

Geochemical Perspectives

The EAG logo consists of a stylized blue circle with a yellow and white triangular shape inside, followed by the letters 'EAG' in blue.

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STEPHEN J. MOJZSIS

**From Early Earth
Biogeodynamics
to Exoplanet
Geoastrometry**

Geochemical Perspectives is an internationally peer-reviewed open access journal that publishes invited contributions from leading scientists in the field of geochemistry.

Each issue of *Geochemical Perspectives* features a single, in-depth article that explores the past, present, and future of a geochemical field – presented in a clear, accessible way by respected members of our community. The articles bring together important scientific discoveries in these areas with the human and, often, the technological stories behind their development, offering insights directly from leading scientists who contributed to shaping and advancing the field.

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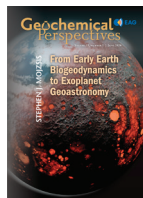
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An artistic rendering of two popular scenarios for the environment of the Hadean Earth blended on a single globe. Landmasses interspersed with impact craters and flooded by shallow seas rich in iron under a bright sky drape the tranquil side of the Hadean Earth's surface (left, at dayside). This modern view contrasts with the commonly held (nightside) idea of a molten Hadean hellscape ill suited for prebiotic chemistry until some later time. IMAGE CREDIT: KATHLEEN EBERT (GEOASTRONOMY.ORG).

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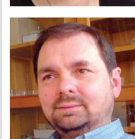
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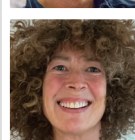
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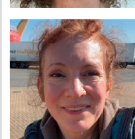
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DEDICATION

To my family: Kathleen, Anna, James, John
A szívemet és a lelkemet tettem ebbe a munkába, értük.

PREFACE

*Younger people, who have not yet reached the middle
of life can bear even the total loss of the anima without injury.
The important thing at this stage is for a (hu)man to be a (hu)man.*

Archetypes and the Collective Unconscious (Carl Jung, 1959)

I was caught a little off guard by a request from our professional society, the European Association of Geochemistry (EAG), to deliberately write about my personal life mixed with some scientific history and musings. After sixty orbits it is probably my turn to write something like this now as a proud member of the European community of geochemists. The experiences which came rushing back while I wrote this compelled me to consider what Carl Jung termed individuation. He wanted to examine, deeply, the topic of how we emerge to become a complete person. That is why I chose the opening quote for this piece. Integration of the shadow unconsciousness as Jung put it, tends to happen at mid-life. Jung thought that this stage would take place after about age 40. My individuation is different from yours, just like yours is different from mine and everyone else's. This is true despite the fact we have the same chemistry, and chemistry requires that the blue colour that I see is the same as what you see. Experience, however, masks composition. It is not guaranteed that individuation will occur unless you allow it; if you are curious about the world, there is a good chance that you will grow more than you imagined. Jung also remarked that "...everyone knows nowadays that people 'have complexes'. What is not so well known, though far more important theoretically, is that (our) complexes can have us". This comment

applies especially well to us in the sciences. When my friend the unparalleled Janne Blichert-Toft invited me to contribute to this series, she assured me that I was to have total freedom to write what I want. The sole governing parameter was that whatever I put together should be a mixture of personal anecdote with scientific vignette. Carrying out this task allowed me the opportunity to reflect on my time thus far (figure below). Just like you dear reader, I could never have imagined the nonlinear path I took. I hope you get a sense of the particular journey I have taken, herein.



Forces of nature. Enjoying the Dettifoss, northern Iceland. Photo credit: N. Brown.

My vital jaunt towards individuation began in the Bronx, that unapologetically notorious borough of New York City. Soon afterwards, I spent my early formative years in a small town in northern New Jersey. Following that, there were eight years in Boston mixed with side adventures in Houston and Budapest. These different life events occurred prior to my reaching the age of twenty five. Those undergraduate years in Boston taught me how to study despite countless distractions. Seeking new fortunes, this time I went to the West and experienced eight years in southern California for my graduate and postdoctoral studies. It was during that time that I learned how to teach myself. The next step was the longest so far, twenty one years in lovely Boulder at the University of Colorado in the foothills of the Rocky Mountains. It was in Boulder that I learned to better manage my time. Let me say, getting a tenure stream faculty job there was like winning the lottery. The Boulder years were punctuated by marvelous research stints in places like Lyon and Nancy (France) and Tokyo. Ultimately, in the darkest days of the coronavirus contagion my family boldly made the decision to move kith and kin to Europe. We returned to our heritage. It was terribly hard to leave the USA and to uproot and upend and throw into chaos my American born children. Yet, these energetic young people, like their parents, are adventurous and resilient and I believe that they understand (or will, eventually) the necessity of change despite the nuisance and the challenge of

spending long times apart from one another. In Budapest I established a research group at the HUN-REN Research Centre for Astronomy and Earth Sciences based at the Konkoly Observatory. I also became a Foreign Member of the Hungarian Academy of Sciences (MTA). While my heritage language skills in Hungarian improved, our two sons became fluent¹. After four splendid years in Hungary reconnecting with close and distant family members in the Pannonian Basin and beyond, we expanded our base yet again. In June 2025 I moved the bulk of my operation to the Bavarian Geoinstitute (BGI) of the University of Bayreuth in Germany. It is there that we are building a new scientific programme in Geoastronomy in an institute renowned worldwide for its experimental and theoretical work on the interiors of Earth and other rocky planets.

I will always be that kid with stars in his eyes. This vision of myself, however, is frustratingly confounded by the daily reality of a venerable image reflected in that most unforgiving of devices: the mirror. Pun intended, it is now time to reflect on my convoluted journey so far.

Gentle Exhortations and Patrician Guidance

Allow me to begin with a few simple admonitions for young and old²: your professional and personal life – intertwined as they are – should not be prevented from taking unexpected detours. I feel strongly that this attitude for reasonable risk allows for great discovery potential. Do not pigeonhole yourself and comfortably remain in narrow topics. By embracing this world view, I have little doubt that you will find episodes of enlightenment along the way. Do not convince yourself that although a topic is interesting, and you have some ideas to test, it is not something that you *do* and therefore it is best to drop it and move on. That would be a grave mistake. Evidently, I am also telling you to steer away from mundane work even if it is very safe and reliable and not open to debate. If you are onto something, but there is a problem that is getting in the way of achieving your goal, sleep on it and leave your comfort zone. If that does not help, find

-
1. Hungarian is the most common variant of Finno-Ugric, unrelated to the more widespread Indo-European variants in Eurasia and beyond. Approximately 46 % of the world's population speaks an Indo-European language as their native language. That is about half of humanity, so if English is your mother tongue, you are fortunate indeed. Hungarian, on the other hand is a fantastically versatile secret language to know. Only 0.3 % of the world population speaks Finno-Ugric languages, which includes all the populations of Hungary + Finland + Estonia and several minority regions in Russia, Romania/Transylvania, Serbia/Banat-Bánság/Vojvodina, and Slovakia/Felvidék; Hungarian is the majority language in the Finno-Ugric group and is represented by about 15 million people.
 2. This turn of phrase is casually borrowed from William S. Burroughs' *Words of Advice for Young People*. It is sometimes mis-attributed to another work of his, the inimitable *Revised Boy Scout's Manual*.

competent and good natured people who you can work with as collaborators. Never give up on a good idea. It is also worth saying that the anticipation of some scientific outcome comes close on the heels of a recent insight.

For those of us who have been fortunate enough to experience it, there is a special joy in having the precious moment to yourself when you realise that you are the first person to discover something. The feeling is magical. For all you know, in a brief time you are alone in the universe with that small (and sometimes, big!) piece of knowledge. These are precious moments. Cherish them and make them more common in your experience if you can.

What I find most compelling about the integration of geology with disciplines such as chemistry, physics, biology, astronomy, and even anthropology, as demonstrated in this work, is that geology, a fundamentally historical science, always has a story to tell. The story, however, requires you to dig a bit deeper to find out who was already there before you. Others will do the same by building on what you have done, sometime, somewhere, in the future. Give appropriate credit and share what you know. The book, *Life, the Universe... and the Scientific Method* by the famous chemist Steven Benner (2008), succeeds brilliantly at this.

Like you, I am intrigued by big questions: What are the origins of stars and planets? How, when, where and even why, did life begin here on our planet and evidently not elsewhere in the Solar System? What are other worlds like? These are the kinds of questions that feed us storytellers. But answering such questions means that we can also easily fall into traps. Dangerously, such tales – especially those composed for “Early Earth” and “Origin of Life” – may be based on mythology, hearsays and misconceptions, rather than inferences and observations. Frequently, what is blurted out by some particularly vocal pundit turns out to be a hodge-podge mixture of fictions with a bit of fact thrown in here and there.³ I heard once on a popular radio programme⁴ that “Nature often astonishes theory”. We are not in the business of telling nature what to do. My friend the astute Craig Manning likes to remind me of the importance of using models to understand data. We build good theories which make predictions for observations. Beware. In open forums or anonymous peer reviews you will undoubtedly run into self-righteous people who both loudly and confidently proclaim that your empirical data cannot be correct. Such people will claim that the data you laboriously collected are somehow erroneous because they do not fit with the latest fad or (their) prevailing world view. Retain a quiet confidence and politely ask such people to go back and fix their model. The talented ones will take up the challenge and respond with a result that satisfies the data. Those who do not take up the challenge are just, to put it politely, blowing smoke.

3. Doublethink (e.g., George Orwell's 1984) is a pernicious indoctrination where two or more conflicting beliefs are either taught or generally accepted as truth, even if they are at odds with your own observations.

4. https://en.wikipedia.org/wiki/Car_Talk

Rather than write something like an owner's manual of a few narrow aspects of geochemistry, or an exhaustive autobiographical sketch of decades of experience, I have opted in this work to do a little of both. I share bits of my history, punctuated by vignettes that present some old ideas with new twists. I hope that you will have a better understanding of why I think the way I do after reading this tome. If or whenever you feel like it, feel free to drop me a message if some of what is written here jogs a thought or motivates an idea. I would be very happy to discuss this with you. If you want, we can meet in person over a coffee at a Goldschmidt Conference, Europlanet Science Conference, or at one of the European Geosciences Union general assemblies.

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Any long list of people who have inspired me along the way is bound to be woefully incomplete and probably insulting to some degree. I instructed myself to leave this writing for last, and it continues to be a work in progress. Let me just be direct with you that the whole idea of writing about myself feels really weird. But that is exactly what I was asked to do! I needed to get over it. As the artistic Greg Szulgit⁵ once shared before my graduate school band *The Long Pig* had its final debut performance⁶ in 1997:

“I suffered for my art, now it is your turn!”

In any event, here at least sprinkled throughout the text contained in this volume is my chance to thank the people who raised me and guided me along the way. I mentioned those who challenged me in positive ways. Challenges and obstacles overcome helped me grow inside and it is a waste of time to write about those who felt compelled to, as the thoughtful Minik Rosing would put it, act in an uncouth fashion. I especially thank those with whom I have shared both triumphs and tribulations.

Janne Blichert-Toft has been the patient and resourceful and kind and knowledgeable handling editor of this manuscript. I am grateful to her for her calm guidance. Special thanks to the reviewers: Andreas Kappler, Charley Lineweaver

5. <https://www.youtube.com/@baconssandwich>

6. Message me if you would like a link to a digital recording of this or any other “music” I refer to herein.

and Nick Arndt who kindly provided feedback that helped to improve the work, however any mistakes or omissions in this work are totally my fault. I hope there are not too many. My most important aim is that this work generates discussion – whether in agreement or disagreement – that yield meaningful results. Finally, I want to express my gratitude to Marie-Aude Hulshoff, Alice Williams and Robert Dennen at the European Association of Geochemistry.

The pride of my professional life is the talent and scholarship of my many undergraduate and graduate students, postdoctoral scholars and research staff with whom I have shared various parts of this journey. I am enormously proud of them. For all you, as well as my mentors, friends, collaborators and competitors, I remain profoundly grateful for the opportunity to learn from you.

FROM EARLY EARTH BIOGEODYNAMICS TO EXOPLANET GEOASTRONOMY

ABSTRACT

Experiencing an international childhood, and an innate curiosity of learning the origin of himself and his surroundings, Steve Mojzsis set out to try his best to make sense of the universe he was born into. This quest will never be fulfilled, but it doesn't prevent him from trying. The ultimate prize is to figure out how the biosphere came into being. The path towards learning began with adventures mostly in North America and Central and Western Europe. To find himself still further meant going, to Africa, Asia and Australia, with expert guidance from the best mentors along the way. Ever the bridge builder, he was not satisfied with staying within one narrow discipline of science for very long before trying a hand at something else, albeit related. In this way he stumbled into biogeodynamics and geoastronomy; we will probably not see spectacular developments in either of these nascent fields until the end of 21st century or long after he is returned to some mineral salts, CO₂ and H₂O. Back on his home world, it is evident that in its first 500 Myr (*q.v.* Hadean eon) Earth's crust co-existed with liquid water; it was affected by late accretion bombardments and harboured chemically diverse hydrothermal systems. Globally active volcanism powered by a hotter

mantle, impact generated topography and inherent differential buoyancy of the crust means that scattered emergent land masses existed irrespective of different estimates for plausible Hadean ocean volumes. Consequently, land surfaces in the first few hundred million years – with diverse subaerial and (sub-)aqueous environments – could bring prebiotic chemical ingredients to reactive concentrations. This active chemistry led to the first life. Yet, the inferred complexity for even the minimum biological entity probably means that both operative and persistent biology in a planetary environment is the most difficult developmental stage to reach. Soon after Earth's formation, its surface had the capacity to host fully fledged (*i.e.* living) biochemistry. While life emerged at the dynamic interface of the planet's primordial geosphere, hydrosphere and atmosphere, nobody knows whether any Hadean environment was ideally suited, or merely good enough, to facilitate its emergence. Given that we do not have time machines to go back and see what happened on Earth, or anywhere else for that matter, we are compelled to tell stories that fit the data. That said, comfortable fictions about what "might" have happened, just because somebody said something (without evidence), ought to be taken with a grain of salt. If we ever are to come up with a plausible pathway to a life giving world, it will be more metaphorical than literal. All of this will likely change if we find an independent origin of life, either on purpose or, more likely in Mojzsis' opinion, by accidental discovery of something strange in the data.

1.

INTRODUCTION – AN UNUSUAL MIXTURE OF CONSONANTS (1965–1997)

*This shower, blown up by tempest of the soul,
Startles mine eyes, and makes me more amaz'd
Than had I seen the vaulty top of heaven
Figur'd quite o'er with burning meteors.*

King John, Act V, Scene II, line 50 (1594–1596, W. Shakespeare)

I like Mondays. And, unlike most people, I have always liked Mondays. It annoys those around me that I can be so cheerful on the first day of the work week. That is a good place to begin my personal version of this *Geochemical Perspectives*. The most important day in history for me was a Monday. It was on that day that I took my first breath on June 21, 1965, at 2:48 PM in Misericordia Hospital, Bronx, New York City (Fig. 1.1).

Figure 1.1

Scientist in the making. What an expressive little creature. As I accumulate years of experience the more I give credit to Nature over Nurture for the life paths we take. Choices are always there. It is up to the individual to decide. Do not be afraid to put yourself in the position that you experience something new. Inquisitiveness is an innate trait in my opinion.



There to greet me in this world were my brave and humble parents, who were immigrants from two very different but somehow complementary European cultures. Although Ireland and Hungary are both small in territory, they are fabulously rich in culture, history, language and passionate opinions. These lands were, however, left impoverished by a series of devastating wars and depredations from stronger neighbours which stretched at least from the 16th century to late 20th century and up until the end of the Cold War in the early 1990s. My mother, Margaret Ellen McKenna (Fig. 1.2) left her country home in Kilmore, County Monaghan, Republic of Ireland as a teenager. She moved, bravely, alone, to the United Kingdom to attend nursing school. Around the mid-1950s she was recruited to work in the United States. After making the sea voyage, she began her new life there and never returned to live in Europe. She deeply distrusted the water and never learned to swim owing to a childhood accident when she fell into a water well and very nearly drowned. The 5 day



Figure 1.2

Margaret Ellen McKenna. The instructions are very specific, and still true today, you may not smile for passport photographs.

ship crossing of the Atlantic to the Port of New York was therefore not at all enjoyable. Like everything else she approached in life, however, she made the best of it and was always ready with a joke and a smile.

Margaret (people called her “Margie” because she insisted not to be called “Maggie”) joined an expansive group of expatriates in the New York City area which included the usual case of a multitude of Celtic cousins, who were the descendants of family members that moved to the USA before the Second World War or even earlier. Margie always remained that sensible and adventurous country girl – the third of 10 children – who struck out on her own. True to her heritage as a member of the musical branch of the McKenna clan, she

enjoyed dancing, drinking, laughing and singing songs. István Mojzsis, my polymath and polyglot father, was quite different. He was a serious faced young (20 year old) trade school student when he participated in the Hungarian Uprising of 1956 against Soviet rule (Fig. 1.3). Like many others in the streets of the capital, Budapest, he faced down tanks with rocks. When this hopeful event was later brutally crushed by columns of Soviet armour, he fled the country along with 200,000 others (2 % of the population!) and became one of the many tens of thousands of refugees resettled in the United States by the Eisenhower administration in Operation Safe Haven. Imagine for yourself such hospitality in the USA in those days. Compare that experience to the nihilism, ignorance,



Figure 1.3

István Mojzsis. When you are young, there is a tendency to have a romantic opinion of the world. In general, those times before age 25 one looks at with great fondness, even when things were coming crashing down all around you.

bigotry and intolerance that seems to be in fashion now. That was a very different era when wisdom and tolerance was informed and tempered by real suffering seared into collective memory. After all, the dual World Wars and the unimaginable horrors of the Holocaust were fresh on peoples' consciousness in the 1950s. For those of you who knew veterans of those wars and spoke to them, you know what I am talking about. Help was offered to those who needed it. In those times appeasement, much less aid and vocal support to totalitarians, was unthinkable.

After a stint in the US Army (Fig. 1.4), my father István (which is the Hungarian form of the name Stephen) worked as an X-ray technician at a hospital in New York City. It was there that my (future) parents met and fell in love. Thank goodness for that. Soon after their marriage, my father changed jobs and took up a lucrative career as a hair stylist because he wanted to make money, he did not have a lot of other skills and could quickly learn the trade. My mother remained in nursing; the two of them worked long hours and had commutes that were often over 2 hours long. They spent 55 years together until my father died a few days before his 80th birthday. My mother passed away a few years later at age 89. I think what drew these two together was the feeling they shared of being fish out of water. We always lived in the shadow of that perspective. Around the house there was always talk of the "Old Country". My sister the talented introvert Katherine Anne Mojzsis (an accomplished fine artist) and I lived and breathed our heritage (Fig. 1.5). Neither of us knew it at the time growing up, because we just thought it was normal, but there was always the sense that we were outsiders in both America and Europe.

When I was four, we moved out of our apartment in the Bronx, the classic immigrant gateway, to literally greener pastures in a medium sized but burgeoning town called Parsippany in northern New Jersey. This place is located about 45 km west of New York City (a.k.a. *The City*, as people call it around there). In 1970, my parents bought a lovely house on a small quiet street, where



Figure 1.4

You are in the army now. Historically, many male immigrants to the United States were compelled to immediately enroll in the military. This tradition probably dates to the Revolutionary War period. Why? Citizenship, training and health care are provided to you, in exchange for your life and your time with Uncle Sam.



Figure 1.5 Living the American Dream. 1971. My sister Katherine (left) and I (right) are living products of the American Dream as children. The dream was realised by my hard working and down-to-earth immigrant parents.

they lived to the end of their days. We had a big house, big cars, big garden, big wages in a big country that was near the peak of its overall prosperity. In those days, instead of being a cash cow for authoritarians and Trickle Down economists, the middle class in America was still relatively secure and could hope to prosper. Trade unions were strong and politics could be civil, even if you disagreed over things, adults realised that differences should be tolerated not attacked all the time. For us kids, the 70s were great because neighbourhoods were bursting with children. Dogs and cats were referred to at that time as pets, not fur babies. We were skin babies. There were always some kind of shenanigans going on around town. Hordes of random children rode around on bikes in various states of disrepair

(whammy bars were a huge thing) and were eminently available to play pick up ball games, construct tree forts in the local woods, or explore the nearby rolling forested hills until dinner time. An amusing albeit vague reflection of those formative times can be found in charming flicks like *The Bad News Bears*. In that bygone era, when helicopter parents were not yet a thing and we just rode our bikes to the shopping centre whenever we felt like it, seems now irretrievably lost, at least in America. That world has been effectively replaced by asphalt and/or concrete under the banal term “development”. The normal way of getting to know one another for good or naught – that we funny primates practiced for millions of years – is steadily being substituted by small glass rectangles that everyone seems to be hunched over all the time. Symptomatic of this new reality is bad posture, bad diet, confusion about who we are as individuals, and widespread anxiety. The next time you are in a restaurant, take account of how many people are sitting at a table together and staring at their mobile phones instead of interacting.

1.1 Being Human takes Practice Interacting with other Humans

To our enormous satisfaction as kids, our town Parsippany was mentioned sometimes on television. The town has a funny name anyway and was the brunt

of several perverse *Saturday Night Live* jokes in the late 70s to early 80s, muttered by the likes of John Belushi and Laraine Newman. These weird comedy sketches went over our heads as pre-teens; I get them now.

Fortunately, for us, the parents of the kids in my social cohort cared a lot about education. Although my own parents may not have understood much of what we were learning at any given time, they absolutely expected that we would become hyper-educated. Another thing that was different is that they never thought learning was a form of liberal brainwashing. My parents got their wish, you might say, big time. Furthermore, it helped a lot for my foundation that our neighbourhood was in a good school district. For those of you who do not know, the regional quality of public education in America differs a lot from place to place. Quality strongly correlates with and indeed depends on, the level of property taxes. These can vary significantly from state to state, and even within a state. Public schools in relatively affluent areas tend to be pretty good. I am a strong advocate for affirmative action programmes to help mitigate this pervasive and perverse inequality. Many bright minds are lost because of social neglect. That should not be allowed to happen in any truly civilised society. How could we?

A talented international businessman friend of mine (the enigmatic Brian Cullen) came up with a classification scheme based on the American presidential administration in power at the time when a friendship took root. One such friendship of mine dates from 1970 at the time Richard Milhouse Nixon was 37th president of the United States. That individual, Mr. sub-sub-sub stardom himself Kevin P. Cavanaugh, is a Nixonian-era friend. He and I are still in touch, having known one another since day one of kindergarten. As six year olds, we made introductions by trying to pull each other's fingers off. Very long term connections made during my years at Brooklawn Junior High School (1977–1979) and Parsippany Hills High School (1979–1983) are Carterian (James Earl Carter) to Reaganian (Ronald Wilson Reagan) in this classification scheme. I do not seem to have any from the Fordian (Gerald Rudolph Ford, Jr.) interregnum (Fig. 1.6). The early 1980s might have been an awful time for progressive politics that clearly set the stage for the Bedtime for Bonzo buffoonery redux

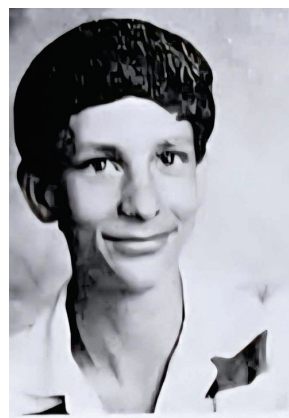


Figure 1.6

You're only thirteen, got a lot to learn. 1978. By the time I was on the cusp of entering high school in 1979, I was already convinced that I wanted to explore the universe. I also firmly believed that there was alien life out there. It was a bit later in life that I learned that there is a huge difference between belief and understanding. From Brooklawn Junior High School year book.



Figure 1.7

Dungeons and Dragons (D&D), like health food, warps your mind, 1979. Any group activity, whether sitting together in a breakout session at a workshop, or simply gathering for a cup of coffee, will nurture both your “self-esteem” and “self-efficacy”. In contrast, spending most of your time hunched over a glass rectangle or squirreled away in your office/cubicle/booth not interacting with anybody is just plain unhealthy. Get out and introduce yourself. Share what you know, because it does little good for anyone to stay locked away in your head. Fantastically, there was a moral debate going on in the mid-1980s about the negative effects of tabletop role playing games like *D&D*. Virtuous panic from some easily roused sectors always tends to be misguided. Keep in mind that populism is the search for the next and nearest outrage. New media has been getting under the skins of self-justified, self-appointed authority figures since the invention of writing (around 6000 years ago), of the printing press (ca. 1440), and the push towards widespread literacy in the 18th and 19th centuries (Crayen and Baten, 2010).

we have been experiencing lately, but they were absolutely great for independent non-commercial do it yourself (DIY) activities which shaped my young mind. Our weekends and vacation times were consumed with marathon *Traveller* and *Advanced Dungeons and Dragons (AD&D)* sessions in the company of the incomparable William D. Martin, Eric R. Bogdahn, Francis Prachthauser, Peter Conrad, Barry Conti and John Bensley. That AD&D (1st edition, mind you) is the best interactive role-playing tabletop game ever invented is a claim that anyone who has ever experienced it can tell you is unimpeachable (Fig. 1.7). The DIY mindset has shaped my life. At least you can say that this helped me with my mapping skills later. Another frequent past time in High School was taking the commuter train with other scruffy stray cats like the creative Michael S. O’Leary and the virtuoso Roman Hrab⁷ to visit the (in)famous and historic

7. <https://romanhrabstudio.com/>

CBGB-OMFUG⁸ night club for its (ir)regularly scheduled \$5/5 bands All Ages Sunday afternoon hardcore punk rock matinee shows. I credit the oracular Blaik Ripton for turning me on to that music with a cassette tape his brother the mysterious Garth Ripton put together in 1981 as a DJ at an Ohio college radio station⁹. This tape has since been digitally reconstructed by me into mpegs; email me if you wish to have a copy as it is epic. Our crappy part time jobs at Corporate McBurger, or whatever you want to call those places, included fast food flipping, house painting, landscaping, or some other poorly paid equivalent¹⁰. In any case, it still meant that we had just enough money in our pockets for train fares to Manhattan, cheap show tickets, and a stop at Ray's Pizza¹¹ for a slice with broccoli on it. We plunged ourselves completely into the world of Maximum Rock and Roll thanks in part to fake identifications that were laughable in how amateurish and obviously illegitimate they were. I am so honoured to have kept these friendships with such exceptional and talented and accomplished individuals for what is coming on half a century. In New York, the places we loved to visit like CBGB and the Rock Hotel (Ritz) on 11th Street between 3rd and 4th Avenues are both long gone, as are very many other cool venues that fell prey to rising property values in the 1990s. Despite its historic landmark status, CBGB was permanently shuttered in 2006 (Fig. 1.8). As usual, life is change.



Figure 1.8

Ode to CBGB-OMFUG. 1981. This public artwork is located at 2 Bleecker Street, Manhattan, in New York City approximately across the street from the former location of CBGB. It sports a superb dedication to the music tradition of a now lost landmark that was a tremendous musical and cultural influence in my life. One thing that underground music traditions taught me was the value of the “Do it Yourself” (DIY) mentality. I have kept that perspective with me my whole life.

8. <https://en.wikipedia.org/wiki/CBGB>

9. If memory serves, this was at Denison University, in Granville, Ohio.

10. Minimum wage was \$3.35/hour at that time.

11. The one on 27 Prince Street in Little Italy, https://en.wikipedia.org/wiki/Ray%27s_Pizza

Another thing that kind of set me apart from most of the other kids, was that I really liked school and studying and learning new things. I just needed to get past the first day of class (see below). Another thing was to overcome peer pressure from those who thought that answering the teacher's questions all the time was some form of treason for every other student in the room. Since when did it become cool to be stupid? Like, since... forever.

Every year, it was the same old drill. On the first day, each of my new teachers would recite the roster list of students' names. Then the instructor would come to mine. Without exception, they would not even try to pronounce it. Most of the time all I got was an exasperated: "Umm, Steffen M....?" and

there would be a round of laughter from the peanut gallery of feathered hair and the Jordache Look (Fig. 1.9). Even now, most of my colleagues are downright shy about it and a brave few stammer out an attempt. Please, try, I admire you for it more than you will ever know. There will never be a mistake in my book if you try. Take your pick, I have heard it all: Mojo, Mochuck, Moses, Mozitch; the inscrutable Everett Shock came up with a good one: "Moe-Jesus." That has got to be my favorite option. You are in luck, sailor!



Figure 1.9

You got the look I want to know better, 1983. I would like to meet at least one person who is happy about their high school graduation picture. It must be one of those universal truths that we laugh at old hairstyles. It is nice to remember, at least, that I once had such a nice head of hair.

The International Phonetic Alphabet (IPA) is here to help you. The IPA code for Mojzsis is Mɔːrɛɪf. You are welcome to look it up and try for yourself.¹² "There is an app for that".¹³ Some practical and lasting legacies of my international epithet are that (1) Thanks to my mother, I have citizenship in Ireland and thus a neutral non-NATO country that is still part of the EU with full privileges in the UK granted by the 1921 Anglo-Irish Treaty; (2) I am not shy about trying my hand at other languages, which is something of an unusual feature for those of my birth nation; and, (3) I have a family name that appears unpronounceable with an unusual mixture of consonants that do not seem to fit a logical sequence to those with sensitive manners.

12. <https://www.vocabulary.com/resources/ipa-pronunciation/>

13. <https://www.howtopronounce.com/stephen-mojzsis/32606809>

Here is a weird screed by some individual with the YouTube moniker @TWCOWS1 that wrote in the comments field about an online lecture I gave a few years ago for an Astrobiology conference held in Vilnius, Lithuania¹⁴:

How does this dude pronounce his last name?? It (sic) looks like someone threw a bunch of letters of the (sic) alphabet into a box, shook them, and then threw them on a table to read!!! (E)very time I see oddities like this, I thank God for the guys at Ellis Island who told these creatures to choose a pronounceable/spellable name for the new country and people they were arriving at. This guy could've gone as Mojish, case closed. But the zoo keepers in Colorado of course would let him get away with his mumbled jumbled name, and even love it, as we love the kiwis in the zoo.

Do you think he had something good to say about the actual content of the lecture? Nah. That this person ended a sentence with a preposition reveals a lot to me. What a dude!

You might be shocked (or not care at all) to learn that the name Mojzsis is not uncommon in northern Hungary (especially around the ethnic Palóc region¹⁵) for its spelling or otherwise. In some parts of the Vág (Slovak: Váh) river region¹⁶ in the part historically referred to as Felvidék (Hungarian: “the Uplands”), it turns out that there are lots of people running around with my family name. Whence came this oddity? Well, it is either derived from the old Hungarian given name Mojs who was an important early settler in the region at the time of the Magyar conquest in the 9th–10th centuries or is the Hungarian transliteration of the Slovak word for the Biblical Moses, Mojžiš. There you have it.

I will never forget the first time I heard “Mojzsis” pronounced correctly by someone who was neither a family member nor a denizen of the formerly sprawling multiethnic patchwork of lands that previously composed the Austro-Hungarian Empire. That honour is held by the late great Professor Bodo Reichenbach, my best German language instructor at Boston University. It was only very recently that I learned the fact that he was born in Breslau (now the city of Wrocław, in southwestern Poland). This must have lent him an advantage. Let me tell you I nearly fell out of my seat when he got it right the first time on the first day of class! As a matter of fact, I have a particular soft spot for people from Central Europe, which makes sense based on what I learned from the results of my 23andMe genetic test results. My genes inform me that there was a lot of love extending between the Balkans and southern Germany. Another thing I learned from this genetic test is that I have a high percentage of Neanderthal genome, which comes as a surprise to nobody.

Boston, about 380 km north and east of my hometown of Parsippany, was the first place I moved to after finishing basic (academic) training. As the principal city of New England, also nicknamed “Beantown”, Boston shaped the

14. https://youtu.be/-jMKoQ7b4Us?si=j63Qat_ayfxjba59

15. <https://en.wikipedia.org/wiki/Pal%C3%B3c>

16. <https://en.wikipedia.org/wiki/V%C3%A1h>

personal and professional trajectory of the rest of my life. It was a place with enormous diversity, which taught me to be more tolerant. It was (and is) a place of political chaos and the kind of corruption that I had only ever read about before, which taught me to be more skeptical of what comes out of somebody's mouth. Living in Boston challenged me in many ways so that I learned to be more independent (Fig. 1.10).



Figure 1.10 Professor in training. The author practicing his skills at office hours with the requisite pile of books (many of which I still own), a sport coat and tie, and assorted cultural artifacts (notice the Ethiopian iconography).

*Let me never fall into the vulgar mistake of dreaming
that I am persecuted whenever I am contradicted.*

Emerson Journals (R.W. Emerson, 1838)

2.1 An Accident Waiting to Happen (1970–1983)

Growing up hearing and consequently learning a weird mixture of Irish brogue (much like The Pogues¹⁷), and Hungarian speech patterns resembling a blend of Béla Lugosi with Anwar Sadat, meant that I talked funny as a kid. Fixing this impediment required years of speech therapy as a child. Another benefit of my upbringing was that we schlepped over to Europe every time my parents saved up enough money to visit our invariably bewildered and amused relatives. I think it was Samuel Clemens who said that travel is the best antidote to bigotry. By the time I graduated high school, I had visited eight countries. Maybe that does not mean a lot to you my dear worldly reader but allow me to remind you that statistics show that even nowadays only about a quarter (23 %) of American citizens have ever visited a foreign country! According to the Pew Research Centre, a curious fact is that this percentage is smaller than the fraction of those who sport (generally very ugly) tattoos (~32 %). Many forget that the USA is large (Fig. 2.1). My first airplane travel was in July 1972. In those days, people still got dressed up before taking a flight and smoked in the cabin. At that time, we also saw the last people walking on the Moon and of course we kids all thought it would be a natural part of our collective future to live off-planet (Fig. 2.2). We were so wrong about that and have only very recently sent humans past the Moon. The priorities of the country shifted dramatically back towards oligarchy. Do you really think we will colonise Mars any time soon? We have not even colonised Antarctica, and all you have to do is open the window there when you need fresh air. We are far from being an interplanetary species and unless we can better manage ignorance, we will long remain so.

Year in year out in my early life, we would leave sunny, hot and humid July conditions (34 °C) at JFK/New York airport, and arrive to chilly (16 °C) Shannon, Ireland. It rained daily, consistently and infuriatingly. Compounding the air sickness and jetlag, we all came down with bronchitis in our summer shorts, thin socks with tennis shoes, and colourful but uninsulated tee shirts. These travels were repeated every 24 months by staggering between Dublin and Budapest, with the diminishing risk of pneumonia thanks (in retrospect) mostly to trial and error. In my later youth, when I became a bit more sentient (I believe I began

17. https://en.wikipedia.org/wiki/The_Pogues

to actually think at age 15, which Jung would argue is precocious), I was able to gaze in some kind of cogent awe at the stupendous Rocky Mountains (Fig. 2.3), day dream while wandering amongst crumbling medieval castles, crawl around in slimy caves and bat infested old mining adits, slide down montane glaciers, glamp under the stars, navigate a canoe through whitewater or gleefully paddle along the sea coast (Fig. 2.4), and tramp through tick infested hills and dales from dawn to dusk.

