there is tailored to each manuscript situation. Note to young scientists – politeness never hurts.

Upon resubmission, the cover letter describing the response to the editorial comments is another variable in the process. A cover letter that argues that the original manuscript was close to perfect and that the reviewers are all idiots, will not lead to a speedy or positive result. In contrast, a cover letter that clearly outlines what was changed (and noting suggested changes that were not made, and why) and how the revisions have responded to the original criticisms, will make the subsequent evaluation process much easier. Depending on the nature of needed revision, the resubmitted manuscript may go through another cycle of full review or it may just be examined by the responsible associate editor. After that second evaluation the manuscript may then be accepted for publication, but more likely will need further minor revision prior to acceptance.

In my ~20 years as an editor I have never seen a manuscript published “as submitted” without revision. Even a great manuscript will need minor revisions prior to being accepted. The average manuscript goes through two or three cycles of revision before acceptance. The current record for *Economic Geology* is 24 hours from submission through review and revision to acceptance. Obviously, this depends on the amount of revision needed and the diligence of the author (and reviewers). The biggest delay in the process by far is the amount of time that the author takes for revision. Most authors turn things around quickly and resubmit in weeks to months but some take a year or more and some never resubmit. This is outside the control of the journal.

There is a hierarchy in terms of familiarity with the details of a manuscript. The first author (and hopefully all co-authors) know every detail because they wrote it, but it is this very closeness that makes it difficult or impossible for an author to critically evaluate their own work. This is why my #1 advice to all authors, but particularly beginning authors, is to always, always have others critically read your manuscript before submitting it to a journal. One cannot critically evaluate one's own writing, because you are too close to it. The reviewers are evaluating specific aspects of the science of the manuscript, *i.e.* their piece of the puzzle – which might be stratigraphy, structure, isotope geochemistry, or



geochronology. They are better able than the author(s) to see flaws, repetition, and particularly lack of clarity. In general, the associate editor is not doing a detailed review but rather is evaluating the overall science in light of the reviewer's opinions and has the benefit of, as the saying goes, "not having a dog in the fight". The editor-in-chief not only is another step away in terms of evaluating the science but also has a slightly different job of being ultimately responsible for the quality of the journal. If the world scientific community has a problem with a published paper, the result is not a "letter to the author", it is a "letter to the editor". It is a responsibility that I and all editors take seriously.

5.3 Evaluating Journal Quality – Impact Factors and Other Measures

There is a longstanding interest in rankings and attempts to adjudicate quality. This applies to journals, universities, and most aspects of human endeavour. One of the most widely used (and abused) is the Journal Impact Factor (Berg, 2016; Hanson, 2018). Its attraction is that it is a simple number that is easily compared for different journals. The problem is that it has many drawbacks and is easily manipulated (Seglen, 1997; Putirka *et al.*, 2013; Bornmann and Marx, 2016; Hanson, 2018). Impact factors with a short citation window of a year or two may work for disciplines like physics where a paper may be "old news" within a year, but poorly or even inversely correlate with quality in disciplines like geology where fieldwork takes years and the description of a classic ore deposit or fossil locality is literally timeless. Journals that publish mainly, or entirely, review articles will be more highly cited in any given field than journals that only publish original research articles. Further distortion occurs in countries where authors have been paid to publish articles in certain journals or even worse, are encouraged to cite publications by colleagues with the intention of inflating impact factors of individual authors and journals (Hvistendahl, 2013). It should be noted that there is not a strong correlation between the impact factor of a journal and that of individual papers within that journal. High quality and highly cited papers can be published in a variety of journals, and every journal will have some papers that are much less cited than the norm. Thus, the impact factor of a journal should not be used to judge the quality of an individual paper.

The most widely used Impact Factor is the *Journal Citation Reports*, an annual publication by Clarivate Analytics (previously the intellectual property of Thomson Reuters); this has been integrated with the Web of Science and is accessed from the Web of Science-Core Collections. In simple terms, the standard impact factor is the number of times papers in a journal have been cited within a 2 year window of their publication, divided by the number of papers published in that journal. Thus, if the average paper in a journal is cited once in that 2 year window then the journal will have an impact factor of 1.0. This is highly susceptible to being skewed by a single paper or a few papers being highly cited whereas the rest are rarely cited or not cited at all. Thus, if a journal published 100 papers and 5 of them were cited 50 times each whereas the rest were cited 1 or fewer



times, then the journal would still have an impact factor of about 3, even though most papers had very little impact at all (as judged by citations). This would put it in the top 30 journals in the combined fields of Economic Geology, Geology, and Geochemistry and Petrology. A modified version of this metric uses a longer time window, 5 *versus* 2 years, for counting citations (Campanario, 2011).

Further factors include timing within the citation window and order within an issue. Since citations are counted on a yearly basis, a paper published in the first issue of a year will have almost twice the “citation window” of a paper published in the last issue of the year. Put another way, a paper published in a December issue basically has only a year to be cited. Similarly, the first paper published in a particular issue of a journal is more likely to be read, everything else being equal, than the last paper in an issue.

This timing issue is particularly a factor in geoscience studies that involve field work. Both the original study and any follow up studies that may cite the original work will require one or more field seasons between the conceptualisation of the study, carrying out the required work, and writing up the results. Thus, even the greatest field-based studies of even the most important ore deposits may not receive citations within the 2 year citation window of the standard impact factor – effectively having an “impact” of zero. This is one of many reasons why comparing the impact factor, based on citations, of papers and journals with different subject matter and different approaches is a seriously flawed process.

Another timing factor is that if, as is increasingly common, papers are published online prior to appearing in print, this will expand the citation window and, thus, significantly increase the impact factor (Krell, 2012; Tort *et al.*, 2012). Having a paper online a year before it appears in print will increase the impact factor of both the paper and the journal. This is not necessarily a good thing or a bad thing but comparing the impact factors of journals with different publication practices compounds the distortions previously discussed.

All of this assumes a level playing field for the papers being published, but there are several ways of manipulating the general factors described above. For example, if an editor writes an annual “overview” of all the papers published in the year, thus citing each paper once, this will increase the impact factor of the journal by 1. If authors, reviewers, and/or editors insert additional citations to either their own or to an institution’s papers or to papers published in a particular journal it is relatively easy to increase the impact factor several fold. In places there are reports of students and junior authors being handed lists of papers that must be cited even if they are not directly relevant to the study at hand (Tang, 2019).

For manuscripts submitted to Economic Geology from some countries it is common for the number of references to be significantly larger than for otherwise similar papers from other countries. This is partly cultural in terms of showing respect and can be as simple as citing multiple papers for a concept that may not even require citation. But sometimes it appears to be an attempt to increase the number of citations. And if authors are rewarded for and/or required to publish in certain journals, then that will increase the pressure on impact factors. Payments



up to \$165,000 for a paper published in *Nature* or *Science* by some universities have been reported (Quan *et al.*, 2017), although this practice has now been banned in most countries (Mallapaty, 2020).

As one example, the most highly cited paper a few years back in a journal with a sharply increasing impact factor was cited within the 2 year “impact window” by 30 other papers, 29 from the authors’ home country and the other by the journal editor summarising papers published in the journal that year. Thus, this one paper yielded an impact factor of 30 (roughly comparable to *Science*) and if such papers comprise up to 40 % of papers published in a given journal it will drive up the impact factor disproportionately to the actual impact of the science.

Text Box 5.1 – Advice to Young Scientists on What and How to Cite Previous Work

To simplify the complex subject of proper citation of scientific articles, there are two primary considerations – attribution and education. Attribution is concerned with tracing the history of ideas to give credit to previous researchers for concepts that are foundational to the current study. This in turn raises the question of how much attribution is enough? At one extreme is a review article that is tracing the history of ideas. In that case it is necessary to document each step in the process, from first formulation of a concept through to the most recent application, with due assessment of the relative importance of the various ideas along the way. At the other end of the spectrum is the practice of citing only the most recent usage (with the assumption that it would cite previous articles and thus, with sufficient effort, one could work back through time).

For a given research paper, the appropriate level of attribution typically will fall somewhere between those two extremes, depending on the nature of the idea being presented. Things that are general knowledge, such as the Earth is round, do not need attribution, whereas for the statement that the sphericity of the Earth is greater than other planets, the reader would likely ask, “*How do we know that?*” A common problem with first publications from a PhD dissertation is excessive attribution, including general concepts or citing textbooks as sources of information rather than primary sources. Another problem is listing a long string of references to back up a specific idea or methodology. Again, the question arises, how much is enough? A useful rule of thumb is to cite first, best, and most recent.

The second purpose of citation is for education. It allows the reader to easily find more information about a subject. This is particularly useful in PhD dissertations but again needs to be tempered in the transition to a scientific journal. As an editor I commonly encounter manuscripts in which every new idea or methodology is followed by a string of 3–5, or more, references. If more than a single reference is necessary stick to “first, best, and most recent”.

Other journal ranking systems have been proposed that do not rely exclusively on raw citations within a short time window. For example, a version of the H index is used by Google Scholar. The raw H index assigned to a researcher or journal represents the highest number “h” of papers by that scientist or journal with at least “h” number of citations. Thus, a scientist or journal with an H index of 20 has published at least 20 papers that each received at least 20 citations. The



H index can be limited to a specified time span such that an H₅ index of 30 means that the journal has published at least 30 papers within the past 5 years with at least 30 citations each. Google Scholar uses an H₅ index for ranking journals.

An additional refinement to citation rankings is based on the concept that not all citations are equal. In the same sense of peer review, which relies on the opinions of experts in closely related fields, the SCImago Journal Rank (SJR) is a measure of scientific influence of scholarly journals that tries to account for both the number of citations received by papers in a journal and the ranking and subject matter proximity of the journals where such citations come from (Guerrero-Bote and Moya-Anegón, 2012; Manana-Rodríguez, 2015). In other words, a given citation is weighted based upon the nature of the journal it comes from; a few iterations of the ranking algorithm quickly converge on modified rankings for all evaluated journals. Although possibly more robust than just a citation count, this ranking system still is susceptible to the biases described above.

5.4 Open Access and the Future of Scientific Publishing

Probably the biggest emerging trend in scientific publishing is open access; a directory of ~14,000 open access journals is at <https://doaj.org>. Although a relatively simple concept, the term open access is used in different ways by different people, with vastly different implications. For many people, open access simply means that anyone can access a publication without any restrictions such as payment, membership, or type of use. This of course avoids any reckoning with the fact that there are costs involved with publication and somehow those need to be paid for. Some would argue that open access merely transfers those costs from users to producers of the information. Society has grown accustomed to free information on the Internet, which has its own issues with privacy rights and income generation from personal data. That is too big a subject to tackle here but it is worth digging deeper into the issues involving open access in the scientific publication world.

Many new “open access” journals charge authors upfront fees that may be even higher than the cost of publishing in more traditional journals. This could be viewed in economic terms as transferring the costs from libraries and users to authors. This in turn raises questions of open access for whom, since many authors, particularly from less developed countries, cannot afford to pay such fees. A further complication is that many “open access” journals tout rapid publication, sometimes with minimal or no review. Thus, the term open access needs to be deconstructed as to what is really meant. Is it the rapid publication (sometimes within hours to weeks of submittal)? Is it the possible lack of robust review that might allow material to be published that would never meet the standard of a quality journal? Is it the assumption that more people will read and potentially cite an open access paper? None of these are necessarily true but all deserve further consideration.



Of particular concern are open access publishing houses that may oversee 100s of open access journals from one central location, such as Switzerland, even though the owners (and profits) may be based in other countries. The journals that do no reviews at all but simply publish for a price are termed “predatory journals” (Grudniewicz *et al.*, 2019). But it is difficult to precisely define what should be considered a predatory journal because there is a continuum of potentially dubious editorial practices (Elmore and Weston, 2020). Some journals ask for reviews within a week or less, which raises questions of how thorough the review could possibly be. Some journals send the reviews to authors but leave the degree of compliance, if any, up to the authors. Some journals enlist “guest editors” to assemble authors for a special issue with enticements of discounts and the prestige of being an editor while requiring little or no actual editorial effort. These journals are using the reputation of the guest editor to lend legitimacy to their otherwise dubious publication practices (Chopin, 2018). In many cases there is little to no selectivity in the invitation to be an editor. Figure 5.3 illustrates an invitation I received recently, with the name of the inviting journal redacted.

Invitation to Become the Member of the Editorial Board/Reviewer Team

We have been devoted to building XXX into one of the world's leading journals. Well-known scholars are cordially welcomed to join the Editorial Board/Reviewer Team.

Have you got an idea of joining us as an editorial board member/a reviewer?

You can find more details at the following link:<http://www.XXXjournal.net>

Privileges of Joining Us as an Editorial Board Member/a Reviewer:

- I. Quickly increase your visibility in your specialized field.
- II. Obtain first-hand information on latest academic discoveries.
- III. Getting an official Certificate (PDF version) released by the editorial office.
- IV. Have your name and affiliation listed on the website of our journal.

Figure 5.3 Invitation to become an editor for a relatively new journal, with enumeration of the “privileges” of so doing (received April 23, 2020).

Some readers of the present article will have experienced such calls to participate. I myself have fallen victim to these practices when I was asked by a colleague to contribute a paper arising from a conference on mineral resources to a special issue of a journal that I was unfamiliar with. It sounded reasonable and at the time I was not very aware of predatory journal practices. I wrote the paper (Meinert *et al.*, 2016) and the publication fee was waived. While I always have my work pre-reviewed by experts prior to submitting it to a journal, as described earlier in this section, I did not realise that some of the other papers in the journal did not receive the same level of review. I now look more carefully at invitations to publish my research.



To be clear, there is nothing about the concept of open access that necessitates lower reviewing standards or higher author costs but some of these things are happening, so it is useful to think carefully about this emerging trend. There also are different levels of open access, typically called *gratis* and *libre*, with different amounts of “openness”. *Gratis* open access allows free access to read papers but does not grant the user the right to make copies, distribute, or modify the work in any way beyond fair use. *Libre* open access also allows free access but transfers additional rights, usually *via* a Creative Commons license, to reuse and modify the research. In addition, gold open access means that all articles and related content are available for free immediately on a journal’s website, usually by requiring the author to pay a fee up front, typically \$2,000–\$3,000. Green open access allows self-archiving by authors after a specified period of time, such as one year, and posting the work to a website controlled by the author, the research institution that funded the work, or to an independent central open repository. As the name implies, hybrid open access journals contain a mixture of open access articles and restricted access articles.

Compounding these issues are government mandates about requiring open access publication for all government funded research. The first governmental mandate for open access in the U.S. was the Omnibus Appropriations Act of 2009 (<https://publicaccess.nih.gov/policy.htm>) that required that “all investigators funded by the NIH submit or have submitted for them to the National Library of Medicine’s PubMed Central an electronic version of their final, peer reviewed manuscripts upon acceptance for publication, to be made publicly available no later than 12 months after the official date of publication”. This was followed in 2013 by a call from the White House Office of Science and Technology Policy that all Federal publications be open access and this policy was implemented over a few years on an agency by agency basis (<https://docs.google.com/spreadsheets/d/1PYOhBh6bglh6BkQFlpvNLOWlpzvQyguWAG8AkQMtU0s/edit#gid=0>).

Shortly thereafter, in what came to be known as Plan S, the European Union announced in 2016 that all “scientific papers should be freely available by 2020” (Enserink, 2016). Plan S continues to evolve with changes and delays in implementation schedules but it appears that the ultimate goal is to have all papers resulting from EU funded research be published in journals that are entirely open access (Else, 2019). This would disallow publication in hybrid journals, such as most scientific society sponsored journals, that publish both open access and regular papers. In response, many journals are pairing with co-branded open access-only journals so that papers requiring complete open access submitted to the hybrid journal would be published by the open access “partner” journal (<https://www.geosociety.org/gsa/pubs/lithosphere/home.aspx>).