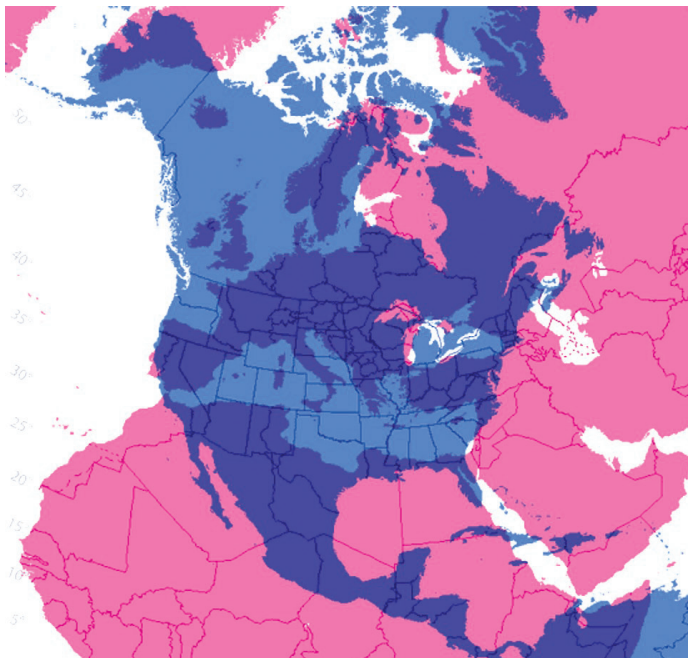


Figure 2.1

Defending American “indifference”. My fellow Americans are roundly criticised for being ignorant of geography, languages, and the world in general. They are not “cosmopolitans”. Remember, this is a country of 340 million people (3rd after India and China in numbers), with every possible human group imaginable (or not). We Americans are inmates of our geography just like everyone else. I argue that *Homo sapiens* are mostly regionally focused with – anecdotally – an average interest radius of ~50 km. For someone in Iowa (can you point to it on the map above?) that knowledge corresponds to being able to name, at best, maybe ten nearby States. For someone in Portugal, that means 10 countries. Hence, the degree of geographic literacy may be equivalent. But the language skills lag. Overlain, the United States equivalently stretches from the Caspian Sea to Morocco. It is well established that people everywhere are generally not very interested in anything that is beyond their geographic radius of knowledge. You, dear readers, are obviously not like this. From <https://imgur.com/50mXW>.



Figure 2.2

Lunar best. Meanwhile, elsewhere in the Solar System. The last people to set foot on the Moon up to now were the Apollo 17 astronauts Eugene Cernan and Harrison “Jack” Schmitt in 1972. Jack took this picture in the Taurus–Littrow valley with the Sculptured Hills in the background. I have had the great honour and pleasure of making Jack’s acquaintance. Photo from NASA/Harrison H. Schmitt.

Few pleasures compare to the end of the day with dinner and rowdy conversation around a campfire. Hunger is the best seasoning so that even a granola bar can be a tiny festive pleasure.

These cumulative experiences, good and maybe not so good, crafted my persona. So much so that I was determined that my work and hobbies should be one and the same. No complaints. Science, and especially geology, always intrigued me and this was my life’s calling. I absolutely knew that I was born to be a professor. People in the stratosphere of research and academia know that making it in science boils down to a game of survival. My famous colleagues William F. “Bill” Bottke and Harold F. “Hal” Levison will tell you that the last ones standing are the ones who are so obviously stubborn that they ignored all practical advice to give up and move on to something else. We are still here because we stuck around. I stayed around and too bad for you, now you are stuck with me! Ha! The point made by Ralph Waldo Emerson at the top of this section is succinct. Even when contradicted by someone, I try not to take it personally. The problem with modern discourse is that far too many of us mistake disagreement with oppression and persecution. We must work at being civil.



Figure 2.3

Rocky heights. In 1981, with a group of fellow high school students, I visited the western United States for the first time. Here I am (50 % leg, it seems) at the entrance to Death Canyon and the Hurricane Pass at the Grand Tetons, Wyoming. Little did I know that I would end up moving to this region twenty years later.

In sixth grade in 1977 at Eastlake Elementary School my natural science teacher was Mr. Heerwagen. I am not sure if I ever learned his first name. The guy was famous for walking around school assemblies with a bullhorn at full blast simultaneously and preposterously demanding silence. There is no question in my mind that he was the first truly inspirational schoolteacher I had. I remember his nickname for me was “Mister Lucky”. We got along great, and it is no accident that I became a geologist. Like many great teachers, he will never know just how important his influence was. I hope I can track him down to send him a copy of this *GP*. Later, in high school, I was lucky with the instructors I had, especially Messrs. Duval (Physics I and II) and Picariello (Earth Science I and II). The inscrutable August (Gus) “Pic” Picariello, was a trained Earth Scientist (Fig. 2.5). Two astonishing things I learned from Gus were (1) the albite-anorthite phase diagram is a lot more than meets the eye, and (2) the 1978 gross out schlock film *Animal House* was a fair rendition of his own experiences as a college student. Now there was something I could look forward to in College. If you have not seen it, the film is about a group of miscreants who revolt against an overbearing administration in their fight for the right to goof off. Yes, it is pure fiction, but some of the antics I witnessed later as a college student were not so far afield from that shown in this and other genre flicks.



Figure 2.4

Traveller. By the time I was 16, my parents felt comfortable enough for me to venture out on my own, even far out of state. One of these early trips, in 1981, was to the south-eastern coast of Maine from Boothbay Harbor up to Mount Desert Island. Photo credit: B. Conti.

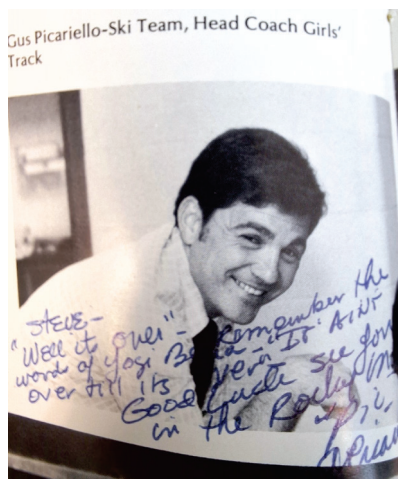


Figure 2.5

Early Earth Science. Between 1981 and 1983, I had the honour to take geology classes with "Gus" Picariello in high school. This man helped me decide that studying Earth was my life's calling. Photo credit: Parsippany Hills High School, 1983 yearbook.

An email message from the legendary Mr. Pic dated September 2016 is a classic: *Stephen, All is well with me, a little older but none the wiser. I am very proud to see that at least one more of my former students has become a success in their field. It does this old man good to see that... Keep trying to motivate those kids, I don't imagine it has become any easier.*

From my Physics I and II instructor in high school, the knowledgeable and friendly Mr. Adrien Duvel, I learned to make sense of celestial motions, relativity and a gentle touch of quantum mechanics. What I was reading about in *Scientific American* was starting to make sense! What a great education I was getting thanks to my parents' exorbitant property taxes. I was so turned on to science at this formative time of my life around 1980, especially in geology and astronomy, that it was evident that this would be a central part of my intellectual life beyond history and philosophy. These teachers in high school were vitally important to my development.

Right now, I should turn to the person who perhaps is the most responsible for setting me on the road to research. I mention this even if his effect was relatively remote. Although we hardly spoke to one another in person, I want to share with you my impressions of the uniquely gifted Carl Sagan. Anyone who met the guy can tell you that he had gravitas. You know what I mean. It is when a certain person walks into a room and everyone just knows that they are there and there is a certain buzz. I have experienced this sensation with the likes of Linus Pauling, Christian De Duve, Lynn Margulis, Claude Allègre, Didier Queloz, Albert Eschenmoser, Leslie Orgel, Francis Crick, J. Craig Venter, Gerald J. Wasserburg, Steven Hawking and Stanley Miller to name a few. Back to Sagan. Around 1978, my little UFO fan club friend Alan Dean Kline and I got together and wrote Sagan a letter to his Cornell University address. We wanted to share our thoughts about alien life with him. He wrote us back! I have no idea where that letter is now, nor do I remember what naïve thoughts we shared with him, but I fondly recollect that the response was appropriately gracious. Later, I got to know Carl somewhat in the mid-1990s when I was still a graduate student; he even cited my doctoral work in his last publications. Besides my father's firm encouragement to stick with it and become a scientist (instead of a medieval historian), it was Sagan's writings and his work in the PBS television show *Cosmos* that gave me the inspiration to learn about the general topic of Origins. It became a lifelong obsession for me to learn more about what makes everything tick.

When it was time for me to choose a college there were four key criteria. It had to (1) be somewhere outside of New Jersey, (2) be within a city that boasted a vibrant music scene, (3) admit me, and (4) have a programme in geology and astronomy, vaguely in planetary science and/or something that I read about in *Omni* magazine called bioastronomy. I chose to attend Boston University (BU) because it chose me (I was admitted), and it was far enough away that people spoke with a funny accent. They even have different words for soda and hoagies/subs (tonic and grinders), it had an exciting music scene, and there was a planetary science programme at BU. As such, it fit my criteria perfectly. My second episode of growing up took place in Boston.

2.2 Bioastronomy and Planetary Biology – The Boston Years with Detours (1983–1992)

After a summer spent backpacking across Europe in 1983, alone, because my friend Robin Roxanne Kline decided in the end to cancel, I moved up to Boston. I found myself in a Back Bay brownstone apartment building on Buswell Street, owned by BU. This was Earth House, a dormitory style residence with a strong focus on the environment and environmental issues, recycling and veganism. Imagine a haven of long-haired hirsute yoginis with the background din of Grateful Dead bootleg tapes on continuous loop. Dig? The place stank of

patchouli oil and cheap incense. On the very first day of Rhetoric class, I befriended the brilliant Paul Fyvolent (Fig. 2.6), who is now a Berlin based media activist, artist, writer, musician and community organism.¹⁸ Breaking with tradition, he and I did not attempt to pry off each other's fingers at that first meeting. At the university, I thought I would begin with a major in Astrophysics, then about 4 microseconds later, reason prevailed and switched to Geology (Fig. 2.7). Long term Reaganian friendships from those days were forged in mutual admiration at diverse academic capabilities and insights. For example, it was around 1984 over some vegetarian meals that I learned of the "Method of loci" (Yates, 1966) from the gifted author Michael Marano. Mike was the 1998 laureate of the Bram Stoker Award¹⁹ from the Horror Writers Foundation. As the youngest of six children, he will be pleased to point out to anyone that his fascination with horror literature is self-evident. Mike, and the mystical Keith Shallcross Schuerholz spent long hours discussing together with me mail order joke/bogus religions like the Church of the SubGenius (Fig. 2.8) and the elaborate Cthulhu Mythos of New England native and horror fiction writer Howard Philipps Lovecraft. In those days (1985–1988) I worked at a place called Newbury Comics which is mostly a record store; it made me some kind of a hero in my friendship circle because at the time it was considered the coolest location in Boston to hang out in, much less work there (Fig. 2.9). There is a special place in my heart for New England's weird horror sub-culture. Related to that, the social life I was cultivating was getting a bit out of hand. Thankfully, I was always a bit too nerdy on the inside to ever stray very far into the Arts, although it seems that most of my friendships are with Life Artists Extraordinaire such as the inexplicable Jason Pickleman a.k.a. Ivan Thorpe (Fig. 2.9).



Figure 2.6

When it is time to change, you have got to re-arrange. Late 1980s. Along with co-adventurers Krisztina Micsinai (right) and Paul Fyvolent (a.k.a. "Fyvvie", at my right wearing hat), I spent some time in Central Europe witnessing the waning days of the Soviet Empire. Photo credit: Mark Richards.

18. <http://www.xlterrestrials.org>

19. <https://www.thebramstokerawards.com/first-novel/marano-michael/>



Figure 2.7

Sidewalk surfing in Boston. 1986. I landed a part-time job at the most popular record shop in Boston. Thanks to my time working there, I got to see and hear a lot of underground music and have abundant stories to tell. Photo credit: Lisa Bancroft.



Figure 2.8

Subgenii, 1985. Behind Charlie's Cheeseburger restaurant, near Kenmore Square, Boston. From left to right: Keith Schuerholz, Sue Gardner (née Lewandowski), Michael Marano (with hat) and the author lurking in the background. Photo credit: Keith Schuerholz.



Figure 2.9

Always a few years ahead of the times, 1986. The author with his pal the late great Jason Pickleman, preparing for another elegant evening cocktail party at our apartment in Kenmore Square, Boston. For some length of time, I did not know Jason's real name. He would introduce himself to everybody with the *Nom de guerre* "Ivan Thorpe". Our shared apartment was located directly above an Indian restaurant ("India Quality"), which gave it a special charm as an aromatic Bachelor Pad. Since then, the actions of so called "urban renewal" have erased much of this gritty history.

My erudite palaeontology professor at BU, maestro Paul K. "PK" Strother eventually took me under his wing and assured me that the idea that the biosphere interacts with the geosphere and *vice versa* is valid and testable. It was Strother who introduced me to the amazing Lynn Margulis. Those two taught a class together called Planetary Biology. Wow! It was like having Carl Sagan's *Cosmos* programme in real life. I had absolutely no idea at the time, but Lynn and Carl co-habited from 1957–1964. Even after I found this out years later (I always seem to be the last to know such things), it never crossed my mind to view these two in any other way except as, separately, magnificent scientists. I admire people based on their individual character and achievements. Paul Strother is probably best known for his work on the classification of the cryptospores, which are used to track the origin and evolution of the land plants. He is still going strong in his sprawling laboratory at the Weston Observatory of Boston College. Paul and his brilliant botanist and science educator wife Cecilia Lenk are true intellectuals. He introduced me to a lot of people, including the famous Australian geologist Roger Buick (Fig. 2.10).



Figure 2.10 Enjoying another dingo's breakfast, 2001. For about a decade in the early 2000s, I had continued run ins with the famous geologist Roger Buick of the University of Washington in Seattle (black hat in photo). Here we are in 2001 with Mark Harrison (red cap and bandana) and Ariel Anbar (left margin of photo). Let it be said that there is simply nothing like having a good look at an outcrop with such fine people.

Nobody who has ever spent any time with Roger will be at all surprised to learn that he and I first crossed paths at a dive bar. I am pretty sure that it was Father's Too near Fenway Park in winter 1986. I was introduced to a man in a leather jacket who looked for all like some wayward a member of a biker gang or Alice Cooper's doppelganger. Be that as it may, almost immediately we clicked. Proof positive of this connection was expressed in how I was immediately roped into that time honoured pastime of Australians – binge drinking – with the challenge of \$20 (USD) that I could not consume a whole pitcher of Narragansett Lager beer in one gulp. What an introduction to gastrointestinal distress the following morning.²⁰ In any event, I won the bet thanks almost entirely to my twenty one year old constitution. Do not ever ask me to do such things now (Fig. 2.11).

Paul and Cecilia were also classmates at Harvard with the world renowned palaeobiologist Andrew “Andy” Knoll. Roger was a visiting scholar with Andy and at a symposium later that same year across the Charles River at Harvard he not only remembered me but further inquired “...how do they let somebody like you over on this side of the river?” I never bothered to follow up with him if he was still sore about losing that drinking competition.

20. In New England, this affliction is affectionately dubbed “The Nasty Narries”.



Figure 2.11

Don't hate us 'cuz we're beautiful. Michael Maiden (left) and the author, as the subjects of a spontaneous photo shoot in the apartment of the unparalleled duo of outrageousness: Lisa Bancroft and Sheryl Joy Seitz (often in the company of Laura Picuzzo). In the background existed an entire wall inexplicably decorated with aluminium foil and a collection of pictures of famous Bauhaus artists including László Moholy-Nagy and Anni Albers. At this time and place, and at this stage of life, we felt like young gods.

Lynn Margulis was an intellectual giant and was an important influence in my early professional life (Fig. 2.12). She is probably best known for using microbiological evidence to substantiate what is known as Endosymbiosis Theory. This is the idea that the cells of organisms like us (Eukaryotes) originate from fusion of certain “Monera” or Archaea and Bacteria (formerly termed Prokaryotes). Earlier in the last century this concept was proposed by the Russian botanist Konstantin Mereschkowsky (1905), and Lynn championed the theory that eukaryotic cell organelles such as mitochondria which produce energy (adenosine triphosphate; ATP) for the cell from respiration, and chloroplasts that perform photosynthesis in plants and algae, are descended from formerly free living prokaryotes. These formerly free living entities were at some point in the past engulfed by a larger cell in the process of endosymbiosis.²¹ Every one of you should know about this fact, because without such an evolutionary step, none of us multi-cellular creatures would be here.

21. Greek: ἔνδον endon “within”, σύν syn “together” and βίωσις biosis “living”.



Figure 2.12

Force of Nature. Lynn Margulis challenged the dominant neo-Darwinian view of evolution, emphasising the role of symbiosis and horizontal gene transfer in evolutionary innovation. It is thanks to her that I understand that beneath our superficial differences as macroscopic animals, plants and fungi, we are all ultimately communities of bacteria. Another thing that stuck with me was that she pointed out the fallacy of the exclusive role of random mutation in evolution thanks to her focus on the evidence from symbiosis. Photo credit: P.K. Strother.

It was much later that I learned just how much she (and many others) helped me in my career from behind the scenes. In my undergraduate studies, besides “Planetary Biology”, I got really turned on to mineralogy and petrology. My first geology professor Mohammed “Ed” Gheith was a classmate of the famous mineralogist Tibor Zoltai the person who determined the structure of coesite (an ultra-high pressure SiO_2 polymorph). Ed introduced me to symmetry operations and in doing so, inadvertently to the work of the favourite graphic artist of all those artsy types stumbling around Amsterdam, Maurits Cornelis Escher. My optical mineralogy, igneous and metamorphic petrology classes were taught by Allan H. Treiman, the noted planetary materials specialist, who has spent most of his career at the Lunar and Planetary Institute (LPI) in Houston. Mineralogy and petrology are interesting, but in my opinion to really understand these fields requires a very good grasp of physical inorganic chemistry.

In my undergraduate days I had convinced myself that there was no real reason for me to study chemistry. How wrong was I! It was a big mistake on my part that I had to work hard to fix later. My professional focus in those years was elsewhere, and I took a sidetrack to geomorphology (the study of landforms). Thanks to Allan’s guidance, I applied for and was admitted to the LPI Internship program in the summer of 1987, well before he moved there after

leaving BU. While at LPI, I worked with the planetary geophysicist Bruce G. Bills. This was my first exposure to a real research network. It was exhilarating! In those days, LPI was directed by the world famous Kevin Burke, with whom I was to meet up again ten years later at UCLA in a completely different context. The cohort of interns was outstanding. Among those stars for the summer that I was there are the leading experimental petrologist Kevin Righter, the planetary physicist Kimberly L. Dow and the STEM educator Aurora Pun. Many other famous people besides in planetary sciences have come through the LPI Internship program, including Laurie Leshin, Jonathan Lunine and David Kring. My summer internship project with Bruce was to map palaeolake shorelines in Nevada using aerial photography and satellite imagery, and to use these as palaeo-tilt meters to understand a little more about the Basin and Range in the western US. It was only the second time I visited the West. I had no idea I would live there in years to come.

My summer internship work at LPI got the attention of the Egyptian-American planetary geologist Farouk El-Baz, who had recently been recruited to lead the new Center for Remote Sensing at BU. Actually, a funny story behind that is how my long time friends Sheryl Joy Seitz and Lisa Bancroft happened to be visiting one of Farouk's daughters at his home and off handedly mentioned to him that their "weird science friend, Steve" had just returned from being a NASA intern in Texas. El-Baz is an interesting man! He was part of the Apollo Program and played a key role in deciding where the first astronauts should land on the Moon. Farouk approached me about a project with him at BU, which turned into a Master's thesis completed in 1992 on aspects of the geomorphology of the Western Desert of Egypt. The desert has always fascinated me, but in the back of my mind there was always something compelling about blending fieldwork with quantitative analysis that I was not getting from working on digital rocks from satellite imagery. It is not that remote sensing is uninteresting (it certainly is), it is just that I was inoculated by that Planetary Biology bug from Lynn Margulis. After long consideration, I firmly decided that I wanted to do something with that. At one point, I wrote to the one and only Christopher P. McKay at NASA Ames Research Center to ask to work on Mars problems, because what he works on is very cool. Chris brilliantly suggested that I apply to the NASA Planetary Biology Internship (PBI) programme. The goal of the PBI internship was to support graduate students to work on projects related in one way or another to NASA's planetary biology mission. There was a menu of different NASA Centers and universities around the United States that participated in it. Chris had been a PBI intern years before with the incomparable USGS biogeochemist Eleanor "Norrie" Ibarra Robbins (we meet Norrie again, later in this booklet). He thought this NASA sponsored programme would be a good springboard for me. It was. Regrettably, however, the PBI programme no longer exists. Its *oeuvre* seems to have been replaced by the (now gone) NASA Astrobiology Institute, which in 2015 was replaced with, what? Some kind of network named NExSS, that I know very little about.

Most biogeochemistry and planetary research initiatives these days are highly specific and do not seem to take in the big picture anymore. In any event, I was about to discover through the PBI experience that my destiny was to take a deep dive into physical inorganic and organic chemistry, blended with solid state physics. Before doing so, however, there was another musical adventure for me to take a deep dive into (Fig. 2.13). By this time, my drumming skills were getting pretty good, and my band *The Third Wheel*²² were getting gigs around the Boston area (unlike a previous incarnation, *The Bedspins* with the clever Gordon Schanz on lead guitar and vocals, along with Andrew K. Morse (rhythm) and Steve Dejesus on bass guitar). It was certainly fun and good for my ego given the excellent and beautiful and creative fans, but I had other plans in mind. Friendships forged in those days turned out to last a lifetime. An important person is the polyhistor Caitlin Aileen Osmond (née West) who inspired me to not neglect my artistic and literary side. Many things bound me to Boston, but my plans involved leaving the USA for a while.



Figure 2.13

Fan club. Valentine's Day 1989. My family has always been musical. Growing up, I learned to read music and play piano, trombone, trumpet, flute and drums. That is me in the back drumming for *The Third Wheel*, upstairs at The Rat club in Kenmore Square, Boston. Brian Cullen had his debut performance as our lead singer, with Eric R. Bogdahn on bass guitar (forefront). Not visible are David A. Petersen (lead guitar) and Paul K. Strother (rhythm guitar). This live performance was memorable because not only did we debut as the headliners, but the club called the police on us owing to the fact that we were too loud even for them. A lo-fi digitised recording of this historical musical event by those Bluesy Roughhousers is available online. Photo credit: David Petersen.

22. <http://lagado.us/muddy-river-records-third-wheel/>

In between graduate studies at Boston University and my new life that was to come in southern California, I saw an historic opportunity in the summer of 1989. The Soviet Empire collapsed in Central and Eastern Europe. It was time to get side tracked, again, but for personal growth reasons more than anything else. The revolutions of 1989 led to the demise of most so-called Communist governments in what was dubbed the Eastern Bloc during the Cold War era. As children, we always lived with the thought that the Cold War could lead to annihilation, which fed into the narrative of some of my favourite apocalyptic films like *Planet of the Apes*, *Damnation Alley*, *Dr. Strangelove* and *Mad Max*. Good times (except for the movie *Zardoz* with Sean Connery, nobody can make sense of that movie). What culminated in the demise of the Soviet Union, however, were protests that began in Poland in 1980. My planetary biologist friend the polyglot and polymath Barbara Kremer at the Polish Academy of Sciences, reminded me that it was actually the establishment of the *Solidarność* (Solidarity) independent trade union movement that paved the way for the changes in Hungary in 1989. The border gate between Austria and Hungary was opened and, soon after, the Eastern Bloc disintegrated. The Berlin Wall fell in November 1989. I took a leave of absence from my BU studies and arrived in Budapest in early June 1990 to spend time in this newly emergent democracy, teach English, improve my Hungarian language skills, play music and go on adventures (Fig.2.14). After sowing my wild oats, living and loving the life of an artist/vagabond and deeply connecting with my heritage, it was time for the sleeper to awaken. It was time to break out. It was time that I found my niche. That was to happen in San Diego.



Figure 2.14

Go East Youngster, 1989–1990. The turn of the 80s to the 90s was a time of unexpected changes. I would say that most people at that time never thought that the Cold War would end so quickly with the abrupt collapse of the socialist systems in Europe. Here is the author at a social event in Budapest involving interspecies communication. Photo credit: Mark Richards.

2.3 Exobiology and Astrobiology – The San Diego Years (1992–1997)

Since the 1960s, the quantitative search for life in the universe was something called Bioastronomy. In fact, there was a course taught by Michael Papagiannis at Boston University that was a big motivation for me to try my hand at planetary science, there. This term is now seldom used, even defunct, and by the time I began my doctoral research at the University of California in San Diego (UCSD) and the Scripps Institution of Oceanography (SIO) in La Jolla, the discipline had been re-named Exobiology. In 1992 NASA established the NSCORT (NASA Specialized Center for Research and Training) in Exobiology in La Jolla to train “native exobiologists”. The general features of the NSCORT were research in cosmic organic, prebiotic, primitive biological, and advanced chemistry. Hot topics

such as the formation of planets, organic chemistry in meteorites and comets, prebiotic chemistry and the search for evidence of the first life were all within the foci of this new centre.

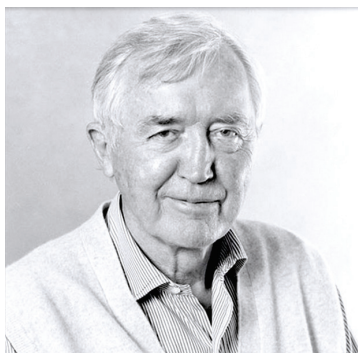


Figure 2.15

Idea man. Gustaf Arrhenius provided a welcoming laboratory environment for me to pursue important questions. While we did not see eye to eye on many things, especially later on, he challenged me to not confine chemistry merely to Earthly pursuits, but to extend what we know from geochemistry to the cosmos. It seemed to me that not only was Gustaf universally kind, but it appeared that he knew everyone. Thanks to him and his many decades of experience (he arrived at SIO in the early 1950s), I became acquainted with an incredible network of very smart people. Photo credit: Scripps Institution of Oceanography at UC San Diego.

It took a lot of effort on my part to make up for my near lack of chemistry knowledge. My greatest motivating factor for learning something new and difficult is to recognise its usefulness in accomplishing a goal. Sponsored by the Planetary Biology Internship and with support of the NASA in Exobiology, I arrived in La Jolla, California in June 1992 to start work with the supergeneralist Gustaf Arrhenius at SIO (Fig. 2.15). This incredible mentor, a true Renaissance Man, introduced me not only to Stanley Miller (the proclaimed at any rate, father of prebiotic chemistry) but also to such immortals in the field as Juan Oro and Leslie Orgel. Before I get to talking about Gustaf, I should mention an unsung hero of that time, the authoritative and stylish Robert Tschirgi, who was always ready to lend me sage professional advice when I most needed it in his quiet manner. The students and

postdocs that I learned prebiotic chemistry and RNA chemistry with are the notable Ramanarayanan “Ram” Krishnamurthy, Stefan Pitsch, Jason Dworkin, Anthony D. “Tony” Keefe and Daniel “Danny” Glover. By the way, if the name Gustaf Arrhenius sounds familiar to you, it is because his grandfather Svante Arrhenius won the chemistry Nobel Prize in 1903. You probably ran into the Arrhenius equation a few times in your geochemistry career. It is the formula used to determine the dependence on temperature of a chemical reaction rate. Another thing was that Gustaf’s maternal grandfather was the renowned Arctic/Antarctic explorer Otto Nordenskjöld. Gustaf’s elegant wife Jenny Arrhenius was the daughter of the Hungarian chemist Hevesy György Károly (George von Hevesy), another Nobel laureate in chemistry (1943). In 1922, de Hevesy co-discovered (with Dirk Coster) the element hafnium ($_{72}\text{Hf}$). The pressure was on. You might say that I had to learn to become a chemist and solid state physicist in the shadow of those with an immaculate pedigree. It was motivating for me to plunge into chemistry with everything I had.

While NASA has its Exobiology Program, the scientific field that studies the origins, early evolution, distribution and future of life on Earth and beyond, is referred to as Astrobiology. One often hears that the central pillar of Astrobiology is the concept of habitability and of habitable environments. In the back of my mind, alarm bells go off at volume 11 whenever someone starts going on about “habitability”. Please indulge me as I share with you my thoughts on this convoluted topic.

2.4 Habitability and Incoherence

The habitability concept enjoys widespread use to the point of near-unchallenged devotion (*e.g.*, Dehant *et al.*, 2019; Kopparapu *et al.*, 2013; Westall *et al.*, 2023). But the whole idea is rather vague. To be frank, “habitability” is a derived notion that is scientifically equivocal (Harrison and Lenardic 2022; Harrison, 2023). Although great progress is being made to figure out planet formation by constructing better forward dynamical models to reproduce what we see in the attributes of planets, we cannot do the same for theoretical habitats and the search for biomarkers on planets around other stars. This drawback arises from the fact that we know nothing about extraterrestrial life that would allow us to judge what is “habitable” (Lenardic *et al.*, 2023). Habitability is not the same as the origin of life.

Let me put it this way: what is habitable for Earth life mostly concerns what is good for the dominant life forms on our planet, microbes. Maybe habitability really refers to the case where some (extremophile) microbes could theoretically be transplanted somewhere else and be expected to survive in a place that was hitherto uninhabited. It seems probable that this experiment has already been passively tried thanks to contaminated spacecraft sent to Mars and Venus that are laden with Earth life (Rummel, 2019). The subsurface of Mars is habitable in theory just by using the above generalist definition, but there is no generally

accepted evidence that it ever had life (*cf.* McKay *et al.*, 1996). This is also true for the small, albeit theoretical, volume of favourable pressure-temperature-liquid water conditions that exist within the upper cloud decks of Venus (Schulze-Makuch *et al.*, 2004; Greaves *et al.*, 2021). Life exclusively confined to a lifecycle in clouds faces immense chemical and physical obstacles (Hallsworth *et al.*, 2021).

You can argue with me all you want about it, but I would say that it is difficult to make the claim that a planet or moon or any place else other than Earth is habitable if we still lack a satisfactory definition for life (Cleland and Chyba, 2002; Trifonov, 2011). It is well beyond the time now to turn the habitability idea around into more useful directions.

Southern California in the early to mid-1990s was fantastic. I was part of the NSCORT in Exobiology. What a life! Mr. Lucky Strikes again! This gave me the freedom to pursue many different subjects beyond geochemistry while being pleasantly ensconced at a famous research institute. The environment at Scripps in those days was intense; it celebrated academic achievement and attracted students who worked hard and played harder. My office was 5 metres from the beach with the floor often covered with the beach sand we tracked in, to the unending annoyance of the custodians. What a place! I sat across the hall from the atmospheric chemist and author of the Keeling Curve, Charles “Dave” Keeling. Others in my immediate neighbourhood were the famous geophysicist David Sandwell and the physicist Devendra Lal. My professors at Scripps included the famed marine chemists Wolfgang “Wolf” Berger, Ralph Keeling (son of Dave Keeling), Miriam Kastner, Andrew Dickson and Joris Gieskes. Workdays began early (5am) with lots of long yoga poses, three espressos and a big breakfast, before taking the bike down to my office in Ritter Hall overlooking the beautiful Pacific Ocean. Surfboards, swim shorts and sandy feet were common sights in the hallways, where we frequently worked well into the night. It was only ever after about 3pm that I would see Harman and Valerie Craig, when I wandered downstairs to meet up with Thomas Pettke for a chat over coffee at the Snackropolis Bufe (along with the ground squirrels). That the bike ride up the hill from Scripps Institution of Oceanography is steep (21 % grade!) meant that I built strong legs on my way to attend classes on the main campus of the University of California San Diego with the chemists Kurt Marti, John Wheeler, Mark H. Thiemens, John Weare and the solid state physicists M. Lea Rudee and Kenneth Vecchio. It always seemed that I was the lone geologist up there, ensconced in courses like Statistical Thermodynamics. The student rosters were filled with very clever people from chemical engineering, chemical physics and organic chemistry. My life was on an orderly trajectory now. The new order imparted in me a better understanding of the life process in general, and this in turn led me to seriously question what we think we know. There are lots of people who knock Astrobiology as a science without data. I think that is unfair. Here are my sentiments on the matter.

2.5 Life Controls Its Own Complexity

The entropy – or measure of disorderliness – of any isolated part of the universe does not decrease with time. Although widely stated, life is not really an example of a net decrease in entropy but can instead be viewed as an example of a net increase in complexity. The thermodynamic reason why there is life at all on Earth is because:

- (1) Our planet is geologically active so that rocks can melt, and
- (2) The Sun is a hot source in a cold background.

Disequilibrium energy from geochemical gradients in rocks and fluids in the crust, or from the light of the Sun, is low entropy energy (*cf.* von Stockar and Liu, 1999). What is meant by that is that this energy can do useful work. Living processes degrade that energy, raise its entropy and send it back to the universe radiatively as lower energy photons. The key feature of life is that it is locally ordered, and it imparts order. It is not about decreasing entropy, which is often used by creationists as an attack.

Local order. The chaotic nature of things can be represented by taking an unbroken egg, breaking it and making scrambled eggs. How do you make it back into the pristine form of an unbroken egg? The answer of course is that you feed it to a chicken, and it will manufacture for you another unbroken egg. We are faced with the terrible problem of understanding the origin of life. What can impart local order? Life begets life, except at the very beginning. There was a time in geological history before a mind bogglingly complex biological machine like a chicken could unscramble an egg simply by making a new one.

Prebiotic chemistry had to contend with the issue that is frequently overlooked by workers in the field, namely that accumulation of change with time in a system tends to an overall increase in complexity. Sounds good, right? That is, until all there is just noise (= “junk”). It is difficult to justify that useful complexity is somehow inevitable when it was in fact needed for the origin of life. Practical data for inheritance that was somehow helpful for the first biological systems had to have originated from natural chemical systems to modulate chemistry before the products became uselessly complex (Neveu *et al.*, 2013). A recurring dilemma is that natural organic chemical reaction networks constructed to mimic the origins of life that are left unattended by living chemists eventually subsume into uselessly complex mixtures. To prebiotic synthetic organic chemists, this is the so-called “asphalt paradox” (Shapiro, 2007; Benner, 2014).

Before life on Earth, runaway “junk” complexity from wild organic chemical reactions in innumerable natural reactors was somehow managed abiotically. After life learned to control complexity, it could be alive because this kind of matter goes on doing something for longer than we expect it to be able to do (Schrödinger, 1944). Complexity originates from enmeshed parts/things

that are connected in some way. The more unique parts that exist in a system, the more connections there are between the parts, and the more complex the system becomes.

Local complexity can appear and propagate. It is easy to produce a complex solution and hard to use it. Simple solutions are hard to produce, but easy to use (Weinberg, 1975). Connections between things typically grow with the number of nodes. If two systems heading towards complexity are not mutually exclusive, in that they form separately but at some later time can encounter one another, then adding even one node means that there is a high chance that complexity will grow faster than in a linear progression (Fig. 2.16a). Staying at one level of abstraction may make complexity avoidable, but as has been shown many times already in prebiotic chemical experiments, when reactions are allowed to go on without human intervention, they ultimately return useless complexity. The only way to reduce complexity is to break the system apart into smaller units, and by removing or refusing linkage of units (Fig. 2.16b). Otherwise, other techniques to deal with the problem of runaway complexity manage it, they do not reduce it. A common management strategy is called coupling. Tight coupling is where two or more components are closely connected to one another and depend on each other to function properly. Loose coupling finds that the components are less dependent on each other and can operate more independently (Fig. 2.16c). In any of these management scenarios, there is a role for separately isolating components as in encapsulation. Encapsulation, such as with a cell, is a management strategy that existed at the origin of life, and which effectively and controllably isolates the different components or groups of different components. To avoid becoming asphalt, early steps in biology must have managed complexity in synthesis including proto-metabolism. Separation *via* encapsulation into a protocell accomplishes this control of complexity (an idea that was presented beautifully by Tibor Gánti in 1997).