Another open access trend is the development of megajournals such as *PLOS ONE*, *Scientific Reports*, and *PeerJ* that publish a very broad range of subject matter with articles being judged on scientific soundness rather than topic or perceived importance or impact. Also very broad in subject matter coverage but



requiring even less peer review, are pre-print servers such as ArXiv (arxiv.org), Esoar (<https://www.esoar.org/faq>), or EarthArXiv (<https://eos.org/science-updates/earth-science-is-ready-for-preprints>) Pre-prints are preliminary versions of articles made available online prior to or without formal peer review. They typically come with a caveat that interpretations are subject to change and that they may or may not lead to actual publication. If articles later are accepted for formal publication, the preprints can be linked to the journal version.

Pre-prints without peer review raise a host of issues that may vary by discipline. The pre-print concept began with physics in 1991 (arxiv.org) and further information can be found at <https://eartharxiv.github.io/faq.html>. Earth science in general and economic geology in particular are not as well suited to a non-peer reviewed process because many geologic occurrences and ore deposits are site specific. A suitably knowledgeable specialist can evaluate the soundness of a mathematical equation or a repeatable experiment but how does one evaluate a claim about an outcrop that only the author has seen? As a specific example, if a manuscript says the XYZ deposit in Tibet contains 1 Mt of Au when in fact it has less than a tenth of that amount, how would one tell whether the statement is true? If another paper then cites the previous paper regarding the 1 Mt of Au, how would the reader of the second paper know that the statement was incorrect? Continuing the trend, if somebody else does a review of Au deposits with a compilation of contained Au, the resulting number will be incorrect even though the compilation itself was done correctly. In this sequence of papers, even though each is citing things properly, and the third author has done everything correctly, their Au number is wrong and the literature is now a mess. We already see this in social media where unsubstantiated rumour and intentional misinformation are rampant (including “medical” information that is costing lives; Larson, 2018).

As the editor of *Economic Geology*, this trend away from peer review gives me pause about the future of scientific publishing and the ability of society to distinguish fact from fiction. We are moving from a system where the scientific journal, peer review, and editing process assured some level of quality, to one where authors can pay to publish, the result is available to all, and the reader is left to make the judgement of quality. Senior authors and experienced researchers may feel comfortable about making that distinction but what about students or young researchers just starting a career? There not only is the decision about what is a trustworthy publication, but also about where to publish. For a tenure track professor is it more important to publish quickly or to “publish well”? Either could be open access, but as described above some open access venues with minimal review can be very quick indeed. The “quickly” part of the question is easy to measure, *i.e.* how many publications resulted from one’s PhD and how many in the first year or two of a professorship? The “well” or quality part is more difficult to assess. My advice is straightforward - always aim for quality and, above all, have your manuscript critically reviewed before submitting it for publication!



6.1 Congressional Fellowship

My first introduction to policy on a national level came when I moved to Washington DC in 2010, when my wife took a position there. Once relocated, I took the opportunity to apply for and was accepted as a Congressional Fellow. The Congressional Fellowship programme is administered by the American Association for the Advancement of Science (AAAS). The approximately 30 Fellows are selected and funded by individual scientific societies such as the American Chemical Society, the American Mathematical Society, and in my case the Geological Society of America and the United States Geological Survey (USGS). The aim of the Congressional Fellowships is to inculcate scientific expertise and to some extent, culture, into the United States Congress. After intense training on the legislative process each Fellow serves a year in a Congressional office or committee, such as the Senate Energy and Natural Resources Committee.

Most Fellows choose a powerful committee or a Senate office due to the larger numbers of staff, opportunity to focus on a particular issue, and the perceived greater importance of the Senate; there are only 100 Senators *versus* 425 Representatives. However, I chose to work in the House of Representatives because I wanted the entire experience of a Congressional office ranging from dealing with constituents, being involved in a campaign (since Congressional Representatives are elected for 2 year terms they are in almost continuous campaign mode), to analysing and writing legislation. I first served in the office of Representative Gabrielle Giffords (8th district of Arizona). There was much to learn and I was immediately thrust into the fire.

In my first week, legislation was introduced about mine safety to honour a long-serving but now retired Congressman who had been involved in such issues. At first glance, who would not be supportive of efforts to make mines safer? And not only was the namesake Congressman a legend, the legislation appeared to align with Representative Gifford's interests since Arizona is a state with substantial mining activity. Since I was generally familiar with resource issues, although no expert in mine safety, I was assigned to analyse the bill which was to be voted on later in the day. Upon digging deeper, it turned out that the bill mandated increased inspections of all types of mines but was based upon and used language relevant to coal mines. It appeared that applying this inspection protocol to metal mines not only wouldn't increase their safety but might actually have the opposite effect.

As I and other staff walked with Representative Giffords from our office to the House floor where the vote would be taken, Representative Giffords asked our opinion of the bill. All eyes pivoted to me since the subject matter was in my



portfolio (as these things are called in legislative circles). I explained my reservations about the bill's language and suggested that it would benefit from some reconsideration. From the look on the Chief of Staff's face I could tell that the rookie (me) had overstepped some sort of line. I learned later that Representative Giffords voted against the bill, one of only a few Democrats to do so. It is not as though I had advised the Congresswoman on how to vote, or would have any standing to do so, but simply that I had (very) briefly communicated a policy analysis that apparently had a significant impact.

From one point of view this is exactly what the Congressional Fellowship programme is designed to do. From another point of view, as laid out by the Chief of Staff to me in a later, private, come-to-the-woodshed meeting, my comments had upended the political process in which (to greatly simplify) votes are counted and coalitions aligned to achieve specific policy goals. Those preliminary caucus meetings had occurred prior to my joining the staff and even beyond the timing issue it is not clear whether a Congressional Fellow would have been part of that political discussion, at least not on my first few days on the job.

So began my education about how legislation and national policy actually comes to pass. With the benefit of hindsight this example is not nearly so momentous as it might sound. Thousands of bills are introduced every Congressional session and the vast majority go nowhere, at least not on the first try. That is how the process works. Some bills were never actually expected to go anywhere, they were introduced to satisfy some constituency, "See, we did introduce the bill that you wanted." That being said, bills that are not acted upon in a current session may be resurrected and/or modified in a later session when the timing is more auspicious. Looking at the bigger picture, many bills ranging from very worthwhile to less so, spend years bubbling below the surface until some event or circumstance brings them to the fore. There is a saying in legislative circles, "Never let a good crisis go to waste" and it is quite often the case that a flurry of bills will be passed during such times. Most such bills are not written afresh but rather had been previously introduced and were "tweaked" to fit the needs of the moment. Thus, one should not discount the effort spent on a particular bill even though few are passed, because one never knows how future developments will affect things. I suspect that the several trillions of dollars' worth of bills passed by Congress in a very short time frame to respond to the COVID-19 pandemic contained more than a few ideas that had a prior life in previous legislative sessions.

Another issue that was just starting to get attention when I was a Congressional Fellow concerned rare earth elements (REE) and as they came to be called, "critical minerals". This was clearly in my portfolio and I was expected not only to analyse any bills or activity concerning critical minerals, but to proactively guide and represent the office on this subject. This included working with other Congressional offices that had related bills pending. Diving deeper into the legislative process, any particular bill has a primary sponsor – the Representative or Senator who wrote and submitted the bill – and multiple co-sponsors, preferably



from both Democratic and Republican offices. This is a delicate political dance because you want to have as many co-sponsors as possible, on the assumption that anybody who co-sponsors a bill will ultimately vote for it, but you don't want to irritate people who might be generally supportive but who don't want to commit to co-sponsorship. In this regard I would discuss strategy with our office Chief of Staff and Legislative Director about what other bills we might want to co-sponsor and, for our own bills, who and how we might want to approach about potential sponsorship. This was an ongoing process throughout the year.

Another way for a Congressional office to control the narrative is to put on a Congressional briefing about a specific subject. Briefings are non-partisan affairs with a panel of experts supplying information and expertise that will be useful for Congressional staff to educate themselves and formulate a plan for how their office will engage in the subject. At this moment in 2010, REE were a hot topic on which everybody wanted to assume a lead position. Being in a small and relatively new Congressional office (Representative Giffords had been in office only 3 years when I joined the staff), this was an opportunity to stake out new ground and a lead position in a field that most Representatives, Senators, and Congressional staff did not have much, if any, background. Because of my expertise in mineral resources I proposed to our Chief of Staff and Legislative Director that we organise a Congressional briefing on REE. I was given the green light to proceed.

Although I have published extensively on this subject and as Editor of *Economic Geology* knew most of the scientific players, I also knew that I could not be on the panel. One of the first rules of "staff" is that we are support and never the lead. Thus, my job was to identify people who could serve on the panel who would have the necessary scientific gravitas, the ability to speak simply to an audience with little to no scientific background, and most importantly in a political setting, represent a broad spectrum of political viewpoints. Text Box 6.1 is the announcement about that briefing. Typical Congressional briefings attract 20-50 attendees. This REE briefing was standing room only, with more than 100 attendees. This is a testimony to the topical importance at that moment in time but also put Representative Giffords' office on the map as the go-to source of information on this particular topic.

Text Box 6.1 – REE and Critical Materials for Renewable Energy

Friday, March 11, 2011

1:30-3:00 pm

HVC-201 Capitol Visitors Center

The **Environmental and Energy Study Institute (EESI)** and **Office of Rep. Gabrielle Giffords (D-AZ)** invite you to a briefing on critical materials, including rare earth elements (REE) and strategic metals. These materials are essential for technologies used in a variety of applications such as cell phones, computers, cars, airplanes, batteries, and renewable energy systems – and therefore critical to our national security and economy. The United States is not self-sufficient in most of these critical materials, and for many of them we are reliant on foreign sources prone to disruption.



For example, more than 97 percent of the U.S. and world supply of REE comes from China, and this supply has been restricted recently for several reasons, including political pressure. This briefing will address the current supply of critical materials, including the newest developments from China, and policy opportunities to strengthen American expertise in the occurrence, discovery, extraction, processing, and recycling of these commodities.

Speakers for this event include:

- **Mark Johnson, U.S. Department of Energy – ARPA-E**
- **Kate Johnson, U.S. Geological Survey Mineral Resources Program**
- **Andy Davis, Molycorp Minerals**
- **Dudley Kingsnorth, Industrial Minerals Company of Australia (IMCOA)**

In 2010, the House of Representatives passed bipartisan legislation (H.R. 6160) that would have established a program within the Department of Energy (DOE) for research and development of REE throughout their life cycle, and broaden existing loan guarantee programs to spur private investment in REE. Sen. Lisa Murkowski (R-AK) introduced similar legislation in the Senate (S. 3521). In the 112th Congress, bipartisan sponsors in the House and Senate plan to introduce legislation to support education and research to rebuild and maintain American expertise in critical materials. In addition, the DOE's budget request for FY 2012 would create a new Energy Innovation Hub focusing on REE.

This briefing is free and open to the public. No RSVP required.

**For more information, contact Larry Meinert at
larry.meinert@mail.house.gov or (202) 662-1892.**

This familiarity with the science and subject matter of critical minerals as well as how the briefing and legislative process worked, became very important in my subsequent job with the U.S. Geological Survey. In fact, one of the experts I recruited for the REE panel was from the USGS and it turns out I would be in that specific job position in little more than a year. None of that was planned but it illustrates how serendipity can work.

A particularly American tragedy occurred on January 8, 2011 when Representative Giffords was shot in the head during a "Congress on Your Corner" event (a public opportunity for constituents to speak directly with their representatives). A man ran up from the crowd and began firing a 9 mm pistol with a 33 round magazine, hitting 19 people, and killing six, among them federal judge John Roll and a 9 year old child, Christina-Taylor Green. I had been at previous district events but was not at this particular one or I would have been sitting at the table with Representative Giffords. Because of my involvement with the office I will never forget that day.

After it became clear that Representative Giffords would not be able to return to public office I moved to another Congressional office, that of Senator Chris Coons (Delaware). He had recently been elected (and thus had room for new staff) to the seat formerly held by Senator Joe Biden who went on to become Vice President of the United States for 8 years and is currently running, at the



time of writing, for President of the United States. There I was able to experience the very different rules and procedures of the United States Senate. Also, because Senator Coons served on a variety of committees, I got to know several subject areas that were new to me such as the judiciary and energy and agricultural policy.

It was a distinct honour to serve in the offices of Representative Giffords and Senator Coons, and the tumultuous set of circumstances made it possible for the rare opportunity of a Congressional Fellow to serve in both the House and the Senate. In both cases I helped staff the respective House and Senate committees dealing with energy, resources, and environmental policy. Learning the internal workings of government was invaluable for my later involvement with the USGS where I would testify before the same committees that I used to staff. Needless to say, this provided invaluable insight that could not have been gained by any amount of study or mentoring.

6.2 U.S. Geological Survey

After the Congressional Fellowship I joined the Mineral Resources Program at the USGS. This was an important transition time because the Program's budget had been in steep decline for several years (Fig. 6.1), and two successive studies by the U.S. National Academy of Science (National Research Council, 1996, 2003) indicated that only a radical change in leadership could save it. I was brought in to provide that leadership to help rebuild the budget, integrity, and scientific focus of the Mineral Resources Program.

The Mineral Resources Program consists of two parts that are budgeted separately due to historical reasons regarding how and when they became part of the USGS mandate. The largest is Research and Assessments. The research part is roughly equivalent to typical university research on mineralogy, geochemistry, geophysics, remote sensing, ore deposit genesis and environmental impacts. The assessment part responds to needs for information about mineral resources on Federal lands and other geographic areas, ranging from documentation of what is known about lands that might be considered for National Park or Wilderness Area status to estimates about known and future resources for strategic planning purposes (*e.g.*, https://www.usgs.gov/energy-and-minerals/mineral-resources-program/science/global-mineral-resource-assessments?qt-science_center_objects=0#qt-science_center_objects). The two parts are complementary and some of the research is aimed at planning for future assessments. The minerals information part collects and analyses information about a broad range of non-fuel mineral commodities ranging from asbestos to zirconium and cement to supply chains. A signature product is the annual Mineral Commodity Summaries (USGS-MCS, 2019).



I subsequently became Deputy Associate Director for Energy and Mineral Resources (adding Energy to my portfolio) where I was partly responsible for the activities of approximately 500 scientists across the country and a budget of \$100M.

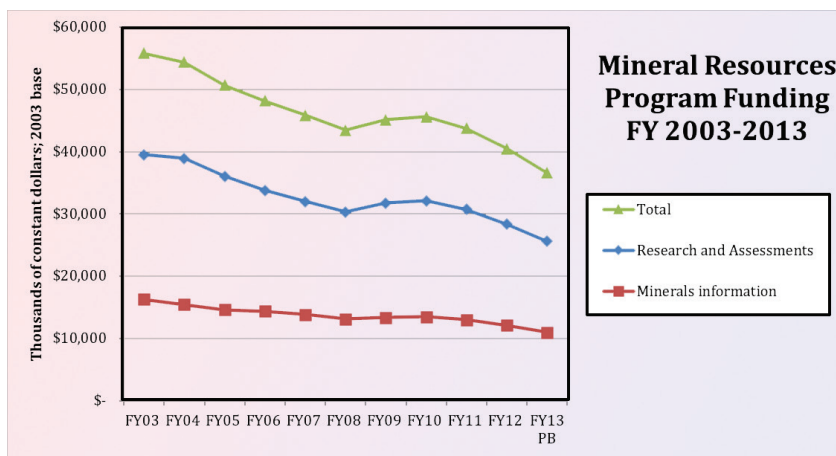


Figure 6.1 Federal funding for the USGS Mineral Resources Program for the decade leading up to my joining the Program in 2012. FY – fiscal year, PB = President’s budget proposal to Congress.