The origins of life community has plenty of dirty laundry, perhaps an inordinate amount of it. A popular but unverified idea that is unjustifiably rife is that life will arise when the right conditions are met. It should be emphasised that the first steps towards operative life are the most difficult (Russell *et al.*, 2014). Not least of all among these first steps is the prebiotic origin of information for inheritance. Considering the various points above, it makes sense to turn our attention to what we know of the geologic environments before life. The problem of complexity in the origin of life might (perhaps) be that order in biology originated from the regular patterns of charge on naturally ordered solids like green rust which have general compositions that vary from $\text{Fe}_2(\text{OH})_5$ (Trolard *et al.*, 1997) to $(\text{Fe}^{2+}(1-x) \text{Fe}^{3+}_x - (\text{OH})_2)_x + (x/n\text{An} - m/n\text{H}_2\text{O})_x^-$ (Génin *et al.*, 2006), where A can be substituted by the anions OH^- , Cl^- , CO_3^{2-} or SO_4^{2-} (Arrhenius *et al.*, 1997). This is a mineral that deserves all the recent attention it garners in prebiotic chemistry.

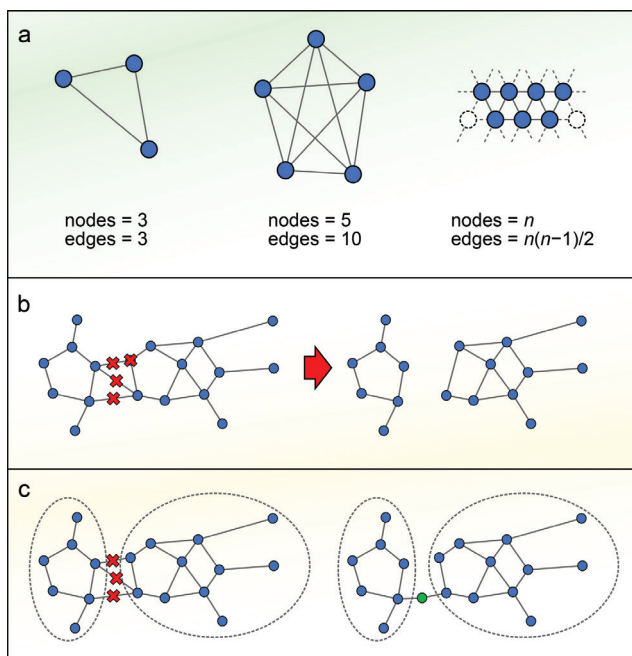


Figure 2.16

(a) It is hard to find proper abstraction by taking away or removing characteristics from something to reduce it to a set of essential characteristics. A proper prebiotic chemical network abstraction requires the construction of many wrong ones before something productive emerges. Errors are allowable, as long as the errors are either benign or, better yet, useful. The natural progress of abstraction in a chemical network can then lead to the “right” solution towards a biological system. The lengthy pathway towards the origin of life (Szostak, 2012) required that subsequent steps were able to implement procreative solutions. (b) To reduce complexity, we can decrease the number of connections (edges in terms of graphs). In practice, this means that some features are deleted or refused, which narrows down the scope. (c) To manage complexity means tight or loose coupling to maintain contacts between partitioned nodes, which can be accomplished by encapsulation. Narrowing down types is a way to decrease cardinality and increase efficacy. A connection can be weakened by introducing an additional intermediate node (green). By isolating and hiding some nodes, no unexpected connections will arise that could prevent the network from proceeding toward more useful chemistry.

2.6 What was before Darwinian Evolution?

These days, there are not many people who had any direct acquaintance with either Stanley Miller, Juan Oro, James Ferris or Leslie Orgel beyond textbooks, or video documentaries. I am deeply fortunate to have known each of them

rather well (Fig. 2.17). Stanley Miller was a quiet man, with an intense albeit perpetually tired gaze that looked out through thick old fashioned (what we use to call “Coke bottle”) glasses. He possessed a quick wit and boundless curiosity and was always kind and courteous to me and eager to talk about the interface between geology and origins of life. There was something about him that I could not quite put my finger on. Something antiquated, like a character from the old 1950s television show *I Love Lucy* or *The Honeymooners*. Miller would share with us stories of his Ph.D. advisor, the renowned Harold Urey, who won the Nobel Prize in Chemistry (1934) for the discovery of deuterium, and with his time interacting with the pioneer Soviet origins theorist Aleksander Oparin. Harold Urey’s students did a lot, not least of which was to create isotope geochemistry. I already mentioned Harmon Craig and I should also mention Gerald Wasserburg, another New Jersey guy and WW2 veteran who was also long time (>60 years) friends of my Ph.D. supervisor Arrhenius. Although Wasserburg was always courteous to me, this was not true for everybody he interacted with. A lot of folks outright feared the man. Others of this ilk were also Mildred Cohn, and Urey’s postdoctoral researchers Samuel Epstein and Robert N. Clayton. I never met Cohn, but I knew the rest. In Europe, the field of geochemistry was formulated by V.M. Goldschmidt working in Norway at the University of Oslo. Many forget that the Finnish chemists Kalervo Rankama and Thure Sahama also published (along with Goldschmidt) a book titled *Geochemistry* in the early 1950s. In that time, Arthur Holmes in Britain showed us how to determine the age of the Earth. All these people, now CO₂ and water and some mineral salts, were giants who set the stage in the mid- to late-20th century for everything we do from cosmochemistry to environmental geochemistry. For our field of science, they were our greatest generation.



Figure 2.17

Legend. January 2002, at the Gordon Research Conference on the Origin of Life was the last time I saw Stanley Miller (to my left) before his passing in 2007. Photo credit: K. Nealson.

Text Box 2.1 – The Father of Prebiotic Chemistry

Back around 1995, I attended a course taught by Stanley Miller at UCSD called Chemical Evolution. One day he stood in front of the class and, in typically demure fashion proclaimed: “The origin of life is the origin of Darwinian evolution”. This made me think of something I had learned a few years before from Lynn Margulis when she shared with us the work of Dobzhansky (1973) and his famous quote: “Nothing in biology makes sense except in light of evolution.” After a bit of thought, I came up with a plausible corollary to that statement, that: “The origin of evolution is the origin of information”. My professional bias informs me that the crustal platforms of rocky planets, like Earth (and possibly Mars) and terrestrial-type exoplanets, provide this ultimate informational template. Perhaps you agree with me? Yet, to understand the propensity for a biosphere to exist, we need to understand planets and to understand planets, we need to study minerals, rocks and stars in an integrative way. I come to this later, when I introduce geoastronomy.

At this time, I wish to share with you the following statement:

*Nothing in the study of planets makes sense
except in light of the galactic chemical evolution of the elements.*

Evolution connotes developmental changes in and of a system over time. This change can arise from intrinsic or extrinsic factors, or both. Accumulation of evolutionary change has the potential to lead to an overall increase in complexity of the system. In biology, if we consider the origin of Darwinian evolution as equivalent to the origin of life (e.g., Neveu *et al.*, 2013), its inception necessitates information storage that is sustained with propagation. Data in biology emanate from genetics as chemical inheritance transmitted *via* the ancestor to descendent relationship in a lineage. This does not violate Cellular Theory, a central tenet to biology and an integral part of the definition of life, which asserts that all living cells must come from pre-existing cells (e.g., Virchow, 1859). The operative term “Cell” implies to us an already fully functional biological entity as we understand it and does not imply origin.

Information in biology is in the form of molecular inheritance transmitted *via* the ancestor to descendent relationship within a lineage. Lineages in biology take the form of a tangled web when considering ancient modes such as plasticity of the early genome (e.g., Vasas *et al.*, 2012). The pervasive role of horizontal gene transfer over the long history of life adds to this entanglement (Griffith, 1928; Daubin and Szöllösi, 2016). The parameter space we are interested in should be defined, but it is difficult to do so solely through analysis of extant biology owing to biochemical and structural changes incurred in the intervening 4+ Gyr of evolution. Darwinism necessitates data storage and propagation with errors using biochemistry, exclusively. The natural origin of information goes together with the origin of life in that it has to follow physical laws (Küppers, 1990). This argument does not violate Cell Theory, which holds that all living cells come from pre-existing cells (Virchow, 1855), nor is it at odds with horizontal gene transfer well documented to occur between life forms including viruses (Koonin and Krupovic, 2018; Irwin *et al.*, 2022). The conflict, however, is with the claim that the evolution of life began without biochemistry *via* intermediaries that were never and shall never be living, such as clays (Cairns-Smith and Hartman, 1986) or prebiotic metabolic cycles (e.g., Tessera, 2018).

A fully functional biological entity is that which is encapsulated, separate from yet in contact with the ambient environment, has metabolism, and carries heritable information to make more of itself (Gánti, 1997). A chemical system that does

not possess these traits together – in the same place and at the same time in the same thing – can probably be said to fall short as a biological entity. A conspicuous drawback to the Darwinism as Life approach, however, is that the doctrine does not explicitly shed light on how life began. Biological evolution accounts only for what is already alive (e.g., Peretó *et al.*, 2009). Therefore, the casual term “cell” implies an already fully functional biological entity and should be used with caution.

Information is different from complexity. It is that which is conveyed or represented by a particular arrangement or sequence of data that arises from the breaking of invariant repetition in otherwise symmetrical order, or what is termed “symmetry breaking” (Collier *et al.*, 1996; Ellerman, 2015). A natural source for the first information for life comes from the basic constituents of the rocky crusts of planets. Minerals.

2.6.1 Mineral and Chemical Evolution Came before Darwinism

During the course of my research, I had had occasion to examine not only simple compounds, salts and oxides, but also a great number of minerals.

Treatise on Radioactivity (Marie Salomea Skłodowska Curie, 1910)

Minerals are naturally occurring structurally ordered crystalline solids with intrinsic symmetry. Minerals comprise most natural solids, including those that make up rocky crust. At temperatures above absolute zero, crystalline solids always contain irregular structures which break from ideal symmetry. Different distortions (*i.e.* defects) in the periodic charged arrangement of atoms exist with respect to an ideal crystalline lattice in three dimensions and are present in certain concentrations (or densities) at any given time (Fig. 2.18). This characteristic makes them the best natural candidates for conveying information to the organic chemical products of prebiotic reactions. Adsorption to mineral and colloid (including glass) surfaces of prebiotically relevant molecules in aqueous solution was modulated by the intrinsic electronic structure of the adsorbent, which effectively imparts electronic and structural changes to the adsorbed ions (e.g., Hiemstra and Van Riemsdijk, 1996). Information transfer and induction scenarios, as well as active catalysis on natural solid surfaces, are an exciting parameter space in the chemical physics of proto-RNAs (e.g., Jerome *et al.*, 2022; Šponer *et al.*, 2023) and proto-cells (Köksal *et al.*, 2022). It therefore makes sense that terrestrial-type planetary crusts composed of minerals are the ultimate templates for abiotic chemistry to transition into living biochemistry (e.g., Hazen *et al.*, 2008).

After 30 years of working on this topic, I am confident that the point I made above applies universally — wherever life has the potential to emerge in our universe.

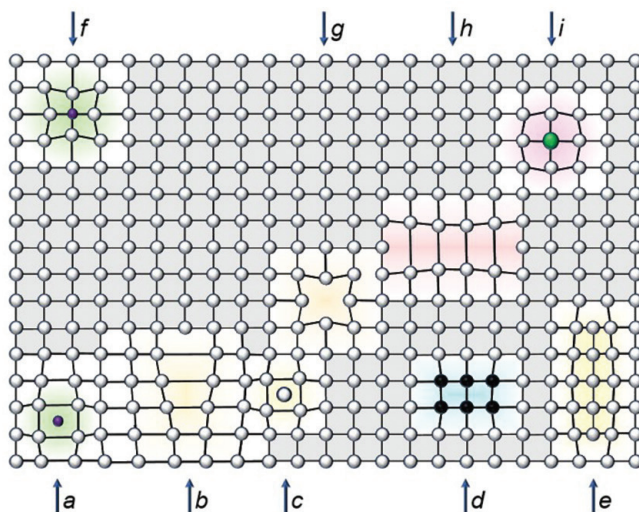


Figure 2.18

Natural crystal defect structures. For simplicity, different structures are represented here in a 2 D primitive cubic grid with thicker lines representative of lattice strain; **(a)** foreign atom as an interstitial impurity, **(b)** dislocation, or stage displacement (*sic*), **(c)** intermediate grid atom, or self-interstitial defect, **(d)** cluster of impurity atoms, **(e)** extrinsic dislocation loop defined as an intermediate grid atom type (*i.e.* local surplus of matter), **(f)** small substitutional impurity leading to lattice contraction, **(g)** vacancy with local lattice contraction and electron density, **(h)** intrinsic dislocation loop, **(i)** large substitutional impurity. Modified from Föll and Kolbesen (1976).

2.7 The Transition from the Non-Living to the Living

Abiogenesis, the transition from non-living to the living occurred on the Hadean Earth over 4 billion years ago. Some have argued that life on this planet was inevitable (DeDuve, 2005; Morowitz and Smith, 2006). It is important to keep in mind that we know next to nothing about the apparent suitability of an environment for life's origin and so we do not know whether biological chemistry is necessarily inevitable even for early Earth. Taking a clue from water hosted abiotic organic chemistry documented for asteroidal meteorites and comets from our own Solar System – for which no evidence exists for an operative biological process (Chyba, 1990; Abramov and Mojzsis, 2011; *cf.* Greenberg and Mendoza-Gomez, 1992; Oba *et al.*, 2023) – we can argue that there are a near infinite number of habitats in all of the galaxies present now and since a few billion years after the start of the Universe, where proto-biochemical pathways arose. Some of these, over some span of time, could reach a certain threshold level that

is very nearly representational of life without ever having achieved an operative biological entity (Marshall *et al.*, 2021). Thus, casual use of the term “inevitable” is as problematic as “habitable” and “habitability” (e.g., Southam *et al.*, 2015). Habitability, much like its congener, “biomarker”, is incoherent. We must better understand the nature of the earliest surface that provided for the origin of life before we can argue whether (or not) any such environments are (or were) suitable. Another thing, who is to say there ever was an “instant” in the origin of life? The knowledgeable Michael J. Russell is an authoritative voice on such matters (Russell *et al.*, 2013 and references therein).

In Volume 13, Number 2 of *Geochemical Perspectives*, my long time collaborator, friend and mentor T. Mark Harrison shared his history of chemofossils and our work together on them in deep time (Harrison, 2024). Here is my opportunity to provide my separate but complementary view of the whole matter.

My first major publication, which made the cover of *Nature* magazine no less (!) and a News and Views piece by John M. Hayes, had a curious beginning that was unrelated to geology and more related to medical mineralogy (e.g., Sahai, 2007). Here is how it happened. It is well known that the activity of life currently plays a leading role in governing the surface geochemical reservoirs of the bioessential elements: C, N, O, S and P. I do not like the term biogenic to refer to these elements, because that is a misuse of the word! These elements are not made by life; they are used by life. But for how long have these bioessential (or, biophilic) elements been worked over by living things? Working with Arrhenius and his research group, it was quickly impressed on me that the unique chemistry of phosphate (PO_4^{3-}) provides a chemical link between the organic (carbon) world and the inorganic (phosphorus) world in the origin of life. This is discussed in another argument, below, but it is worth noting that the participation of phosphate in living systems is so fundamental that it almost certainly rests at the origin of life itself (Brady *et al.*, 2022). Organophosphate chemistry governs growth and reproduction of all life, and what is important for this argument, becomes concentrated in P-rich organic matter accumulated in sediments. Experiments performed by Benjamin Gedulin as a Ph.D. student in Arrhenius’ laboratory in the early 1990s showed that the formation of authigenic basic calcium phosphate (apatite; $\text{Ca}_5(\text{PO}_4)_3(\text{OH})$) is inhibited by Mg^{2+} in aqueous solution over a range of salt content and pH. He found that instead of basic calcium phosphate, other phosphate minerals with structural magnesium precipitate instead. After doing a bit of research in the phosphate chemistry literature (which can be rather esoteric), I was able to confirm that others had observed similar outcomes. Previous authors hardly ever made much of this observation, nor related it much to the geologic record, except for some prescient French literature (Lucas and Prévôt, 1984, 1985).

In 1992–1993, it dawned on me that based on the work of Gedulin and Arrhenius, the association of apatite in sedimentary precipitates like banded iron formations could be used as a biomarker mineral. It may be that banded

iron formations can only be made by life (Kappler *et al.*, 2005). Much remains to be done to test that hypothesis. In any case, here is the background to the idea that phosphate minerals are biomarkers and the P-containing minerals were instrumental to the origin of life. This idea led me in some fruitful directions.

2.7.1 Life chose Phosphate for Good Reasons

Phosphate, and phosphorus have historically *not* been a central topic of geochemists interested in the origin of life. That cohort seems much more concerned with CHON chemistry. Phosphate minerals are poorly soluble, they do not do much of anything with organic chemicals in solution, and the element has just one isotope (^{31}P) which makes it boring for isotope geochemists unless one studies the oxygen isotopes in the phosphate group, like our esteemed colleague Ruth E. Blake (*e.g.*, Blake *et al.*, 2001). As a matter of fact, phosphate anions (ortho-, oligo-, organo-) are a basic constituent of all life; condensed phosphate (P-O-P) provides the structural backbone of RNA and DNA, as well as the energetic bonds in the currency molecule of metabolism: adenosine triphosphate (ATP). There is an importance in phosphate. Numerous functions of phosphate in biochemistry were summarised by Westheimer (1987). There are other molecules that are isoelectronic or that otherwise vaguely resemble phosphate in functionality. Discussions elucidating vanadate and arsenate as alternatives were previously also presented by Davis (1958).

For an ion to form an ester linkage between at least two molecules and still protect the compound against surrounding nucleophiles by use of a remaining charge, the linking ion must be at least trivalent, leaving little choice other than phosphate. With its localised negative charge, phosphate is especially effective at stabilising esters against hydrolysis which acts as the major decomposition reaction in aqueous environments. In principle, vanadate (VO_4^{3-}) and arsenate (AsO_4^{3-}) could be acceptable substitutes. Yet, compared to phosphate these are at very low crustal abundances (except locally) and they are more susceptible to reduction. Both vanadium and arsenic are at ~2 ppb concentration in seawater, V is about 100 ppm in continental crust, 266 ppm on average in basalt, and likewise As is 1.7 ppm and 1.5 ppm, respectively. Compare this with 750–1200 ppm for P in igneous rocks such as apatite. While vanadiferous magnetite is known as an ore mineral, there are no dominantly vanadium magmatic minerals; V minerals tend to be secondary and formed at low temperatures at the surface. Arsenic forms the common sulfide arsenopyrite (FeAsS). If you want to read more about the stability of phosphates of different compositions, you are more than welcome to have a look at Mojzsis and Arrhenius (1998) in which we wrote about using phosphates as a biomarker on Mars, or Mojzsis *et al.* (1999) which probes more deeply the prebiotic context of phosphate that is now being strongly directed by the excellent work of, for example, Matthew “Matt” Pasek and colleagues (*e.g.*, Pasek, 2008).

I wonder why more people are not working on the problem of a marker that shows life is not present? It would be useful to make the distinction between Biomarkers *vs.* Anti-biomarkers.

2.7.2 Anti-Biomarkers

Biominerals are naturally occurring crystalline solids which form in or close to biological organisms due to physiological mediation. To make sense of the interaction between abiotic phosphate mineral formation, and phosphatic biomineralisation, knowledge of the solubilities is crucial as is laboratory experiments in sterile aqueous media. In the phosphate system, $M^{2+}(\text{OH})_2 - \text{H}_3\text{PO}_4 - \text{H}_2$ in natural waters, the concentration and relative proportions of available divalent metals (M^{2+}) in solution, mainly Ca^{2+} , Fe^{2+} and Mg^{2+} , must be considered because they have a strong effect on the solution behaviour of phosphates. River water and seawater compositions are relevant end members. The ionic radius of Mg^{2+} (0.066 nm) is less than that of Ca^{2+} (0.099 nm), and Mg^{2+} readily substitutes into M^{2+} sites in crystal structures and *decreases* solubility owing to lattice contraction. In modern seawater, Mg/Ca ranges from about 4 to 6, whereas river water is generally <0.45 . Experiments show that within this large range of Mg/Ca , phosphate precipitates with the broad composition of a mineral that most of you have probably never heard of, whitlockite (Fron del, 1941; Hayek and Newesley, 1958). The general formula of whitlockite is rather different from that of apatite and is part of a family of minerals that include the common meteoritic phosphate merrillite ($\text{Ca}_9\text{NaMg}(\text{PO}_4)_7$). According to Keppler (1968), it is $\text{Ca}_9(\text{Ca}_{1-x}\text{Mg}_x)(\text{HPO}_4)(\text{PO}_4)_6$, with $0 \leq x \leq 1$ (e.g., Gopal *et al.*, 1974). What sets whitlockite apart from all the other phosphates, is not only that it is the phosphate phase composition which precipitates out of natural waters, but that the two PO_4^{3-} groups are structurally connected by a bridging proton in the unit cell that allows it to condense into polyphosphates at heating by a de-protonation. The significance of that for prebiotic chemistry is discussed elsewhere (Mojzsis *et al.*, 1999). What matters is that we might expect the protonated calcium magnesium phosphate – whitlockite – to precipitate out in natural waters where life is not present. If this interpretation is correct, then the mineral whitlockite in sedimentary chemical precipitates like banded iron formations, carbonates and cherts could serve as an *anti*-biomarker. I think ideas centred around anti-biomarkers deserve further tests.

2.8 Akilia, Thirty Years On

The role of phosphate in the origin of life led me to think about its function in the first organisms since phosphate linkages act as the structural backbone to RNA (ribonucleic acid) and DNA (deoxyribonucleic acid), both of which serve as information molecules to all living things.

The catalytic function of RNA as a solution to the problem of the co-origin of genetic information molecules has led to the concept of an RNA World (*e.g.*, Gilbert, 1986). This RNA World is thought to have existed prior to the emergence of the contemporary DNA + Peptide World of all life, which existed before the last universal common ancestors (LUCA). It has long been known from phylogenetic studies of gene families that the LUCA (Woese, 1998) gave rise to the three domains of life (Fig. 1.29). Further, the root of the universal phylogenetic tree is probably bacterial (*e.g.*, Pace, 1997; Moody *et al.*, 2024). If we accept the RNA World concept, then we have to accept the role of phosphate in the origin of life.

The following chemical arguments arise from the RNA World Hypothesis of T. Cech and S. Altman and its successful outcomes (Bartel and Szostak, 1993; Joyce and Orgel, 1993):

- 1) The likelihood that life could have started out as a self-replicating system using a very different molecular basis than phosphate, such as chemical compounds containing a sulfhydryl group (-SH), or vanadates, and arsenates is probably nearly zero.
- 2) Condensed phosphates (ATP) are used for energy storage in all life (Pinna *et al.*, 2022).

There is recent work which favours the idea that eukaryotes are embedded in the archaea (*cf.* Fig. 2.19). Thus, the 3 domains could be replaced with a 2 domain tree (Hug *et al.*, 2016; Mahendrarajah *et al.*, 2023).

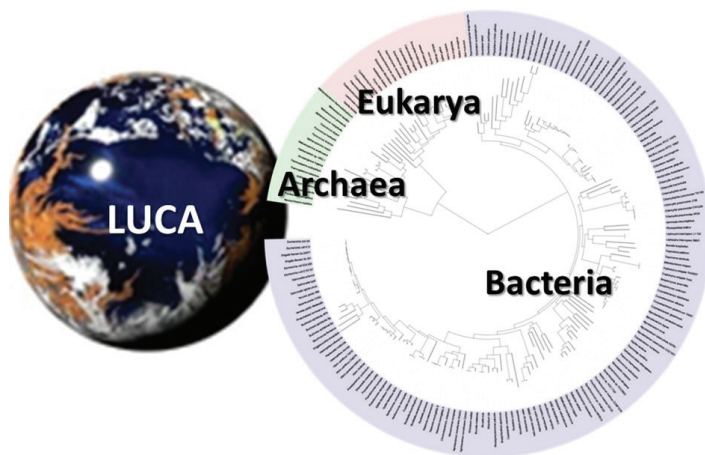


Figure 2.19

The Last Universal Common Ancestors (LUCA). Ultimately, DNA appeared as the stable biological information centre with error correction, but still with mutation and recombination. The crystallisation of the genome of life occurred at the time of the universal ancestor cells (a.k.a. LUCA). Recent analysis has shown that this community of organisms existed on Earth already in the Hadean eon. Phylogenetic Tree graphic generated from <https://itol.embl.de/>.

These observations link the participation of phosphate not just to early life, but also to its origin. It is implausible that at some point after the inception of life that the most fundamental biochemistry “switched horses mid-stream” over to phosphate. If phosphate has played a role in life from the beginning, and phosphate minerals are of low solubility, I would expect authigenic sedimentary phosphate precipitates to appear in association with life’s remains in sediments. The theory was that if life was not present, the prevailing phosphate phase might be whitlockite, and without any associated carbonaceous material. With this in mind, I began to explore how far back we could go with phosphate when I sought to reach “the bottom of the sedimentary pile” (Hayes, 1996).

Up until the mid-1990s, just about everyone thought that the oldest sedimentary rocks were to be found within the rocks of the Isua Supracrustal Belt in West Greenland (Black, 1971). As mentioned already, some great and creative geologists, like my friend the late legendary Warren B. Hamilton, suggested that there could **not** be rocks older than about 3.8 Ga because of asteroid bombardments that destroyed the crust (Hamilton, 2019). The evidence for a late heavy bombardment was always on weak foundations. As we shall see later and which was also discussed in a previous volume in this series, it turns out that there was no reason at all that older rocks could not exist on Earth. As usual, it took a lot of convincing to get people to abandon the old paradigm even if it was based on little or no data. As Mark Harrison and Adrian Lenardic have pointed out²³, hearsays and mythologies have unfortunately been a heavy handed guide to our thinking of Deep Time, especially with such topics as plate tectonics. I believe very strongly that we must break out of this pattern, or continue such paths of willful ignorance at peril to our field of science. Mind you, I too have fallen into the trap of believing in proclamations made by self-proclaimed “Early Earth Experts” based on no information. The late heavy bombardment was one of these claims that could not stand up to the data.

In my early search for the oldest rocks of sedimentary protolith, I began with those that are not so messed up by metamorphism. The oldest relatively unmetamorphosed sediments are found in the 3200–3500 Ma (*e.g.*, Pidgeon, 1978) Warrawoona Group of the Pilbara Craton, Western Australia. Another place is the Onverwacht Group of South Africa and Eswatini (*e.g.*, Barley *et al.*, 1979; DiMarco and Lowe, 1989). These sediments were originally deposited mostly in a marine setting, with abundant and well preserved different sedimentary structures, some of which represent shallow water and subaerial facies. Observations from these rocks have been taken to mean that mild oceanic conditions existed at least 3.5 billion years ago. Structures resembling stromatolites – microbially mediated sedimentary structures – and very rare microfossils are attested in both the South African and Western Australian rocks (*e.g.*, Awramik *et al.*, 1983).

23. <https://www.elementsmagazine.org/triple-point/>

Before leaving Boston University in the summer of 1992, I reached out to the ideas-woman and biogeologist Norrie Robbins (who shared a connection to P.K. Strother through the famous Al Traverse) to ask her for some samples of Isua banded iron formations (BIFs). She very enthusiastically wrote back to me. Norrie sent me a package of numerous rocks she had acquired from the paternal Peter W.U. Appel at the Grønlands Geologiske Undersøgelse (Geological Survey of Greenland; now called GEUS) along with a reprint of her paper with data on these same samples (Robbins and Ilerall, 1991). This was great! I could hit the ground running with my project. By around mid-1993 I was busy making thin sections of many different chemical sedimentary precipitates of different ages from throughout the Archean, looking for phosphates. It was in 1994 that the breakthrough happened. Almost as soon as I looked at thin sections of these various BIFs from Isua, as well as from samples of West Pilbara BIFs on loan in late 1994 from the Japanese field geochemist Kenichiro Sugitani, I noticed that apatite grains in these rocks sometimes had carbonaceous material associated with them. There was never another phosphate phase in any of these rocks (*cf.* the unproven anti-biomarker mineral whitlockite was absent, as indeed it is very rare on Earth). Many of the apatites looked like they had inclusions and/or coatings of carbonaceous material in transmitted light microscopy. Then I tried something that the legendary Devendra Lal suggested: A light etching with dilute nitric acid could be used to remove the phosphates. When I did that, I could see that the residues at the bottom of the etch pits were sometimes littered with carbonaceous material.

This got me thinking: “Were there any rocks of sedimentary origin, preferably chemical sedimentary origin, like BIFs which formed as precipitates on the ancient seafloor, that could be older than the *ca.* 3.8 Ga rocks of the Isua belt?” Talk about timing! By early 1996, I seemed to have the answer to this question fall on my lap. A research group at the Australian National University (ANU) in Canberra, led by the well-known Archean field geologist/geochronologist Allen Phillip Nutman had been working in West Greenland since the late 1970s. In a paper published in the journal *Precambrian Research*, he and a host of authors including Vickie C. Bennet, Clark R.L. Friend and the incomparable Victor “Vic” McGregor published a big review paper that re-defined the Eoarchean terrane of southern West Greenland as the Itsaq Gneiss Complex, with many samples that had U-Pb zircon geochronology performed on them by the ANU Sensitive High Mass Resolution Ion MicroProbe (SHRIMP). In that manuscript (Nutman *et al.*, 1996), on page 5, Table 2, there was the following line of text under the title *Chronology of the Itsaq Gneiss Complex*:

Supracrustal rocks older than 3870 Ma, Akilia and nearby islands

After picking my jaw up from the floor with the understanding that this was more than just a clue that even older rocks of sedimentary protolith exist than those at Isua, I wrote an email (this was in 1995!) to Dr. Nutman at ANU asking about the samples. He replied positively! Yes, he wrote, I could have small splits of the rock. After a month or so, a small bag of sand arrived in mailbox.

When I requested the actual rock sample – as opposed to pretty sand – in a follow up message, the Akilia rock arrived in my mailbox in San Diego about a month later. I immediately got to work on it. There is no question that this rock was partially affected by silica mobility so that there are some strongly recrystallised parts and a few areas that are less so (Fig. 2.20). In the finer grained areas, I found the same association of apatite with carbonaceous material that I noted



Figure 2.20

Akilia quartz-pyroxene rocks. This is what the actual field exposure of the Akilia rocks looks like. This area is located about 30 km south of Nuuk in southern West Greenland. Finely and coarsely alternating bands of magnetite, amphiboles and pyroxenes (black + green) and quartz (white) are evident. These rocks are innocuous looking, but cause some to lose 10 points of IQ on contact. (Note hammer for scale).

in my younger samples. It was time to find a way to test if these could be biological remains. I knew about the pioneering work of the amazing Manfred Schidlowski on carbon isotopic evidence for life in the past 3.8 billion years (Schidlowski, 1988), but this was a whole new challenge. The carbonaceous features I saw associated with the apatite grains in all of the BIFs I examined, including the Akilias, were small. It would require a new kind of analysis technique to interrogate them, and preferably one that could be done *in situ* to preserve petrologic relationships. For a perspective on how this unfolded, I invite you to read what Mark Harrison remembers from those thrilling days.²⁴

Akilia²⁵ is a rather large but uninhabited island found in the southern Faeringhavn terrane of the Itsaq Gneiss Complex off the coast of southern West Greenland. It is part of an archipelago of islands in the eastern part of the Davis Strait about 30 km south of the town of Nuuk that has beautiful outcrop exposures. These islands include Angissorssuaq where Peter D. Kinny sampled a banded tonalitic gneiss (GGU 110999) that he reported (Kinny, 1986) with a U-Pb zircon age of 3820 Ma. Up to around the mid-1990s, this was the oldest rock in Greenland,

24. *Geochemical Perspectives*, vol. 13, no. 2, p. 281–282.

25. <https://en.wikipedia.org/wiki/Akilia>

and it still garners a lot of interest. Of course, there are people who still argue over the ages of these rocks, but this has settled down in the last few years. I come back to this, shortly.

In the meantime, remember what I wrote about being stubborn and not giving up? This advice really matters in “Early Earth” studies. Harmon Craig used to say “For every geochemist, there is an equal and opposite geochemist.” Say what you want about him, and he may have been an unfriendly character towards everyone (Note: he and his wife Valarie were always very kind to me), he was certainly direct and kept us all honest. He did not suffer fools, ever.

2.8.1 Why Carbon Isotopes?

A lot of people in the geochemical community seem to just take it for granted that the $^{13}\text{C}/^{12}\text{C}$ value of carbonaceous materials can be used as a reliable biomarker. For the oldest rocks that are all recrystallised and do not preserve any original sedimentary structures, *chemofossils* such as isotopic signatures, rather than morpho-fossils in the form of small fossil shapes, are the only resort to finding past evidence of life. There was controversy about this as a biosignature from the beginning of organic geochemistry. For a nice recent review of the various arguments concerning the isotopic evolution of carbon, I direct you to the paper by Zeichner *et al.* (2024). How does it work? Organisms that make their own food, termed autotrophs, have metabolisms that tend to discriminate against the odd stable isotope ^{13}C in the fixation of inorganic carbon (e.g., atmospheric CO_2 , $\delta^{13}\text{C} = -7\text{‰}$; marine bicarbonate, $\delta^{13}\text{C} = 0\text{‰}$; non-marine waters, $\delta^{13}\text{C} = -5\text{‰}$). The first observations of the isotopic fractionation of $^{13}\text{C}/^{12}\text{C}$ by organisms (plants) were made by the Swedish geochemist Wickman (1952) and immediately countered (and contradicted as a biomarker) by Harmon Craig (1953, 1954). Parallel work on the same problem was also carried out by Baertschi (1953), but that is often forgotten, unfortunately; all of these authors observed that modern C3 plants had a relatively constant $\delta^{13}\text{C}$ value of -27‰ , which is different from the grasses and plants of the C4 type, which are slightly enriched in ^{13}C relative to C3 plants and autotrophic microbiota. Residues (*i.e.* carbonaceous materials) left behind by autotrophs carry this carbon isotopic signature, which is quite different from abiotic/inorganic carbon ($\delta^{13}\text{C} = 0$ to -11‰ or so). The history of using carbon residues as a biomarker in ancient rocks goes surprisingly far back in history, at least to the ruminations of the founder of geology, James Hutton in the 18th century. Hutton specifically noted that fossils (including organic matter) were what remained of life from long ago. The principal source of organic matter to ancient sediments is from the waste products, secretions and physical structures of the dead remains from both auto- and heterotrophic organisms. This organic material is composed mostly of carbohydrates, proteins and lipids, which vary in abundance depending on the organism (Egon and Degens, 1967). Of these key components to sediments, lipids are most resistant to decomposition in the sedimentary medium (pH, UV, thermal effects) or biochemical breakdown (microbial activity including

enzymes). This is because lipids are rich in C-C bonds, which are difficult to cleave. Bacteria are up to 10 % dry weight, lipid (Romankevich, 1979), which is a good example of generic bioorganic carbon that ends up in sediments. Differences in the isotopic composition of individual organic compounds, such as the lipids, create a modified signal of the original bulk organism after burial. It is noteworthy that the relative enrichment of ^{12}C by 0.2–0.3 % (note: percent) in the preferentially preserved lipid fraction is what is stored as a chemofossil.

Any carbonaceous material contained in a rock older than about 3.5 Ga or so should also be graphitised because every rock older than this has been strongly metamorphosed. That is to say that every one of the oldest rocks which I know about reached metamorphic conditions at some time or another during residence time in the crust that variably crystalline graphite is all that remains from previous “organic matter”. **This is not true for all old rocks**, only those older than about 3.5 Ga. There are some 3.3 Ga rocks from the Barberton region in South Africa that are minimally metamorphosed and contain non-graphitic carbon. The origin of crystalline graphite in sedimentary organic matter was reviewed by Grew (1974) and Landis (1971). I like original references, and so should you! It is never bad to cite the original work! This is one of those best practice exercises that unfortunately have become increasingly rare because either it is hard to track down the original reference (the “Elsevier Effect” as my friend Francis Albarède reminds us), or the attitude is that “old” means “not relevant anymore”. For example, I have attended many Goldschmidt Conference talks by junior scientists that blissfully repeat work done decades ago. It pays to dig deeper in your read of the literature before you start spinning your wheels and have someone like me raise a hand to ask you about it. Be prepared.

The point that Manfred Schidlowski and others have made over the past fifty years or so, and that I agree with, is that the overwhelmingly dominant process giving rise to the formation of graphite in the crust is the transformation and graphitisation of bioorganic matter. That is not to say that there are no inorganic/non-biological sources of graphite. The abiotic origin of graphite vein deposits was proposed based on carbon isotope data for epigenetic graphite in Sri Lanka (Weis *et al.*, 1981) and New Hampshire (Duke and Rumble, 1986), as well as graphitic particles associated with seafloor hydrothermal vents (Jedwab and Boulegue, 1984). These graphite particles tend to be isotopically heavy (relatively enriched in ^{13}C) compared to those of biological origin, in accordance with their abiotic origin possibly from carbonate reduction reactions ($\delta^{13}\text{C} = -5$ to -7 ‰; Deines and Gold, 1973).

Unfortunately, there is so much polemic debate over the nature of the earliest records of life. Such is the case that the whole field concerning the origin of life in general and any suggested traces of emergent biology has been harmed. Remember my quote from Harmon Craig about geochemists? Researchers (and reviewers of papers) working on the Origin of Life can be far more aggressive than any geochemist.

According to Vic McGregor, the famous geologist who lived in the town of Atammik on the shores of the Davis Strait about 75 km north of the Greenland capital Nuuk, the Greenlandic (Kallaalisut) name “Akilia” was given to the island because it means “across the way/on the other side”. I have never verified this statement, but it does appear that Akilia is an important place name root word in Greenlandic. Vic, along with the storied Brian Mason (McGregor and Mason, 1977) and William “Bill” Griffin (Griffin *et al.*, 1980) had sampled Akilia and several other islands, including Qilangarsuit and Innersuartuut, and reported geochemical and metamorphic field petrology observations. As described in detail in Mark Harrison’s issue of *GP*, we measured the carbon isotopic compositions of tiny graphitic inclusions in the Akilia, Isua and West Australian rocks and published the work in *Nature* magazine (Mojzsis *et al.*, 1996).

For those of you curious about my take on the firestorm of controversy that my publication from my Ph.D. thesis of 28 years ago created, you are now in for a treat. I will break down for you the arguments and counterarguments as I see them. Sure, this is inherently biased but let it be said that I have not spent my career chasing challenges to my doctoral work. I would encourage you to look at the published work and come to your own conclusions. How about we review the evolution of the so-called “Akilia controversy” as so eloquently put by Whitehouse *et al.* (2009)? Writing this now motivates me to compose a 30th Anniversary paper on the discovery of the Akilia rocks (*i.e.* 1996–2026). It is worth debating evidence of the earliest life. Keep an eye out for that. Check out this quote from one of the flock of papers written to refute the Akilia work. What I find amazing is that the editors of *Precambrian Research* allowed this tone to reach the printed page.

*The possibility that any trace of early Archean life that may have existed in southwest Akilia surviving these multiple episodes of intense ductile deformation... appears **miraculous**. Yet, such a **miracle** was claimed by Mojzsis *et al.* (1996) and received worldwide publicity.*

J.S. Myers and J.L. Crowley (2000)

Go figure. Numerous controversies erupted since the publication of part of my thesis in Mojzsis *et al.* (1996). It seems that the root cause of the whole controversy about whether pre-3.83 Ga rocks from Akilia and *ca.* 3.8 Ga rocks from Isua – both in West Greenland – could contain evidence of early life stems from the **pernicious conflation of belief versus understanding**.

2.8.2 Tearing down Old Buildings²⁶

From the start the objections over Akilia were fuelled by the idea espoused by the late Stephen Moorbath and Warren Hamilton that anything older than about

26. Einstürzende altbauten *vs.* https://en.wikipedia.org/wiki/Einst%C3%BCrzende_Neubauten

3.8 Ga on Earth had to have been destroyed by asteroid bombardment (Moorbath, 2005). The proposed age >3.8 Ga for the Akilia quartzite containing graphite particles (Fig. 2.21) would put its deposition prior to the increasingly dubious concept of the late heavy bombardment (LHB) of the inner Solar System (*e.g.*, Norman, 2009). Some people seriously objected to these conclusions we reached about life before 3.8 Ga merely because it did not fit the heavy bombardment narrative. As we will see later, much work by several groups in the last few years shows that there was no spike in bombardment at 3.8–3.9 Ga on the Moon or anywhere else in the Solar System. We and others also pointed out that there is no obvious physical barrier to life's emergence even as far back as *ca.* 4.3 Ga or so. When I asked a number of people about why they espoused the bombardment

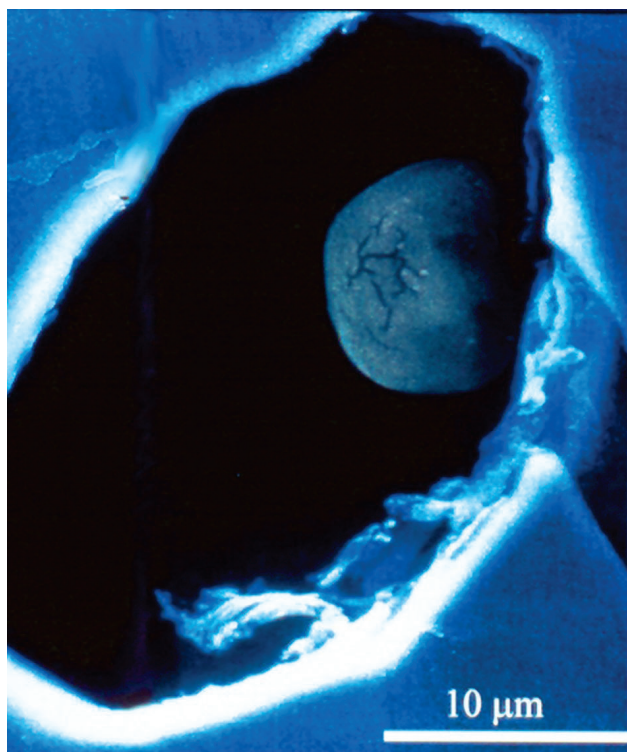


Figure 2.21 Carbonaceous material in the Akilia rock. Scanning electron micrograph of a void left after treating Akilia sample 92-197 with 2 % nitric acid and etching for 30 minutes at 25 °C. The etching process reveals an acid resistant residue of carbonaceous material typical of that which was measured by ion microprobe in our publications. Remarkably, there are some authors who claim that none of this material exists. Write me a short proposal to work on this material and I will send you your own thin section and you can see for yourself.

hypothesis and how come they used it to justify the absence (in their minds) of any rocks older than about 3.8 billion years, along with why this rules out also any possibility at all for there ever having been a very early origin of life, I kept getting similar vague answers along the lines of: “well, it is self-evident, isn’t it? Just look at the surface of the Moon.” The pre-conceived notion that life could not have existed before the start of the Archean (4 Ga) became entrenched to the point that it still influences science policy. For example, the planetary science and astrobiology decadal report (NASEM, 2023)²⁷ of the US National Academy of Sciences (NAS), section Q9.4c, had the following remarkably strident text:

*What Is the Spectrum of Abiotic Processes for Which Abiosignatures Exist and What Subset of Those Abiosignatures Can Mimic Biosignatures on Earth?*²⁸ The literature related to claims regarding the discovery of the earliest signs of life on Earth is replete with examples of false positive detections. For example, initial claims regarding the biological origin of isotopically light graphite in ~3.8 Ga rocks of the Akilia and Isua terranes of Greenland (Schidlowski et al., 1979; Mojzsis et al., 1996), were based in part on a lack of recognition that metamorphic decomposition of iron carbonate to form graphite and magnetite imparted an isotopic fractionation between graphite and carbonate that mimics that of photosynthetic metabolisms. Initial claims regarding the biogenicity of these graphite occurrences have largely been overturned in favor of an abiotic origin (van Zuilen et al., 2003).

Besides being patently wrong, another negative impact of such treatises is that they tend to not only guide policy, but also where funding goes and to whom. As the old saying goes:

*First they ignore you, then they ridicule you,
then they fight you, and then you win.*²⁹

Nicholas Klein (1918)

Key objections were raised about the Akilia work specifically, and the use of chemofossils generally. I present a list of the geochemical and geologic challenges that arose:

- 1) Did the apatite hosting the graphite particles form only 1.5 Ga ago? (Sano et al., 1999)
- 2) Are the cross cutting orthogneisses, which define a minimum age of the Akilia quartzites, only ca. 3.6 Ga? (Whitehouse et al., 1999, 2001)

27. <https://www.nationalacademies.org/projects/DEPS-SSB-19-17>

28. In other words: *what range of abiotic processes produce abiosignatures, and which of these can be mistaken for biosignatures on Earth?*

29. This popular quote is mostly misattributed to Mohandas Karamchand Gandhi (Mahatma; 1869-1948) and found on posters in lots of college dormitory room walls, next to spent water pipes and candy wrappers. Instead, it originates from American labour leader Nicholas Klein in a 1918 speech. In it, he described the stages of social change and movements, ultimately concluding with eventual triumph after overcoming initial opposition.

- 3) Do the dated orthogneisses actually cross cut the paragneisses (metamorphosed sedimentary protoliths) and thus provide a minimum age of the supracrustals at 3.83 Ga? (Myers and Crowley, 2000)
- 4) Is the quartzite really a quartzite, or is it some metamorphic product of metasomatism of an ultramafic rock? (Fedo and Whitehouse, 2002; Whitehouse and Fedo, 2003)
- 5) Do the Akilia graphites even exist at all? (Lepland *et al.*, 2005)
- 6) Even if the graphite exists in the Akilia rocks, and they are sediments, and they are old, could the graphite have been produced by decarbonation? (Van Zuilen *et al.*, 2002)

Point #1. Sano *et al.* (1999) reported a 1.5 Ga U-Pb age for ~20 μm diameter apatites from the Akilia quartzite. This was taken to mean that the apatite crystals were young and formed much later than the rock. But, as explained in Mojzsis and Harrison (2002a), documented hornblende and mica ages are regionally reset at *ca.* 1.5 Ga which is indicative of a thermal event above ~400 °C at that time, not a crystallisation age (Fig. 2.22). More insight into the metamorphic history of the Akilias compared with the Eoarchean Nuvvuagittuq Supracrustals was recently published in Tropper *et al.* (2025).

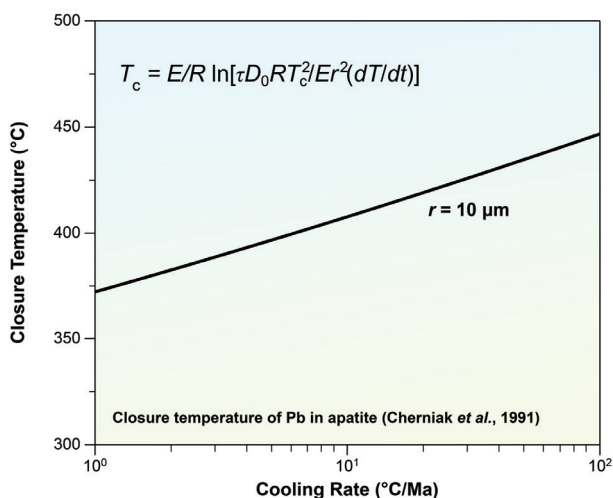


Figure 2.22

Closure temperature of Pb in apatite. Radiogenic Pb is not quantitatively retained in apatite around 25 μm in diameter at temperatures above 400 °C, which would be during regional slow cooling (1–10 °C per Myr) or during a transient heating event that persisted for several million years. It is well documented that the region of southern West Greenland, where the Akilia rocks are found, experienced a thermal excursion to temperatures exceeding 400 °C at about 1,500 Ma. Thus, Pb-Pb apatite ages of approximately 1,500 Ma should therefore be expected. Image credit: M. Grove.

Point #2. Are the cross cutting gneisses only about 3.6 Ga? Mojzsis and Harrison (2002b) pioneered the use of ion microprobe U-Th-Pb zircon depth profiling to show that only the oldest (*ca.* 3.83 Ga) components of the zircons in the cross cutting orthogneisses on Akilia could be original to the rock. All other younger ages (3.6 Ga, 2.7 Ga) share mineral chemical qualities consistent with metamorphic origins.

Point #3. What about the structural relationships between the supposed cross cutting gneisses? Are they genuine? Do they show that the Akilia supracrustal rocks are older than 3.83 Ga? Manning *et al.* (2006) mapped at the appropriate scale (1:250) to show cross cutting relationships (Fig. 2.23). Hence, the supracrustal rocks are at least 3.83 Gyr old.

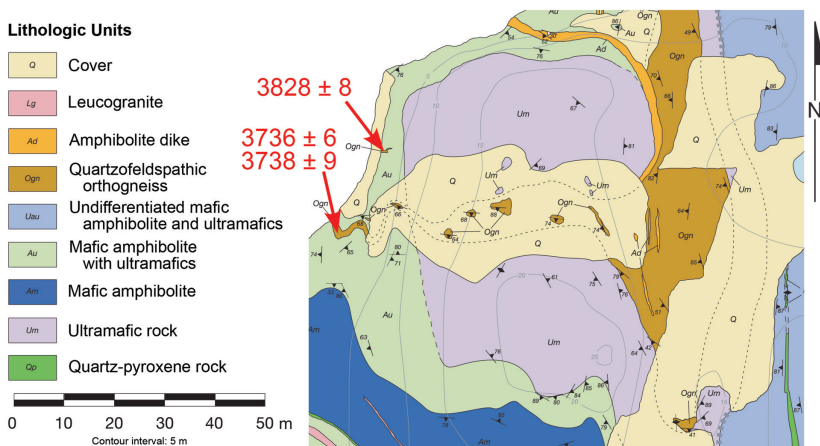


Figure 2.23

Mapping at the appropriate resolution to make sense of field relationships. Rocks from terranes that experienced multiple episodes of deformation and show evidence of a protracted history of thermal events and recrystallisation, must be mapped at the appropriate scale to guide both sampling and interpretation of the geology. As shown in this close up image of our map published in Manning *et al.* (2006). Please refer to that publication for a better version of the colour legend. Various cross cutting relationships with transecting granitoid orthogneisses delimit the minimum age of the supracrustal rocks on Akilia to about 3830 Ma. Map reproduced with permission from the American Journal of Science.

Point #4. Could the quartzite be a metasomatic product of, for example, fluid interactions with an ultramafic precursor? This was a surprise to me, since the compositions of these rocks were widely reported in the literature. Nevertheless, the following objection was raised:

We proposed that the quartz-pyroxene rocks on Akilia originated as ultramafic intrusions or volcanic rocks... After crystallization, these rocks were compositionally modified during repeated episodes of metasomatism... and metamorphism.

Fedo and Whitehouse (2002)

Four observations indicate that this hypothesis is implausible. As stated in Manning *et al.* (2006): mixing relationships, absence of metamorphic zoning, and combined O and S isotopes, all point to a probable banded iron formation as the sedimentary protolith of the Akilia quartz-pyroxene rock. In fact, any other protolith, especially an “ultramafic” rock, for something of the Akilia composition cannot be explained by physical chemical means. The Akilia quartz-pyroxene rocks are the metamorphic products of an original banded iron formation.

Point #5. Does graphite even exist in these Akilia rocks? You can imagine that this criticism was a real head scratcher for me. I asked myself: “How is it possible for anyone to miss these features if they know how to use a normal petrographic microscope?” Take for example, what the late inscrutable Stephen Erwin Moorbath wrote for *Nature* about it:

This persuasive discovery [i.e., the absence of graphite] seems an almost inevitable, yet highly problematic, consequence to the increasing scientific doubts about the original claim. We may well ask what exactly was the material originally analysed and reported? What was the apatite grain with supposed graphite inclusions that figured on the covers of learned and popular journals soon after the discovery? These questions must surely be answered and, if necessary, lessons learned for the more effective checking and duplication of spectacular scientific claims from the outset.

Moorbath (2005)

The source material for this screed were two papers that claimed neither graphite inclusions nor graphitic matter of any kind are present associated with apatites in the Akilia quartz-pyroxene rock (Lepland *et al.*, 2005; Nutman and Friend, 2006). This was a deeply uncomfortable time for me. Some of these people, very strangely including former co-authors (!) claimed carelessness. The works of McKeegan *et al.* (2007), and subsequent publications (Papineau *et al.*, 2010) that documented such inclusions independently, seem to have halted this criticism. What do you think about it? Why has the controversy over whether graphitic carbon is in the Akilia rock now become silent? Is the “controversy” resolved? Curious to try your hand at the sample? Write to me if you would like to have some Akilia quartzite. You are free to make your own thin section and document the graphite + apatite associations for yourself. The first criterion, of course, is that you know how to operate a petrographic microscope (a criterion apparently absent or lacking in various contrarian publications). That is how I feel about it.

Point #6. Was the isotopic light carbon described in Mojzsis *et al.* (1996), and verified by McKeegan *et al.* (2007) and Papineau *et al.* (2010) **generated by abiotic reactions?**

OK. So, even if the Akilia rocks are sediments, and they are at least 3.83 billion years old, and even if they do contain graphite associated with apatite, then now the carbon isotopic signature should be considered untrustworthy?

The US National Academy document that I cited above reported that van Zuilen *et al.* (2002, 2003) showed iron carbonate decomposes to graphite with the same $^{13}\text{C}/^{12}\text{C}$ as photosynthetic remains. This is simply untrue. Rather, van Zuilen *et al.* (2002, 2003) specifically pointed out that decomposition of siderite to form graphite created average $\delta^{13}\text{C}$ signatures of only about -15‰ . This is fully 2 % more enriched in ^{13}C than the documented Akilia graphite particles (e.g., Zeichner *et al.*, 2024). It is noteworthy that van Zuilen *et al.* (2002) were very specific when they said *their study does not include Akilia rocks and our conclusions about the origin of graphite and apatite-graphite association in Isua cannot, without additional petrographic and chemical analyses, be applied to the more extensively metamorphosed rocks from Akilia island*. Further, van Zuilen *et al.* (2003) noted that ...the (abiotic)³⁰ mechanism for low $\delta^{13}\text{C}$ of graphite inclusions in apatite (Mojzsis *et al.*, 1996) currently remains unexplained.

In a nutshell, Chapter 5 of my Ph.D. thesis as reported in the Mojzsis *et al.* (1996) paper documented $\delta^{13}\text{C} = -37 \pm 3\text{‰}$ (errors on the mean) values in graphite inclusions in apatite crystals in the oldest known terrestrial rock of sedimentary protolith (Manning *et al.*, 2006). The $\delta^{13}\text{C}$ of ordinary sedimentary organic matter averages -25‰ over the last 3.5 billion years (Schidlowski, 1988; Krissansen-Totton *et al.*, 2015; Zeichner *et al.*, 2024), compared to inorganic carbon at 0‰ . You may ask, as we did, if this is proof of life at the Hadean-Eoarchean transition.

Here are the exact words we used in our *Nature* paper to frame our observations:

Unless some unknown abiotic process exists which is able both to create such isotopically light carbon and then selectively incorporate it into apatite grains, our results provide evidence for the emergence of life on Earth by at least 3,800 Myr.

Mojzsis *et al.* (1996)

Unless you destroy the graphite, this isotopic signal can be preserved even into the diamond phase. Hence this may be used to argue for the inherent power of chemofossils and isotopic signatures as tracers in general over things like morphological fossils. Frankly, it has been known for a long time that once graphite forms, the extremely slow self-diffusion of carbon atoms within its structure allows for an isotopic memory of the original organic source to be

30. My insertion here of “abiotic”.

maintained (Dienes, 1952; Feldman *et al.*, 1952; Kanter, 1957; Feates, 1968; Deines, 1980). Why is this forgotten only because a rock is very old. Or is it forgotten simply because the original research papers documenting this are old?

Finally, it is nice to see that other more recent methods, not yet in use in the mid-1990s, such as Fe isotopes (Dauphas *et al.*, 2004) and new results from K isotopes (Long *et al.*, 2025), independently confirm a sedimentary identity for the Akilia quartzite. It is gratifying to see other, new people, work on this problem. It would help move the field forward, and give us a better idea of when life started on Earth.

2.9 Guardrails to the Origin of Life

Maybe life is common in the universe. Nobody knows this yet, and we may not know it for a long time. I will be the first to tell you that there is a big difference between belief and understanding and hope and delusion. I neither believe, nor understand, arguments for life on, in or around Mars, Venus, the Jovian moon Europa, Saturn's moon Enceladus, or in spectra from extrasolar planets.

The foundational argument in favour of life's commonality appears to stem from the fact that the elemental underpinnings of biology are compounds made mostly of the reactive elements hydrogen, oxygen, carbon, nitrogen, sulfur, phosphorus, as well as certain alkaline earth metals (Ca, Mg) and transition metals, such as Fe, Ni and Co (Fraústo Da Silva and Williams, 2001). Two important points are worthy of examination:

- 1) The argument of commonality of the biophilic elements is circumstantial and does not translate into an estimate of how common life in the universe is (Lineweaver and Davis, 2002).
- 2) The early appearance of life on Earth is not itself an argument for abundant life in the Universe because we do not know how life began, and we cannot assess a planet's proclivity to host a biosphere before we have found a second example either in our Solar System or around another star.

Biochemistry presumes that non-living matter has reached a level of chemical self-organisation, a biophysical threshold, to support Darwinian evolution (*e.g.*, Yarus, 2010). It remains unclear whether this level of support can be considered incomplete, because we do not yet know the degree of sophistication required for a system to reach a developmental threshold that qualifies as being alive. My preference is that the basic molecular components leading to life are the same as those of the biological processes we already know. It is also significant that we do not know precisely when fully fledged biochemistry began on our planet because we do not have a geologic record of that early time.

As we have discussed in the previous pages, geochemical data in the form of characteristic isotopic ratios in carbon, sulfur and iron show that life began early and probably prior to the start of the continuous rock record at about 3.85 Ga and maybe before 4.1 Ga (Bell *et al.*, 2015). Together, this can be taken to mean that the origin of life on Earth came about in the twilight of the Hadean eon or around 4.35 Ga (Genda *et al.*, 2017; Benner *et al.*, 2020). Information theory coupled to molecular clock analysis also points to the origin of the genome of all existing life, and therefore of the Last Universal Common Ancestors (LUCA) before 4 Ga (Feng *et al.*, 1997; Hedges, 2002; Battistuzzi *et al.*, 2004; Moody *et al.*, 2024).

2.9.1 Abiogenesis in the Solar System

With this backdrop it must be emphasised that contemporary theories for the origin of life rely on the concept of abiogenesis. The prevailing idea is that life's origin takes place when conditions allow for matter which is not alive to undergo a suite of increasingly complex chemical reactions and reaction-product interactions to transition into Darwinism (Szostak, 2012; Benner, 2023; Hirakawa *et al.*, 2025). Of the terrestrial planets in our Solar System, only Earth appears to have hosted a persistent biosphere. Maybe there was life on Mars, but there is no sign of it; perhaps it never reached the level of complexity to leave a trace of itself as an interpretable fossil. There is the slim chance that martian life might still be lurking somewhere deep in crustal rocks and sediments away from the harsh surface zone, but we must be aware of the assumptions we make for the kind of evidence we are searching for (Michalski *et al.*, 2018). Mercury never had conditions for a biosphere (*e.g.*, Mojzsis *et al.*, 2018). Arguably, Venus has been too inhospitable for biochemistry over most, if not all, of its history (Hamano *et al.*, 2013; Turbet *et al.*, 2021; Warren and Kite, 2023; *cf.* Way and Del Genio, 2020). Icy moons around the gas giants in the outer Solar System are documented to host the chemistry that may be conducive to life (Postberg *et al.*, 2023), but there are severe physical, chemical and temporal limitations to a biosphere within any of these worlds (Gaidos *et al.*, 1999), including those in the trans-Neptunian region (Mojzsis, 2021).

Rocky objects on the order of Venus-mass or larger have the capacity to sustain geologic activity from intrinsic radioactive decay, thus opening the possibility for dark biospheres to exist and persist even in the outer regions of the Solar System or between the stars (Stevenson, 1999; Abbott and Switzer, 2011).

2.9.2 We Might not ever Know the Origin of Life

There must be a chemical pathway which leads to life, and the challenge is to find it (Fig. 2.24). We may never know the precise circumstances of our own origins; there might be “the” pathway rather than “a” pathway. As such, there could be an elegant solution to the problem waiting to be discovered. As both the legendary Albert Eschenmoser and my doctoral advisor Gustaf Arrhenius often

told me: “Even if a pathway for the origin of life is found in the laboratory, it does not necessarily translate into what happened in Nature!” When we eventually discover a prebiotically plausible means to achieve abiogenesis, it may be more metaphorical than natural (Eschenmoser, 2011).

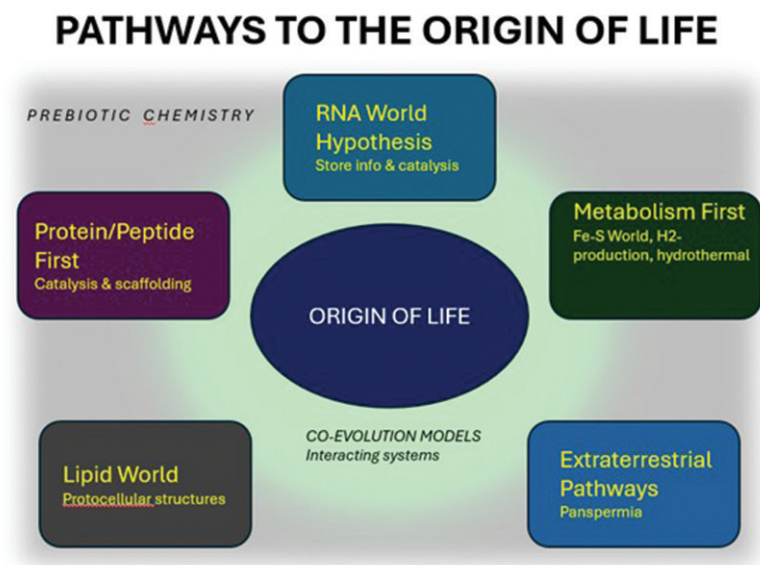


Figure 2.24 Find a way. The different avenues currently being explored in origins of life studies. Not all of them will necessarily be relevant to the goal.

There is much more I could write about my experiences up to the time I moved from San Diego to Los Angeles in 1997. One thing is for sure; I wanted to try even more new things in geochemistry and beyond, and not spend the rest of my professional career defending my Ph.D. thesis (Fig. 2.25). Success does not mean that you are right. Let me cite my excellent friend Janne Blichert-Toft’s experience as expressed in her Urey Award Lecture at the 2025 Goldschmidt Conference in Prague:

Your Ph.D. does not have to define you!



Figure 2.25 Earth in time. The origin of life on our planet seems so complex and out of reach now, that to the casual observer it seems like a miracle had to happen. Science tells us that there must be a way. Here, I am standing in the Hverir (also called Námaskarð) area of Iceland, which is a splendid place to let your mind wander on such topics. Photo credit: N. Brown.

And so dear reader, here ends this part of my *Grimoire Scientifique*. The following comes to mind:

In science, it is easy to produce a complex solution, but hard to use it. Simple solutions are hard to produce, but easy to use. This principle serves as a useful mental model to eliminate improbable options for a given problem.

How the origin of life came about is a prime example of such a problem.

If science is a constellation of facts, theories, and methods collected in current texts, then scientists are (those) who, successfully or not, have striven to contribute one or another element to that particular constellation.

The Structure of Scientific Revolutions (Kuhn, 1962)

Here is the next part (do not worry, there is another part yet to come). I wish to contribute to “a constellation of facts” (as Thomas Kuhn pointed out) that lead to testable hypotheses. I turn my attention to Earth as both a biologically and geologically dynamic planet in the galactic context, in a constellation of exoplanets. This is because I want to combine biogeodynamics with geology and astronomy. Geoastronomy as a new discipline has long been a dream of mine. My journey to the topic is rather different from most exoplanet scientists owing to the fact that I came from Geology, rather than Astronomy. This provides me, I hope, with a useful perspective.

3.1 About My Overall Scepticism Regarding Debates over Life’s Origin Here or on Exoplanets

Frankly speaking, I find it strange that in origin of life studies it is uncommon to downright rare to come across discussions of *why* there is life? We are so concerned with tracking clues to natural processes and coming up with explanations for these processes, as Thomas S. Kuhn put it (above) that we forget fundamentals. How come there is hardly ever any concern about why a particular process should be operative? Why did it follow that process as opposed to some other eventuality? Which is it? Is life either very strange or mundane? Please do not take a middle ground and say it is both. Science thrives on debate; if everyone simply prefaces anything they are about to say with a platitude, then we are condemned to mediocrity. Not everything that pops into our heads is valid.

Here is the thing: I think it is wrong to waste our time trying to compare Mars to Earth (Fig. 3.1). It is wrong to think that we will discover something on Mars that will be an equivalent record of early life on Earth. To make such a claim pre-supposes that the level of complexity of prebiotic chemistry on Mars reached sufficient sophistication to leave a record of itself. For those of you who think there is or was life on Mars, please tell me, where is it?

In my opinion, once an operative biosphere gets started on a planet, it is hard to get rid of it. A biosphere, especially for a neighbouring planet in our solar system, ought to be obvious. Life chemically changes its environment at the very least locally, most probably regionally, and arguably, globally. Mars to me looks thermodynamically dead in its crust. Sure, there is plenty of evidence for volcanism, but not now and not recently.

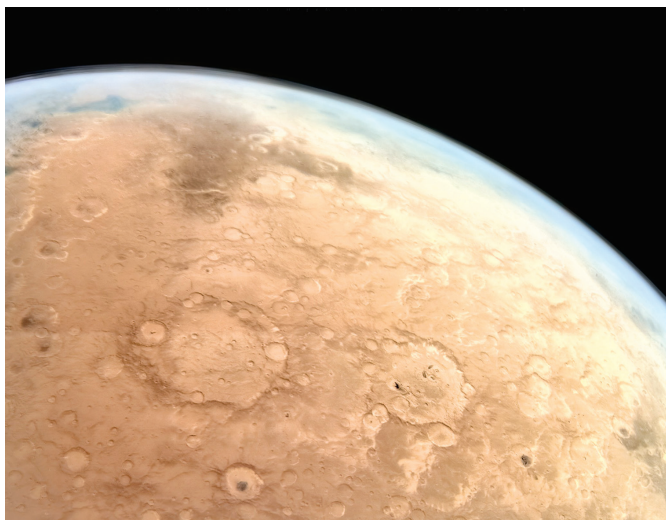


Figure 3.1 Martian dreams. Superficially, the red planet looks the most Earth-like of all our inner Solar System planetary siblings. Yet, it is *not* like Earth, and it *was never* like Earth. The better way of looking at this planet is that it was always *like Mars*. Image credit: UAESA/MBRSC/HopeMarsMission/EXI/AndreaLuck.

Maybe you can argue that martian life is hidden deep underground, frozen and in hibernation in permafrost, hiding inside rocks, or as some idea makers suggest, Mars (like Earth?) hosts a shadow biosphere. Absence of evidence is not evidence of absence you say? I say not.

It seems illogical to call something dead if it never had life (*i.e.* Dead World). Reach out to me if you disagree and have actual data to back up your counterarguments. I am very happy to entertain debates over this topic, especially those that threaten to change my mind.

Before I left San Diego in November 1997 to start yet another new chapter in my life (Fig. 3.2), there were some important things that I had to learn. First was to understand that the biggest mistake I think that someone like me can make is to go ahead and just assume that the harder you work, the more your partner will appreciate you. Maybe some people get this kind of appreciation, but my experience has generally been the opposite. Working too much creates a resentful partner who wonders why you are never there, not someone who appreciates you more. Who wants to share life with someone who is away all the time in the laboratory or at some conference somewhere, or in the field for weeks or months, at a time? It is so strange to look back and see just how painfully long it took me to understand that I should have a life outside of work. It is important to pay attention to your home because when the time comes, no mass spectrometer or pet cat/dog/goldfish will hold your hand when the darkness

comes over. Instead, when you work, do not try to just work hard, work smart. This was explained to me long ago by wise people, and it took a long time for the advice to stick: Make your time matter. If this sounds obvious, then how come more of us do not do it? Fortune favours the bold and punishes the foolhardy. Which side of this equation are any of us on at any moment?



Figure 3.2 Going local. Living in southern California attuned me to experiences in mountains and desert that I had never appreciated before. Here I am on my way up Mount San Gorgonio (3506 m) in southern California. Photo credit: T. Rahn.

My scientific life and social chaos in the mid- to late 1990s was absolutely over the top and I had to find a way to get better control of my time and myself. I also needed to learn to sleep more. It helped that I had incredible friends like the cheerfully brilliant Christine Salomon around to remind me that having fun and being open to feeling love is as important as work and the pure passion of the mind. Many other close companions in those San Diego years, like David Rowley, Milton Garces, Tony Keefe, Pepita Laralldede, and the best soul neighbours anyone could have hoped for: Claudio Orso and Rian Brown, encouraged – rather than discouraged – me to keep my head in the clouds and treasure the stars in my eyes. They helped me believe in living life to the fullest even when there were others trying to tear it all down.

There are many of you out there who can relate to Sayre's Law³¹. How is it that we go about fighting so hard over so little to the detriment of us all?³² Going beyond petty grievances, motivation is amazing when harnessed appropriately. For example, when I learned in summer 1997 that I was to be awarded two postdoctoral fellowships after I came back from six weeks of fieldwork in West Greenland, it left me with only about six weeks to write my Ph.D. dissertation to meet the deadlines to accept them! I therefore devoted myself entirely to finishing my thesis. Working day and night and listening to classical music (Liszt Ferenc, principally) and movie soundtracks (notably by Basil and Zoë Poledouris), meant that I both made the deadline and passed my Ph.D. defense. My doctoral study took 4 years and 6 days from start to finish. You might ask, why the rush? I sincerely felt that there was no time to waste. I had other things in mind. My optimism was at a high point, but I had no crystal ball to inform me what was coming next. Consider this: knowing the future kills hope.

3.2 L.A. Man (1997–2000)

An unexpected, infrequent event contains much more information than a more regular happening.