The first step was understanding the budget realities and determining a plan to turn the situation around. For example, was the decline illustrated in Figure 6.1 emblematic of a general decline in government funding or was it specific to the Mineral Resources Program? Since comparison of Federal agencies with different functions would not necessarily be valid, I searched for comparables that might be more instructive. Table 6.1 illustrates one such comparison and that is the resource information gathering functions of the U.S. Geological Survey and the U.S. Department of Energy.

The USGS compiled most information about resources of the United States until 1977 when the Department of Energy was created. Following creation of the Department of Energy, the Energy Information Agency (EIA), within the Department of Energy, collected and analysed information about production and usage of energy resources (oil, natural gas, and uranium) whereas the comparable function for mineral resources was performed by the National Mineral Information Center (NMIC) within the U.S. Bureau of Mines and subsequently in the USGS Mineral Resources Program. During the previous decade, funding for EIA had grown significantly whereas funding for NMIC was stagnant or declined. This is shown by a sharp difference in the requested funding for FY12 (Table 6.1), the year I joined the USGS. The case to be made was that information about mineral resources was arguably as important as information about energy



resources. Thus, the operative question was how and to whom that argument should be presented?

Table 6.1

Comparison of enacted *versus* proposed funding for Federal agencies with comparable information gathering functions: the National Mineral Information Center which is part of the USGS Mineral Resources Program and the Energy Information Agency which is part of the U.S. Department of Energy. FY – fiscal year.

Comparison of Information gathering Funding	FY10 Enacted	FY12 Request	Change
National Mineral Information Center	\$15.90M	\$13.25M	-17 %
Energy Information Agency	\$29.04M	\$37.40M	+29 %

Since the budget for the USGS and the Mineral Resources Program is set each year by the United States Congress, it was important to build or rebuild the relationship with Congress. I did this by presenting numerous briefings for individual Representatives, Senators, and their staff to help them better understand the importance of mineral resources to the health, well-being, and economic prosperity of the people of the United States. This is where the emerging issue of critical minerals came into play; it moved mineral resources from a niche issue that was only of importance to a narrow constituency, to a subject of national and international importance. The REE briefing that I had organised for Congresswoman Giffords’ office in 2011 suddenly became essential background for discussions about the budget for the USGS Mineral Resources Program.

I also became involved with policy at the Executive Branch level, including co-chairing the White House National Science and Technology Council: Subcommittee on Critical and Strategic Mineral Supply Chains (2016). I spent five years working on the policy implications of potential scarcity (Nickless *et al.*, 2015; Meinert *et al.*, 2016) and supply disruptions (Ali *et al.*, 2017) of critical mineral commodities such as REE that are essential for many technological, renewable energy, and national defense applications (Eggert *et al.*, 2016). I testified on this subject several times before Congress and also spearheaded USGS activities that led directly to recent Executive (Presidential Order 13817) and Secretarial (Department of Interior – S.O. 3359) orders. These orders have major impacts on the Nation’s defense, intelligence, and manufacturing communities (Fortier *et al.*, 2018). I also represented the United States in meetings at the European Union (EU), the European Commission (EC), the Organisation for Economic Cooperation and Development (OECD), and China and Japan. These meetings ranged from policy and regulation to research and data sharing on specific topics like critical minerals.

All of the above activities raised the profile of the USGS Mineral Resources Program, such that increased funding for the Mineral Resources Program became a possibility for the first time in more than a decade. I go through this background

in some detail to illustrate what may not be an obvious connection between budgets, Congressional briefings, and international events relating to the price and availability of REE that fall into the general category of critical minerals, as will be discussed in the next section.

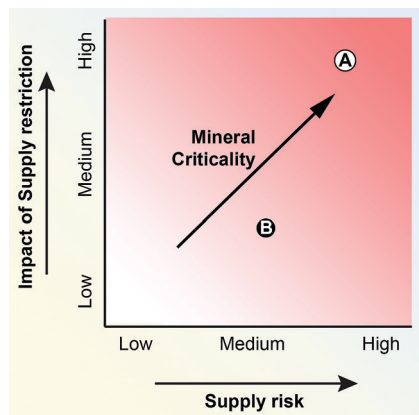
6.3 Critical Minerals

The underlying issue of the availability and sustainability of mineral resources is important to understand at both a scientific and policy level. Starting with pre-historical societies and continuing through the Iron and Bronze Ages up to modern technologies that use almost the entire periodic table, mineral resources have been the building blocks of all human civilisation. This general subject was covered by a previous issue of *Geochemical Perspectives* (Arndt *et al.*, 2017), including the concepts of scarcity, economics, and the environmental consequences of use. Within the general field of mineral resources there is increasing concern about resources that are considered “critical” or “strategic” for various purposes ranging from defense, to basic industries such as steelmaking, to emerging technologies such as renewable energy and electric vehicles (<https://www.usgs.gov/media/images/critical-minerals-renewable-energy>).

One of the early uses of such terminology was by the Paley Commission following World War II (Paley Commission, 1952), but a turning point occurred in 2008 when the National Research Council (2008) of the United States Academy of Sciences issued a comprehensive report on critical minerals with a simple graphic that allowed people to see easily the relationship between the risk and impact of supply disruption (Fig. 6.2). This was followed by many other studies of critical minerals that extended the concepts (Fig. 6.3) and graphics, with axes for environmental and other considerations (Fig. 6.4).

Figure 6.2

Illustration of the contributions of supply risk and impact of supply disruption to mineral criticality (National Research Council, 2008). In this qualitative diagram, mineral A has both a higher impact and higher risk of a supply disruption than mineral B.



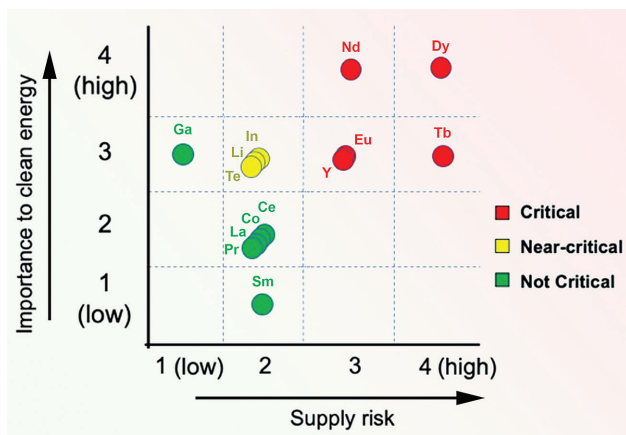


Figure 6.3 Plot of energy critical elements on the supply risk - supply disruption diagram (U.S. Department of Energy, 2011).

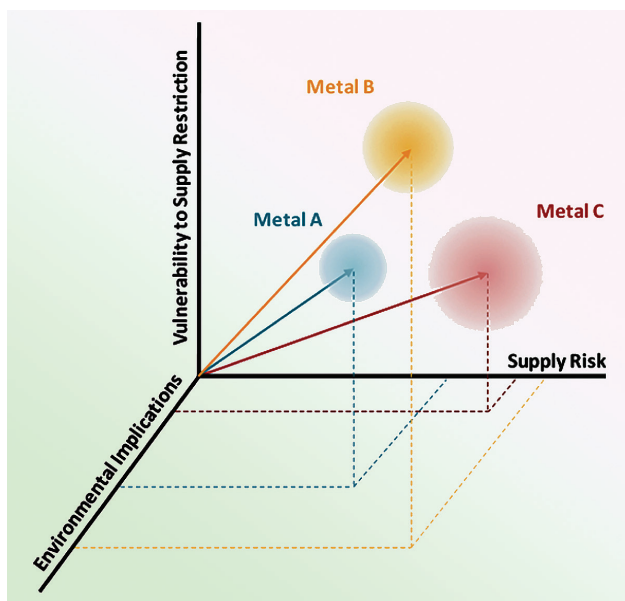


Figure 6.4 A third axis adds environmental considerations to the supply risk - supply disruption diagram to allow distinctions such as moderate environmental impact and supply risk for metal A, large environmental impact and supply risk for metal B, and high supply risk but relatively low environmental risk for metal C (reprinted from Graedel et al., 2012 with permission; copyright 2012 American Chemical Society).



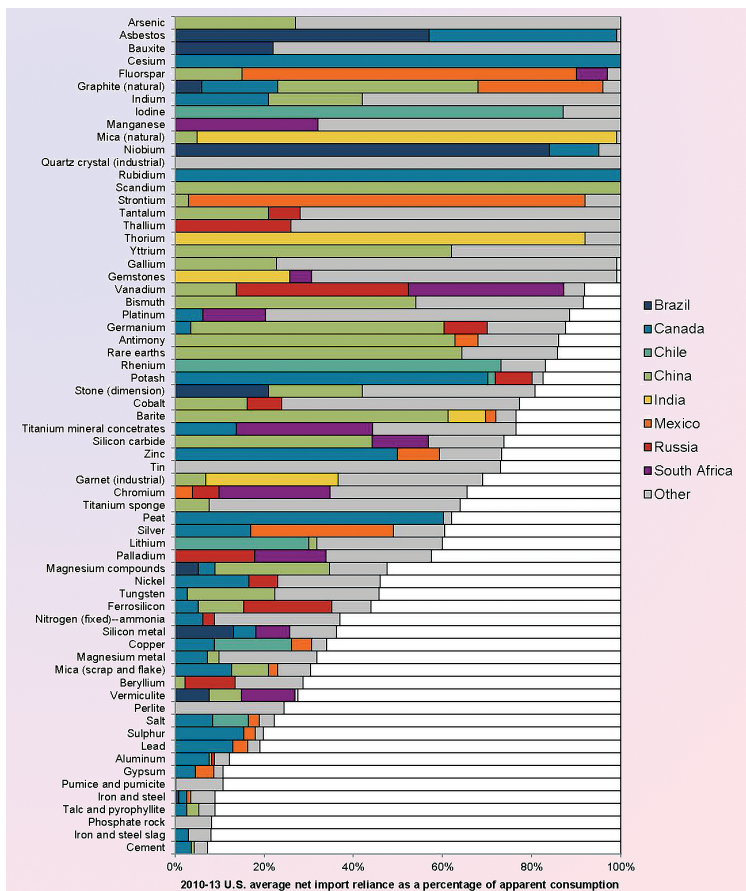


Figure 6.6 Average net import reliance of the United States by top eight source countries for 66 commodities for years 2010-2013 (U.S. Geological Survey, 2019).

The methodology for screening potentially critical minerals is based on the geometric mean of three fundamental indicators: supply risk (R), production growth (G), and market dynamics (M), as illustrated in the following equation.

$$C = \sqrt[3]{R \cdot G \cdot M}$$

These indicators capture different aspects of criticality: R is an assessment of production concentration at the country level weighted by each country's governance rating (Fig. 6.7), G captures changes in the commodity's market size and reliance on geological resources, and M captures the commodity's price sensitivity to changes in its market. These indicators indirectly capture variation due to substitutability, recycling, and by-product dependency.



6.4 Sustainability and Recycling

Criticality and supply chain disruption are only part of the total cycle of mineral resource use. Other considerations include resources from recycling, sometimes called “urban mining”, and production of certain elements as a by-product of the mining of major commodities: for example almost all the world’s Te comes as a by-product of the mining of porphyry Cu deposits. This means that for some mineral resources, by-product elements are relatively price in-elastic such that even a significant price increase will not result in production of more of that element. Thus, for major elements like Al, Fe, and Ni the supply will roughly follow demand as both are mediated by price, whereas for the more than 20 elements illustrated in Figure 6.9, price increases will not result in commensurate increases in production unless new deposit types can be identified that could be mined mainly for the by-product elements.

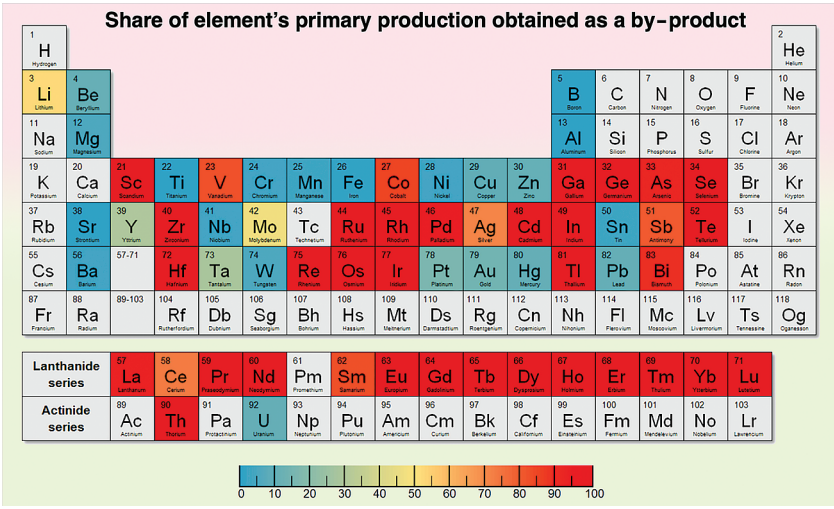


Figure 6.9 Share of element's primary production obtained as a by-product (Nassar et al., 2015).

Recycling rates vary by element and use, ranging from very high for Pb, which can be efficiently recycled from batteries, to close to zero for materials like REE which are used in small quantities in various devices and are thus difficult to separate from a particular use and from each other (Fig. 6.10). One way to think about the potential for recyclability is the amount and value of an element in a particular device relative to the difficulty (cost) or number of steps necessary to extract that element. For example, smart phones and computers are notorious for having small amounts of many different elements that are difficult or not

economic to separate from the whole (Graedel *et al.*, 2015). Thus, they tend to be melted down in bulk, and separation of individual metals only occurs at the end of the process. But even low value commodities can be recycled if the individual metal can be easily separated from the total (Fig. 6.11).

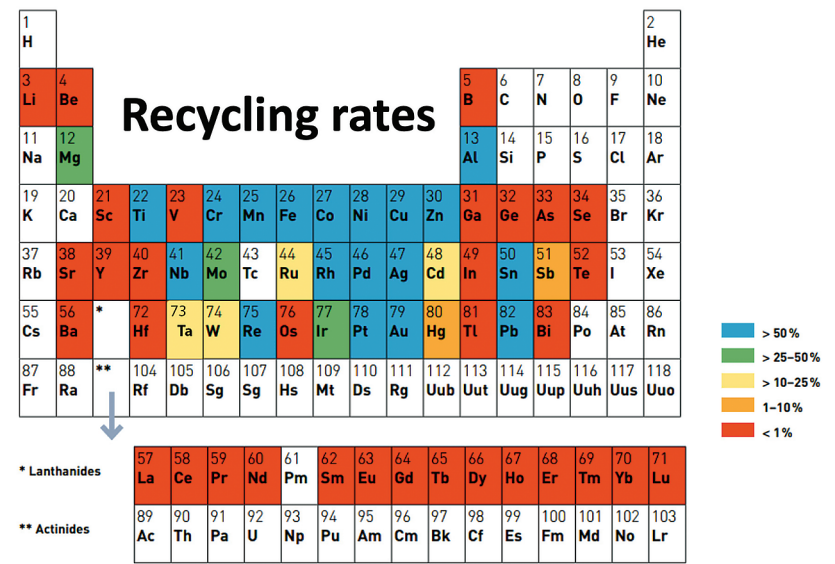


Figure 6.10 End of life recycling rates for 60 metals (after Graedel *et al.*, 2011; UNEP, 2011).