A Mathematical Theory of Communication (Claude Shannon, 1948)

Already you have seen that my career took some detours, and that I get restless in my science. In any case, my postdoctoral studies strongly dictated the direction of my research in the early to mid-2000s. I was slowly moving away from my singular focus on geology. The reason for this stems from the fact that we seem to have run out of a rock record on Earth older than about 4 billion years. My attention began to turn to meteorites, pre-solar materials and logically, to the stars and planets around them. By about the mid-2010s, I had come face to face with the Fallacy of Silent Evidence³³ when it comes to a missing rock record of the first half billion years of Earth history. History has the tendency to hide both surprising things and the mechanisms for making them. Who would have ever thought I would run out of rocks?

Recall that earlier, I shared with you that the talented people in the UCLA ion microprobe laboratory made it possible for me to measure the carbon isotopic compositions of tiny graphite particles I found in the oldest rocks of sedimentary origin thus far identified on Earth. The UCLA years from 1997 to 2000 were, for lack of a better word, thaumaturgical. I was a postdoctoral researcher funded

31. https://en.wikipedia.org/wiki/Sayre%27s_law

32. "The reason university politics are so vicious is because the stakes are so small" – H. Kissinger.

33. *Argumentum ex silentio* is to conclude without evidence, because history hides the evidence. This is a terrible problem that Earth Scientists always face and, unfortunately, are loathe to accept.

by dual National Science Foundation and University of California President's postdoctoral fellowships to pursue cutting edge science with the best instruments available at the time. I had professional and personal freedom, with no teaching duties, no service, no family (yet) and back again to enjoying the single life (Fig. 3.3).



Figure 3.3

Keep your eye on it. Up until graduate school, my eyesight was good. As soon as I reached age 30, eyeglasses became a part of my life. Photo credit: C.E. Salomon.

To be clear, it was not my intention to live *la vida loca* into my early 30s. At that time around 1995 I was confident that I wanted to start a family. Fate, on the other hand, had something else in store for me. I did not become a parent until a dozen years later when my genius daughter Anna Caeden Mojzsis entered this world in 2007 during a blizzard and fire drill. For most people, 42 is a late start for fatherhood. Despite the wild imaginations of musical influences like Tyrone Davis³⁴ and Gibby Haynes³⁵ you cannot turn back the hands of time. Along with my gorgeous daughter Anna C. Mojzsis, my wizardly two sons James Matthias Ebert Mojzsis and John Stefan Ebert Mojzsis keep me youthful. Children teach the parent to intrinsically appreciate the fact that the universe will continue to go on without you.

34. https://en.wikipedia.org/wiki/Turn_Back_the_Hands_of_Time (https://www.youtube.com/watch?v=j-opxZJvIZ0&list=RDj-opxZJvIZ0&start_radio=1)

35. https://en.wikipedia.org/wiki/Gibby_Haynes

3.3 Take Your Time, But Do Not Drag Your Feet

You will very often hear in the astrobiology literature and in research presentations that there are three key requirements for the origin of life. These are frequently cited as liquid water, a “source of energy”, and availability of organic chemical building blocks (Fig. 3.4). Liquid water provides a medium for chemical reactions, energy drives these processes towards complexity, and organic compounds act as the building blocks from which life can emerge and evolve. This list misses an important point that should be emphasised by all geologists: time.



Figure 3.4 The four requirements for life. Nearly everything geologists study and interpret to compose a story, takes time into account. The same goes for the origin of life, because it is probably not something that can happen without enough time available for it to happen.

- 1) **Liquid water** tends to be abundant in the cosmos where it is stable under the appropriate pressure and temperature conditions. These conditions are satisfied in planetary bodies. Such bodies can host “cloaked” oceans within warm planetary crusts or under ice shells, or “naked” oceans on solid surfaces under an atmosphere. As a solvent for reactions, water allows organic molecules to dissolve and react. Further, liquid water serves as a transport system for waste products and nutrients in living systems.

- 2) **Energy resources** are often invoked, vaguely, as the second term. But what is really meant here is that free energy from chemical disequilibrium is needed. This disequilibrium energy arises from the exchange of the Earth system with its surroundings primarily through the exchange fluxes of solar and terrestrial radiation. It is the flow of electrons facilitated by these exchanges that drives the chemical reactions necessary to build more complex molecules from simpler ones. These energy sources are sunlight (photosynthesis) and geothermal energy (chemosynthesis).
- 3) **Organic matter** forms the building blocks of biological chemistry. The principal building blocks are amino acids, nucleotides and lipids, corresponding roughly to the Three Pillars of Life: Metabolism, Information, and Compartmentalisation.
- 4) **Time** is necessary to be considered in this list because liquid water must be sustained in a geologically stable environment, where reliable and long lived energy resources are available for long enough for building blocks of bionts to assemble into progressive structures (Fig. 3.5). As we will see later, it is evident that conditions suitable for life were in place within 100 Myr of the formation of our planet and by that time the universe was around 8 Gyr old already and had synthesised all the necessary nuclides that compose both life and a life giving world like Earth. Some very smart people, like my friends Mike Russell and Nick Arndt hold the view that life forming reactions happen quickly and repeatedly if the conditions to maintain life are re-set. Russell imagines that life may have been wiped out through the Hadean, only to reappear, rapidly, time and again. I hold a different view: For most of the Hadean eon, habitats for life were common. The argument that making life over and over again was possible appears to contradict the claim that the “first steps to life are the most difficult” (Russell *et al.*, 2013).

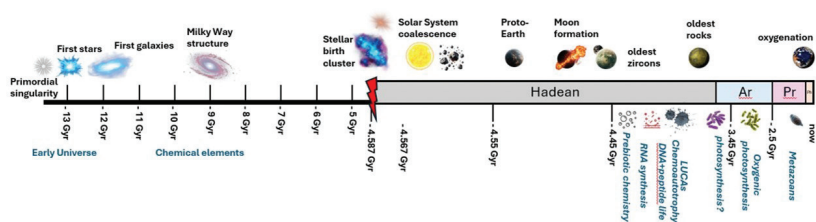


Figure 3.5

Universal time. Events on the left half of this timeline are shown in linear units of 10⁹ years (expressed as Gyr “ago”) beginning with the early Universe. The right side of the timeline – after the lightning bolt symbol – is expressed in log₁₀ units of 10⁶ years. This changeover in scale is at approximately the mean lifetime of molecular clouds in the galaxy (~20 Myr) and approximates

the lifetime of the Sun's birth cluster. It serves the purpose of highlighting important events in the early history of life leading up to the present time. LUCA = last universal common ancestors; Ar = Archean eon; Pr = Proterozoic eon; Ph = Phanerozoic eon.

In the late 1990s, America's economy was relatively healthy and appeared to be headed towards a major deficit reduction thanks to competent leadership of the William Jefferson "Bill" Clinton presidential administration. As mentioned, owing to my dual postdoctoral fellowships, I had my own research and salary money. I also have had the privilege of working with the famous Kevin D. McKeegan and the influential and indomitable Craig E. Manning, with whom I enjoyed field work and sharing ideas. Outstanding technical and scientific advice came from Christopher D. Coath, George Jarzebinski, Marty Grove and Oscar Lovera. My LA office mates were the exemplary Axel K. Schmitt, Cecile Engrand, Mustafa Fayek, Sandeep Sahijpal and James Lyons. Graduate students in the CAMECA ims1270 ion microprobe lab (Fig. 3.6) included Elizabeth "Liz" Catlos and Christopher "Chris" House. It is noteworthy that Chris House was supervised by the illustrious palaeontologist J. William "Bill" Schopf. For those of you who know Bill Schopf, he is a complicated guy. If you already are aware of his personality and that he is highly competitive, it comes as less of a shock when you meet the man in person. Having met Bill again in recent years at various conferences, I can say that he has rather mellowed out a bit (he talks to me now). Perhaps it can be said that this is what happens when you reminisce

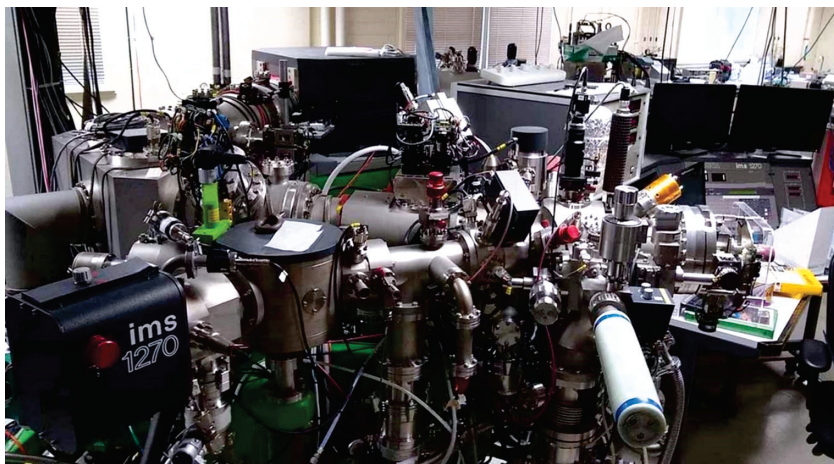


Figure 3.6

A versatile geochemical tool. When I arrived at UCLA in the late 1990s, I was absolutely thrilled to work on the CAMECA ims1270, which at that time had been recently commissioned by T. Mark Harrison and developed with Kevin McKeegan and colleagues. We postdocs and students both admired and deeply respected this pretty device which opened up worlds for us.

about something in more than a superficial manner. By doing so, you come to understand that past arguments or differences (or even out and out fights), are of small consequence in the great scheme of things. Such is the case with my normal cordial interactions with previous academic adversaries. And, no, not everyone I have crossed paths with has similarly come to this level of enlightenment. You know who you are. For that cohort: my door is always open at least to discussion, if not reconciliation. It is worth it to eliminate resentment just because you do not see eye to eye. To quote the enlightened Paul D. Hudson (H.R.)³⁶ “Put a smile on your face and join the human race” (Fig. 3.7).



Figure 3.7

In the company of rocks. Geologists have the unenviable problem that they cannot just look at a terrane and accept it for its mere beauty. They are compelled to analyse it for the tales it can tell about the origin of the landscape. Marcus Aurelius wrote that *anything in any way beautiful derives its beauty from itself and asks nothing beyond itself. Praise is no part of it, for nothing is made worse or better by praise.*

36. [https://en.wikipedia.org/wiki/H.R._\(musician\)](https://en.wikipedia.org/wiki/H.R._(musician))

Down the hall from me in the UCLA Geology Building was the multi-talented William “Bill” Moore, a postdoc and avid singer/songwriter who worked with the geodynamical guru, Gerald Schubert. Many of you knew Gerry and use his books co-authored with another giant in the field Donald “Don” Turcotte, but I did not learn until very recently (sadly, from his obituary) that he and I were born in the same place (Bronx). We were gestated 26 years apart. Idiomatically speaking, in Los Angeles, I was living in the Life of Reilly³⁷. I will forever be grateful for what I learned there. My UCLA years set the course for a good portion of my subsequent time on the faculty at the University of Colorado, where I was going to spend the first decades of the 21st century, from 2000–2021. More about that most major step in my professional existence comes a bit later.

3.4 Exobiology Transmuted into Astrobiology at the Turn of the 21st Century (1997–2003)

The great development of science in the last century is intimately connected with its divorce from philosophy.

What is Science? (N. Campbell, 1953)

I lived in Los Angeles for 3 ½ years until December 2000. It is, as you well know, a giant, sprawling, epic city with a nightly story that repeats the Q. Tarantino flick *Pulp Fiction* in some way or another. The artistic and deep minded Krisztina Micsinai, with whom I shared time and space before we each sailed on to other destinations, designed the characteristic pendulum necklace that Uma Thurman wore in that famous movie poster. Take a close look and you will see this glass and silver necklace around the neck of her character Mrs. Mia Wallace³⁸.

Around late 1997 was when the wider community learned that NASA had decided to use the momentum from the 1996 discovery of claimed microfossils in martian meteorite *ALH84001*, the 1995 confirmation of planets around other stars (exoplanets), and our work in 1996 on the oldest plausible evidence for life before 3.8 Ga, to establish the NASA Astrobiology Institute (NAI)³⁹. This organisation lasted for about twenty years before being rather abruptly phased out in December 2019. I would say that it could better be described as having been terminated, cancelled or cut. Many people had submitted proposals for the next round of the Astrobiology Institute and then later discovered that the

37. The phrase likely originates from a popular song in the late 19th century called “*Is That Mr. Reilly?*”, which described the comfortable and carefree life of a man who suddenly became wealthy. The phrase means that someone is enjoying a life of leisure and luxury, but it has also come to mean “luck”.

38. https://en.wikipedia.org/wiki/Mia_Wallace

39. NAI was an organisation within NASA composed of an acronym enclosed within an acronym.

programme was scrapped, and it was all a waste of time. This outcome was in no small part due to what I feel were inherent structural weaknesses of the leadership. From the start, I thought the whole endeavour was an odd idea that almost seemed to be slapped together in haste, and thus suffered from initial conditions. One big problem for me was that there was not going to be an actual “Institute” building anywhere. Instead, the whole thing was supposed to operate as a virtual institute. Whoever thought that was a good idea? Politically expedient perhaps, but impractical. A virtual institute meant there would be no central place to meet and mingle in a brick and mortar structure, but rather the research was going to be distributed across the country to various universities and research centres (including NASA research centres). This was always a dangerous choice in my eyes because humans crave structure, identity and place. Many held the default thought that maybe that the NASA Ames Research Center in Moffett Field, California, was the headquarters for NAI. This was never true, at least on paper.

I believe that science is done by people who must closely interact with one another, so that the opportunities for success increase when chance conversations lead to breakthroughs. Such a scheme is especially compulsory in something as transdisciplinary as Astrobiology. You need to be in the same building. Without a meeting place to facilitate such interactions, people will instead stick to their own locale and wait around until the next conference or workshop where everything is going on at once with hundreds of people, inefficiently. At such big meetings people sometimes talk about science, but many just wander off to socialise and talk about something else. Think about these huge meetings like the American Geophysical Union with over 25,000 of attendees. It is overwhelming and frankly, depressing. After about five minutes in such a sea of people, I want to leave out of despair of having a substantive conversation (which is what I am supposed to be doing when attending such things). The first (interim) director of the NAI was Scott Hubbert from NASA, and the first director was the very amicable and open minded Nobel laureate Baruch S. “Barry” Blumberg. These founding directors, followed by the talented Carl B. Pilcher, did a lot to keep the young NAI afloat and it had the fresh energy to generate excitement. I think it was thanks to the hard work that these people put into it at the start that the whole NAI thing lasted as long as it did.

Astrobiology, much like the exobiology and bioastronomy fields that preceded it, is very concerned with the notion of habitability. As I wrote earlier, habitability is a concept without much substance. Another lingering criticism that you often hear about is that astrobiology is a science without data. I think this is wrong thinking. Data were almost immediately forthcoming from early Earth geology and from the nascent field of geobiology and life in extreme environments. In my opinion, the problem comes from assuming we know what habitability is. By taking this assumption and applying it to other worlds, we are in danger of fooling ourselves. Another thing, just because we do not understand how life began, does not mean that there must be some near supernatural means of achieving it. I think that most planets we would casually term habitable using the poorly defined parameter space we have now, do not have life on them at all.

What motivates you? I have asked many people this question. You would not believe the diversity of answers I get. When I ask them in confidence to be honest with their answer, the result is fascinating. What is your reason for sticking with science? I will not compile a list of what I have been told, but it ranges from the ecstasy of discovery to the agony of trying to prove others wrong.

*People in this world look at things mistakenly and think that what they do not understand is the void ⁴⁰. This is not the true void.
(Rather) it is bewilderment.*

The Book of Five Rings, The Book of the Void (Miyamoto Musashi, 1645)

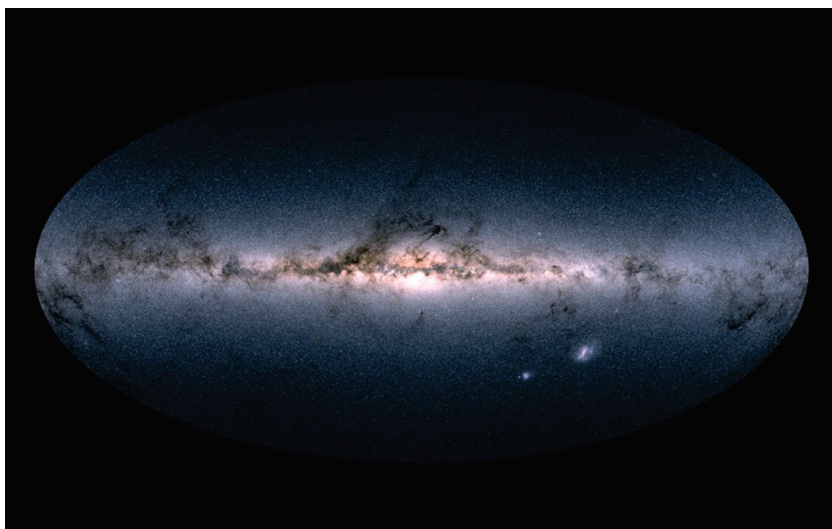


Figure 3.8

Gaia. The GAIA mission was recently retired by the European Space Agency. The discoveries from this spacecraft continue to transform our understanding of the nature of our home galaxy, of our neighbours (e.g., the Magellanic Clouds) and the stars within. From ESA/Gaia/DPAC.

3.5 The Plurality of Un-Inhabited Worlds

For good or for ill, Earth is our universal benchmark for a terrestrial planet. The broad category of “terrestrial planet” also encompasses Mercury, Venus and Mars, and the minor planets in our Solar System that are solid, composed of rock

40. According to Musashi-san, the spirit is nothingness, which is different from the concept of non-existence.

and metal, and sometimes wrapped in fluids. There are at least tens of billions of such worlds in the Milky Way Galaxy. The *GAIA Survey*⁴¹ of the European Space Agency was tasked with mapping the positions and radial velocities of billions of stars in the Galaxy and in the near galactic neighbourhood. The image in Figure 3.8 was taken by GAIA. It shows about 2 billion stars, or about 1 % of the total stellar population of our galaxy, the Milky Way. Probable star populations for the Sun-like stars (classes F-, G- and K-) are 3 % (6×10^9), 7–8 % (15×10^9) and 12 % (24×10^9), respectively. It is estimated that for FGK stars, 100 % of these harbour planetary systems (Cassan *et al.*, 2012; Lineweaver and Chopra, 2012; Winn and Fabrycky, 2015; Dong *et al.*, 2021). The occurrence of planets with radii between 0.5 and 1.5 Earth radii ($r_{\oplus}$) orbiting in the region of space around a star where liquid water can be stable on a planet's surface for billions of years (e.g., Kopparapu *et al.*, 2013) for those stars with effective temperatures between 4800–6300 K, is estimated to be around 37 % (Bryson *et al.*, 2021). This in turn corresponds to 45 billion FGK planetary systems of which 17 billion planets are in the conservative habitable zone. For exoplanets of whatever characteristic you seek with respect to proclivity for life or any environment imaginable, the population statistics are on your side that there is something out there that satisfies your criteria.

Notwithstanding the excellent odds for the existence of a planet with some kind of life somewhere nearby, no signs of any kind of extraterrestrial life have so far been verified (Lineweaver *et al.*, 2004; Frank and Sullivan, 2016; Schuch, 2011). Importantly, we are barely able to detect low mass and long period planets around other stars which are the most likely to have life. We will have to wait and see what we find (Fig. 3.9). I predict that by mid-century (*ca.* 2050), another life bearing world will be found in our galactic neighbourhood (Fig. 3.10).

It makes sense at this juncture to distinguish between the type of life that existed on Earth for over 4 billion years and life capable of interstellar communication. The latter has existed for roughly 150 years or about 0.000003 % of the history of life on Earth. How much longer will we survive? Can any of us imagine our civilisation persisting for another thousand years? Nick Arndt cautions me that **this** should be factored into any estimation of the probability of finding a technologically advanced civilisation on another planet around another star.

Many interesting scientific leads arise if we ponder that which is *un*-inhabited. What if there never was life in some place that is otherwise deemed habitable now or in the deep past? What physical or chemical process or lack thereof could have prevented its origin? We can speculate further. Maybe a minimum length of time is needed to transition from the non-living to the living under a wide range of special prebiotic chemistry conditions requires more than 30 Myr or so, which also corresponds to the lifetime of a thermal regime inside the largest carbonaceous asteroids that satisfies the stability of liquid water

41. <https://sci.esa.int/web/gaia>

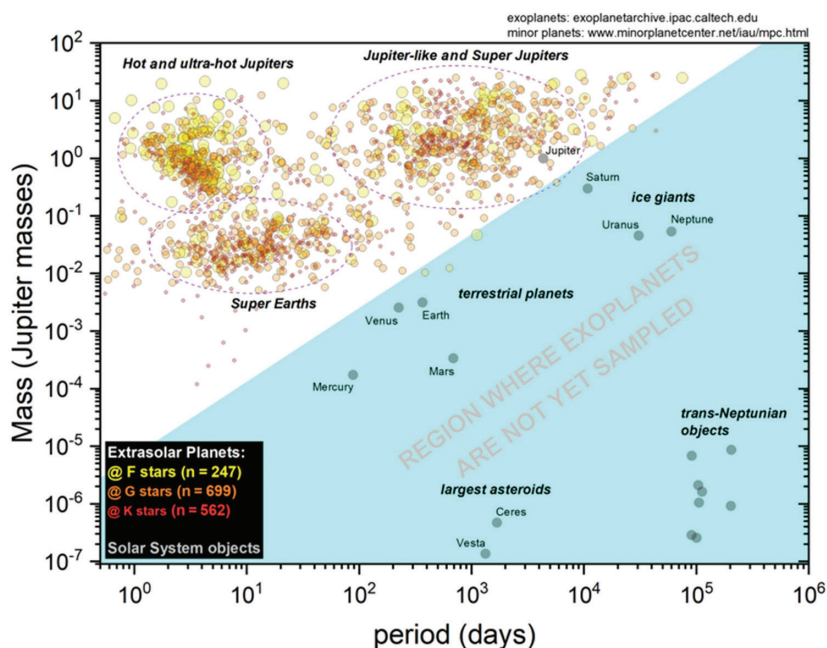


Figure 3.9 Planet soup. This figure illustrates the relationship between the mass and orbital period of various celestial objects including Solar System planetary bodies and extrasolar planets. It categorises objects into groups like “Hot Jupiters”, “Super Earths” and “terrestrial planets”. Highlighted in cyan are areas of ongoing discovery. Symbol sizes for extrasolar planets are coded for the kind of host star for the exoplanetary system. Source data: exoplanetarchive.ipac.caltech.edu.

(Abramov and Mojzsis, 2011). Maybe the mix of chemistry lacked certain key elements or compounds at the correct steps in the process, or there was no way to blend chemistry from different sources that was needed to progress to proto-biochemistry because mixing was impeded. It could also be that the timing was such that crucial stages in the process towards operative biochemistry were curtailed because of endogenous factors (*e.g.*, planetary object was too small and cooled too quickly to melt rock and re-set redox gradients, or was too large and never left the magma ocean stage) or exogenous factors (not the right kind of late impactor flux), or early stellar activity (flares). The answers will very likely have to wait until we discover an independent origin of life somewhere, and probably then, around another star. Some have argued that regardless of imperative, the nature of biochemistry is universal and that in our Galaxy there are millions, or perhaps billions, of life bearing planets. This idea is called the Universal Nature of Biochemistry (Pace, 2011). All the same, this attractive (and probably correct)

idea falls within the Fallacy of Single Cause⁴²: Everything that we know of biochemistry is strictly limited to one example from Earth. The best test of life's chemical universality will be to find this somewhere else.

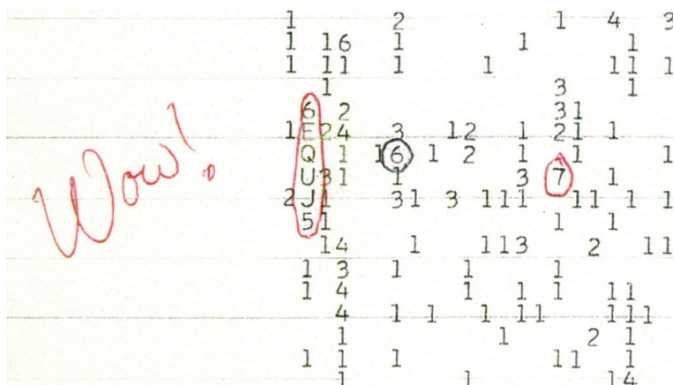


Figure 3.10

Is somebody out there? The so-called “Wow!” signal was a strong, narrow-band radio signal detected in 1977 that was thought to be a candidate for extraterrestrial intelligence (circled areas). Recently, it was proposed that the signal was caused by emission from a cold hydrogen cloud, triggered by a powerful transient radiation source such as a magnetic flare or soft gamma repeater (Méndez *et al.*, 2024). This event caused the hydrogen cloud to suddenly brighten at the 1420 MHz hydrogen line, producing a powerful, short lived signal. If so, this is not an alien communication. From the Big Ear Radio Observatory and North American AstroPhysical Observatory (NAAPO).

Regardless of my gnawing doubts about astrobiology, I was delighted when UCLA became one of the founding members of the Astrobiology Institute. Another founding member was the University of Colorado at Boulder, where I was later to take up a tenure stream faculty position and spend most of my career. The benefits of being part of the NAI were based on the momentum generated by origins of life studies in the mid-1990s, and, I firmly believe, on the successes of the NASA Specialized Center for Research and Training in Exobiology to build a nascent community of origins of life researchers.

Geochemical Perspectives is published by the European Association of Geochemistry. My life, personally and professionally, is now in Europe. Consequently, I would like to see something like a more structured Origins Institute created here in Europe as a permanent organisation along the lines of a Max Planck Institute or perhaps something different. If only something like that could come to fruition, it would benefit the general field of “Origins” (Life and

42. Also known as causal reductionism. This is when one assumes a singular uncomplicated cause of an outcome when in reality it may have been caused by any number of requisite causes. The logic of causal reductionism can be reduced to: “A caused B to happen; therefore, A was the only cause of B” (even though X,Y,Z,...etc. also participated in leading to B).

the Universe) greatly, because there would be a go to place for such things that everyone in the world would be aware of. There are many small examples of such institutes in the UK, France, Switzerland, Netherlands, Denmark, Norway and so on. The Max Planck Society in Germany has unique resources, and they tried at least twice in the 2000s and as recently as 2019 to create a Max Planck Institute for Origins. From what little I know, the effort tragically collapsed for some reason, and I wonder if it will ever happen that a large Institute of Origins will be established in Europe. Somebody out there must pick up this torch, because it too late in my career for me to do this as it requires an investment of 30 years to do it.

Stepping back a little, I wanted to mention that at the time that I wrote the postdoctoral support proposals to both the NSF and the UC President's Office, my idea was to not just keep carrying on with my Ph.D. thesis studies. I had other fish to fry and felt strongly that it was time to move on to other topics. One of these was to make use of the Hadean zircons that had been discovered in the early 1980s from some outcrops in Western Australia. My intent was to test directly, whether Earth in its first 500 Myr was an uninhabitable place as many seemed to believe. Just because we did not know anything about the environmental conditions of the Hadean Earth from direct analysis, did not keep certain people from imagining what it could be like. In my work on early life, I was told to my face that life was "impossible" before 3.8 Ga because of so many reasons like Earth was an ocean of magma, had a steam atmosphere, or was bombarded by comets and asteroids to oblivion. There are a lot of folks out there who have a view of the Hadean that is defined by the name itself rather than what it is. How did this "eon without data" come to be named, and what is its association with realms infernal if any?

3.6 Defining the Hadean Eon

Many of the inexplicables that afflicted the ancients are with us commonplace rational facts and operations.

Of Stars and Men (Shapley, 1958)

The prevailing view is that the chemical steps toward life's origin happened in the first 500 Myr, in what is termed by (most) geologists the Hadean eon⁴³. This early time is viewed in contrasts. Either it is where hellish landscapes prevailed under a menacing sky, or it was instead a time where quiet seascapes nurtured biochemical entities and later, even, microbial communities (both possibilities were reviewed by Arndt and Nisbet, 2012). The idea that planetary conditions

43. Priscoan (or Priscoan period) is a term derived from the Latin *priscus* meaning "ancient". This is a less desirable term (in my opinion) because hardly anyone uses it, and the word "period" is a fundamental unit of geologic time that sub-divides "eras". I would argue that neither period nor era can be used for this earliest time where no geologic record exists *per se*.

after formation must thermally settle down to allow for living beings has a long scientific history. Gottfried Wilhelm Leibnitz (1646–1716), the great natural philosopher and co-inventor of the integral calculus, described in his 1680 work *Protogaea* (Eckhart, 1719) the idea that our planet began as molten rock and metal before cooling to form a primitive crust (scoria) and that abundant glass quenched by primordial water would have covered the surface of the young planet (Mather and Mason, 1939). This dramatic background has coloured our view to such a degree that the term Hadean has the immediate effect of invoking a shamefully hot and hellish landscape of the Classical Judeo-Christian style. Such preconceived notions continue to affect most people's perceptions of the Hadean Earth (Fig. 3.11). Many would argue that life could not get started in the early days because they imagine that everything was a molten hellscape thanks to late heavy bombardment by asteroids and comets. As I mentioned in Section 1 of this work, the claim is based on a guess that is in turn based on the assumption about the deleterious nature of late accretion.



Figure 3.11

Falling sky. This image is the classical and rather exciting view of the Hadean eon on Earth. Nearly everything we thought about how awful this environment must have been since replaced by a more benign history. From Mojzsis/ChatGPT.

On top of that, there is some debate over the very definition of the Hadean that goes back to the origin of the term as coined by the great American geologist/geobiologist Preston Ercelle Cloud. He intentionally named it as an interval of time between Earth's formation roughly 4.5 billion years ago (4.5 Ga) and the time "...for which no certain (rock) record has been discovered on Earth" (Cloud, 1972). The infernal picture of the Hadean was never Cloud's intention. Rather, he meant it to invoke the Classical Greek sense of a dark and mysterious place akin to the realm of the underworld. Again, by definition, the Hadean-Archean

boundary is not a specific event in the geologic record, but merely the age of the oldest rock thus far discovered (Awramik, personal communication 2003). Thus, based on this informal definition the time between the end of the Hadean and the subsequent Archean eon corresponds either to the oldest rocks of the Acasta Gneiss Complex in the Northwest Territories of Canada at *ca.* 4 Ga (e.g., Mojzsis *et al.*, 2014), or to the rare *ca.* 3.83 Ga paragneisses documented in the southern Færinghavn terrane within the Itsaq Gneiss Complex of southern West Greenland (Nutman *et al.*, 1996; Bleeker and Stern, 1997; Gradstein and Ogg, 2004; Manning *et al.*, 2006). The International Commission on Stratigraphy has proposed that the Hadean-Eoarchean boundary be set at 4 Ga, regardless of whether there is geological significance to this number (Cohen *et al.* 2013). The Hadean eon needs a beginning (Fig. 2.5), maybe this is the timing of the first solids, or that time of the Moon forming event at 4.51 Ga (Barboni *et al.*, 2017) and possibly somewhat later (Connolly and Bizarro, 2016). My preference would be for the Moon forming event as that start of the Hadean eon.

As a matter of fact, the name Hades itself has an etymology that fittingly translates to “unseen one” in Classical Greek (Kerényi, 1951). Following tradition, it remains the case that a clear definition for the Hadean continues to be murky.

My quality of life moving from San Diego to Los Angeles in November 1997 was on an upswing, not the least because of a boost in salary. When I learned that I was going to be honoured with two postdoctoral fellowships, I could finally have some peace of mind as far as the finances go. Looking around and making inquiries at the university, I learned that the scholarly and congenial Peter M. Narins from the Integrative Biology and Physiology, and Ecology and Evolutionary Biology departments at UCLA, had a small house to rent. It was close to my new job!

Like I mentioned already, I was determined to try new things in my postdoctoral years and to not just keep chasing the Akilia “controversy” and defending my work on early life. That said, it was not over yet. Before moving to LA, I made a list for myself of what I wished to learn to improve my knowledge of the “Early Earth” from a far more practical perspective based on metamorphic field studies, and the union of stable isotope geochemistry/crystal chemistry with geochronology. These were just the kinds of things that the folks at UCLA were good at, and I set about trying to learn from their expertise. Here is the to-do list I came up with (in no order), that was in part driven by the vociferous Akilia debates:

- 1) Find a set of reliable criteria that could be used to determine protolith of high grade metamorphic rocks so there is no confusion about what they were originally.
- 2) Determine ways in which crystal chemistry and U-Pb zircon geochronology can be combined to reconstruct original igneous (or not) *vs.* metamorphic *vs.* hydrothermal ages to transcend arguments

over “inheritance” in that the apparent age of the rock is not what it seems. Recall, any geochronology gives you an “event”, and it is up to us to figure out what that event really means.

- 3) Go beyond the preserved rock record to the Hadean zircons and geochemically explore this resource to see if we could make sense of these geological “dark ages”.
- 4) Test the idea that bombardment of the Hadean/Eoarchean Earth would necessarily sterilise the planet. Assumptions about the bombardment could hold us back.

If I say that I worked hard and played hard in San Diego, it is because there was so much catching up to do, academically. I was surrounded by so many brilliant people and felt that I was far behind in everything. Those years taught me how to teach myself, to refine my goals and to parameterise my expectations of what can be achieved. In Los Angeles, work took over my life, and I spent long hours in the laboratory preparing samples, learning new science, collecting data, interpreting results, and writing. I was under no illusion that it would be easy to realise my dream of becoming a professor somewhere unless I put in all my effort.

3.7 Jack Hills, and Finally a Hadean Record of Something

Everything we assumed about the first 500 Myr and the conditions for life’s origin(s) was challenged by the reality of the discovery of >4 Ga zircon crystals in younger *ca.* 3 Ga quartzite rocks from the Narryer Gneiss Complex in Western Australia (Froude *et al.*, 1983; Compston and Pidgeon, 1986). Since that time, more Hadean zircons have been discovered (Harrison, 2009) including in the Barberton Greenstone Belt of South Africa (Drabon *et al.* 2021; Fig. 3.12).

Zircon ($\text{Zr}(\text{SiO}_4)$; zirconium orthosilicate) is a mineral that tends to crystallise from evolved melts such as those that constitute the continental crust. But this mineral can also be found in other types of rocks (even gabbros). Zircons are dense, resistant to weathering and can survive many crustal recycling processes including partial melting of their host rock. Since they were discovered, the isotopic, elemental and mineral inclusion mineralogy of the Hadean zircons have been shown to be similar to those of modern granites and granitoids (Maas *et al.*, 1992; Amelin *et al.*, 1999; Mojzsis *et al.*, 2001; Trail *et al.*, 2007a,b; Hopkins *et al.*, 2008) that form as relatively wet melts at relatively low temperatures (Watson and Harrison, 2005), under oxidising conditions (Trail *et al.*, 2011), probably (but not, definitively) from subducted hydrated oceanic crust (e.g., Campbell and Taylor, 1983; Ge *et al.*, 2023).

The last chapter of my Ph.D. thesis in 1997 concerned the documented occurrence of pre-4 billion year old mineral grains from the Narryer Gneiss Complex (Mt. Narryer and Jack Hills) in Western Australia and my plans to work on them soon. In that chapter, I thought about ways these oldies could tell

us more about the Hadean Earth, and it was obvious to me that this amazing geological resource was not being investigated enough. Sure, now and then very clever people touched the old zircons, folks like the world famous Yuri Amelin, Alex Halliday, and Malcom McCulloch. Sitting in Mark Harrison's office one day at UCLA in late 1998, I stood up and made the "research pitch" to him that I thought it would be worthwhile to investigate the Hadean zircons with the new analytical powers he had available in his lab.

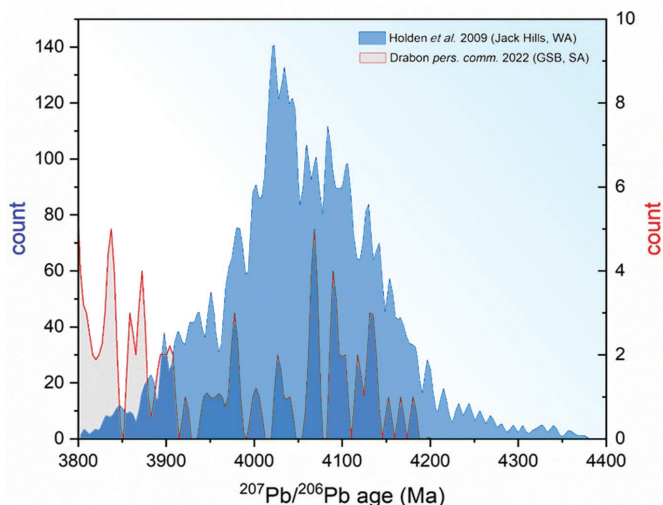


Figure 3.12

The oldest direct geological records on our planet. Shown here are population-age data for the oldest zircon ages expressed in millions of years (Ma) against the number of zircons yielding a particular age (count). The blue data field are from Holden *et al.* (2009) for the Jack Hills in Western Australia. Superposed on those data are new results from another Hadean zircon locality in the Green Sandstone Bed (GSB) in the Barberton Greenstone Belt of South Africa. Note the scale difference for the two data sets. GSB data courtesy of N. Drabon.

Perking up in characteristic style with a wry smile on his face, I remember Mark saying to me: "You know, I have been wanting to do this kind of thing for a long time! For example, wouldn't it be cool to look for evidence of the decay of 244-plutonium!"

Then, he went on about how such a measurement could be made in theory, as well as trying our luck in the search for other daughters of extinct nuclides like ¹⁴²Nd. Of course, it would help if we had the sample! How?

I remarked: "Let's do it. Whatever it takes. Let's go there, get our own samples and do the necessary tests ourselves."

Previously, I brought up the idea of working on the old Jack Hills zircons in late July 1997 with the inscrutable John S. Myers in one of the small storm reinforced huts built on top of the Isua Supracrustal Belt in West Greenland⁴⁴. As the Hungarian saying goes, such talk is all too frequently fuelled by liquid courage⁴⁵ rather than realistic principles. Can you imagine how many publications any of us would have based on booze fuelled proclamations? To no avail. My many subsequent attempts by available channels (email, telephone) to follow up on promises of Jack Hills samples were met with radio silence. That is, until I was ultimately told to buzz off and wait my turn "...until (so and so) finishes writing up a paper on these grains".

I was getting nowhere with this, I was/am impatient and had to try another way. Soon after, we I met up with the unique Bob Pidgeon at the 1998 Goldschmidt Conference in Toulouse, France, over a meal and some drinks (see footnote). After a short while, the three of us resolved to just go out to the Narryer area and collect our own samples at both Mount Narryer and the neighbouring Jack Hills. I remember very clearly when we met Bob in the lobby at the Ice Breaker party. He had a big grin on his face and was wearing a t-shirt with a crystallographic drawing. With the drawing were the words "Zircons are forever". Class act. Soon after, I wrote a proposal to the Director's Discretionary Fund of the Astrobiology Institute to pay for a small party of us to go down to Australia and pick up rocks. It was funded (Fig. 3.13)! Anyhow, when I later shared the news that I would collect my own samples and no longer required cooperation with my erstwhile obstructionist, you can guess the incandescent reaction I got. Email is unforgiving. Indeed, it can be downright uncouth. We and our esteemed colleague Frederick "Rick" Ryerson will recall this particular procrastinator who denied me the promised Jack Hills' samples while sitting together one afternoon (probably at a bar somewhere). I was jokingly likened to a certain 'n'er do well cartoon duck in the Warner Brothers' *Looney Tunes* franchise⁴⁶. That label – which I wore proudly – had us laughing with the lateral lisp "disth-picable" all the way across the equator to Australia! Ha. My second paper to *Nature* magazine (January 2001) also made the cover story. I was told that people in the business were beginning to get the idea that Mojzsis was not

44. This collection of huts was affectionately dubbed Appelstat after the Dutch-Danish-Indonesian (born in Java!) geologist Peter W. U. Appel. A native Danish speaker might complain that the proper name for the place ought to be *Æbleby*. In any case, when I last visited the place in 2021, two of these structures were still standing after twenty-five Greenlandic winters.

45. As such, "liquid courage" is an international euphemism for alcoholic beverages (Hu: folyékony bátorság). If memory serves, Johnny Myers and I drank a vile mixture of Gammeldansk, Akvavit and Ginger Wine during our conversation about the old zircons. As the saying goes: "When the wine goes in, strange things come out."

46. Daffy Duck's only friend was the superpowered Bugs Bunny. I am thoroughly convinced that the two cartoon characters were based in no small part on the Road movie series that starred Bob Hope and Bing Crosby.

going away. That said, it would be disingenuous of me if I made the claim that having two cover papers in *Nature* magazine had nothing to do with me landing a tenure track job at the University of Colorado at Boulder.



Figure 3.13

Mob on walkabout. Shown here are a gaggle of famous geologists having a look at the Mt. Narryer region of the Narryer Gneiss Complex (NGC) in 2001. From left to right: Bob Pidgeon (orange hat), Sasha Nemchin (arms crossed), Joe Kirschvink (hands on hips), Munir Humayun (back turned), Mark Harrison (big smile) and Trevor Ireland (UNOCAL hat). The NGC encompasses rocks of the Jack Hills and Mt. Narryer outcrops, on the northwest corner of the Yilgarn Craton, Western Australia.

There was a lot of healthy opposition to our findings from the Jack Hills zircons that a hydrosphere was already present on Earth at about 4.4 billion years ago and that probably continental crust was present also at that time. Yet, this work was never as vociferously debated as the Akilias. That is the case even if both publications presented testable hypotheses that have since been progressively investigated and continue to yield results.

With all of this going on, I gradually learned to navigate the intense (even, actinic) spotlight that was shone on me for playing a role in these discoveries. At first, it was nerve wracking because who is ever trained to talk to journalists from our profession? But then I learned. People say that I can be gregarious, and some would say loud and outspoken. With practice, I found a voice in public service. It was now the case that I was being asked to participate in international popular science programmes such as those produced by the BBC, PBS in the USA, and NHK in Japan. These experiences helped me to hone my skills at public speaking and to build a better, quieter and more confident self-image. Quiet confidence

does a lot to increase the efficacy of sharing the excitement of scientific inquiry and discovery with interested non-scientists. That said, it never seriously crossed my mind to become some kind of professional science populariser in the ilk of Bill Nye, Michio Kaku or Neil deGrasse Tyson. The singular Carl Sagan was and continues to be in a class by himself because like Charles Darwin (another great science populariser of his time; people seem to forget that), Sagan was writing scientific research papers and popular science literature to the end of his life.

Besides working on the fabulously productive Hadean zircon record of the earliest Earth, I tried my hand at writing a proposal to the US National Science Foundation (NSF) in 1998 to its (very unfortunately, now defunct) Life in Extreme Environments (LExEn) programme to continue our work on the Akilia. I got the money! That modest 3 year project was to go back to the islands off the coast of southern West Greenland (in the Davis Strait) and carry out more detailed analysis including mapping at appropriate scales and to address the criticisms of the Akilia work. We sought to learn more about the geological history of the southern part of the Itsaq Gneiss Complex on our own (Fig. 3.14). Our whopping field programmes in 2000 and 2004 in the area and the samples collected are still useful (*e.g.*, Tropper *et al.*, 2025). I have counted >20 publications from that single NSF LExEn project. Regardless of this kind of progress, it is unfortunate that in all subsequent years NSF rejected every single one of my proposals. It did not matter that they touched on a wide range of topics, and in multiple different programmes from Instrumentation to Geobiology to Petrology/Geochemistry, they were rejected. Thankfully, NASA and its Astrobiology and Exobiology programmes sustained my research run at the University of Colorado for more than two decades.

By the end of 1999, I had enough experience in working with the ion microprobe on stable isotope geochemistry and U-Pb zircon geochronology to begin collecting together new data for the purpose of publishing papers on topics well beyond my Ph.D. thesis work. These included the first multi-collector SIMS analyses of O and Pb isotopes in Hadean zircons (Mojzsis *et al.*, 2001), depth profiling of U-Th-Pb and geochronological analysis of zircon at sub-micrometre scales (Mojzsis and Harrison, 2002b), as well as studies of granulites from south-central India (Mojzsis *et al.*, 2003). Another thing that happened in 1999 (besides the silly and impending Y2K scare⁴⁷) was that, suddenly, there were lots of tenure track academic jobs opening up, including in the broad area of Astrobiology. Mr. Lucky strikes again. Looking back, I think I can count five from that time (Maryland, Hawai'i, Seattle, Carnegie-DC, and Boulder). As I mentioned earlier, the economy was humming along well in those days and the mood of the nation was upbeat. Clearly the two go together. If most of the population feel good about how things are going, then guess what? The economy is up. Yet, all of that came to a crashing halt on January 20, 2000, thanks in no small part to the coup of hanging chads in Florida.

47. https://en.wikipedia.org/wiki/Year_2000_problem



Figure 3.14

Yo-ho-ho. Sometimes the weather can be pretty good, even in southern West Greenland on the shores of the Davis Strait. You will hear it said that this country has three seasons: July, August and Winter. Here, Craig Manning and I are navigating around between islands hosting outcrops of some of the world's oldest rocks, including those of sedimentary origin. Our craft was a simple Boston Whaler. Photo credit: C.E. Manning.

What a farce, and the world has been paying the price for it over the past quarter century.

While attending one of what was to become a gallant parade of interview talks at UCLA (where I stayed until December 2000), we were visited by the ingenious James Farquhar who described how multiple sulfur isotopes (usually measured as ^{32}S , ^{33}S , ^{34}S and expressed in the conventional delta notation as $\Delta^{33}\text{S}$; lately ^{36}S is also measured) preserved excesses and depletions in the minor isotope ^{33}S relative to that predicted by mass dependent processes in the ancient rock record. James, working with perceptive Mark Thiemens went on to show how these mass independent fractionation (MIF) signals can tell us something about the history of atmospheric oxygenation (Farquhar *et al.*, 2000). This was ground-breaking stuff! Again, as with all such discoveries, there was a fierce pushback by some researchers who expressed doubts about the nature of the analysis. At the time, it was obvious (to me, anyhow) that a lot of this kind of opposition arises because it violates somebody's pet theory that is already resting on weak foundations.

It came to my mind that beyond the application to atmospheric evolution that James Farquhar was talking about, that the multiple S isotopes could also tell us about photochemistry on Mars from analysis of martian meteorites (Greenwood *et al.*, 2000), the history of sulfur metabolism, and in addition, of rock protolith (Mojzsis *et al.*, 2003). With Kevin McKeegan and Chris Coath I set to work with the ims1270 in multi-collector mode to test if we could find the same signals as James and colleagues had found. We did. At another Goldschmidt conference, this time in 2001, there was a vigorous debate over whether the MIF values were artifacts of, either or both, the sample preparation and laser fluorination procedure used by different laboratories. A large group of geochemists had gathered to listen to competing talks for and against the MIF data. All presentations in this cantankerous session used some variation of laser fluorination techniques except for the one I gave, which reported Kevin's, Chris' and my multi-collector ion probe data. At the end of the session during question/debate time, another isotope pioneer Douglas "Doug" Rumble III stood up and asked the session chairs if he could present his supporting evidence for MIF sulfur isotopes. It was his intention to show that the work was not some kind of analytical artifact (funny, I recall that nobody had any qualms about the ion probe data!). On the other hand, the indefatigable Hiroshi Ohmoto and his co-authors presented a legitimate alternative hypothesis for the signal that had nothing to do with a record of the past atmosphere. If memory serves, the back and forth went something like this:

Pro-MIF participant: "Our data reproduces the results that Jim Farquhar shows from the same rocks."

Anti-MIF participant: "Well, I think that you experience the same problem with your sample preparations."

Kevin McKeegan, standing up: "Let me make this absolutely clear for everyone, with the ion microprobe analysis, the only preparation step involves polishing the sample."

There is no business like show business like no business I know⁴⁸, but as with science, this was a classic mic-drop moment⁴⁹. The atmosphere was electric and frankly speaking, it seems that such open and healthy debates are becoming increasingly rare. I attribute this to political trends that stifle any kind of debate that might hurt someone's feelings, and hope to see us get back to constructively arguing with one another. Fear of offending someone somewhere for a perceived slight is detrimental to a functional society. This kind of cowardice allows demagogues to take power. For example, when in 2025 I attended the Goldschmidt conference in Prague, the Europlanet Congress in Helsinki, the European Geosciences Union assembly in Vienna and the American Geophysical Union meeting in New Orleans, I witnessed very little debate at all. Furthermore,

48. <https://www.youtube.com/watch?v=PliQMsdQ0Uo>

49. https://en.wikipedia.org/wiki/Mic_drop

there were lots of completely unnecessary “thank you for the very nice talk” comments preceding every darn question to any speaker. On what grounds do we judge a talk to be a “very nice talk”? Just ask the question.

After making the rounds of my own in the tenure track interview process, and having some “false positives” from a couple of places (including one particularly close to home that called a failed search, twice, if you can believe it; if I was the Dean, I would have been pretty upset by it), I hit the proverbial jackpot. My polychronic colleague Bruce Jakosky called me up at my office in UCLA: He was offering me a job as tenure track Assistant Professor at the University of Colorado in Boulder!

After jumping around for joy, I realised that this news was profoundly life changing. Colorado in general, and Boulder in particular, is a wonderful place to live. Mountains, deserts, plains, forests, rivers, lakes, glaciers and wildlife abound there. Wide open spaces are plentiful, and I was to move to the close in (but nevertheless far out) city of Boulder.

It was surprisingly difficult for me to leave Los Angeles. I had really grown to like the place. For those of you who say otherwise and are somehow shocked that someone could enjoy LA, may I ask you, point blank: “Have you ever lived there?” One of the friends from that formative time, the talented physicist Monika Kress, always seemed to share my enthusiasm for exploring LA. Getting stuck on a freeway does not count as a reason to hate the place. I had to say goodbye, but at the same time I was ready for another big change and the chance to break out into more independent directions.

The ideas that germinated in my time at UCLA gradually came to fruition in various NAS funded projects and in the dynamic research environment of the Center for Astrobiology that Bruce Jakosky had established in Boulder. Besides me, he also recruited to Boulder’s Astrobiology program the unique Norman R. Pace, one of the godfathers of modern geobiology and microbial ecology, and a tremendous mentor to me and many others. Around the same time, the legendary Peter Molnar joined the faculty of Geological Sciences at Boulder, and he was always a reliable source of wit and knowledge (but not necessarily, wisdom). I was determined to do something new as a young professor and try my hand at metamorphic field petrology coupled with stable and radiogenic isotope geochemistry of the oldest terranes and begin delving more into planetary sciences. Boulder was building its planetary geology programme despite some resistance from those who thought that more resources should be devoted to the same old. Planetary sciences in Boulder included a growing list of people besides Bruce. One of these was the newly hired planetary scientist Robert “Bob” Pappalardo. Others there included the energetic Larry Esposito, Nick Schneider, Fran Bagenal and local exceptional talent at the Southwest Research Institute’s field office in Boulder with the amazing cast of Harold F. “Hal” Levison, William “Bill” Bottke, Luke Dones, Alan Stern, Robin Canup, David Grinspoon, Robert

E. Grimm and many more who came later. I remember fondly that Hal, Luke and Bill were all at my job talk in early 1999 when I did not know whether I would have a permanent job in my academic future.

It was becoming clear to me now: The more I worked on the problem of the geology of the origin of life, the more I found that Hadean Earth was entirely conducive to its origin. It ought to be, because life is here after all. Yet, despite a flurry of activity in the last two decades, several key outstanding questions remain about how Hadean Earth – the first 500 million years – functioned, and what these means for the origin of life. Here are the ones I will touch on now:

- (i) What kind of crust could have existed in Hadean times?
- (ii) When did Hadean Earth have liquid water at its surface?
- (iii) Was Hadean Earth a “Water World” as many claim?
- (iv) Did late accretion bombardment modulate Earth’s proclivity for the origin of life?

In those cantankerous segments of the Earth Science, Biochemistry, Biophysics, Organic Synthesis and other communities that concern themselves with biopoiesis (the process by which living organisms develop from nonliving matter), we should have the ability to arrive at a consensus on the answers to these questions. I would say that one of the biggest reasons we have not converged on a view of Hadean Earth is that we collectively could do a lot better job of sharing what we have learned with the wider community of geologists and biologists. Everyone seems to forget that Earth is pretty good at erasing its past.

3.8 Absence and Ambiguity in the Earliest Geologic Records

Geodynamics concerns the inner workings of solid planets, and thus how the interior is expressed in the exterior crust and fluid envelope (Turcotte and Schubert, 2002). Any discussion of the origin of life in a planetary context must consider terrestrial planet geodynamics and its relationship to the surface zone. This begins with defining the two basic modes of mantle convection that we observe in our Solar System: single lid convection and plate tectonics (Davies, 2009; Korenaga, 2013). Debate is strenuous to say the least over which was operative – single lid or mobile lid – on early Earth. Otherwise, Mercury, the Moon, and the dwarf planet Ceres⁵⁰ have little in terms of active geological processes at the present time.

50. Ceres shows evidence of recent cryovolcanism, but this is far from the equivalent to melting of silicate rocks.

Observations of Mars and Venus show that neither has a lithosphere that is broken up into discrete plates in the plate tectonics sense, but there are some such as the energetic Jean Bedard and others argue for large horizontal displacement of the crusts of Venus and maybe Mars (Fig. 3.15). A caveat to this statement is that nobody is quite sure whether either of these ever had subduction, much less plate tectonics at some time in their distant pasts. Instead, today, these planets have mantle regimes that behave under what is dubbed single lid convection. The term “stagnant lid” is frequently used to describe this geodynamic scenario. This term is something of a misnomer because the single lid is neither stagnant nor is it necessarily rigid: it can be locally mobile, extensively deformed over hemispheric distances and is commonly affected by volcanic activity mostly in the form of discrete convective upwellings of plumes (*e.g.*, Weller and Lenardic, 2018). Convection in Mars and Venus takes place beneath the single lid. Their mantles can still melt and degas to create crust and atmosphere, especially *via* plumes, but this is a one way mass transport. Under this convective regime, there is little or no effective downwelling of material from the surface back to the mantle. But the crust cannot thicken forever. Advocates of the stagnant (or squishy) lid propose that the lower part of the crust periodically founders, possibly because basalt converts to dense eclogite (*cf.* Roman and Arndt, 2020; Arndt, 2023). These arguments are central to the ideas of those who talk about sagduction as an early process. Sagduction is the alternative idea to subduction which involves vertical tectonic movements. The effective recycling of crust is the most important difference between single lid convection (Mars, Venus) and plate tectonics (Earth) for the long term sustainability of the biosphere. That is because for the former effective recycling of surface components, such as sediments, is stymied or may not take place at all. Unless rocks can react with the fluid envelope of the atmosphere and hydrosphere during weathering,



Figure 3.15

Gallery of Solar System terrestrials. A terrestrial planet is, by definition, one that is dominantly composed of silicate and metal, with or without an external fluid envelope. It is generally assumed that such planets form close to their star. From Wikipedia.

denudation, erosion and deposition, and return this material to the mantle, there can be no planetary scale geochemical cycle. Single lid convection is likely the most common convective mode for the silicate mantles of rocky planets, and the default mode for those without liquid water oceans at the surface that interact with the crust (Rosing *et al.*, 2006).

The overall decline in preserved continental crust with increasing age is based on the interpretation of the detrital zircon record which shows a roughly 1.5-2 Gyr e-folding time. The e-folding time is the time interval T in which an exponentially growing quantity increases or decreases by a factor of e (Fig. 3.16).

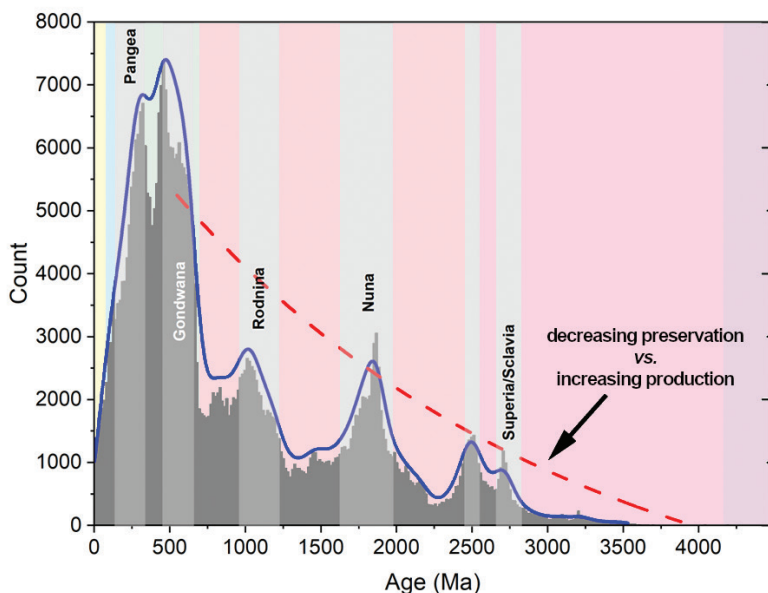


Figure 3.16

Which do you prefer? Histogram of $^{207}\text{Pb}/^{206}\text{Pb}$ ages filtered for $\geq 90\%$ concordant detrital zircons from samples collected worldwide and calculated from their present day U and Pb isotope ratios (Wu *et al.*, 2023). The geochronological data correspond to the age of crystallisation of the parent igneous rock. Analysis of 402,249 detrital zircons shows several peaks in their U-Pb crystallisation age populations (counts), overplotted with a Kernel Smoothing Distribution (violet curve). The preservation potential of rocks means that there is an overall decrease in counts/occurrences with increasing age. The red dashed line shows an exponential decay fit to the pre-Phanerozoic (>543 Ma) data, with an e-folding time of ~ 1.4 Gyr. The peaks tend to coincide with documented periods of supercontinent formation (vertical gray bars). Data compilation from Wu *et al.* (2023).

The residence time of the lithosphere is the average length of time that it will remain as a geochemical entity. To compute it, we can take the total amount of crust + lithospheric mantle and divide it by its rate of destruction or production (*i.e.* flux). Values for residence time are different for oceanic crust (short; about 200 Myr) *vs.* continental crust (long; several billion years). The residence time for the combined oceanic and continental lithosphere has been estimated to be about 500–750 Myr (Caro *et al.*, 2006). Residence time estimates for the Eoarchean lithosphere are twice this value (Saji *et al.*, 2018). This is about half the observed e-folding time for the pre-Phanerozoic (>542 Ma) continental crust, but close to the average mixing timescale since the Archean of about 420–440 Myr for primitive mantle, recycled continental crust and mantle residue (Guo and Korenaga, 2023). Assuming that the upper limit for the residence time of 750 Myr is a good estimate for the half-life of continental crust, then the e-folding time comes out to be ~1.4 Gyr, in agreement with both the detrital zircon record cited above, model calculations of crustal reworking (Korenaga, 2021a). If this is the complement of the Earth’s cooling rate (see below), it is important to keep in mind that the zircon record is strongly biased to continental crust, but is not exclusive to it. Zircon is most commonly found in granites and granitoids which constitute the major rock fraction of the continents (Rudnick and Gao, 2003), but can also be found in other rocks. That said, the amount of zircon in mafic rocks is miniscule compared to felsic lithotypes. The red dashed line in Figure 2.16 can therefore be interpreted to represent decreasing preservation of continental-type rocks over geologic time rather than increasing production of continental crust with time. Interestingly, if you fit an exponential to the excess temperature in the Archean of 300K above today and use a cooling rate of 150 K Gyr⁻¹ (*e.g.*, Herzberg *et al.*, 2010), the following e-folding time for the cooling rate of the Earth can be approximated by:

$$T \approx \frac{\Delta T_{\text{excess}}}{dT} \approx \frac{300\text{K}}{150\text{K/Gyr}} = 2 \text{ Gyr}$$

which is pretty much the same as the crust preservation e-folding time. Simply put, I would say that the increased preservation of crust by implication must have more to do with cooling of the planet and decreasing effectiveness at recycling, rather than by early destruction from asteroids or absence of continental landmasses as suggested by some.

It is often said that the biggest problem with studying the history of plate tectonics is that the process erases evidence of its past existence (*e.g.*, Müller *et al.*, 2008). This is because plate tectonics just keeps recycling oceanic crust as it has for billions of years. Although most of Earth’s crust by surface area is oceanic (~60 %), by volume it (surprisingly perhaps) is continental. The mean age of continental crust (*ca.* 2 Gyr) is 36 times greater than that of oceanic crust because its buoyancy prevents it from subducting except for loss to subduction *via* erosion, rifting and intraplate melting (Armstrong, 1991). As previously mentioned, age curves for crustal growth are heavily biased by selective preservation of the geologic record on established continental crust, which tends to stay preserved

and hosts zircons that are easily dated (Hawkesworth *et al.*, 2019) with the effect that less data for the existence of crust are preserved the farther back one goes in time. Furthermore, even if there is some evidence for plate boundary processes akin to plate tectonics found in one ancient outcrop somewhere, it does not prove that this was a global phenomenon at that point in time. Taken together, maybe plate tectonics has been around since the Hadean, maybe not (Korenaga, 2013). What does seem certain is that degassing of volatiles, including water, commenced very early. It is hence evident that crust including a mixture of oceanic and continental crust has existed on Earth for the last 4.4 Gyr and has been interacting with liquid water since that time.

I got to know the wily Warren Hamilton well in my time in Boulder, since he was just down the road in the Colorado School of Mines in Golden. What a great guy! Up until very recently, he was the only member of the US National Academy of Sciences in the State of Colorado. Warren and I disagreed on just about everything geological, but he was always very cordial, and we had good fun talking about rocks over craft beers in downtown Golden. Beer drinking and the joy of fieldwork were some things that we could both agree on. Here is the last correspondence I had with him, on January 10, 2016 (he died October 26, 2018). Names are redacted to protect the guilty:

“Hi Steve,

Plz look at the pictures and captions in my paper as sent you last week. I reject the “resurfacing” of Venus as nonsense, and regard the planetary surface as being as old as the Moon’s. And a number of illustrations in both Mars and Venus sections show “volcanoes” unlike any on Earth, and I maintain that they are impact melt constructs.

My whole pitch is that foolish assumptions were made 30–40 years ago by dominant nitwits, and have been mindlessly accepted by succeeding generations of sheep. This is enforced by the continuing control of peer review by ideologues. Thou shalt not buck ABCD, 123456, @\$!%^\$and, *etc.* and get grants. My evidence is in the imagery. Many more Venusian examples are illustrated in my prior Venus papers, copies on request. So yes, what I am saying is directly contrary to what everyone “knows.” Look at the pictures and see what you make of them. There’s theory too: the geodesy of Venus disproves the “resurfacing,” but for that you would have to read my text (and see geoid and topo maps such as I reproduced in earlier papers).

Warren”

Whatever you think of the man, he was always active and never shy about sharing the world’s expertise in his own opinion. And he was rich in opinions. I really believe that the world needs people like this to keep us on our toes whether you agree with them or not.

To end this section, and picking up on Jung, we want to fulfill our evolving selves. “The meeting of two personalities is like the contact of two chemical substances: if there is any reaction, both are transformed,” Jung wrote. It is evident that previously held ideas about the physical-chemical-mechanical nature of Hadean Earth are undergoing transformation, forced by the weight of the growing evidence. To help guide experiments seeking to understand key steps in abiogenesis and the chemical origin(s) of life on the archetypal terrestrial planet, I take some time now to review what is known about the nature of Earth’s hydrosphere, crust and atmosphere in the first few hundred million years. I pose the question: what could this mean for the pathways that led to Darwinian evolution?

3.9 Hadean Ocean Inventories

La chimie crée son objet.

Lecture at the Collège de France in 1864 by Marcelin Berthelot

A popular idea – one almost completely unsubstantiated – is that before plate tectonics became a dominant physical process on Earth, the crust did not effectively recycle itself and no crustal dichotomy of oceanic (basalt) and continent (granite) existed. Some have further argued that our planet existed as a Hadean “water world” with essentially no landmasses (*e.g.*, Russell, 2018). It is an important point to address. Earth’s current inventory of surface water in the oceans including the crust is 1.7×10^{21} kg (1.4 oceans; 2.8×10^{-4} Earth masses). Nearly all this surface water is in the oceans (1.39×10^9 km³) with the remainder found in groundwater, hydrated minerals, ice and atmosphere (Fig. 3.17).

With the contemporary surface inventory I just described, a world spanning ocean would be about 2 km deep in the absence of any land masses to displace the water. Presently, land area is 29.2 % of the total surface area of the planet so that the average ocean depth is about 3.7 km. In terms of bulk Earth composition, the rest of the water is locked up in nominally anhydrous minerals in the mantle and as hydrogen and oxygen in the core.

Estimates for Earth’s water have large uncertainties. Mantle water estimates range from 0.5 oceans (Smyth and Jacobsen, 2013; Pearson *et al.*, 2014) up to the storage capacity of about 11 oceans (Hirschmann *et al.*, 2005). A conservative estimate is that the equivalent of 6 oceans resides in the mantle (7.8×10^{21} kg). The core may hold about 5 oceans’ worth of water (Li *et al.*, 2020) or about 6.5×10^{21} kg. An estimate for the bulk water content of Earth (core + mantle + crust + hydrosphere + atmosphere) is thus 1.74×10^{22} kg, 2.9×10^{-3} Earth masses, or interestingly, around $\frac{1}{4}$ of a lunar mass and roughly equivalent to the total volume of Jupiter’s “ocean moon” Europa (Mojzsis, 2021). This value is 6 times greater than some previous estimates from coupled dynamical and geochemical models (Morbidelli *et al.*, 2000). Maybe these estimates are all wrong. There are



Figure 3.17

Planet Ocean. As Arthur C. Clarke is widely claimed to have remarked: “How inappropriate to call this planet Earth, when clearly it is Ocean.” Magnificent image taken from space showing our planet as a sapphire blue globe, flecked with soft wisps of cloud and capped by brilliant white fields of polar ice. In this image, the Pacific Ocean is at the centre, and the North American landmass (Baja California) can be found at the NE edge of the scene. From Google Earth.

many uncertainties involved in these calculations. Previous estimates for the core were unconstrained and thus generally no values were provided. We can regard ~0.29 wt. % of water for the whole Earth as a reasonable value. The fate of this water after the Moon formed was that it and other volatiles (CO_2 , N_2) in Earth’s magma ocean could be released to the surface during differentiation, cooling and mantle solidification (*e.g.*, Tikoo and Elkins-Tanton, 2017). That said, water is highly soluble in melts at high pressure and the release of water will happen with magma freezing. The amount of degassed water that is translated into ocean volume at the surface is uncertain, but there have been estimates from about 0.5 to about 2 times the present ocean volume. No estimates have been encountered in the literature that deviate from this range. Coming back to surface reservoirs of atmosphere elements for Earth and Venus, it is significant that the masses of carbon and nitrogen in Venus’ atmosphere are like Earth’s (Lécuyer *et al.*, 2000). This can be interpreted to mean that the carbon and nitrogen surficial inventories were established during the magma ocean stage for both planets (Gaillard *et al.*, 2022). Such early degassing of water comports with the Hadean zircon oxygen isotopic evidence. More direct inferences come from hydrothermally altered (serpentinised) rocks from the *ca.* 3.8 Ga Isua Supracrustal Belt in southern West Greenland; these have been used to argue that the Eoarchean oceans were up to 26 % more voluminous compared to the present (Pope *et al.*, 2012; Dong *et al.*, 2021). If one was to add another quarter ocean volume, it would increase ocean depth by about a 1 km over the whole Earth if continental freeboard (the relative elevation of continental landmasses compared to sea level) is removed entirely.

Again, if we accept the idea of extra water in the early oceans, then the average depth of the oceans in the Hadean in the absence of significant land masses and the extra water would be about 3 km, a bit less than the current ocean depth of 3.7 km owing to continental displacement. Doubling ocean depths in this case to about 4 km would require an increase in the volume of the oceans of about 55 %. This may not be unreasonable given all the other uncertainties with such calculations (Kasting and Holm, 1992). Increasing Hadean/Archean Ocean volumes to within such maximum plausible limits simply brings the depth into the range of contemporary values (4 km). In ANY of these scenarios, there would still be dry land in the Hadean just from emergent volcanic edifices (*cf.* Arndt, 1999). The volume or thickness of the continents has little to do with this. On the modern Earth, this is exemplified by Iceland. Iceland is a volcanic island with a surface area of approximately 103,000 square kilometres that formed along a mid-ocean ridge. Iceland is a massive, active landmass, rather than a small, singular volcanic cone that might be a good candidate analogue for a Hadean landmass. For another point of view, see Arndt and Chauvel (1991).

After arranging my professional and personal life and signing the contract to become a tenure track assistant professor of geological sciences at the University of Colorado in Boulder, I packed my bags and moved from the California coastline to the edge of the Rocky Mountains. After spending some time in Las Vegas and Zion National Park, I alighted on New Year's Eve, December 31, 2000, along with my traveling companion and new fiancé Gina L. Cianciola in my little black Honda Civic Si hatchback. This tiny car (nicknamed "kocsi") was packed with everything that otherwise would not fit in the moving van sent ahead to Boulder. We arrived at our small apartment and two metres of snow! After 8 ½ years in southern California, I was back somewhere that had deep winters. I had not experienced proper snow since leaving Boston in 1992. It took some time to get used to shovelling and navigating icy roads and driving in blizzards (Fig. 3.18).



Figure 3.18

The Boulder Flatirons. From most vantage points in the city of Boulder one can see The Flatirons. These crags consist of conglomeratic sandstone of the Paleozoic (Carboniferous) Fountain Formation. From Wikipedia.

Boulder is the largest population centre in its eponymous county and is located about 50 km northeast of the capital city of Colorado, Denver. It is a popular tourist destination, and a centre for athletes who like to train at altitude (1655 metres). The population of Boulder County, of which Boulder (city) is the main population centre, grew by almost 60k in the time I lived there. Boulder also holds the distinction of being the most educated city in the USA. It has also long been a haven for hippies, bohemians and alternative lifestyles. What I found remarkable is how deeply the place is culturally fixed to the late 1960s, an era that preceded my move there by over three decades. Owing in no small part to the fact that the University of Colorado (dubbed CU, rather than UC; this to avoid confusion with the University of California, and/or with U of C which stands for the University of Chicago) hosts more than 31,000 total undergraduate and graduate students, this place has a well deserved reputation of an educated and artsy population even if it is stuck in some kind of time warp. In other ways it is vastly forward looking: The city and surroundings also host many co-dependent scientific institutions that are variably associated with CU academic departments such as LASP, CIRES, INSTAAR, CASA and so on. Then there are the federal institutions like NCAR, NOAA, USGS, NBS and others. I have already mentioned SwRI, but there are other independent unrelated (but not tangential) research institutes in the area. The place is awash in acronyms to say the least and I used to create a kind of diagram for people visiting the place – including prospective students, postdocs and faculty – that portrayed the whole alphabet soup of institutions and the degree of separation from the university, that was like an onion skin model.