However, even if recycling was 100 % efficient, it still would not eliminate the need for new mineral resources due to three factors. First, a growing world population means that more resources are required unless *per capita* consumption and standards of living go down proportionally. Second, even if the world population stabilises at some point, rising standards of living would require more resources *per capita*. Put another way, bringing the poorer half of the world’s population up to the living standards (adequate food, housing, energy, *etc.*) of western European countries would require a significant amount of new resources. Finally, even if population stabilised at an acceptable standard of living, more resources would be required due to the sequestration of elements like iron, copper, and aluminum into buildings, cars, bridges, and other things that have a usable lifetime of decades, centuries, or longer. Thus, the ideal of a “circular economy”, expressed as living within the resources we already have, is largely not feasible, at least not with our present technology. It is not that we can’t be more efficient by design and practice, but simply that recycling by itself cannot replace the need for new supplies of mineral resources. In addition, some resources such as energy, fertiliser, and paint are dissipated by use and can’t be collected or reused.



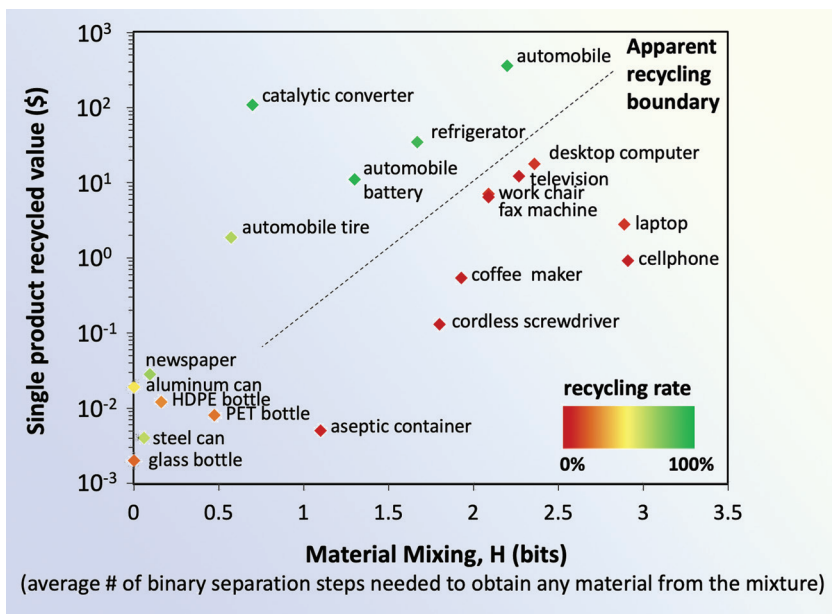


Figure 6.11 Recyclability of various items as a function of value and the difficulty of separating the valuable component (modified from Dahmus and Gutowski, 2007).

6.5 Reserves, Resources, and the Future

Even though modern concepts of sustainability, criticality, and a “circular economy” affect government policies on many different levels, important underlying concepts include the long term availability of mineral resources and the “carrying capacity” of planet Earth (Malthus, 1798; Meadows *et al.*, 1972; Sverdrup and Ragnarsdóttir, 2014; Tucker, 2019). Many studies have predicted exhaustion of mineral resources (*e.g.*, Sverdrup and Ragnarsdóttir, 2014) and the one thing they all have in common is that every prediction about the exhaustion or peak production of resources by a particular date has been wrong. This is well illustrated by the famous bet between Julian Simon and Paul Erlich about the price of five benchmark metals, chromium, copper, nickel, tin, and tungsten, 10 years in the future (Sabin, 2013). Even though Dr. Erlich was quite confident that prices would have to be higher in the future due to resource scarcity, he lost that bet because prices were actually lower, both in real and inflation adjusted dollars.

It is important to clarify the terms “reserves” and “resources”. These terms are poorly understood by many and widely misused, particularly in the well known *Limits to Growth* study of Meadows *et al.* (1972) and more recent



incarnations (Cohen, 2007; Sackett, 2014; Ragnarsdottir and Sverdrup, 2015). Reserves have a defined meaning as codified by several widely used standards such as those promulgated by the Australian Joint Ore Reserves Committee (JORC), South African Mineral Resource Committee (SAMREC), and Canadian NI43-101 (discussed in an earlier *Geochemical Perspectives* in more detail; Arndt *et al.*, 2017).

In simple terms a reserve is a known quantity of a resource as established by drilling or sampling and typically is expressed as X tons of material with an average grade of Y at a cut off grade of Z. This results in a calculated amount of contained metal that potentially could be recovered, based upon assumptions of production cost, metal price, and technology. Resource is a broader and more general term than reserve and includes material that may be less well characterised, possibly of lower grade, and less certain to be economically recoverable. Resources can be converted to reserves by additional drilling or changes in economic factors such as price or technology (Doggett, 2007). However, it is important to understand that neither reserves nor resources are the same as “all there is”.

This is the fundamental flaw of many studies, such as Meadows *et al.* (1972), that assumed known reserves, or some multiplier thereof, were “all there is” and that by applying a given annual rate of consumption one could model how long the resource would last before disaster ensued. A little appreciated fact is that increasing world population and standards of living lead to more production which in turn requires larger reserves to sustain that production; thus, world reserves of almost all commodities are larger now than they were 50 years ago, despite 50 years of production, and most will be larger still 50 years in the future (Kelly *et al.*, 2005). This is because the time value of money makes it uneconomic to spend infinite amounts to convert all suspected or likely resources into reserves. In practice, most companies do not drill out more than about 20 years’ worth of reserves and some large mines have had ~20 years’ worth of reserves for more than a century, as continuing development drilling plus exploration proves additional reserves.

Another flaw in previous resource modelling studies is that resource use does not proceed full bore until the last unit of an element is consumed and then disaster unfolds. Rather, resource use follows the basic economic laws of supply and demand. If the price of a commodity rises then this will both increase supply because previously marginal deposits will be put into production or unknown deposits will be discovered and developed. Rising prices also will decrease demand because some uses of that commodity will no longer be economic and either production will decrease, thrifting (reducing unit consumption) will occur, or other materials will be substituted. This economic forcing will gradually reduce the need for the commodity in question and bring production in line with the available reserves, even though short term supply disruption or imbalance is possible.

This does not mean that we should be unconcerned about resource adequacy. We should be very concerned. But we should not confuse the adequacy of mineral resource supply with the policy actions needed to address the needs



of future generations for mineral resources. A more likely cause for concern than exhaustion is the consequence of resource use. The world is currently facing this in regard to climate change caused by human activity, particularly the increase in greenhouse gases in the atmosphere as a result of burning fossil fuels.

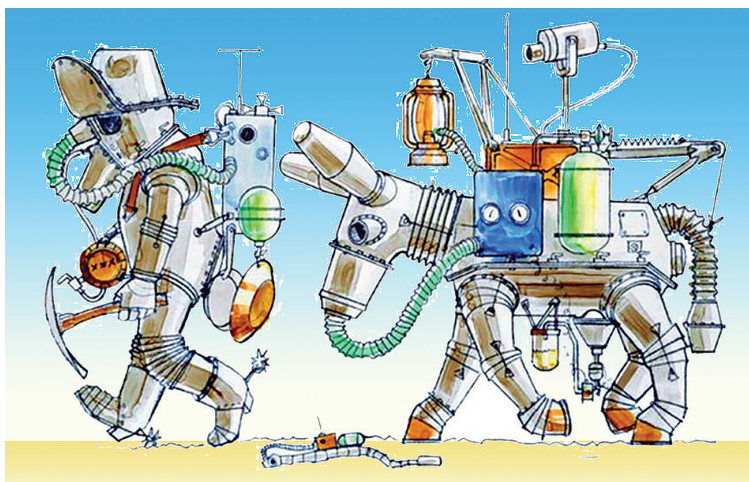
This general problem of the consequences of resource use is brought into focus by asking what is the carrying capacity of planet Earth (Tucker, 2019). In this sense Malthus (1798) was right, unchecked population growth is the fundamental problem. This was less of an issue when the total human population was fewer than a billion people, as it has been for most of human history. But in the past century world population has zoomed past the billion mark and currently exceeds 7 billion. Again, the problem is less about having sufficient resources to feed, clothe, and house that many people but rather the consequences of use of that much material. One could even argue that the severity of the current COVID-19 pandemic is partly a result of the Earth's high population density. And as Tucker (2019) poses the question, if 7 billion people is not too much is 10 billion, 20 billion or 70 billion? This is the existential policy question that society has yet to address and that our economic, political, and religious systems may not be ideal for solving.



7.

SPACE RESOURCES

Concern about the adequacy of mineral resources on Earth has led some people to propose that space resources might be an alternative solution or perhaps an opportunity to “get rich quick” (e.g., <https://www.rt.com/business/424800-first-trillionaire-spaceminer/>). A somewhat humorous illustration of this concept in terms of a “space prospector” is illustrated in Figure 7.1. Others have pointed out the fallacy of such thinking due to the high energy cost of escaping Earth’s gravity and the need for a viable business model (Meinert, 2019). However, NASA and the space community (Space Resources Roundtable, <https://isruinfo.com/public/>) recognise that human travel to and future habitation of celestial bodies such as the Moon and Mars will require utilisation of resources found in space, particularly water, as it is not economically feasible to “slip the surly bonds” (i.e. gravity) in order to transport the needed quantities from Earth. Thus, *in situ* resource utilisation (ISRU) on asteroids, Mars, and the Moon is becoming an increasingly important avenue of research (Mousel *et al.*, 2020). Geochemists will play a critical role in this endeavour by characterising minerals and processes, especially using remote and robotic methods.

**Figure 7.1**

Cartoon illustration of a hypothetical space prospector (from <https://clip-ground.com/lunar-pro prospector-clipart.html>).

My involvement with space resources started at the intersection of research on mineral resources, supply chains, sustainability, public policy, and potential funding synergies between NASA and the USGS. I was interested in leveraging the centuries of knowledge about exploration, discovery, and production



of resources on Earth with the very new but growing field of space resources. For me that required a fairly steep learning curve about the “space” part of the equation, ranging from orbital mechanics to cosmochemistry.

Some things are fairly similar in that many of the rocks and minerals on the Moon and Mars are analogous to those on Earth. There are lava flows and igneous rocks on both the Moon and Mars, and the early history of Mars was marked by abundant water and sedimentation, with some processes such as erosion and dust storms continuing to the present. However, there are important differences as well; Mars, the Moon, and asteroids have much lower gravity than Earth, lack geological processes such as plate tectonics and active hydrothermal systems, and have little to no atmosphere to prevent meteoric bombardment and solar radiation from being dominant erosional processes (Matsumoto *et al.*, 2020). The constant rain of impactors ranging from dust-sized particles to major bolides results in most celestial bodies having a surface regolith of impact breccias including relatively fine grained material, that in itself might be a resource as radiation shielding or as a raw material for building and manufacturing.

Unlike Earth, most celestial bodies possess close to their original composition since they lack many of the geological processes that differentiated and concentrated a variety of ore metals, forming “the manifold complexity of the earth’s crust.” (Lindgren, 1933, p. 894). For example, there will not be rich gold veins or large porphyry copper deposits on any celestial body. However, there may be other geologic processes, such as magmatic differentiation, that were active. For most asteroids and the Moon, there has been little change, other than cratering, since the time of formation. Mars was more active in its early history but even there the past several billion years have been relatively quiet, geologically speaking (National Research Council, 2007). Thus, the identification of potential resources in space, such as water for propellant and regolith for manufacturing and radiation shielding, will be different than on Earth. Nevertheless, what has been learned about exploration, discovery, and production of resources on Earth will still provide a framework for the development of resources in space. The rest of the section will outline this framework.

7.1 Orbital Terminology and Energy Cost of Space Travel

Most geoscientists have not thought about nor have any experience with space travel or logistics, so a short summary is in order. The energy cost for transportation in space is described by ΔV , the total velocity change that a spacecraft must undergo to move from location A to location B as given by the rocket equation:

$$\Delta V = v_e \ln(m_i/m_f)$$

where v_e is the velocity of the engine’s exhaust, and m_i and m_f are the initial and final mass of the spacecraft, respectively (Jedicke *et al.*, 2018). In other words, this equation describes the amount of propellant necessary to move a spacecraft and its cargo \pm human crew to a given location. For traditional transportation on Earth this would be analogous to the amount of fuel necessary to move a



truck, train, or airplane between two cities. To reach lunar orbit, about 80 % of a rocket's total mass must be fuel, given present technology, a very different situation than on Earth.

Due to Earth's gravitational field, the largest energy cost for space resources is in escaping from the planet. Returning to Earth also requires energy to offset the force of gravity and to avoid burning up upon re-entry through the atmosphere. In addition, moving about in space requires some, but much less, energy. For example, transport in space might involve moving from Low Earth Orbit (LEO) to Medium Earth Orbit (MEO) or to Highly Elliptical Orbit (HEO) or to Geosynchronous Earth Orbit (GEO). In addition, there are several Lagrange points where the gravitational attractions of different bodies, such as Earth and the Moon, are balanced such that a spacecraft may be "parked" to make observations or to serve as a supply station for propellant or other resources (Fig. 7.2).

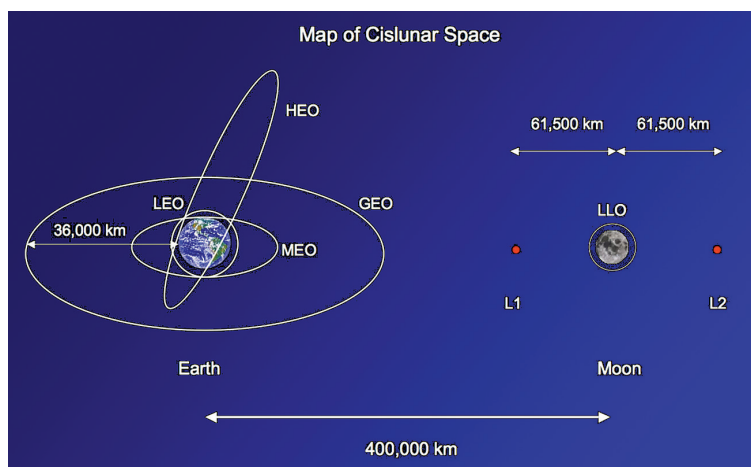


Figure 7.2

Map of cislunar space (the volume circumscribed by the moon's orbit around the Earth) showing location of Low Earth Orbit (LEO), Medium Earth Orbit (MEO), Highly Elliptical Orbit (HEO), Geosynchronous Earth Orbit (GEO), Low Lunar Orbit (LLO), and Lagrange points L1 and L2 where the gravitational attractions of the Earth and Moon balance out, such that a spacecraft may be "parked" to make observations or serve as a supply station for propellant or other resources (image from <http://www.spudislarresources.com/index.htm>).

The location of refueling stations in space (at LEO, GEO, or a lunar Lagrange point) sharply lowers the cost of deep space exploration, and thus the potential is improved for habitation or resource production on other celestial bodies, assuming that there are extraterrestrial sources of fuel. The relative energy costs in terms of ΔV to reach different locations in space are shown in Figure 7.3.

In all cases it requires more energy to go against gravity than with it, but every movement requires at least some energy. The importance and energy



costs of these various locations within cislunar space might be described in real estate terms as “location, location, location”. It is not clear how evolving space law (Mousel *et al.*, 2020) might deal with conflicting claims for use of particularly desirable locations in space but that topic is beyond the scope of this article.