Besides the local martian specialist Bruce Jakosky, other faculty members in my department that I immediately connected with the famous clay chemist Katheryn Nagy with whom I shared my office cluster, as well as other fellow faculty members in Geological Sciences with shared interests in geodynamics, mineralogy and all things Earth: Joseph R. Smyth, Hartmut Spetzler, Roger Bilham and the illustrious Peter Molnar. Soon after my arrival, I introduced myself to Peter to talk to him about shared interests. I was encouraged to do so by my UCLA colleague An Yin before I left Los Angeles. It was a great way to get to know a great mind. I also learned that Roger, Kathryn, Peter and I all had another thing in common: we shared a Hungarian heritage. Those first years, I took the opportunity to organise with them a small faculty seminar series that was nicknamed “The Hungarian Seminar” where we just talked about new science that was keeping each of us up at night. My appointment to the faculty of the College of Arts and Sciences within CU came along with a generous start up package and membership in the fledgling Center for Astrobiology. I used these resources to prepare my laboratory for heavy mineral separation (zircon, apatite, sphene, sulfide, chromite, *etc.*) for electron- (at CU) and ion-beam (elsewhere, mostly UCLA) analyses. Another focus was to get up to speed with teaching. That was hard. It became a passion of mine to develop undergraduate and graduate students in astrobiology, geobiology (which was just getting started) and cosmochemistry (for which there was a general lack in those days of courses,

anywhere). To share my love of fieldwork with students from many departments, I recreated a course in Planetary Field Geology (Fig. 3.19). Most of these courses are still being offered in Boulder. It was difficult to balance all these activities with trying to start a new home with a new wife in a new city, and there were lots of challenges along the way least of which was to ration my time. On top of that, it was time to recruit graduate students. I had no prior experience with this.



Figure 3.19

Which way do we go? For most of the 2000s, I led field courses in the Western US to teach students in the planetary sciences about real work examples of geology in action that could inform their own research. Here I am navigating near Teakettle Junction on the way to Racetrack Playa, Death Valley, California.

When it was said that I had moved to Boulder and that I was looking for students, there was a very nice groundswell of interest from the broader academic community, which I appreciated very much. One early application caught my attention thanks to strong endorsements from the community of Astrobiologists at NASA Ames Research Center, principally Lynn Rothschild and Linda Jahnke; they told me about a clever young student from Québec named Dominic Papineau who would be applying for a Ph.D. position with me

in Boulder. Of course I hired the guy! He was great. This young man was full of energy and ideas, and willing to get projects started, and he had a good biology and geology background. Frankly, Dominic was probably the best student one could hope for as a newly minted Assistant Professor because he had fire inside. He was confident, driven and positively obsessed with his work, and good at writing papers. Now, in 2025, he is Senior Research Scientist at the Institute of Deep Sea Science and Engineering of the Chinese Academy of Sciences in Sanya, China. Previously, he was on the faculty of the University College in London, and before that, as an Assistant Professor at Boston College in Massachusetts. I am very proud of his accomplishments.

One of the first Ph.D. projects that Dominic and I sought to “get off the ground” was to figure out how both nitrogen and the MIF sulfur isotopes preserved in ancient rocks could provide new insights into the evolution of microbial metabolisms. Recall, I was inspired by Mark Thiemens and James Farquhar about this topic. Dominic immediately set out to find a suite of samples that could be used to test the idea that the demise of the MIF sulfur signal could be traced to specific rocks. This work resulted in a slew of important publications (Papineau *et al.*, 2005a,b,c; Papineau and Mojzsis, 2006), one of which was co-authored by Juha Karhu and showed that MIF sulfur faded after the time of the Paleoproterozoic Snowball Earth episodes, which ended about 2.3 Gyr ago and that the MIF signal vanishes at around 2.42 Ga in the Paleoproterozoic Huronian sediments and in between Snowball events (Papineau *et al.*, 2007). That said, under certain circumstances it is possible to have a small MIF sulfur signal even today when modern volcanic dust gets into the stratosphere (Martin *et al.*, 2014). Working with the energetic Jeffrey J. Walker, a Ph.D. student with the excellent Norm Pace, Dominic led a study of the microbial diversity of the Shark Bay stromatolites (Papineau *et al.*, 2005a) that conclusively demonstrated that the cyanobacteria which populate such structures are a thin film that overlies a diverse community of anaerobic microbes including Proteobacteria and Purple Non-Sulfur bacteria. Work with our colleague Bernard Marty on nitrogen isotopes in ammoniated phyllosilicates in ancient rocks (Papineau *et al.*, 2005c) proposed that the nitrogen fixers were also present at the time of the Last Universal Common Ancestor (LUCA) population. Before graduating from CU and moving to become a postdoc with the renowned biogeochemist Marilyn Fogel at the Carnegie Institution of Washington, D.C., Dominic used samples we collected in the Isua Supracrustal Belt to show the widespread preservation of MIF in pre-3.77 Ga sediments. This work firmly established him as a fixture of the community of geobiologists. He and I went on many field adventures together in the early 2000s, to northern Finland, Western Australia, the western US, northern Québec and southern West Greenland. He continues this tradition today with his own students and postdocs. The “capstone” project to the sulfur work that we accomplished in the early to mid-2000s was published in Mojzsis (2007). Since that time, I have continued to dabble with MIF sulfur with our more recent paper with Caro *et al.* (2025).

Yet another great Ph.D. student, also from Francophone Canada (!), was the attentive and dedicated Nicole L. Cates. Here, again, I was directed to a student by a colleague at Vanderbilt University, Calvin F. Miller. Of course I hired her! Nicole brought different and much needed skillsets to my now growing field programme. She became a talented field metamorphic petrologist who, along with Martin Guitreau at Clermont-Ferrand, I have had splendid visits to far flung places in pursuit of the world's oldest rocks. Nicole's first project with me was to make sense of the extent of supracrustal enclaves in the archipelago of Eoarchean crust off the coast of southern West Greenland and south of Nuuk (Cates and Mojzsis, 2006). When we learned of the new discovery by Canadian geologists of likely extensive Eoarchean rocks of the Inukjuak terrane in northern Québec, we became interested in seeing how these compared with our experience in West Greenland (Cates and Mojzsis, 2007, 2009). With the excellent Nicolas Dauphas we wondered what (if any) geochemical signatures of the original mineralogy could be preserved within the Nuvvuagittuq rocks that could reveal information about Eoarchean surface conditions (Dauphas *et al.*, 2007). Nicole's Ph.D. thesis was absolutely jam packed with new data for Earth's oldest rocks (Fig. 3.20), and it was splendid to have her remain as a postdoctoral researcher in my lab before she moved back to her hometown of Winnipeg, Manitoba, Canada, in 2017.



Figure 3.20 Nuvvu Crûe, 2018. Working on old rocks means gathering in far flung places. Here we are in northern Quebec within the Nuvvuagittuq Supracrustal Belt. Left to right are: Fanny Thibon, Dustin Trail, Sarah Davey, the author, Nicole Cates, Elizabeth Bell, Nigel Kelly, Jonathan Oulton, Martin Guitreau and Guillaume Caro.

The common thread uniting all this work that we accomplished was to gain better understanding of the relationship between the hydrosphere and the lithosphere in the Eoarchean from direct analysis of rocks of marine sedimentary protolith. This work on the ancient oceans from studies of rocks like banded iron formations (Młoszewska *et al.*, 2012, 2013) ran in parallel to our research into the metamorphic petrology and geochronology of the oldest gneisses of igneous

origin in the Eoarchean Inukjuak terrane (Guitreau *et al.*, 2013; Roth *et al.*, 2013) and the older pre-3.9 Ga Acasta Gneiss Complex (Mojzsis *et al.*, 2014; Guitreau *et al.*, 2014; Roth *et al.*, 2014).

I take some time now in the next section to explore what ancient ocean inventories might mean for the prevalence of dry land and catchment basins for water and reactants at concentrations required for prebiotic chemistry (*e.g.*, Damer and Deamer, 2020; Sasselov *et al.* 2020).

3.10 Emergent (i.e. Dry) Land Existed on the Hadean Earth

Be patient, for the world is broad and wide.

Of the Nature of Flatland (Edwin A. Abbott, 1884)

It has long been argued that continental crust requires, and is required for, the long term stability of liquid water on Earth's surface in a feedback loop. The common view is that continental crust is the product of planetary scale tectonic transport of water to the mantle *via* oceanic crust enabling the production of felsic magmas by altering solidus temperature, viscosity, and phase relationships during magmatic differentiation (Campbell and Taylor, 1983). This orthodoxy may require some reformation considering the heresy of apparent granitoids on Mars (Sautter *et al.*, 2016) and granitic components including ilmenite granite fragments found in some meteorites (Bonin, 2012). It seems that granitic crust is in all actuality a more common planetary phenomenon than we previously thought. Thus, we ought not to discount its presence elsewhere in the solar system, and on rocky exoplanets when they can be imaged someday.

If there is buoyant continental crust on a rocky planet with water oceans, then it can form landmasses. *THAT* is the relevance of continental crust for life in general. Evidence for freshwater interactions on Hadean Earth with buoyant felsic crust that constituted dry land has come to light (Gamaleldian *et al.*, 2024). This observation refreshingly forces our perceptions to change about how much dry land *vs.* ocean was around at the time life began. One of the many important aspects of dry land in models for the Hadean Earth stems from the fact that sediments shed from buoyant silica-rich (*i.e.* felsic) crust *via* subaerial weathering of silicates captures CO₂ *via* the so-called Urey reaction (Urey, 1952). This process could have been an important one in preventing a runaway CO₂ greenhouse atmosphere from forming on Earth leading also to corresponding loss of surface H₂O (Walker *et al.*, 1981; Kellogg *et al.*, 2019). In contrast to weathering of land, seafloor alteration is often regarded by those who run atmospheric models as a relatively poor mechanism to draw down atmospheric CO₂ (Caldeira, 1995). The seafloor weathering process, however, can be significant when integrated over geologic (100 Myr) timescales (Brady and Gíslason, 1997). It is noteworthy that the rocks composing the oldest greenstone belts are composed of volcano-sedimentary successions that are rich in carbonate, probably from seafloor

weathering and sequestration of carbonate, especially at the ocean ridges. Early Earth escaped the fate of Venus by avoiding a runaway greenhouse even with 30 % lower luminosity of the young Sun (Sackman and Boothroyd, 2003; Ribas *et al.*, 2005) because it has sustained intense aqueous weathering of silicates over geologic time. Silicate weathering and deposition of sedimentary carbonates as well as carbonatisation of oceanic crust means that sequestered atmospheric carbon as carbonate in the crust can be delivered to the mantle and be stored there (Wang *et al.*, 2020). These kinds of sustained weathering reactions remove atmospheric carbon and, although they happen on the seafloor, these are most effective when emergent land is present.

Most of the Earth's emergent land surface is made up of continental crust with a veneer of sediments. Granite-granitoid rocks are the major principal constituents of the upper continental crust. Several famous papers reveal that the average composition of Phanerozoic upper continental crust is granodioritic, whereas the bulk composition yields an average intermediate or "andesitic" bulk composition (Taylor and McLennan 1995; Rudnick and Gao, 2003). Although young oceanic arcs are regarded as a production site for proto-continental crust in an oceanic setting, the intermediate to felsic igneous rocks documented in modern oceanic arcs are tonalitic to trondhjemitic in composition for the most part and have lower incompatible element contents than the Phanerozoic average upper continental crust. Juvenile oceanic arcs require additional processes such as intracrustal (re-)melting to get transformed into mature continental crust enriched in incompatible elements. For example, Neogene granitoid plutons commonly outcrop in the Izu Collision Zone in central Japan, where the northern end of the juvenile Izu-Bonin-Mariana island arc system has been colliding with the mature Honshu arc for the last 15 Myr (Saito *et al.*, 2007, 2012). The plutons in this area are composed of various types of granitoids ranging from tonalite to trondhjemite, granodiorite, monzogranite and granite and their incompatible element abundances are comparable to the average upper continental crust (Saito and Tani, 2017). Young island arc systems as exemplified by those in the western Pacific (*e.g.*, Izu-Bonin) are analogous to continental nuclei in the Hadean.

As mentioned, the oldest zircons thus far discovered on Earth indirectly show that water has been interacting with and altering crustal melts for 4.4 Gyr and that the melts recorded by the Hadean zircons include those consistent with granite/granitoid compositions including (mostly) tonalites as well as (some) granites (Blichert-Toft and Albarède, 2008; Hopkins *et al.*, 2008; Borisova *et al.*, 2022). Indirect evidence for subaerial weathering in the Hadean includes oxygen and silicon isotopes in zircon, the trace element chemistry of zircon including crystallisation temperatures, and the mineralogy and composition of zircon mineral inclusions (Trail *et al.*, 2018). It is important to note that many of the same low temperature aqueous alteration processes which produce ^{18}O -rich clays relative to the mantle oxygen isotope value also play a role in drawing down atmospheric CO_2 *via* silicate weathering. Thus, the Hadean zircons hint at the establishment – already in the Hadean eon – of feedback loops which could stabilise the early climate against an initial moist CO_2 runaway

greenhouse effect. A runaway greenhouse would be the expected result of a dense atmospheric regime after magma ocean degassing. Significantly, it is the integration of clays into the nascent rock cycle, and assimilation into the Hadean crust of these weathering products along with the hydration of mafic/ultramafic crust, that can lead to ^{18}O -enriched granitic magmas. One signature of the incorporation into intra-crustal melts by clays and clay-derived rocks (ranging from shales to greywackes) is the degree to which aluminum becomes saturated in such magmas. Zircons from S-type (sedimentary) granitic magmas show Al concentrations up to about 10 ppm compared to much lower (≤ 1 ppm) contents in I-type (purely igneous) magmas (Trail *et al.*, 2017; Wang and Trail, 2019). Documented Al contents in some of the oldest zircons show that about 10 % derive from peraluminous S-type magmas, an observation entirely consistent with the presence of primary muscovite inclusions expected to form from strongly peraluminous melts (Hopkins *et al.*, 2010; Harrison *et al.*, 2017; Carley *et al.*, 2022). Besides enhancement of the ^{18}O and Al content of Hadean magmas, clays can also carry lower $^{30}\text{Si}/^{28}\text{Si}$; such low Si isotope ratios are imparted to a sub-population of the oldest zircons (Trail *et al.*, 2018). Clay formation on the Hadean Earth already began to contaminate crustal melts 4.3 Gyr ago. Other evidence for the emergence of continents comes from argon isotope degassing data which favours rapid and early continental growth, such that models predict that approximately 20 % of the present continental surface area was exposed by the end of the Hadean (Guo and Korenaga, 2020; Korenaga, 2021a). Evidence from the Hadean zircons does not point to strictly chondritic mantle reservoirs and a solely (ultra)mafic crust. Instead, a geodynamic portrait emerges of the Hadean Earth's crust with multiple rock types, including granite-granitoid proto-continents with mafic-ultramafic oceanic crust including volcanic islands. On this basis, surface water catchment basins, aquifers and evaporative environments that could serve as a cradle for an early biosphere were present in the Hadean eon (Korenaga, 2021b). Only after the Hadean, however, does direct evidence for some dry land exist from examples provided to us from the geology of the Eoarchean (≤ 3.9 Ga) onwards.

The geology of scattered Eoarchean terranes in places like southern West Greenland, northern Québec (Canada), northeastern China and Western Australia provides evidence for the availability of subaerial crust for weathering reactions, sediments forming on land (sandstones, quartz-pebble conglomerates) and runoff into the oceans (Cates *et al.*, 2013).

Indirect evidence from strontium isotopic signatures in Paleoproterozoic sedimentary rocks point to land surface exposures (not equivalent to the volume of continental crust) of as much as 10 % by about 3.7 Gyr ago (Roerdink *et al.*, 2022). This value equates to $1/3$ of the present land area of Earth, or approximately the size of modern Asia. A much larger possible range of values for emergent *vs.* submerged landmasses comes from the record of extensive continental flood basalts of submarine origin from the Meso- to Neoproterozoic, which are interpreted to indicate mostly submerged continents with less than 4 % subaerial exposure (Flament *et al.*, 2011, 2013), or equivalent to ~ 85 % of Australia. That

these submarine continental flood basalts were prevalent at ~ 2.7 Gyr ago means that low lying continental crust was easily flooded by small changes in sea level at that time (Arndt, 1999) but, importantly, this estimate does not account for how much land was subaerial at a particular time. Analysis of the three oxygen isotopes in shales traces a change in water-rock interactions at *ca.* 2.5 Gyr ago that could be due to rapid exposure and weathering continental crust (Bindeman *et al.*, 2018). Other similar work based on oxygen isotope data analysis of *ca.* 3.2 Ga old hydrothermally altered oceanic crust places a minimum estimate of 3–5 % continental area exposure at that time (Johnson and Wing, 2020). A middle ground estimate would be around 5 % subaerial exposure for the late Hadean to the Eoarchean (≤ 4.2 –3.8 Ga; Rosas and Korenaga, 2018). If such a land area is divided up into island arc-type landmasses distributed over the surface of the Hadean Earth, the resulting area of land available would be equivalent to approximately 90 % of the area of the Australian landmass or twenty times the subaerial exposure of the Japan island arcs (Fig. 3.21).

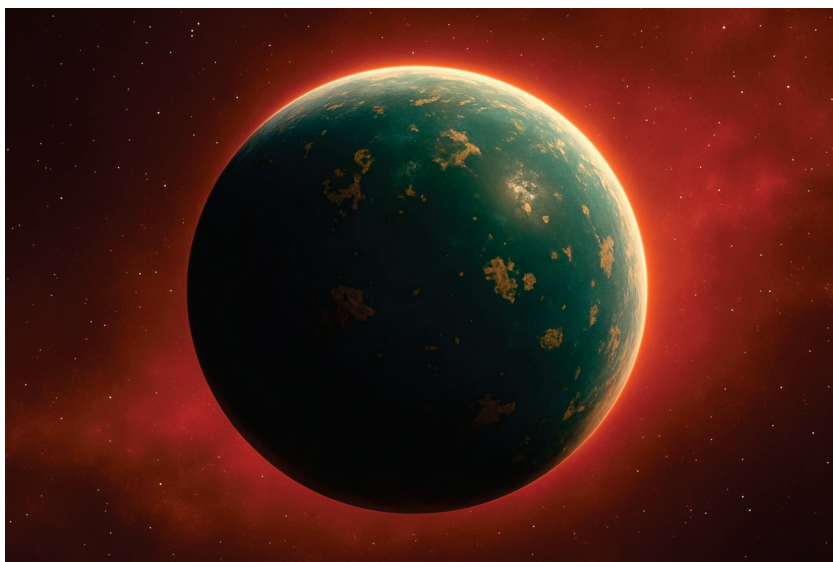


Figure 3.21

A conceptual model of the late Hadean Earth at *ca.* 4.0–4.3 Ga. Abundant small proto-continental masses, akin to immature to mature island arcs principally at ocean-ocean subduction zones scatter the surface of the planet. They are bathed in ferrous iron-rich seawater under a dense atmosphere with a bright sky. From ChatGPT with parameters from S. Mojzsis.

How about catchment areas for reactive concentration on Hadean dry land surfaces? What of Hadean lakes? The Japan archipelago alone hosts approximately 3000 bodies of freshwater in the form of lakes and ponds but not including rivers. This accounting for proto-continental nuclei does not include

what are expected to be much more numerous volcanic ocean islands akin to Iceland, Hawai'i, and Tristan da Cunha, each of which hosts standing bodies of surface water of various volumes from a few cm³ all the way up to Lake Toba on the island of Sumatra in Indonesia at 250 km³. It seems safe to state that there always has been emergent land on Earth including in Hadean times. This is good news for prebiotic chemists who would argue for the need to bring components to reactive concentration, which is very hard to achieve in a place like the open ocean (*cf.* Russell *et al.*, 2014). Catchment areas for meteoric waters, like ponds and lakes, would be effective places to concentrate the ingredients of life (Fig. 3.22). I would argue that lakes and their smaller cousins, ponds, on the Earth are primordial phenomena.

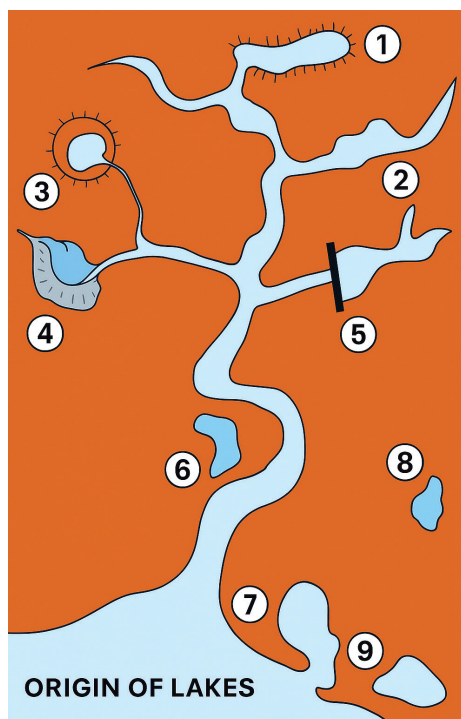


Figure 3.22

Land of lakes. Judging by observation, it is safe to say that with any reasonably sized landmass, water will pool into lakes on surfaces. Most of the time, these water bodies have outlets that ultimately lead to the sea or are connected to it indirectly (6, 8) as shown above. In some cases, however, draining basins may be entirely confined. Lake Types: 1. Glacial, formed by scouring from glacial activity, 2. Tectonic, formed by tectonic movement, 3. Volcanic caldera, or impact structure, 4. Hydrothermal field, formed by pooling of water from hydrothermal vents at the surface, 5. Dammed, formed by landslides, lava extrusion, tongue of glacier, etc., 6. Oxbow, formed by meander in river,

7. Lagoon, formed by active longshore transport of sediments at coastline,
8. Perched or regressed, from sea level fall or land rise, and
9. Endorheic, formed by internal drainage (any of the above processes 1–8) with no outlet to the sea/ocean.

At my lab in Boulder, we were exploring lots of new things, but I was far from done with the Hadean zircon story. Remember when I first brought up the conversation with Mark Harrison and he shared his vision of measuring the fission decay products of ^{244}Pu ? This measurement of plutogenic xenon isotopes was soon realised in collaboration with the brilliant Grenville Turner together with Jamie Gilmour at the University of Manchester in the U.K. (Turner *et al.*, 2004, 2007). Other work, that related the hafnium isotopic evolution of the Earth as captured by the oldest zircons was also spearheaded by Mark Harrison (Harrison *et al.*, 2005) and was the *coup de grace* for the idea of a “lunar type Hadean Earth”. The separation of the silicate reservoirs on Earth was very early, possibly around 4.5 Ga, which meant that crust was there from the beginning.

In hindsight, I suppose that none of this should have really come as a surprise.

While teaching the large introductory geology course “Earth System History” at CU in the mid-2000s, I took the opportunity to tout geology as a discipline worthy of consideration as a major course of study for the students seated before me. It is not like I think everyone should be in geology, just some people who may not have been exposed to it before. Sometimes this strategy of sharing about geology worked. For instance, I came across an inquisitive undergraduate student who showed immense interest in geochemistry and geohistory. This very bright student, Dustin Trail, was a Computer Science major at the time who had a lot of experience in applied math. As far as I could tell, he had maybe a passing exposure to geology in some environmental science class he had taken previously as an elective⁵¹, and was eager to learn more about it. This young man came to absolutely every office hour I hosted for this and every subsequent course I offered. It did not take very long to persuade him to work as an undergraduate assistant with me and soon he was coming up with projects of his own. The natural consequence of this was that he would do a Master’s degree project with me, and he chose to work on the Hadean zircons we had collected over the years. His M.Sc. thesis was at least equivalent to most Ph.D. theses in the department at Boulder and completed in two years and was based on two important publications (Trail *et al.*, 2007a,b) that elaborated on the Hadean zircons. The first of these was a concerted effort to unite O isotopes, rare earth elements and Ti in zircon thermometry to try to narrow down the

51. In the US college education system, an elective course is a class that students can choose to take that is not required for graduation in their major. The beauty of such courses is that they allow students to explore subjects that interest them beyond the mandatory curriculum in their major field of study. Electives are an opportunity to potentially discover new passions. Many people discovered geology in this manner.

properties of the protoliths to the Hadean zircon record. The other was a bolder project proposing that ultrafine analysis of the growth zones of Hadean zircons from depth profiling might yield information about thermal effects to the crust before the start of the rock record (Fig. 3.23).



Figure 3.23 Field folk, 2007. The author, with Dustin Trail (centre) and Nicole Cates (right) in the Stillwater Complex, Montana, USA. Most of my science from 1997 to 2021 was field based, and supplemented by laboratory analyses.

Before Dustin graduated from CU with the exceptional work he did for his Master's thesis, I told him it was time to go to another place and that he should widen his scope. He got several good offers but wisely decided to work with one of the best experimental petrologists/geochemists in the world, the truly original E. Bruce Watson at Rensselaer Polytechnic Institute (RPI) in Troy, New York. As a native Coloradan, but intrepid adventurer, Dustin was going all in for his Ph.D. and beyond. He made such a great choice to work there. The discovery that he may perhaps be best known for is the Ce/Ce* redox meter for zircon. His most famous publication (Trail *et al.*, 2011) settled the debate over the oxygen fugacity evolution of the terrestrial mantle and showed that it has been little changed since *ca.* 4.3 Ga with obvious repercussions for the kind of secondary atmosphere that degassed from our planet in its earliest days. Following his work with Bruce and a brief postdoctoral stint at RPI, Dustin moved to take up a faculty position at the University of Rochester in western New York state, where he and a talented group of young professors are leading that department to new heights.

Now that we can be confident that granitic crust was present since very early, probably soon after the Moon-forming event (Sleep *et al.*, 2001), what more can we say about it and what insights arise that would be useful for people like prebiotic chemists to be aware of?

3.11 Primordial Crust was Diverse but Likely Dominated by Ultramafic Components

A faith which cannot survive a collision with the truth is not worth many regrets.

The Exploration of Space (Arthur C. Clarke, 1951)

During the Apollo Era (1963–1974), it was suggested that in analogy with the Moon, Earth’s earliest crust was at least partly anorthositic⁵² and formed as a rocky skin floating atop the post-terrestrial magma ocean just as observed for the post-lunar magma ocean (Windley, 1970). Geochemically and geodynamically, this is an unlikely outcome for planets that are broadly Earth-like in mass and composition. The lunar composition is enriched in Ca and Al compared to the terrestrial mantle leading to the early crystallisation of plagioclase in the lunar magma ocean. Whereas for Earth, plagioclase ($\rho = 2680 \text{ kg m}^{-3}$) starts to transform at shallow depths of about 40 km to aluminous garnet ($(\text{Mg}, \text{Fe}^{2+}, \text{Ca})_3 (\text{Al}, \text{Cr})_2 \text{Si}_3 \text{O}_{12}$; $\rho = 4000 \text{ kg m}^{-3}$). This stabilisation of garnet sequesters much of Earth’s interior Ca and Al into a dense phase that resides deep in the mantle. In the Moon’s mantle, contrary to that of Earth, plagioclase is stable to several hundred kilometres depth which allows it to segregate and then ride on top of the Moon’s magma ocean. Mars is an intermediate case. It probably had a magma ocean but without a lunar-like anorthositic floating crust (Elkins-Tanton *et al.*, 2003, 2005; *cf.* Dohm *et al.*, 2018), and was large enough to stabilise garnet and, like Earth, sequester aluminum (Borg and Draper, 2003). Based on the above arguments, it seems that Earth, Mars and probably Venus began with a mafic (basalt) and world encircling ultramafic proto-crust. On Earth and probably Mars, this was in contact with liquid water for a long time (Abe, 1993). Alternatively, it has been proposed that the post-magma ocean proto-crust formed as a dominantly felsic and hydrous component from melt fractionation that was effectively recycled in the Hadean and was the source of the Hadean zircons (Turner *et al.*, 2025).

Such felsic crust would be relatively buoyant, which eliminates arguments that Hadean Earth was a “Water World” with no emergent landmasses whatsoever. Time to put that idea to rest.

52. Anorthosite is a rock containing the minerals plagioclase, pyroxene, and/or olivine in various proportions, along with some amphibole, magnetite and others. A notable feature of anorthosite is that it comprises the highlands crust of the Moon and contains no quartz.

The theoretical⁵³ first actual solid rock rind at the interface with the atmosphere – as opposed to slurry (liquid + crystal mush) – is expected to have formed once temperatures at the interface fell below 1780 K corresponding to the low pressure mantle solidus mineral composition of olivine + orthopyroxene + clinopyroxene + plagioclase (Hirschmann, 2000; Sossi *et al.*, 2016). This mineral assemblage, dominated by olivine and pyroxene, defines the P-T-X field of komatiite (*e.g.*, Viljoen and Viljoen, 1969; Arndt, 2003). Komatiite is one of those distinctive lithologies of the Archean supracrustal belts that are composed of the metamorphosed equivalents of volcanic-, plutonic- and sedimentary-derived rocks that are sometimes referred to as “greenstone” when of greenschist metamorphic grade. Supracrustal belts are tectonically juxtaposed to granitoids and gneisses and sometimes intruded by them. They are very rarely associated with their original basement rocks. Komatiite may have been a common feature of the Hadean crust. Of note is that it has extremely high eruption temperatures (~1800 K) and chemistries that are close to mantle peridotite compositions, even for Phanerozoic komatiites (Aitken and Echeverría, 1984). For example, the model komatiite of Huppert and Sparks (1985) has a solidus temperature of 1746 K, well above the melting temperatures of any other surface rock. A particular class of komatiite, termed aluminium-depleted komatiites (ADKs; a.k.a. Barberton-type) are found to be more prevalent in older Archean terranes (Arndt *et al.*, 2008), a feature which is attributable to hotter mantle temperatures at that time. Another class of komatiite, the Al-undepleted (AUK; a.k.a. Munro-type) is also represented. I will take the risk here and suggest that these rocks were likely representative of common Hadean crust. Several features of a hypothetical crust built on the komatiite model are noteworthy (Table 3.1). Foremost of these are mechanical as well as thermal properties, including high melting temperature and thermal conductivity ($k \approx 1\text{--}5 \text{ W m}^{-1} \text{ K}^{-1}$) (Clauser and Heunges, 1993).

Owing to their ultra-magnesian composition and high eruption temperatures, komatiite lavas erupted as turbulent fluid flows that cooled by conduction but also relatively quickly by convection (Huppert and Sparks, 1985). If komatiites flowed over ground composed of rocks with lower melting temperatures, they melted the ground to form deep thermal erosion channels into the underlying rock before cooling some distance away from the source of eruption, sometimes thermally eroding channels tens of metres deep (Williams *et al.*, 2000). Magmas of a vast array of compositions can ascend through the modern lithosphere in different ways. On the one hand, well established pathways in the lithosphere can lead to almost continuous transport of basaltic magma from deeper crustal magma chambers. Both eruption rates and lava volumes tend to be relatively small in such systems, with typical values less than $500 \text{ m}^3 \text{ s}^{-1}$ and below 1 km^3 , respectively (Ryan *et al.*, 1981). Conversely, for komatiite lavas that come from a deep source, eruption temperatures are high so that new conduits can be formed through the lithosphere, leading to flood

53. Of course, there are plenty of people who would argue with me about this. Some would say that this primordial crust was felsic as opposed to mafic or ultramafic.

magmatism ($1\text{--}10^3 \text{ km}^3$), shield volcanoes ($0.1\text{--}10 \text{ km}^3$) and lava fields with small cinder cones ($<1 \text{ km}^3$). These would be common volcanic features of the Hadean Earth's surface (Fig. 3.24).



Figure 3.24 Hadean landscape. A dense early atmosphere under a slightly dimmer young Sun. The seas, rich in dissolved ferrous iron, would have been slightly turbid/ greyish owing to precipitates of Fe-carbonate. Volcanic islands ought to have been commonplace and there was abundant opportunity to concentrate prebiotically relevant chemicals in proximity to energy resources and whatever was raining from the sky. From ChatGPT.

The key feature of komatiite that sets it apart from other mafic rocks is its unique composition. A limit of 18 % MgO separates komatiites from less magnesian volcanic rocks such as picrites or magnesian basalts which are contemporary rocks of exceptionally high Mg content. The cumulate zones in komatiites can have MgO values as high as 50 %, but the eruptive liquids that generated them were no more than about 30 % MgO. The term komatiitic basalt is applied to some volcanic rocks containing less than 18 wt. % MgO that can be linked, using petrological, textural or geochemical arguments, to komatiites. Owing to this unusual composition, the density of solid komatiite is about 2800 kg m^{-3} , which is higher than that of typical upper crustal rocks such as granite (2700 kg m^{-3}). So, besides thermally eroding underlying rocks like granite or sediments, komatiite can assimilate rock by melting and create a local density inversion by being much denser than the rocks beneath it. Rocks of komatiite composition are distinctive in that silica is low, typically 40–45 wt. %; potassium is very low, less than 500 ppm ($\text{K}_2\text{O} < 0.17 \text{ wt. \%}$); and sodium is also very low

(≤ 0.6 wt. %). In terms of trace elements, komatiites are low in the incompatible elements Ba, Cs and Rb. Conversely, they are extremely rich in Co (≥ 100 ppm), Ni (>1300 ppm) and Cr (>2500 ppm).

The reason for citing the values for these different elements is that each is of low abundance in contemporary crust (oceanic and continental) and very low in seawater. They are nevertheless absolutely crucial as metallic centres to enzymes such as replicase (Co) without which life as we know it is not chemically possible.

Thus, I would argue (as others have), that the special composition of Earth's early mafic-ultramafic crust chemically templates the first biosphere.

A consequence of abundant ultramafic crust in contact with water is its reactivity. Water reacting with ultramafic (peridotitic) rocks hosting abundant olivine and pyroxene leads to new minerals (serpentine, brucite and magnetite) and free H_2 along with a positive volume change of ~ 30 %. As such, these dense rocks convert to mechanically weak and less dense (2600 kg m^{-3}) serpentine. Serpentinisation is the hydration of (peridotitic) olivine $(Mg,Fe)_2SiO_4$ and orthopyroxene $(Mg,Fe,Ca) (Mg,Fe,Al) (Si,Al)_2O_6$. For olivine, this becomes: $6[(Mg_{1.5}Fe_{0.5})SiO_4] + 7H_2O \rightarrow 3[(Mg_3Si_2O_5(OH)_4)] + Fe_3O_4 + H_2$. Non-serpentinised mantle has a density of 3300 kg m^{-3} , which can buoyantly support both dense komatiite and its far less dense product, serpentine. The generous amount of dihydrogen gas produced in these reactions provided energy resources to early life (e.g., Russell *et al.*, 2010).