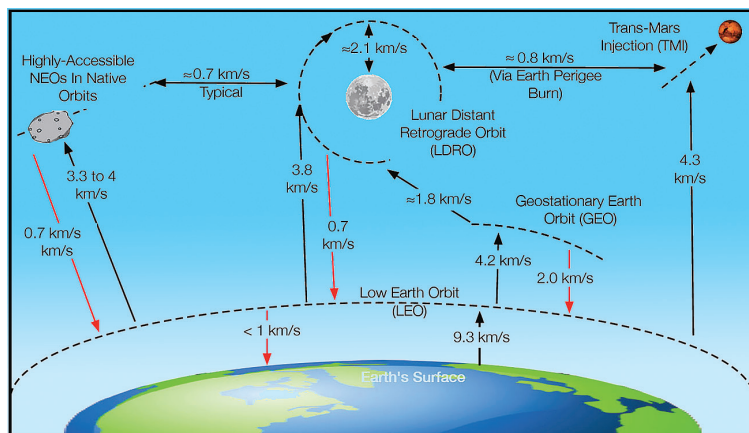


Figure 7.3 Illustration of energy (expressed as Δv in km/s) necessary to travel from Earth surface to various orbits and celestial bodies (modified from Sercel, 2016). Impulsive Δv 's achieved with chemical energy such as rockets are shown with black lines, whereas Δv 's achieved with aerobraking or aerocapture are shown with red lines.

7.2 Economics of Space Resources

The main barrier to the utilisation of space resources is the cost of transportation and overcoming the force of gravity (Jedicke *et al.*, 2018). This is particularly true for transportation to and from Earth but is generally the case for any space travel. This is the main flaw in some news accounts about space resources that only consider the contained resource in a celestial body and portray its value as if it were back on Earth, without considering the costs of discovery, production, and transportation (critical factors also to consider for the value of Earth resources). Thus, although it is true that some asteroids contain significant quantities of relatively uncommon metals such as platinum group elements, it is grossly inaccurate to report a value for that contained metal based on Earth prices without considering the extraction and transportation cost, which likely will exceed the value of the metal itself. This is true for taking the resource from Earth to space as well as for bringing the metal from space to Earth.

For example, the current cost of transporting a litre of water to the Moon surface is ~\$35,000 (Kornuta *et al.*, 2019). Thus, there is a strong business case for producing water in space where it is needed but not for bringing such water



back to Earth. The same applies to metallic resources; the highest cost mine to produce element X on Earth is much cheaper than transporting that element from space to Earth, even if the space resource were larger or higher grade and there was proven extraction technology (which doesn't exist at present, although development of such technology could also benefit terrestrial production).

A viable business case to transport resources from space to Earth might be possible if unique and high value products could be manufactured in space due to the low temperature, low gravity, and high vacuum conditions that are not present on Earth. One example is the possibility of manufacturing single, continuous-crystal fibre optic cables that have much higher bandwidth than those manufactured on Earth, and where the mass of material to be transported is relatively small (<http://madeinspace.us/mis-fiber>).

The main business case for developing space resources is their use in space or *in situ* rather than transporting them to Earth (Anand *et al.*, 2012). The most obvious and likely candidate for *in situ* resource utilisation (ISRU) is water, which has multiple and indispensable uses as propellant and life support for agriculture and respiration. It is relatively straightforward to separate water into hydrogen and oxygen by electrolysis, and solar energy provides abundant and uninterrupted power in space. Water is known to be present in permanently shadowed craters on the Moon (Colaprete *et al.*, 2010; Li *et al.*, 2018; Rubanenko *et al.*, 2019), at high latitudes and in the shallow subsurface on Mars (Orosei *et al.*, 2018), and in C-type asteroids (Rivkin, 2012). Little is known about the distribution, concentration, or purity of this water and these are all critical factors in the economic evaluation of this potential resource. The technology to extract and produce this water in space is at a rudimentary stage but with the alternative cost of \$35,000/litre lifted from Earth, it is not hard to imagine that the technology could develop quickly.

For example, United Launch Alliance (ULA), a joint venture between Lockheed Martin and Boeing Co. that provides launches aboard Atlas and Delta rockets, has stated a willingness to pay \$3,000/kg for propellant delivered to LEO and \$1,000/kg for propellant delivered to the lunar Lagrange point L1 (David, 2016). This would provide the commercial basis for the development of a lunar mining industry for water (Sowers, 2018). In addition, government agencies such as NASA that would benefit from access to propellant in space may well enter into long term contracts to encourage the development of this valuable resource, which would lower the cost of space travel for everyone. Figure 7.4 illustrates a cost estimate of propellant delivered to various locations in space from Earth, relative to producing propellant on the Moon and then transporting it to where it is needed (Kornuta *et al.*, 2019).

Although water is present and could be extracted on each of the Moon, Mars, and asteroids, there are significant differences among these sources, both positive and negative. The Moon is by far the closest object to Earth and thus transportation costs and travel time will be much lower than that of either asteroids or Mars. As a training ground for the development of remote technology and techniques, the Moon's proximity would allow repeated trips back and forth



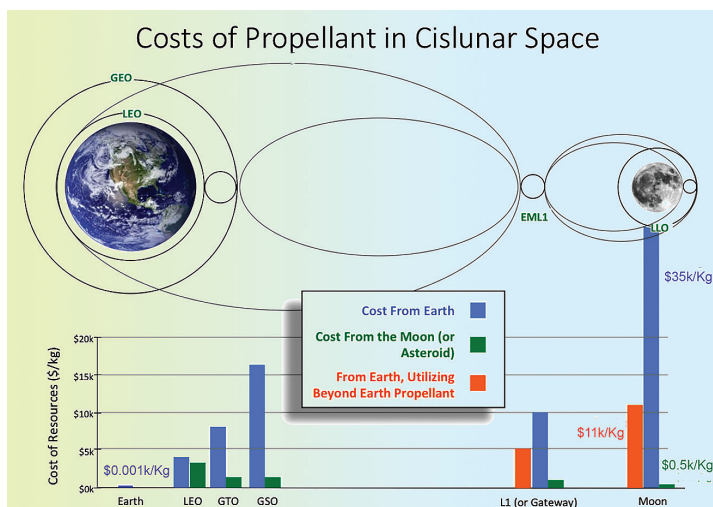


Figure 7.4 Cost of propellant in cislunar space that is transported from Earth, from Earth with refueling at GEO on the way to more distant points, and from the moon (modified from Kornuta *et al.*, 2019). Abbreviations: EML1 = Earth-Moon Lagrange point 1, LEO = Low Earth Orbit, GSO = Geosynchronous Earth Orbit, GTO = geostationary or geosynchronous transfer orbit, LLO = Low Lunar Orbit.

in a relatively short time frame. The Moon also is smaller than Mars so there is less gravity to overcome (1/6 *vs.* 1/3 *g*), and it lacks an atmosphere so there are not dust storms (as on Mars) that can cover solar panels (<https://phys.org/news/2019-02-nasa-rover-mars-years.html>). Mars has the advantage of abundant carbon dioxide in the atmosphere that, along with subsurface water, would enable plant growth and the production of methane and oxygen. Although methane has a lower specific impulse (energy) than hydrogen, it is a much easier fuel to store and handle. Asteroids are abundant throughout the solar system, and although not as close as the Moon, there are enough near-Earth asteroids ($\Delta V < 3$ km/s) that the transportation cost and travel time would not be much greater.

Asteroids have even lower gravitational fields than the Moon, and likewise no atmosphere. Thus, maneuvering around them is relatively straightforward, as was recently demonstrated by the Japanese spacecraft Hayabusa2 that landed on and extracted samples from the asteroid Ryugu (Fig. 7.5) in February, 2019 for eventual return to Earth (<https://www.nytimes.com/2019/02/21/science/ryugu-asteroid-hayabusa2.html>). Unlike the Earth, Moon, and Mars, asteroids tend to be more homogenous and little changed since primary accretion from the solar nebula. Thus, although there are differences in composition among asteroids, individual asteroids will consist of the mineral assemblage that reflects the location of its origin within the proto-planetary disk.



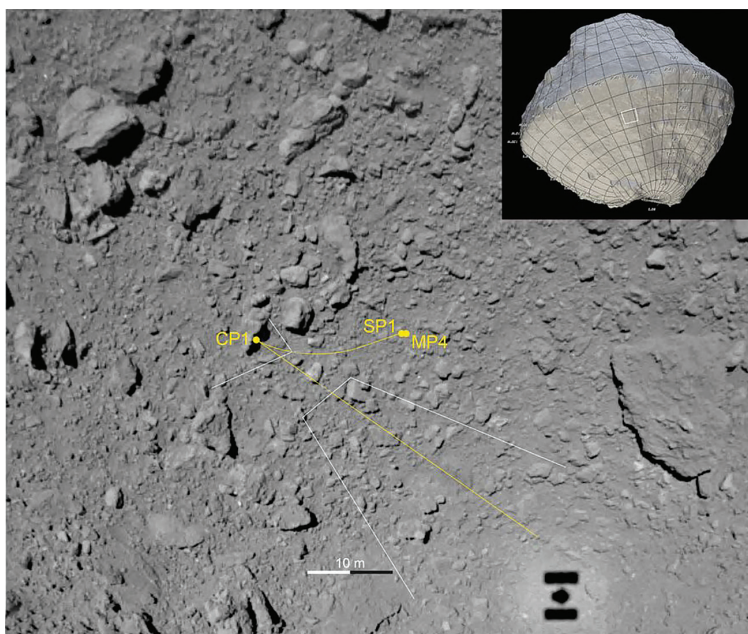


Figure 7.5 Hayabusa2 lander context image with its location on Ryugu shown in the inset. The lander descent and bouncing trajectory is indicated in yellow. Shadow of the Hayabusa2 spacecraft is in lower right (from Jaumann *et al.*, 2019 with permission from the American Association for the Advancement of Science).

Asteroids have a variety of compositions as deduced from meteorite analogues and spectral measurements. They can be roughly divided into two types, achondrites and chondrites (Weisberg *et al.*, 2006). The achondrites melted in their early history, largely due to heating from short lived radioactive elements such as Al^{26} , and the larger ones segregated into metallic cores and rocky crusts; asteroids that are fragments of the metallic cores are the target for potential recovery of metals such as iron, nickel, and platinum group elements (Mittlefehldt *et al.*, 1998). The chondrites did not melt and consist of accretionary particles called chondrules that approximate the composition of their original position within the proto-planetary disk (Desch *et al.*, 2018); some of the chondrites are carbonaceous and water-rich and these are the targets for potential recovery of water. This water is mostly in the form of hydrous minerals like serpentine that formed as alteration of primordial minerals such as olivine, due to interaction with original interstitial ice (Holm *et al.*, 2015).

The carbonaceous (C-type - CI, CM, CR, C2) asteroids like Ryugu have abundant carbon as well as water (in the form of ice or hydrated minerals) and thus could produce hydrogen, oxygen, and, like Mars, methane (Rivkin, 2012).



There is a strong correlation between the carbon and water content of carbonaceous asteroids (Fig. 7.6) and since carbon is relatively dark it makes remote sensing (from satellite or Earth-based telescopes) of the albedo, and hence the carbon-water content, of asteroids relatively straightforward.

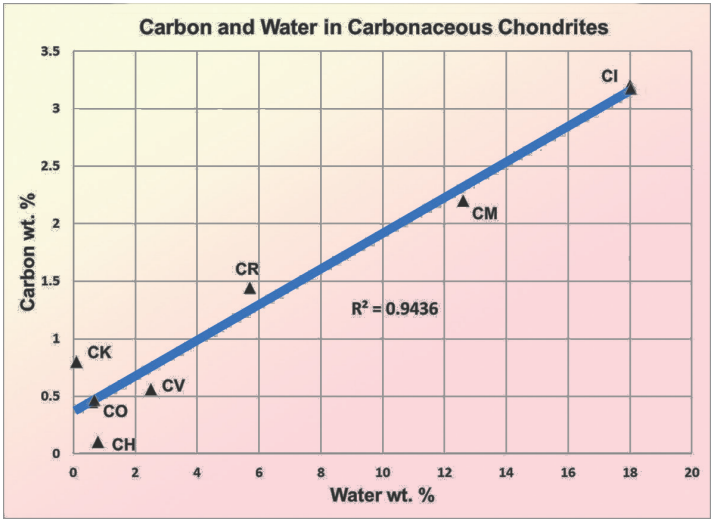


Figure 7.6 Correlation of carbon and water in carbonaceous chondrites (modified from Bonal *et al.*, 2016).

Overall, Mars has a broader range of mineral resources than either the Moon or asteroids due to being geologically active early in its history and having had more of an atmosphere as well as surface water and chemical weathering in the past (<https://spacescience.arc.nasa.gov/mars-climate-modeling-group/past.html>). Mars is farther from the Sun than either Earth or the Moon and thus receives less solar energy, but the presence of some atmosphere and gravity as well as a similar length of day would make it a more familiar living environment for human habitation, albeit more difficult to get to, than either the Moon or asteroids (Musk, 2017). Thus, the choice of which celestial body will be the first to produce mineral resources likely will be both a technical and political choice; governments and, increasingly, private companies have been known to announce a destination and then develop the technology to make it happen.

7.3 Production of Resources on the Moon and Asteroids

Only a few days away, the Moon is accessible for launch at any time, unlike asteroids and Mars, which have their own orbits around the sun and therefore have relatively narrow launch windows for when it is practical to send spacecraft. The



Moon's proximity permits remote control of machines by operators on Earth – with a much shorter lag time for signal receipt (one way is ~ 1.5 s) – prior to human arrival. Thus, production facilities and housing could be established without requiring people, and their needs for food, water, *etc.* This proximity also makes the trip beyond LEO safer, as aborting a mission is easier and the short travel time means that multiple trips can be planned. For all of these reasons the interest in developing mineral resources and human outposts on the Moon is more advanced than for either Mars or asteroids. Some plans focus on the permanently shadowed craters in the lunar polar regions that have water as ice (Li *et al.*, 2018; Rubanenko *et al.*, 2019). One approach would be to mount large solar reflectors on the crater rims that would focus concentrated sunlight onto production facilities on the icy crater floor (Fig. 7.7) (Kornuta *et al.*, 2019). The solar energy would heat the ground inside a capture tent (Fig. 7.8), with cold traps that would condense the sublimated water vapour into containers (Sowers, 2018). The water would then be delivered to a central collection point for storage or shipment to a cislunar supply station, with only 17 % of the gravity of Earth to be overcome for the latter (*e.g.*, Fig. 7.3).



Figure 7.7 Illustration of a potential lunar water production facility with solar reflectors on the crater rim and water cold traps on the crater floor (modified from Kornuta *et al.*, 2019).

Similar solar heating of ice or phyllosilicate minerals on asteroids could also be used to liberate water from regolith and underlying rock. The almost nil gravity of small asteroids would require a slightly different approach to contain the water vapour. One company (<http://www.transastracorp.com>) has proposed surrounding small near-Earth C-type asteroids in a containment bag while a solar lens focuses concentrated sunlight onto the surface, a process called optical mining; the thermal shock fragments the asteroid surface to release the contained water (Fig. 7.9). The water vapour would then be collected in a cold trap similar to the proposed lunar facility, for subsequent transport to a cislunar supply station.



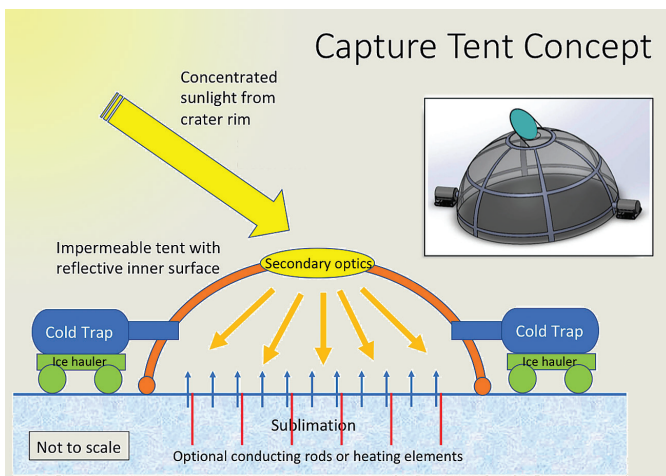


Figure 7.8 Illustration of a potential water production tent on a lunar crater floor. Heating from reflected solar energy causes sublimation of water ice from the crater floor and water vapour is then captured at ambient crater temperature in mobile cold traps that can move to a collection point for shipment (modified from Sowers, 2018; Kormuta *et al.*, 2019).

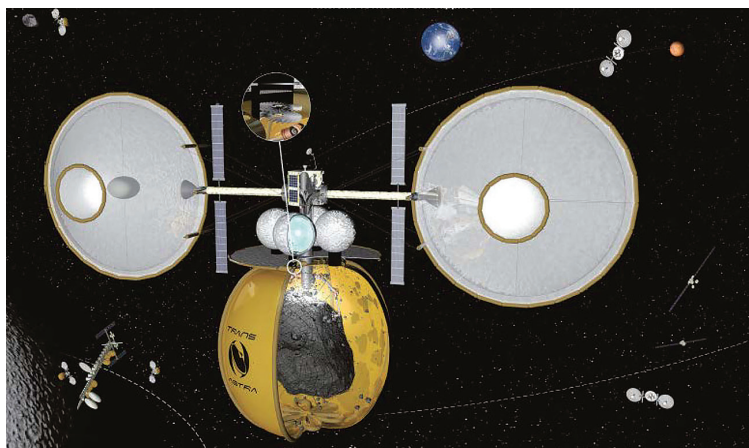


Figure 7.9 Illustration of water mining from near-Earth C-type asteroid. Solar reflectors concentrate sunlight into a focused beam that causes rapid heating and spalling of asteroid surface and the release of contained water that is then captured by cold traps for transport to cislunar orbit (from Sercel, 2016 and <https://www.transastracorp.com>; image credit Trans Astronautica Corporation).



Although the first targets for asteroid mining would be the more accessible near-Earth bodies, the Main Asteroid Belt at a distance >1 astronomical unit (AU) from Earth contains 10^6 times more material by mass than the near-Earth asteroids (Taylor *et al.*, 2018). This represents a huge resource supply if humans continue to explore throughout the solar system.

In addition to structural materials for buildings or spacecraft, the other resource needed for long term space exploration or habitation is bulk material for radiation shielding. This could be any of the loose regolith materials known to exist on the lunar and Martian surface and on some asteroids (Dula and Zhenjun, 2015). Such regolith could be used as is, or manufactured into blocks to be used as structural material (Fig. 7.10), with robotic processing (Hubbard *et al.*, 2013; <https://www.offworld.ai>) prior to human arrival. As with water, it is necessary to assess the distribution and characteristics of this regolith resource at the locations where it might be produced. Is the regolith one metre or tens of metres thick? Are there boulders or hardpan that might interfere with the equivalent of a bulldozer moving the material around? Such resource assessment is standard practice on Earth and needs to be extended to celestial bodies. The U.S. Geological Survey has done a preliminary assessment of asteroid resources for water and iron, to demonstrate the feasibility of such an approach (Keszthelyi *et al.*, 2017). They have also completed a model assessment of lunar resources (Keszthelyi *et al.*, 2019).

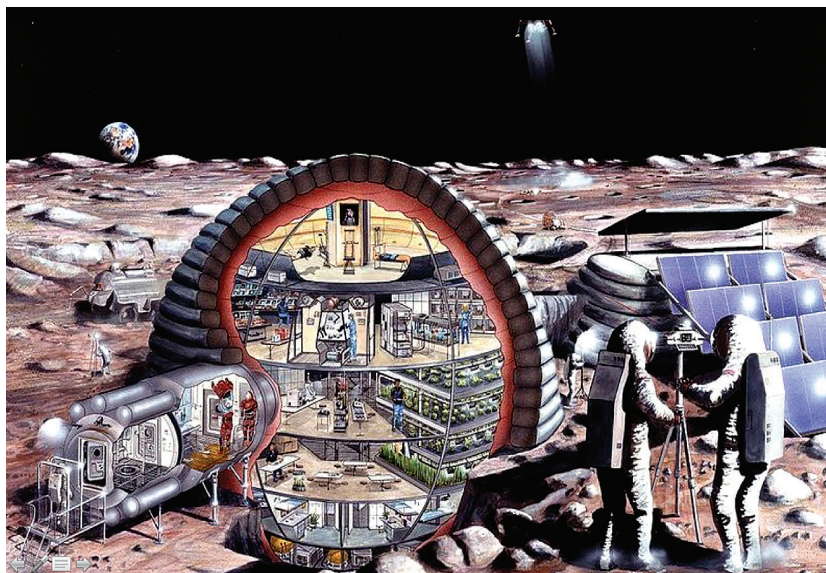


Figure 7.10

Illustration of a lunar habitat that uses regolith material formed into blocks for structural purposes and radiation shielding. Regolith processing could be done robotically prior to human habitation (from NASA, https://spaceflight.nasa.gov/gallery/images/mars/lunarbases/html/s89_20084.html).



7.4 Future Research

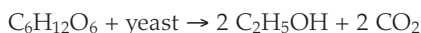
Models of potential space resources are a good first step, but just like with resources on Earth, eventually it is necessary to conduct representative physical sampling to assess and characterise better the resources prior to spending significant funds for development and production. Possible models for this are the ICDP and IODP drilling programmes on Earth. This is one area where the emerging field of space resources has much to learn from the centuries of experience on Earth; there is no substitute for physical sampling by trenching or drilling to produce a bankable feasibility study (Meinert and Williams, 2018). NASA took a step in this direction with the Resource Prospector mission but unfortunately that project was cancelled in 2018 while still in the development stages (<http://www.planetary.org/blogs/jason-davis/2018/20180503-resource-prospector-timeline.html>). However, this mission recently was resurrected and is now called VIPER (Volatiles Investigating Polar Exploration Rover). It will be launched in 2023 (<https://www.space.com/viper-nasa-moon-rover-launch-delayed-2023.html>). *In situ* resource characterisation probably is less important for asteroids because of the homogenous composition of individual asteroids and the fact that they can be accurately and relatively cheaply characterised by satellite and earth-based telescopes without expensive physical sampling missions. But even asteroids may yield surprises in the subsurface and some level of physical sampling can lessen that risk. As space travel and commercialisation of it are increasingly shifting from government to private industry leadership, innovation, and funding, perhaps this is an opportunity for the mineral resource industry on Earth to get involved in the first mine in space.

In conclusion, if humans are to visit or live on celestial bodies beyond Earth orbit for extended periods of time, as has been proposed by several nations and some private companies, then it will be necessary to utilise resources in space. It simply is not feasible to lift all the needed materials, such as water, propellant, and building materials, from Earth's gravitational grasp. This provides the business case for developing space resources; not bringing them back to Earth but producing and using them *in situ*, in space or on the Moon or Mars. The technology exists to do this but it remains to be demonstrated that it can be done on a commercial scale. Private enterprise is leading the way but government support, in the form of supply contracts (such as the ongoing NASA contracts to carry cargo to the International Space Station) or exploratory missions like VIPER, could go a long way to making it happen faster and ensuring success. But like the concept of ocean floor mining on Earth where “out of sight, out of mind” has delayed full consideration of environmental impacts, the issues of environmental disturbance and contamination due to space travel or space mining have not yet received any significant consideration.



8.1 History of Wine and Terroir

Geology and geochemistry are not only independent (and interdependent) sciences but they also underlie and support many other fields. These include my personal passion for wine that has been manifested in studies of *terroir*, and for the past ~37 years, operating a small home winery. Human interest in wine predates written records, as evidenced by archaeological finds in China, Georgia, Greece, Iran, and Turkey dating back some 9,000 years and by a fully functioning winery established in Armenia more than 6,000 years ago (McGovern, 2003). Since ripe grapes and other sugar-containing fruits will naturally ferment with indigenous yeasts, it could be argued that a rudimentary form of wine actually predates humanity and that the world's first chemical equation is:



Regardless of that chicken and egg conundrum, there is abundant historical evidence that wine and winemaking go back many millennia and that people have long appreciated the mystery and magic of good wine, including the observation that some places seem to produce better wine than others even when broad characteristics of geography and climate are similar. This interest in place has been referred to as *terroir* (French meaning “land” from the medieval Latin *terratorium*) and includes many different aspects of the physical environment.

Terroir involves the complex interplay of climate, soil, geology, and viticulture that influences the character and quality of wine. Although the term originated in France in antiquity (Seguin, 1986), *terroir* increasingly is being used in other parts of the world to explore differences at the scale of appellations to individual vineyards to within-vineyard domains (e.g., Wilson, 1998; Moran, 2001; Macqueen and Meinert, 2006; Swinchatt *et al.*, 2018). One common illustration of the importance of *terroir* is the occurrence of adjacent or nearby vineyards that produce strikingly different wines even though many of the measurable aspects of climate, viticulture, and winemaking technique are very similar. It is also common, although usually incorrect, to point to a single factor as the explanation: “It’s the soil.”, “It’s the water.”, “It’s the limestone.”, *etc.*

Terroir is the integration of individual factors that contribute to wine quality, and to make matters even more complicated there is the variable of time. What may be “good *terroir*” in one year may be less so in another. For example, in years that are relatively warm and dry, vineyard “X” with a particular slope, elevation, sun angle, and soil type may produce better wine than vineyard “Y”, whereas the reverse may be true in years that are cooler and wetter. Finally, there are human controlled variables such as grape variety, rootstock, canopy management, fertilisation, and irrigation; not to mention the role of culture and



personal preference in deciding what constitutes good wine in the first place. Thus, it is necessary to attempt to separate cause and effect, ideally while holding other factors relatively constant, so that factual documentation of temperature, solar radiation, water availability, soil texture and composition, and other physical factors can be distinguished from romantic imagination, *i.e.* a “taste of place” that may be sensed by an individual but cannot be scientifically documented.

Some wine myths include the demonstrably false notion that minerals in the soil make their way through the plant to the grapes and subsequently into the wine. This is reflected in some winewriter terminology such as “minerality” which implies that there is something in the soil that can be tasted in the wine. This would seem to find some support in the fact that many wines have “chemical fingerprints” that can be used to trace their origin but most of the measurable trace elements have no sensory effect; it is plant physiology, not geochemical composition of soils, that controls the ripening and sensory characteristics of the grape (Taylor *et al.*, 2002; Greenough *et al.*, 2005; Koundouras, 2018). Thus, if soil mineralogy and geochemical composition do not show up directly in the grape and ultimately in the wine, what is the terroir effect and how do we explain the repeatedly observed difference between wines from nearby vineyards “X” *versus* “Y”?

A first step is to consider differences in water availability to the grapevine during the growing season, as this may be the single most important variable in terms of ultimate wine quality (van Leeuwen *et al.*, 2009; Matthews, 2015). The first order control on water availability is climate and more specifically rainfall and humidity (Gladstones, 1992; Jones, 2018). Too much water, as in many tropical climates, is incompatible with quality wine. Zero rainfall, such as in the Atacama Desert in northern Chile, also would be incompatible with quality wine in the absence of irrigation. In general, it is desirable for grapevines to have only limited access to water in order to avoid excess vine vigour, *i.e.* growing more leaves *versus* fully ripening the fruit (Smart and Robinson, 1991; Koundouras, 2018).

The timing of water availability during the growing season also is important. For example, the benefit of moderate water deficits for red wine grapes has been demonstrated by numerous workers in terms of higher anthocyanins and tannins, features characteristic of high quality red wines (Roby and Matthews, 2004; Keller, 2008; van Leeuwen, 2018). In a location with too much rainfall (or at the wrong time), a soil that is free draining would be a positive feature whereas soil with clay, which can hold water, could be negative. In contrast, a location with too little rainfall (or not at the right time) might benefit from deeply weathered soils with a high clay content and a pore structure that can retain water. Thus, neither clay-rich or free-draining soils are necessarily good or bad, but in a given context these might be essential considerations. Documenting measurable physical characteristics is a goal of terroir studies, in order to attempt to understand how they affect grapevine physiology and wine grape characteristics. The fact that soil mineralogy and chemical composition cannot directly be tasted in finished wine does not mean that they have no effect and, more importantly, documenting what can be measured is an essential first step in the understanding of terroir.



8.2 The Components of Terroir

8.2.1 Geology

The physical variables affecting terroir are complex. For example, the geologic history of a region can include thousands to millions of years of weathering that formed the soil profile, including its horizons, clay content, and mineralogy. Even further back in the geologic and tectonic history of a region, faults or other geologic boundaries may have influenced variable water holding capacity of soils near the surface in a vineyard or district. For example, one of the most famous correlations between subsurface geology and wine quality is the repeated offsets along step faults of the basement rocks in Burgundy (Fig. 8.1a). The subsurface faults, only identified in the past century, show a simple correlation with appellation boundaries that date back several centuries, if not millennia, in terms of perceived vineyard differences and wine quality. It is not that the faults created magical terroir, but rather that they strongly influenced the location and amount of weathering of subsurface rock types, which led to the amount and kinds of clay, and thus water-holding capacity of these weathered rocks. This in turn can affect grape ripening and sensory characteristics. Thus, the bedrock is not reflected directly in the taste of the wine but rather the faulting caused variable degrees of weathering and soil formation. This then led to differences in the content of water-holding clay that in turn influences differences in grapevine physiology and grape composition, thus creating demonstrable differences in wine quality. In this regard, the “terroir effect” is directly related to the geologic history but not in the sense that anyone can taste the rocks in the wine.

Most terroir study is focused on individual vineyards or districts (Swinchatt *et al.*, 2018). However, some correlations can be made at regional to global scales, such as the worldwide lowering of sea level during the glacial maximum about 17,000 years ago and the locally abundant sediments produced by glaciers in many disparate parts of the world (Fairbanks, 1989). For example, more than 90 percent of Washington State vineyards are located in areas affected by glacial outburst floods (Meinert and Busacca, 2000) that formed coarse gravels and well drained, nutrient-poor soils (Fig. 8.1c). Many other wine producing areas of the world also have links to this glaciation and sea level change event and thus have some common terroir links even though they are thousands of kilometres apart.

A prime example of the indirect effects of glaciation can be seen in the Graves-Medoc region of Bordeaux, France (Wilson, 1998). Outwash gravels from glaciation in the Pyrenees Mountains along the French-Spanish border and the Massif Central in central France overloaded the Garonne and Dordogne rivers with coarse gravels leading to the Gironde Estuary, which itself had been enlarged and deepened by the lowering of sea level. Each period of glaciation produced its own series of gravel outwash floodplains along the rivers and the best (First Growth) vineyards are mostly on the same type of gravel. Names such as Chateaux Lafite-Rothschild, Haut-Brion, Latour, and Mouton-Rothschild are



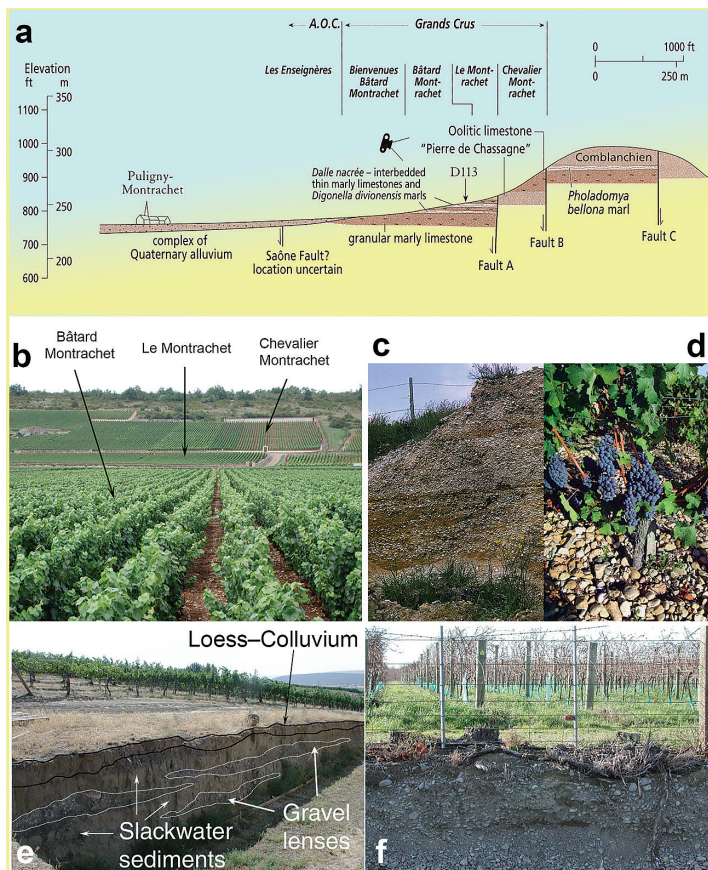


Figure 8.1

(a) Cross section through the Puligny-Montrachet vineyards, Côte de Beaune area (Burgundy, France) showing subsurface faults and facies changes (based on seismic, electrical resistivity, and geologic data) that underlie property boundaries between Grand Cru (Great Growth) vineyards and those of lesser quality. The better vineyards are those on the upper slopes. D113 is a local road. Modified from Wilson (1998). (b) Position of Chevalier Montrachet, Le Montrachet, and Bâtard Montrachet Grand Cru vineyards on a south-east-facing slope in the Côte de Beaune area. Vineyards are separated by stone walls that have existed for centuries and commonly demarcate property boundaries, as well as underlying geologic discontinuities such as faults, geological formations, or facies boundaries. Photograph by Meinert. (c) Günz Pleistocene gravel terrace in Bordeaux (France). Modified from Wilson (1998). (d) Merlot vines growing on Günz terrace gravels at St. Julien in Bordeaux. Modified from Wilson (1998). (e) Cut bank in the Tappeil vineyard in Red Mountain (Washington, USA), exposing a 3–4 m cross section of Quaternary loess, slackwater deposits, gravel lenses, and loess-colluvium. Photograph by Meinert (2001). (f) Streamcut bank exposing gravel substrate of vineyards in the Gimblett Gravels appellation in Hawke's Bay (New Zealand). Photograph by Meinert (2004).



well known to wine-lovers throughout the world and each of these estate vineyards is located on these gravel terraces (Fig. 8.1d,e). The most famous is the Günz Gravel, home of many First Growth wines. Recent work has distinguished at least six subdivisions of these gravels that can be correlated with different vineyards (Becheler and Tastet, 2010).

Less well known are the gravel outwash plains of the South Island of New Zealand. These were fed by the extensive and repeated alpine glaciations of the Southern Alps that form the north-south backbone of the South Island. These gravels form the substrate for many of the vineyards in the Marlborough area of New Zealand and some of the wineries of this region focus on the coarse gravels for their best vineyards (<http://www.stoneleigh.co.nz/>). Another area in New Zealand, Gimblett Gravels, is perhaps the first viticultural region in the world to define itself specifically on the basis of the gravel (Fig. 8.1f). Legally, wines from this appellation have to consist of at least 95 % grapes grown on the Gimblett Gravels (<http://www.gimblettgravels.com/index.htm>). Again, it is not that the gravel directly affects the taste of the wine but that the drainage characteristics of this gravelly soil are an important part of proper ripening of the grapes that then form the basis of great wine.

8.2.2 Climate

Having considered some of the physical variations that are part of *terroir*, it is also appropriate to discuss some aspects of climate, vineyard management, and winemaking that affect the ultimate quality of wine. At the risk of being repetitious it needs to be stated again that none of these effects individually are the determining factor, other than in a negative sense when they are outside a window (of temperature, rainfall, permeability, *etc.*) that is permissive of the making of quality wine. On the climatic front, temperature is the most important variable and can be measured in a number of ways such as growing degree-days, the Hüglin index, or the biologically effective degree-day index, but the simplest measure is average growing season temperature (April through October in the Northern Hemisphere and October through April in the Southern Hemisphere), which has been shown to be functionally equivalent to the others but more widely available and easier to use (Jones *et al.*, 2010; Jones, 2018).

The more complicated indices account for differences in elevation, latitude (hours of sunlight), humidity, and other factors that affect the nature of the growing season. For example, warmer conditions early in the growing season that hasten bloom and shoot growth are generally positive whereas hot conditions toward the end of the growing season may lead to excessive sugar accumulation and result in high alcohol wines (Keller, 2015). Where climatic conditions are marginal on the hot or cool side, then physical aspects of *terroir* can come into play. For example, in the Finger Lakes region of New York, the temperature moderating effects of glacial lakes allow *vinifera* grapes to be grown in an area that otherwise would be inhospitable to fine wine production. This *terroir* effect can be clearly seen in a satellite image that shows the snow-free margins of lands



adjacent to the Finger Lakes due to the “lake effect” (Fig. 8.2). This is yet another result of the world wide glacial maximum and sea level change that formed the landscape of many present day vineyards around the world.



Figure 8.2

Satellite photograph taken in early winter demonstrating that the mesoclimates of most vineyards in Ontario (Canada), and New York state (USA) are tempered by large bodies of water, including Lake Ontario (upper left) and the glacially carved, north–south trending Finger Lakes (lower part of photo) of New York state. The climatic tempering is evidenced by the lack of snow near the larger of the Finger Lakes. Image from NASA.

At the other end of the spectrum is the microclimate on the scale of individual grape clusters within a vineyard. Here the effects of sunlight, wind, humidity, and berry temperature have a direct impact on berry growth and ripening. Within limits, higher sunlight and temperature lead to larger berry growth without loss of solute concentration, skin tannins, and anthocyanins (Spayd *et al.*, 2002; Roby and Matthews, 2004; Dokoozlian, 2006). Some vineyards are chosen for the coarse cobbles that can reflect sunlight during the day and store heat during the night (Meinert and Busacca, 2002). For a given vineyard location - latitude, elevation, slope, and orientation will each affect sunlight exposure, as well as wind circulation and morning ground fogs. In addition, there are viticultural variables such as canopy management, planting density, row spacing, and cover crops that can each accentuate or ameliorate other microclimatic factors (Kliewer *et al.*, 2000; Reynolds and Wardle, 2009).

8.2.3 Biology

Predominant over all of the above variables, which may be regarded as permissive rather than determinative, is the choice of grape variety (genotype) and to a lesser extent, rootstock. As documented by numerous studies over the years (Amerine



and Winkler, 1944; Gladstones, 1992; Jones, 2018) different grape varieties are best suited for different climatic conditions. Taken together, the physical conditions of terroir modify, enable, and ameliorate the overall climate setting to allow particular grape varieties to develop to full potential. To produce quality wine the chosen grape variety must reach full ripeness. Therefore, early ripening varieties (Riesling, Pinot Noir) are best for areas with cooler, shorter growing seasons whereas later ripening varieties (Zinfandel, Nebbiolo) are only practical in areas with warmer, longer growing seasons.

For a given region or climatic zone one can then look at physical terroir factors such as slope, elevation, soil structure, and solar radiation to select preferred sites for the desired grape variety. Further modification can be achieved by vineyard management practices such as drainage tiles, row spacing and orientation, cover crops, canopy pruning, crop load (yield), fertilisation, and irrigation. Also involved are microbiological factors such as yeasts and bacteria that can imprint sensory characteristics on top of all the physical and cultural practices described above. The two best known are “earthy, musty” flavours that are imparted by *Brettanomyces* yeast and by the bacteria *Streptomyces spp* (Barate *et al.*, 2012). It is ironic that some of the “earthy” flavours that some winewriters passionately ascribe to terroir are actually biologic (and could be described as poor sanitation practice) rather than a function of soil or a “sense of place”.

In the end, the winemaking process can modify the initial starting material, the grapes, in a variety of ways that are part of the human creative process. Like chefs who could prepare a particular dish such as chicken in many different ways ranging from mild and delicate to hot and spicy, the winemaker through the choice of yeasts, malolactic fermentation, oak barrel treatment, fining, aging practices, *etc.* can produce distinctly different wines from a given cuvée of grapes. Conversely, a winemaker can aim for a similar wine style from grapes grown in different regions and under sharply different conditions. For example, it is relatively easy to control the acid content of grapes and wine by careful selection of harvest maturity, fermentation practices, and possible acidification; this allows the resulting wine to have some of the crisp, tart characteristics of a cool climate region such as Sancerre, France or Marlborough, New Zealand. Where viticultural and enological practices are prescribed either by cultural tradition or by rules (legislation or appellation regulations), this leads to a wine style that can be identified as characteristic of a region. However, other styles of wine could be made from those grapes and that region. There are even regions that do not yet have grapes or wine but that researchers are already experimenting with grapes that could grow there. The most extreme example is not even on Earth; people are looking at what grapes might be best suited for future human settlement on Mars (https://www.washingtonpost.com/world/europe/white-wine-on-the-red-planet-scientists-in-georgia-are-hunting-for-a-perfect-martian-grape/2019/01/06/c28d3570-fe21-11e8-a17e-162b712e8fc2_story.html).



8.3 Making Wine

As a winemaker for more than 35 years, I now realise that I had the good fortune to grow up with wine and unbeknownst to me at the time, it was very good wine. My father was involved with international sales for a relatively small American chemical company that did extensive business in Europe, particularly Germany. Through acquaintance with leaders of some large European chemical companies, one of whom had a seat on the German wine board, my father was able to import excellent German Rieslings, particularly from the Rheingau region, to our home in Ohio. Of course, I knew nothing of terroir in those days and it was not until a river trip down the Rhine in 2019 that I realised the special geological setting, influenced by the underlying rift valley, that made the Rheingau different than other appellations in the area (Fig. 8.3).

We had wine on the table for many dinners. Like most children I could not understand why adults liked the stuff. Sometime between high school and college I began to understand that this wine was different to ordinary wine, that it was in fact, extraordinary. This early exposure to wine is like experiencing art, language, or music at an early age; the brain and general awareness develop differently (Habibi *et al.*, 2018). To this day I am still learning about those differences.

In graduate school in California I had the good fortune to be in the middle of the California wine country at a time when the wine industry was rapidly expanding. Visiting wineries and learning about the winemaking process was a frequent weekend adventure. Having a scientific background allowed me to converse with winemakers at a technical level and I began to read enological textbooks available from the country's premier wine programme at University of California - Davis.

This learning process continued when I moved to Washington State in 1981 because the wine industry there was just beginning to see the same kind of expansion that had occurred a decade earlier in California. There were about 10 wineries in Washington when I arrived and more than 500 when I left two decades later. In addition, Washington State University (WSU) was home to the state's only enology and viticulture programme, which was to prove instrumental to my later terroir studies and winemaking activities. Being on the geology faculty at a Land Grant college like WSU exposed me to agriculture in general and agronomy and viticulture expertise in particular (Land Grant colleges were established by the Morrill Act of 1862, signed by President Lincoln, to focus on the teaching of practical agriculture, science, and engineering). Like my geological education described in Section 2, my developing education in wine and terroir was aided substantially by being in the right places at the right time, first in Ohio, then California, and finally Washington.

My first vintage as a winemaker was in 1983 when I made a Riesling and a Merlot. The former was probably a homage to my initial experience with Riesling as a youngster and the latter was a recognition that Washington was growing excellent Merlot grapes. In a sense this was my first experience with terroir. The Riesling was terrible, and only partly because of my then novice winemaking





Figure 8.3

(a) Map of the Rheingau Valley where the northerly flow of the Rhine River shifts to roughly East-West due to the underlying pull-apart rift valley. (b) Bend in Rhine river at transition from North-South to East-West flow. (c) Steep south-facing slope in Rheingau region with schist outcrop in centre of photo. Photographs by Meinert, 2019.

skills. The terroir of the hot flat plains of Eastern Washington was not nearly as well suited for Riesling as the cool but sunny, steep south-facing slopes of the Rheingau Valley (itself the result of a pull-apart rift basin that deflects the predominantly North-South orientation of the Rhine River to East-West; Fig. 8.3) in Germany. In contrast, with the same novice wine-making skills, the Merlot was not too bad. As any winemaker will attest, the quality of the grapes is the most important part of a great wine and in Eastern Washington I had access to great grapes, thus partly offsetting my rudimentary winemaking skills.

As I forged friendships with winemakers in Washington State and sourced grapes from their vineyards, I was basically apprenticed to some of the best winemakers in the state, learning on the job as I crafted increasingly complex wines. It was not just having access to great grapes but also learning about what happens in the vineyard throughout the growing cycle ranging from rootstock selection, to cover crops, and canopy management. Increasingly this knowledge intertwined with my geological background as the connection between



glaciation, geologic history, and where the best grapes grew became clear. This led directly to a collaboration with a WSU soil scientist, Alan Busacca, as we deciphered the relationships among past glaciations, outburst floods, slackwater deposits, and prime vineyard sites. This in turn led to a series of publications on various appellations in Washington State (Meinert and Busacca, 2000, 2002; Busacca and Meinert, 2003).

When I first started making wine, I was focused on individual grape varieties and mostly made a red wine that was 100 % Cabernet Sauvignon. Complexity of the resulting wine came from different yeast varieties to bring out various flavours, and different types of oak barrels that contributed not only complementary flavours but also a slow controlled oxidation and evaporative concentration due to the limited porosity of the oak staves and the additional complexity of different grain structures of wood from various countries. Not surprisingly there is a terroir of oak forests as well as wine.

Initially when we tried to isolate different factors of terroir, we focused on reducing the number of variables such as comparing Cabernet Sauvignon made from vineyard X *versus* the same Cabernet Sauvignon clone from vineyard Y using the same winemaking techniques. This made scientific sense but I gradually found out that the best winemakers typically added small amounts of other grape varieties to their best wines in the manner of the great first growths of Bordeaux which traditionally (and by regulation) use mixtures of either Cabernet Sauvignon or Merlot with lesser amounts of so-called blending grapes such as Cabernet Franc, Carmenere, Malbec, or Petit Verdot. It is somewhat like cooking where a freshly caught fish or perfectly ripe eggplant is very nice cooked by itself but can reach a much higher level when prepared with the right combination of ingredients such as butter, garlic, pepper, *etc.* This forced me to reassess my own winemaking philosophy away from 100 % varietal wines, and for the past two decades I have been making a single wine, a Bordeaux-style blend of dominantly Cabernet Sauvignon with lesser amounts of Merlot, Cabernet Franc, Carmenere, Malbec, or Petit Verdot, depending on the vintage, and thus, grape quality and availability.

The winemaking process is a geochemical laboratory unto itself, and because most people do not have personal experience with this, other than from the consumption end, I will illustrate the process from my experience over the years. As previously explained, it all starts with the grapes and for the past ~15 years I have imported them by ship from great vineyards in Chile. The grapes arrive in plastic picking bins (Fig. 8.4a) that hold about 8 kg each so that the weight of the grapes in individual bins will not self-crush. Next, the grapes are loaded into a hand-powered stemmer-crusher (Fig. 8.4b), which crushes and separates the individual grapes from the stems, leaves, and “material other than grapes” (termed MOG) which may include spiders, bird nests, gloves, and other random material. The resulting crushed grapes, called must, are transferred to large (100–200 litre) plastic fermentation vats after measuring the sugar and acid content (Fig. 8.4c) and adding yeast to a small amount of separated juice (Fig. 8.4d). I use different yeasts for the different grape varieties to bring out desired characteristics such as tannin texture, spiciness, and volatile aromatics.





Figure 8.4 The initial winemaking process. (a) Wine grapes arrive in plastic picking bins. (b) Stemmer-crusher separates grapes from stems and leaves. (c) Grape juice starting to ferment with inoculated yeast. (d) Measurement of juice sugar content.

The grapes start out at about 26 Brix (% sugar) and active fermentation (the equation at the beginning of this section) will produce large amounts of CO_2 , which will form a protective blanket over the fermentation vats to protect the fermenting must from contact with air. Within a week or two, fermentation will get down to about 5 Brix, at which point CO_2 production will slow down and there will not be enough to protect the wine from oxidation. At that point the must needs to be pressed to separate the liquid from the grape skins and seeds, so that the still-fermenting wine can be put into barrels under airlock to continue the journey to a finished wine.

The change in colour of the developing wine is dramatic (Fig. 8.5a), as all of the colour and most of the tannins and flavour are leached from the grape skins into the wine. The partly fermented wine is then transferred to a wooden basket press (Fig. 8.5b), whose technology has not changed much in millennia. The grapes are pressed (Fig. 8.5c) to liberate the wine from the grape skins, that





Figure 8.5

Grapes into wine. (a) A hygrometer is used to measure the declining sugar content from about 25 % on the left in bright red juice to about 2 % in the dark purple-red wine on the right. (b) The partly fermented wine is transferred to a wooden wine press. (c) The enthusiastic pressing crew squeezes the last drop of wine from the grapes. (d) The basket press is disassembled to reveal the tightly compressed grape skins, called the cake, that can be used for compost or re-fermented and distilled into grappa. (e) The wine is then transferred to a mixture of American and French oak barrels, each fitted with an airlock that will allow the diminishing production of CO₂ to escape while keeping air (and unwanted oxygen) out.



will tightly compress into a disk called the cake (Fig. 8.5d). The cake can be used for compost or re fermented and distilled into high alcohol grappa. The wine that flows out of the grapes due to gravity is called the free run and the wine that comes out with pressing is called press wine, that will become increasingly darker and more tannic the harder the press. The free run and press wine are combined into new American and French oak barrels that are each outfitted with airlocks to allow CO₂ to escape while keeping air out (Fig. 8.5e). The remaining fermentation in the barrels, until all sugar has been converted to alcohol, takes several months.

Once primary fermentation is complete, human activity slows down but the wine continues its journey over the remainder of the year. A natural malolactic fermentation occurs about three months into the barrel-aging process. Malolactic fermentation is caused by lactic acid bacteria *Oenococcus oeni*, and various species of *Lactobacillus* and *Pediococcus* that reduce the acidity by converting tart-tasting malic acid, naturally present in grape must, to softer-tasting lactic acid. This results in a smoother mouth feel and fuller body of the finished wine. Every 3-4 months the wine is transferred (called racking) from barrel to barrel with the settled sediment discarded. Over the course of a year this will clarify the wine of the finely suspended yeast cells and skin particles that make the unfinished wine cloudy.

After about a year in the new oak barrels the wine is ready for bottling, after the all important blending trials. This is the final assemblage of all the component parts into the finished wine. There are 3-4 grape varieties, 2-3 different yeast varieties, and 2-3 different types of oak barrels, each with its own flavour profile ranging from smoky to sweet vanilla. The multiple perturbations of these end members are tasted



Figure 8.6

Assemblage and bottling. (a) Tasting of the various end member components (grape varieties, yeasts, barrels) to determine the final blend for bottling. (b) Bottling consists of corking, labeling, and capping.



in 20 % increments (Fig. 8.6a) to decide what the optimum balance of the final blend should be. The wine is then put in clean new bottles, corked, labeled, and capped (Fig. 8.6b). From there the wine goes into the cellar for bottle aging and periodic enjoyment.

I mostly make wine for my own enjoyment and an expanding group of friends. Once I was persuaded to enter my wine into a competition of amateur (non-bonded) winemakers and much to my surprise and delight, it not only won a double gold medal (selected from all the initial gold medal wines in a second tasting) but was also selected as best of show (Fig. 8.7) at the Amenti del Vino wine competition (<https://www.amentidelvino.com>).

With time both my terroir studies and my winemaking became increasingly international. I have published studies on the terroir of the famous Tuscany region near Florence, Italy (Costantini and Meinert, 2003), the Finger Lakes of upstate New York (Meinert and Curtin, 2005), the basins of western Colorado

(Meinert and Nelson, 2006), and the renown Malbec vineyards of Argentina (Apcarian *et al.*, 2007). Up until 2005 I had used grapes exclusively from Washington State in my winemaking. But due to my increasing terroir activities in South America in 2005 I starting bringing grapes up from great vineyards in Chile. At this point my “Bordeaux-style blending grapes” shifted from Cabernet Franc, Merlot, and Petite Verdot to Carmenere and Malbec. This resulted in an intensely flavoured, inky dark wine that with my 30 years of experience with various yeasts and oak barrels became a wine that was not only not bad, but actually pretty darn good. My father passed away in 2007 but I think that he would have really liked this wine and would have been proud that it all started many years prior with the Riesling that he had imported from the Rheingau in Germany.



Figure 8.7 Medals and Best of Show designation for the Meinert Wine Cellars 2008 Cabernet Sauvignon (with 15 % Carmenere and 5 % Malbec) at the 2009 Amenti del Vino wine competition.



9.1 Family

This issue of *Geochemical Perspectives* has covered a broad range of topics and the common thread is that they are all things I have experienced during my scientific career. But one thing I have not covered, and it may be the most important of all, is my family. Part of this is because, like most professionals, our family life is a haven from what we do on the job. Also, as scientists we have been trained to separate the personal from the professional, the data from the interpretations. Until the present manuscript I don't think I ever used the personal pronoun "I" in any of the hundreds of scientific papers I have written. In the introduction I stated that part of the target audience for this *Geochemical Perspectives* issue is the early career scientist. Most young scientists, whether or not they have, or intend to have a family, will have questions about the role of family in the development of their careers. So, here is my story.

Like some of us, I encountered my future spouse in graduate school. We met on a geology field trip when my errant toss of a Frisbee accidentally hit her in the nose, drawing blood and a fiery look of "Who was the idiot who threw that thing?". The fire caught my eye. We have many similarities and differences. We both went to large (~5,000) urban high schools and small (<3,000) liberal arts colleges. We both studied science but also had significant non-science interests; in addition to her geology major my wife studied piano at the Oberlin College Conservatory and continued harpsicord lessons in graduate school at Stanford. She is short and I am tall; she is American of Chinese heritage and my ancestors are mostly German and English; and our two children are a mixture of all of the above (Fig. 9.1).

My children, Kim and James, grew up in a small university town in eastern Washington State. Kim was born during my wife's final year of law school and James after she had already launched her professional law career, so they both were raised by full time working parents. They went on more than their fair share of geology field trips, but geology never caught their interest. When I did geology field work during the summer, Grandma Meinert would fly out from Ohio for weeks at a time to help manage the household and produce midwestern culinary delights such as homemade meatloaf with catsup for the main course and jello topped with marshmallows and maraschino cherries for dessert.

Even though my wife was the best musician in the family, due to her intense legal practice I was the Suzuki parent for violin and viola lessons (in the Suzuki music training system a parent learns along with the student and participates in practices and lessons). Most evenings, I cooked dinner, with the aim that whenever my wife made it home from a long day at work, dinner would be waiting. A supportive spouse is an essential part of a two career family. Who does which



part is less important than the assurance that we are in this together and will do whatever it takes to help both parties be successful. Somewhat like the old adage, “Choose your parents wisely”, it is important to choose your partner well because nobody can do it alone.



Figure 9.1 2013 Family photo – left to right, the author, Georgia Yuan, James Yuan Meinert, and Kimberley Yuan Meinert.

Kim and James both participated in family winemaking activities and had hands-on experience harvesting grapes in the vineyard and all the steps of crushing, pressing, and bottling the wine. To this day their friends remark that they “*seem to know a lot about wine*”. They also travelled with me on some field excursions and sabbatical trips to the far corners of the world. A highlight was when they were 13 and 10 years old. We took them out of school for a 6 month, around the world trip with stops in New Zealand, Australia, Thailand, Hong Kong, Japan, China, and Poland. We had no checked luggage, just one carry-on bag apiece, plus a violin and viola for daily practice. They learned what essential meant for travelling light!

Both children went to small liberal arts colleges in the U.S. Midwest, one graduating as a poet and the other as a philosopher. After working for several years and then graduate school, they now are both accomplished adults; one is a policy analyst for the U.S. Congress and the other is an environmental lawyer. Being a proud parent is my continuing role in life.

9.2 The Future

As I recollect my career, I am struck by how much has changed since I began this journey. For example, my first research job as a beginning graduate student at Stanford University was to re-programme the computer, a Digital Equipment



Corporation (DEC) PDP-8 (Fig. 9.2), that ran the MAGIC IV matrix correction programme for the electron microprobe, the main instrument that was essential to my studies of skarn mineralogy. To put this in context for users of modern personal computers with terabytes of memory, the PDP-8 had a whopping 4086 words (12 bit) of memory, and input was by a series of toggle switches on the front panel with which we could programme the computer in binary code machine language.

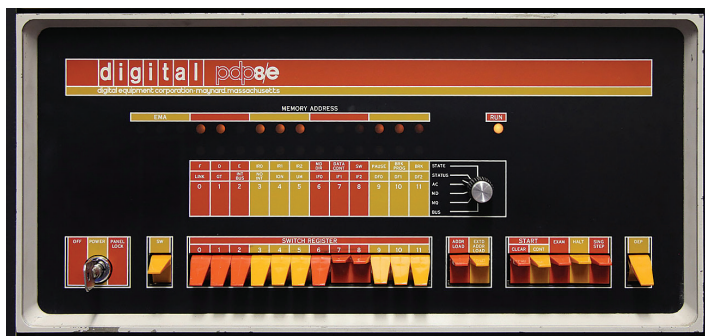


Figure 9.2 Digital Equipment Corporation (DEC) PDP-8 computer of the type the author used in 1976. Toggle switches in bottom row could be used to input machine language commands.

In contrast, other things, such as the importance of careful observations, meticulous scholarship, and clear writing, has not changed much at all. But at this point I will look to the future, based upon my life experience, to offer some thoughts about what is important and what is not, emerging trends that may affect the careers of today's young scientists, and finally some advice that I wish I had received at the start of my career.

I started this *Geochemical Perspectives* with a section on education. As a lifelong student and professional educator, I would rank it first among all human attributes and achievements. We may not be the only species that passes on information to our young, but we certainly are unmatched in regards to the amount and quality of education that we transmit. Not only is there no need to reinvent the wheel, we don't need to rediscover calculus, nuclear energy, jet aircraft, or the Internet; we can build on them. Not having to start from scratch gives each generation an advantage over the preceding one, and taking advantage of every educational opportunity is the best thing we can do for ourselves and our children.

This is not only true with formal education but also the opportunities to read, create art and music, and to explore nature. As a child I loved to read. Every week I would go to our local library where I would check out an entire shelf of

books to read and exchange the following week, for a new shelf of books. Admittedly, it was a small library, but I read everything they had to offer and I suspect this fostered some of the cross-disciplinary aspects of my career.

Along these lines, my advice is to try not to be channeled into a narrow discipline, even though many would counsel to focus on studies that might lead to gainful employment. This applies to the topic of graduate research as well. Although the maxim, “follow your passion” has some merit, few of us know at an early age what we want, or are cut out to do; I certainly didn’t. Instead, my advice is to go to a good institution with lots of smart people and pick some budding young star to latch onto; learn what they do and try to improve on it. The exact subject is less important than the spark of insight that they might provide.

As I write this, the world is grappling with the effects of the COVID-19 pandemic. This has and will change many aspects of life, including education. Currently, most universities are closed and many classes are being taught online. Although eventually the pandemic will ease, it is unlikely that education will return to exactly the way it was done before. Online and self-directed learning will become much more important, if not the new normal. Some benefits of the “old ways” will be lost and other new benefits will emerge. This is evolution applied to education. Do not be a dinosaur.

In this *Geochemical Perspectives* I discussed at length the changing landscape of scientific publishing. This will have a profound effect on our science and society. As an editor of a scientific journal I am too preoccupied with helping the current system function, to be a useful prognosticator of the future. The trend towards “community evaluation”, as playing out in social media, is too powerful to be ignored and it is up to the younger generation reading this article to help shape it. There are experts and expertise in most fields. How do we build on that and not rely on crowd sourcing to determine what is true, in a race to the lowest common denominator? Similarly, claims by some current political leaders that facts don’t matter, or rather, that they are entitled to their own “facts”, are worrisome. As scientists we need to resist the transition from evidence-based policy to policy-based evidence.

There was a television gameshow a few years back that offered contestants a “lifeline” whereby if they didn’t know the answer to a question, they could poll the studio audience for the majority opinion. This got to the correct answer much more often than the contestant’s random guess, but “better than random” is not the same as correct. I remain concerned about the movement away from expertise and peer review.

The section about government service and public policy may be new to many readers of *Geochemical Perspectives* volumes. This is one area in which scientists can and should be much more active. I can honestly say that the year I spent as a Congressional Fellow in Washington DC, working on policy and legislation in both the Congressional and Executive branches of the United States government, was the most interesting, challenging, and influential thing I have done in my life. Every U.S. scientist should consider doing this during their career



and I suspect that there are similar opportunities in other countries. The more dysfunctional some of our governments become, the more important it is to involve scientists and scientific thinking into the process. Not only will you help the process, your view of the world and how it works will be forever changed.

Finally, and most geoscientists will not need too much persuasion on this topic, good wine is wonderful and great wine can be transcendent. The opportunity to apply geochemical insight to a totally different field is both rewarding and may lead to entirely new careers. Not only do I enjoy making wine and cooking a great meal, I have been known to share both with friends!

In the skarn section of this *Geochemical Perspectives*, I described what it is like to work as a geological consultant and interact with private industry. I do this not only with my expertise in exploration for skarn deposits, but also with wine and terroir. I have done many studies in this field and have consulted for wineries and vineyards in several different countries. That, and my winemaking activities, allow me to basically have an entirely separate career.

I will close these final thoughts, that in general are looking forward, with a look back to my very first publication on wine and terroir. Figure 9.3 is reproduced from that article along with its caption that stated, “Some samples required repeated evaluation.” May your samples and life be similarly worthy of repeated evaluation.



Figure 9.3

The author, Larry Meinert, (left) and colleague Alan Busacca tasted barrel samples of wine from many of the vineyards described in one of the first U.S. terroir papers (Meinert and Busacca, 2000). Some samples required repeated evaluation.



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