In the early summer of 2006, Gina and I learned that we were going to be parents. When she shared the news with me, I can easily say that it was at that moment, the happiest day of my life. My parents, I think, were beginning to believe that they would never have grandchildren after long years of waiting for something to happen. I remember, clearly, calling them both to share the news, and my mother crying out: "Oh my God! Stephen, I hope you are not joking with me!" On the other hand, my father was a bit more diplomatic and talked about how my life would never be the same again. He was right about that, and so was everyone else I know who shared the same thing. Our daughter Anna was born on a Wednesday in late February 2007, after the seventh consecutive weekend of heavy snow (anyone else would call these things a blizzard) in Boulder, Colorado. What a day. This was the same date of a significant tornado outbreak in the southern United States. Welcome to the world, Anna! Somehow with some measure of clairvoyance, I had planned ahead for such events and traded in my AWD Subaru Forester for a supercharged Toyota Tacoma 4WD light duty truck. Good thing because the road from Longmont, Colorado where we lived, to the birthing centre at Boulder Foothills Hospital (where all of my children were to be subsequently born) was closed to traffic and we were forced to take a long detour. This lovely little girl was born dramatically during a fire alarm. She is now grown to become a brilliant and beautiful young woman pursuing a nursing degree, in the footsteps of her Irish grandmother. I am extremely proud of her. This child was, however, a very restless sleeper, and we, as new and inexperienced parents

Table 3.1

Some representative major element compositions expressed in the conventional oxide (wt. %) for some average Al-depleted Barberton type komatiites (ADK; n = 36) and average Al-undepleted Monro type komatiites (AUK; n = 10) compared to theoretical mantle rock composition (pyrolite) and average Ivuna class carbonaceous chondrite (CI). Data compilation from data reported in Ringwood (1979), Palme and O'Neill (2014), and Sossi *et al.* (2016).

	ADK	AUK	Pyrolite	CI
Major elements				
SiO ₂	r	45.23	45.10	33.64
TiO ₂	0.42	0.20	0.20	0.11
Al ₂ O ₃	4.51	3.66	3.30	2.42
Fe ₂ O ₃ *	12.66	12.20	8.00	36.20
MnO	0.20	0.22	0.15	0.38
MgO	26.06	32.16	38.10	24.23
CaO	7.34	5.28	3.10	1.92
Na ₂ O	0.62	0.44	0.40	1.00
K ₂ O	0.04	0.17	0.03	0.10
P ₂ O ₅	0.05	0.02	0.02	0.23
SO ₃ †	0.01	n.d.	n.d.	13.36
Mg#‡	67	69	80	37

*Expressed Fe as total iron, with no assumptions of corrections made for FeO vs. Fe₂O₃.

† n.d. No published values available.

‡ Mg# = (Mg/Mg + Fe) × 100

far from any family members to support us (they were all in either Connecticut or New Jersey, the ones farther afield were in Europe), did not get much in the way of sleep for the first 2.5 years. We were basically alone to learn that lack of sleep will not kill you (even if you are so exhausted that you might feel like you are on death's door). Frankly, it seems to be the normal thing in America to be alone. The place is very lonely compared to other countries that I have lived in.

That year, 2007, was pivotal in many ways, not just personal but also professional. I was up for tenure at that time. If I was to get tenure, it meant I could stay and develop my career as a professor. Otherwise, I would have to go back to Plan B and buy that classic Cadillac I was thinking about in Havana for a colourful road trip across Cuba. Which was it going to be? Joking aside, it was a deeply awkward time. After 7 years' probationary period as a tenure track Assistant Professor at the University of Colorado, you are normally brought up for tenure review. I could have done this earlier, but why rush the process? Especially since at the same time I was going through a series of battles in the

literature over the so-called “Akilia controversy”, and with those conflicts both on and off the field becoming increasingly uncouth, it was nice to know that my work was being appreciated. That is the thing about academics: For many of us, just a small token of appreciation is enough to make you feel that maybe you might just be doing something right after all. It takes a lot of nerve to be an academic in the field of geochemistry – as I have written about in the first part of this memoir – and at times it seems to just boil down to a game of survival. Are we academics just stubborn or simply crazy? Probably both.

At the same time I assembled my tenure portfolio, I mentioned that we were brand new parents with nerves that were feeling pretty raw. Imagine if you will, in my tenure case there no less than nine external letter writers submitted evaluations of my credentials. The achievement of tenure remains a near unique level of job security in the US. I wonder how much longer the tenure system will last in the US given the kleptocratic farce that now metastasises there? Of course, there was a crisis for me brewing in the background of my tenure review. I was told by members of my committee that eight of the nine external letters received very strongly supported my case, and some of these even expressed shock that I was not already tenured long ago. One, however, made his/her opinion unequivocally clear that I should be denied promotion on account of “... not having done anything of consequence...” in my career. Keep in mind, the process is transparent to the tenure committee and to the voting faculty of the department, but all correspondences are otherwise kept completely confidential to the candidate. I only know a small amount of what went on and prefer to keep it that way. Alright, but you might say: “Ahh, take a chill pill Moe-Jeezus, one out of nine ain’t so bad!” Sure... there was a crisis anyhow. It seems that such a negative review had never before been received by this department (at least, in living memory) and at first the faculty as a whole did not know how to deal with such an eventuality. Many shared with me their surprise at the vitriolic letter. I, on the other hand, was just disappointed. After being thrown into turmoil, the collective decision was made to request four more letters! There you have it: before it was all over, I was vetted for tenure by 13 of my peers. As it happened, twelve of the thirteen letter writers strongly supported my case, and after this rigamarole my tenured faculty colleagues in the department voted (almost unanimously) to promote me. Through it all, my tenure committee including the aforementioned Bruce Jakosky and Joe Smyth were steadfast in their support and viewed the whole thing as an annoying “Tempest in a Teapot”⁵⁴. Our (*non*-interim) Dean of the College of Arts and Sciences at that time (the excellent Todd Gleason) personally called me up to congratulate me on my successful promotion. He understood well that this was a deeply unpleasant situation, but he also had the experience to understand that such events in top flight programmes were not uncommon owing to base human weaknesses. The dean shared with me much later that he was surprised that the university was caught off guard like that.

54. *Excitabat enim fluctus in simpulo ut dicitur Gratidius*. De Legibus, Cicero (1st c. BCE).

The injury to my pride was a learning experience, I learned to just let the whole thing slide and take it as a growth experience. I told you, that academic life is a game of survival.

For a few years afterward, individuals would come up to me in confidence at different conferences and other events to say that they were one of the supporting letter writers. To those whom I shared the story of my experience (usually lubricated by a few pints), they expressed dismay at the drama of it was described to them. There are other of my colleagues, all deeply talented and worthy of tenure who did not get tenure. They were not as fortunate as I was. The whole thing is something of a black box.⁵⁵ The tenure process should not be so sloppy.

Around this same time (2007), I was contemplating the creative work of the magnificent Norman H. “Norm” Sleep and the ever inventive Kevin J. Zahnle. These two maestros had been working for some time on the effects of late accretion on the emergent biosphere. I thought about how this work could be taken a few steps further. Others, including the founder of contemporary impact science and deep thinker H. Jay Melosh and the brilliant and creative geophysicist David J. Stevenson and their different collaborators, had been working separately over the course of the 1980s–early 2000s on whether impact bombardments could have frustrated the origin of life. Earlier in my career, I had teamed up with the well known cratering/impact process specialist Christian Koeberl and the reflective Graham Ryder to write a couple of papers on looking around for evidence of late bombardments in ancient Earth materials (Ryder *et al.*, 2000; Mojzsis and Ryder, 2001), as well as with the clever Ariel Anbar with Zahnle as co-author (Anbar *et al.*, 2001). It seemed to me that we needed to go back to this problem with a new approach. After reading the work of the field geologist/meteoriticist/physicist David A. Kring and his talented graduate student Oleg Abramov, I reached out to them both. I learned that Oleg was finishing up his Ph.D. and was in search of a postdoc! It took a while, because the process of obtaining a NASA postdoctoral fellowship is time consuming and highly competitive, but he was awarded one and came up to Boulder. We immediately set to the task, and Oleg brilliantly accomplished coding a 3 dimensional model of the thermal fields of impacts over the whole Earth’s crust over hundreds of millions of years corresponding to the late Hadean (*ca.* 3.9–3.8 Ga) bombardment epoch (Abramov and Mojzsis, 2009). That work showed, conclusively, that there was no realistic bombardment scenario that could wipe out a microbial biosphere on Earth. It turns out that the reasons for this are straightforward: the bombardment does not happen all at once, and the time between very large impacts that can cause regional damage is longer than the cooling time of an individual impact. Thus, there were vast volumes of Hadean crust in which a sub-surface biosphere could ride out a bombardment

55. The phrase “The best revenge is massive success” is widely attributed to Frank Sinatra, another New Jersey guy.

(Abramov *et al.*, 2013) and the same would also be true for Mars (Abramov and Mojzsis, 2016). We even tested the idea of the survivability of life within the thermal evolution of asteroids (Abramov and Mojzsis, 2011) and in the context of the oldest terrestrial rocks, the Acasta Gneisses (Mojzsis *et al.*, 2014). It is now generally accepted that whether or not a late heavy bombardment ever existed, at least on Earth microbial life would survive it (Grimm and Marchi, 2018). You might say that if there were any impact bottlenecks to the survivability of the biosphere, they must have been at the very beginning, perhaps within the first 100–200 Myr of Earth's history.

3.12 How Late Accretion Affected the Crust

The tempo and intensity of early bombardment to the inner Solar System by comets, leftovers of primary accretion (planetesimals) and asteroids remain long standing problems in planetary sciences. Recent progress has sharpened our focus. Bombardments fundamentally contribute to several key physical and chemical aspects of the evolution of the terrestrial (a.k.a. silicate or “rocky”) planets, the largest of the asteroids, as well as icy objects of the outer Solar System. The planetary scale effects of bombardments range from profound to subtle, and include (i) modifications in surface morphology expressed as cratered terrains, (ii) compositional changes *via* delivery of exogenous materials to the crust or deep interior, melt mixing and differentiation of meteoritic and crustal components, (iii) alterations to primordial atmosphere compositions and atmospheric densities, and thus strong forcing on palaeoclimate, and (iv) defining the initial conditions that helped to determine the overall thermal structures of the affected worlds. Impacts on Earth have also had important biological consequences over geologic time.

Although the data are under debate, a signal of the cumulative effects of this bombardment has been traced from cosmochemistry, cratering statistics and interpretations of geochronological data from lunar rocks and meteorites. Indirectly, numerical models have attempted to do the same, but without the benefit of observational time constraints (Clement *et al.*, 2019; Nesvorný *et al.*, 2023). Bombardment, a term used interchangeably with late accretion, refers to the protracted barrage by relatively small bodies that did not grow into planets (Mojzsis *et al.*, 2019). Primary accretion refers to bombardment that accompanies planet formation and can include planet-sized objects and mergers. Late accretion is reserved for the protracted bombardment subsequent to the formation of Earth's Moon and up to the present.

The chondritic relative abundances of the highly siderophile elements (HSEs), principally of the Platinum Group (Os, Ir, Ru, Rh, Pt, Pd) are regarded as a signature of cosmochemical pollutants to the mantles of Earth, Moon and Mars by the earliest phase of late accretion (*e.g.*, Walker, 2009; Bottke *et al.*, 2010; Brasser *et al.*, 2021). Interpretation of the HSE data does not directly translate into

tempo of late accretion, only the cumulative mass, but coupled with dynamical simulations yields an estimate for the overall mass augmentation of about 0.5–0.7 wt. % to the planet's total mass since Earth effectively completed its formation after the chemical closure of its core (Willbold *et al.*, 2011, 2015; Day *et al.*, 2016; Frank *et al.*, 2016).

Two opposing paradigms describe the time dependent flux of late accretion, a spike in the impact flux and a gradual decline. The first argues for a burst of relatively short duration in the intensity of impact bombardment hailed as a “lunar cataclysm” or, more commonly, “late heavy bombardment” (LHB); this is assumed to have affected the whole Solar System (Ryder, 1990, 2002; Tsiganis *et al.*, 2005) at around 3.9 Ga, or perhaps earlier (Morbidelli *et al.*, 2012, 2018 and references therein). The LHB is largely implied by interpretations of uncorrected $^{40-39}\text{Ar}$ chronology from lunar samples (*e.g.*, Cohen *et al.*, 2005; Fernandes *et al.*, 2013) and has been promulgated by several popular dynamical models involving late stage giant planet migration (*e.g.*, Gomes *et al.*, 2005). Although the LHB idea is now out of favour, mostly for lack of evidence (Zellner, 2017; Mojzsis *et al.*, 2019), the giant planet migration remains valid.

The second concept proposes an overall monotonic decline in the bombardment rate, which is the interpretation most broadly consistent with crater counting studies (Hartmann, 1970; Neukum, 1983, Neukum *et al.*, 1970, 2001; see Werner and Ivanov, 2015, for a review). Recent work has successfully described a timeline relating variably retentive radiometric ages of meteorites from the asteroid belt to dynamical models that invoke early giant planet migration (Fig. 3.25). Such reconciliation of data with models shows that giant planet migration points to an intense ~30 Myr influx of comets to the entire Solar System manifested in radiometric age data. The absence of wholesale crustal reset ages after ~4.45 Ga for the most resilient chronometers from Earth, Moon, Mars, 4Vesta, and various meteorite parent bodies confines the onset of giant planet migration to *ca.* 4.48 Ga as described in Mojzsis *et al.* (2019) and confirmed and expanded with much more data in Walton *et al.* (2026). Some estimates place this as early as 4.53 Ga (de Sousa Ribeiro *et al.*, 2020). Waning impacts continue to strike the inner planets up to the present day through a protracted monotonic decline in impactor flux, in agreement with predictions from crater chronology. It appears that we have now transcended the inconsistency between the two different models for late accretion cited above, which also has a strong bearing on Hadean Earth's proclivity to host a nascent biosphere (*e.g.*, Maher and Stevenson, 1988; Fritz *et al.*, 2014). At least from the point of view of bombardment, there is no obvious barrier to the origin of life on Earth since at least 4.4 billion years ago.

Contemporary crust production on Earth, dominated by oceanic crust at mid-ocean ridges is approximately 20–25 km³ per year; higher heat flow may have boosted this production in the Hadean by a factor of ~5–10, which

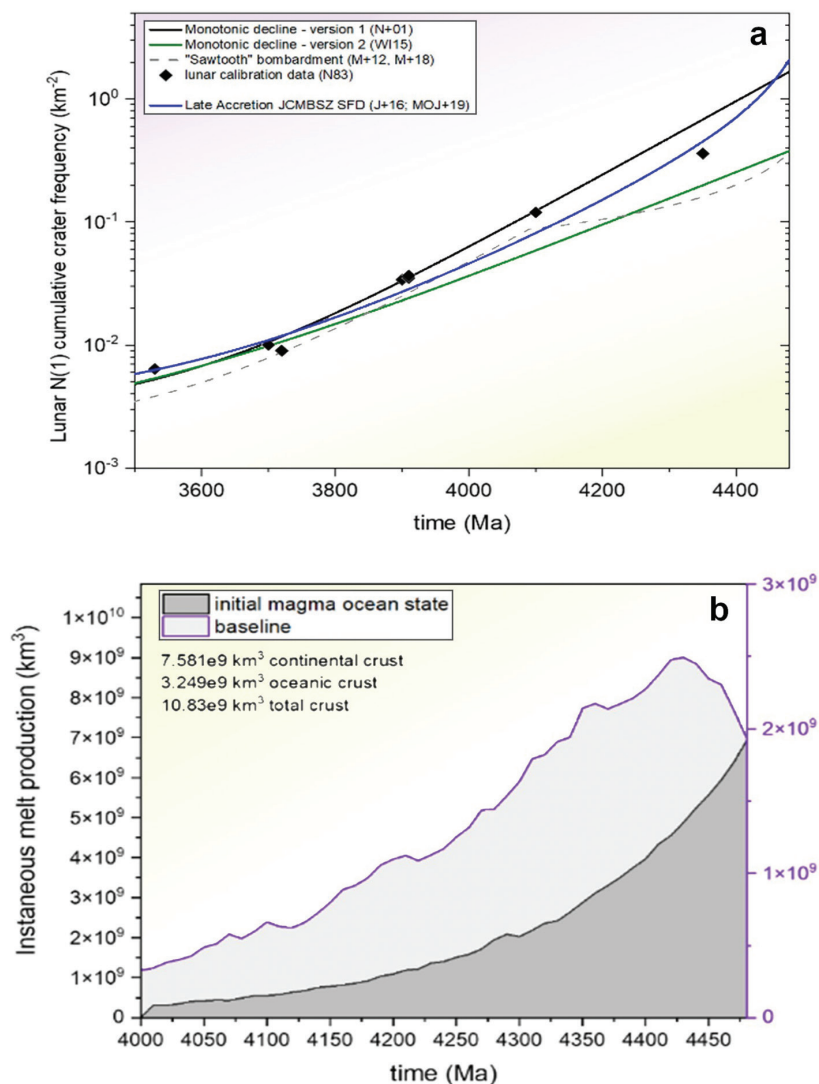


Figure 3.25

Mapping the falling rain of rocks. **(a)** Lunar impact fluxes from various sources. The differential number of lunar craters with diameter >1 km $N(1)$ is plotted as a function of time (Ma) and per unit surface (km^{-2}) for several scenarios. **(b)** Late accretion-derived instantaneous and cumulative melt production (please refer to the original paper for an explanation of the legend). Modified from Mojzsis *et al.* (2019).

still falls 7 to 8 orders of magnitude short of the exogenous melt production by impact bombardment. The contemporary crust has a volume of 10.83×10^9 km³, of which (surprisingly) 70 % by volume is continental crust (Schubert and Sandwell, 1989). With waning late accretion, the crust remained stabilised for the first steps towards biochemistry after about 4.4 billion years ago.

Drama notwithstanding with the ultimate resolution of my case, I now had tenure and could look forward to job security. Along with that came my first sabbatical leave from university, another nice tradition in the academic sphere that I sincerely hope is preserved. A sabbatical is an opportunity for academics to formally or informally take time off from teaching and service to the college, focus on research and perhaps try a hand at something new. This was also perfectly timed in the case of our new baby. With encouragement from some of my colleagues in the department such as the structural geologist Karl Mueller, I wrote proposals to the International Fulbright Program⁵⁶ and to the (now defunct) CU College of Arts and Sciences program, for sabbatical support to visit the laboratory of the magnificent Bernard Marty at the Centre de Recherches Pétrographiques et Géochimiques (CRPG) in Nancy, France. With a six month old baby in tow and our cat Hugo staying with family back east, we traveled to France. While I was there, I met up with Bernard's team composed of Laurent Zimmermann and Pete Burnard, and colleagues including Marc Chaussidon, Christian Lenard and Guy Libourel. About a month before leaving Nancy to return to Colorado, another long standing collaborator, the introspective Guillaume Caro, took up a permanent research position there. The years since then have seen many changes in my professional life, but the city of Nancy and CRPG will always remain in a special place in my heart.

Besides getting to live in Nancy, I was able to go farther afield in France, to Grenoble where I also met with my ever knowledgeable mentor in all things komatiite, Nick Arndt (Fig. 3.26), Lyon and to Paris, and thus better experience the wonderful culture and people and of course get to know my amazing colleagues there better. In Paris, I was honoured to connect at the Institut de Physique du Globe de Paris (IPGP) with the ever dapper and imaginative François Robert, and colleagues Mathieu Gounelle, Pierre Cartingy, and James Badro (who had just moved there) and many others. Paris is astonishing. Just the metro is a whole other world. In fact, the intellectual landscape of Europe should be a draw for anyone.

56. The Fulbright Program was founded in 1946 and is, arguably, the U.S. government's flagship international educational exchange programme. As envisioned by Senator J. William Fulbright, its aim has been to increase mutual understanding between the U.S. and other countries through personal contacts, cooperation and collaboration. I applied for a Fulbright grant to support my research in France. Sadly, the entire programme is currently under serious threat of becoming de-funded - or even cancelled - owing to political pressures.



Figure 3.26 Where the mountains meet the river (Grenoble, 2007). I love to visit France. Here, the author enjoys the mountain ranges close to Grenoble with the Char treuse to the north, the Vercors to the west and south, the Belledonne chain to the east, and the Oisans to the southeast. These massifs are part of the French Alps and offer varied landscapes and outdoor activities such as hiking, skiing and of course feasting on delicious French cuisine. Photo credit: K. Konhauser.

Lyon, however, was even more impactful. And as I was to find out later, it was to become an important part of my academic story. It was in an extended visit to Lyon and the École Normale Supérieure de Lyon (ENS) that I cemented my life-long friendship and scientific collaborations with the incomparable Janne Blichert-Toft and the magnificent Francis Albarède. I also met Bruno Reynard, Razvan Caracas, Bernard Bourdon, Caroline Fitoussi, Isabelle Daniel and Gregor Golabek, all of whom I continue to maintain connections with. Aside from its beauty and culinary expertise, some people call Lyon the “second capital of France”, but I worry about using that phrase because the place is second to none. I find Lyon to be unique, and its history and proximity to some of the best vineyards in the world to be an enormously appealing draw. It is a vibrant centre for scholarship with its flagship institutions ENS and the Université Claude Bernard Lyon 1. While I was visiting Lyon in 2008, Nicole Cates came to visit us in France and together we met with Janne and her Ph.D. student Martin Guitreau in Lyon to discuss ways forward with previous sampling campaigns completed in the Nuvvuagittuq Supracrustal Belt in northern Quebec and anticipating upcoming sampling and field mapping during summer 2009 in the Acasta Gneiss Complex in the Northwest Territories, also in Canada (Fig. 3.27). The outcomes from these meetings with Janne and Martin were the eventual publication of a suite of papers uniting U-Pb zircon geochronology with Lu-Hf and Sm-Nd analyses of these rocks (Cates *et al.*, 2013; Guitreau *et al.*, 2013, 2014; Roth *et al.*, 2013, 2014; Mojzsis *et al.*, 2014). It was an exciting time, and one where big changes were on the horizon. That is to say, I was beginning to feel restless.



Figure 3.27

Deep times in the Acastas. I have been to a lot of incredible places in the world and have been witness to numerous geological marvels, but few can compare to the Acasta Gneiss Complex, Northwest Territories, Canada. Left to right: Dustin Trail, Wouter Bleeker, Nicole Cates, Martin Guitreau, the author, Otto van Breemen, Peng Peng.

You can't get away from yourself by moving from one place to another.

Ernest Hemingway (The Sun Also Rises, 1926)

When someone in academia shares with you that they are beginning to feel “restless”, take it seriously. In my case, I was anxious for a change of topic and even a change of location. In 2010 with encouragement from many colleagues, I began to apply to professorships in Europe, out of curiosity about what was available and possible outside of North America. The outcomes of that, again, changed my life’s course.

Although my field studies were extremely satisfying, there was a growing awareness in my mind that working with Earth’s geologic record was potentially a limiting factor to progress what I wished to do and which I was later to learn would become the field of “biogeodynamics”. To begin with, I wanted to go beyond the fact that liquid water is necessary for biology on a planet and delve more into what makes water and crustal processes so interesting for the function of a planet that has the potential to host a biosphere. To my mind, this became the all important overarching question that geologists could wrap their brains around.

3.13 Hadean Bio-Geodynamics

The importance of liquid water for any discussion of the crust stems from the generally well known fact that the viscosity of silicate rocks follows an Arrhenius form. As can be seen, this translates into extreme sensitivity of viscosity to temperature changes. Given this behaviour, viscosity change dramatically ($>10^{12}$ Pa s) over a typical temperature range of conditions expected for Earth's lithosphere (450–1850 °C). When, in the single lid convective system, convection is confined to the boundary layer deep in the mantle since the surface layer is too cool and therefore too viscous to deform (*e.g.*, Cushman-Roisin and Beckers, 2011). Yield strength is the stress point at which a solid material such as rock ceases elastic deformation and begins plastic deformation, so that in a single lid scenario convection is stymied in the shallow mantle. A closer look at how yield strength changes within typical lithosphere helps us understand how the crust can break to allow for plate tectonics. As mentioned, viscosity from diffusional creep increases rapidly as temperature drops so that in an anhydrous system, at shallower mantle depths, where it is cooler, viscosity should be very high, and the crust stays put. To have plate tectonics, the viscosity contrast between the lithosphere and the underlying mantle should be $<10^4$ Pa s, or 10^2 MPa in the yield strength (*e.g.*, Korenaga, 2021a). Although debated, this condition is regarded as difficult to achieve without liquid water at the surface to directly interact with a hydrated crust, which weakens the lithosphere by thermal cracking (Korenaga, 2007). Arguably, a liquid water ocean stable over geologic timescales helps plate tectonics by helping the crust behave in a way that allows plate tectonics.

In early 2008, NASA made the decision to expand on an old idea. When I was less than 3 years old (in March 1968), President Lyndon B. Johnson announced the establishment of the NASA Lunar Science Institute (LSI) in cooperation with the US National Academy of Sciences. The idea for this was to promote scientific cooperation and research on lunar materials ahead of the Apollo programme. It was also a time when the so-called Lunar Receiving Laboratory was finished and ready to work on samples brought back by the astronauts the following year (1969). Interestingly, forty years later to the month, the NASA Lunar Science Institute (NLSI) was re-born and began operations with a call for proposals. In Boulder, Bill Bottke at the Southwest Research Institute brought together a group to pitch a proposal for an NLSI node in Boulder. I was asked to participate in the proposal and also to spearhead the recruitment of Ph.D. students if we were successful. After some deliberations, the Boulder team came up with the acronym CLOE, for Center for Lunar Origin and Evolution. It was a great proposal! We got funded! Right away, I set about recruiting people for our graduate program. I have found that my success with very good students strongly correlates with whether they were directly recommended to me by a colleague. By the time we received news that NASA would fund the CLOE proposal, I had two excellent prospects for Ph.D. students: the deeply organised Michelle Hopkins and the focused and independent Elizabeth Frank. Michelle had completed a Master's thesis under

the supervision of Craig E. Manning and T. Mark Harrison at UCLA on the inclusion mineralogy of the Hadean zircons coupled with thermobarometry. Elizabeth had finished an undergraduate honours thesis with E. Bruce Watson at RPI working on the self-diffusion of sulfur in sulfides. Both had excellent credentials from outstanding advisors. These two young and dynamic women hit the research ground running in Boulder and immediately became part of the Planetary Science community by linking up with both the Geological Sciences and the Astrophysics and Planetary Science Departments at the University of Colorado, as well as the Southwest Research Institute.

My group was growing in numbers and in talent. Besides Oleg Abramov and Nicole Cates, we welcomed Michelle and Elizabeth, as well as Analisa Maier, who did a Master's degree project with me after taking some of my undergraduate classes. We also had some visitors and were planning to put together a field campaign to track down other localities of Hadean zircons in North America, specifically in Wyoming and Montana, as well as the Thelon Basin and Assean Lake Complex, both in Canada. Around this time, I also was cementing my relationship with NASA as my principal source of research funding with the NLSI and the Exobiology program. The idea was to construct a geology based "Mission to Early Earth", as we called it at the time. But again, the itch to move and try something new was beginning to get very strong. I needed a change from Boulder, and the University of Lyon (Claude Bernard Lyon 1) was an opportunity to do this.

Throwing caution to the wind, I decided to give it a try. The Dean of my College was very understanding (and wise) and suggested that I take unpaid leave of absence. I did and packed my belongings and moved to Lyon in 2011. It was a whirlwind time, but also a golden opportunity to test my will and determination to take my science further in new directions.

Of the multitude of things that were on my mind by joining the Lyon Group, with Janne Blichert-Toft, Francis Albarède, Bernard Bourdon, Caroline Fitoussi, Martin Guitreau and Greg Golabek, was to take the ideas that were germinating in my mind about when the first crust could have existed even before the Hadean zircon record. Why should we care, why should I care, about this topic? Mostly because of the lingering question of whether plate tectonics is something that is necessary to maintain a persistent biosphere on a planet. Lots of people claim that it is without a detailed understanding of why or how or when.

3.13.1 Maintaining a Persistent Biosphere on a Planet

What makes the plate tectonic process so favourable for a biosphere at the planetary scale is that it is possible for a layer of crust in contact with the atmosphere and hydrosphere to be effectively recycled back into the mantle by reliable subduction. Unlike more local or even provincial processes, such as transient or local subduction, which come and go in different patches of crust

(Stern and Gerya, 2018), plate tectonics is a global process that regulates the long term geochemical cycles of the planet, including the carbon cycle, resuscitation of nutrients (e.g., phosphorus), and renewal of the reactivity of rock by bringing fresh lithospheric material back to the surface (Stern and Gerya, 2023). A two way mass transport can take place between the relatively oxidised surface zone and the relatively reduced interior (mantle) that is chemically renewed by melting. Whether or not plate tectonics existed on Hadean Earth or was a hybrid between single lid and mobile lid scenarios (e.g., Crameri and Tackley, 2016; Gerya, 2022), is unclear. Earth appears to have had surface water for most of its history, as indicated by the ^{18}O -enriched Hadean zircons which require that water-rock interaction took place before approximately 4.4 Ga. This observation places the hydrosphere to within 100 Myr or so of the Moon's formation. It also allows for subduction to start very early in Earth history. Subduction is not synonymous with plate tectonics (cause and effect). Because we think the Hadean Earth was different (higher temperatures in both crust and mantle, intense impact bombardment, etc.), various alternatives to plate tectonics have been proposed to have operated in the deep past (Stern, 2018). Besides single lid convection, these alternative scenarios are: sagduction⁵⁷, squishy lid, episodic or intermittent subduction (including local subduction), and heat pipe (Moore and Webb, 2013). It is important to emphasise that each of these are numerical models that make several assumptions about how they are set up and all must consider the thermal history of the planet. A key concept when discussing the thermal history of Earth is the Urey ratio (Christensen, 1985). The value $\text{Ur}(0)$ is the ratio of a planet's internal heat production to its surface heat flux. The convective Urey ratio $\text{Ur}_C(0)$ is slightly different in that it is the ratio of internal heat generation in the mantle over the mantle heat flux (Fig. 3.28). In this analysis, the contribution of continental crust is subtracted from both the internal heating budget and the surface heat flux because the continental crust does not directly participate in convective heat transfer from the interior.

Right now, we are entering a cross over in the decay of the nuclide ^{238}U , which governs intrinsic radioactive heating of Earth's mantle, with the decay of the nuclide ^{232}Th (Fig. 3.29). The other contributing isotopes ^{235}U and ^{40}K , are effectively extinct. In addition to these four isotopes, ^{26}Al and ^{60}Fe contributed to internal heating in the first ~3 Myr or so of the Solar System (e.g., Castillo-Rogez *et al.*, 2009). If Earth formed quickly and early, it would have inherited these isotopes from the interstellar medium during the formation of the protoplanetary disk, with some components (notably ^{26}Al , but also ^{60}Fe) being mixed in heterogeneously during its subsequent evolution (Bizzarro *et al.*, 2007; Davis, 2022). Uranium, thorium and potassium share the geochemical characteristic

57. This process involves the gravity driven sinking of dense, volcanic-sedimentary belts (e.g., "greenstone belts") into lower density, underlying buoyant granite-granitoid crust. This vertical deformation creates characteristic dome and basin structures, where high density komatiites 3.3 g/cm^3 or iron formations 4.6 g/cm^3 sink into lighter 2.7 g/cm^3 felsic crust, acting as a form of partial convective overturn.

of being incompatible lithophile elements during igneous differentiation of the Earth, and, as a result, become concentrated in the Earth's continental crust over geological time, particularly in the uppermost continental crust and perhaps also some deep reservoirs (Labrosse *et al.*, 2007). This may not be the case for exoplanets significantly more massive than Earth, but still rocky, such as Super-Earths which are several times more massive than Earth, or another class, Mega-Earths that have ultra-high densities as well as large masses. Understanding the nature of these planets is frontier science.

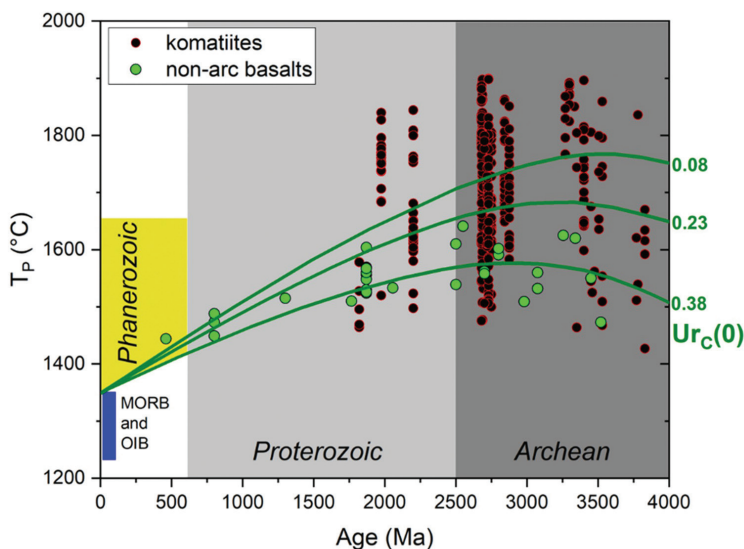


Figure 3.28

Variation of Earth mantle temperature through time, reflecting the style and frequency of volcanism, oceanic crust composition and tectonic style(s). Shown are secular thermal Earth models for ambient mantle (green curves; Korenaga, 2008a,b) compared with petrological estimates of mantle potential temperature (T_P) for non-arc lavas and a class of ultra-magnesian rocks termed komatiites, with the ages (Ma) indicated on the x axis. Number next to each green curve is the model present day Urey ratio $Ur_C(0)$. To calculate mantle potential temperature, I use the relation that others have used, namely: T_P (°C) = $1463 + 12.74MgO - 2924/MgO$ (Herzberg *et al.*, 2007; Herzberg and Asimow, 2008), where MgO is the primary magma content of komatiites from Herzberg *et al.* (2010) and Frank *et al.* (2016). The range of T_P for plume related magmas of Phanerozoic age shown in yellow is from Herzberg and Asimow (2008) and Herzberg and Gazel (2009). The blue region corresponds to temperatures for contemporary mid-ocean ridge and ocean island basalts (Arndt *et al.*, 2008). This figure contains lots of data that have not been plotted previously but which do not change the story. Rather, it reinforces the conclusion that the Urey ratio is probably close to 0.38. Whichever model one chooses, planetary cooling is evident and a natural consequence of intrinsic decrease in heat production from radioactive decay. Figure modified and expanded from Korenaga (2008a) with new data.

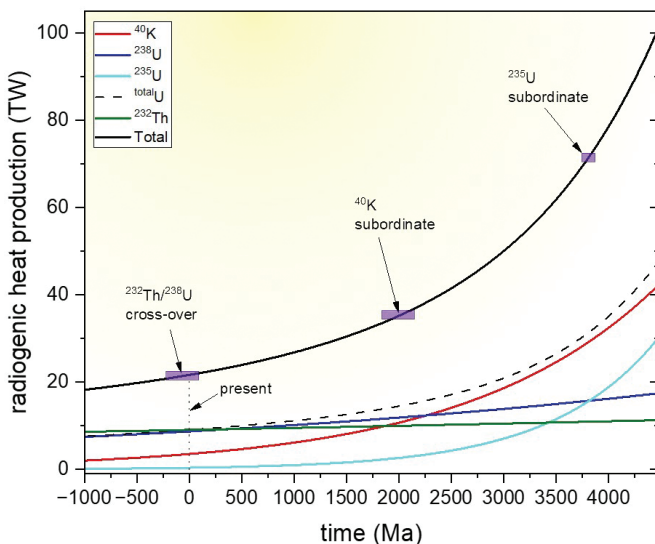


Figure 3.29

Internal heat from radioactivity. Relative contributions of only the radioactive nuclides ^{40}K , ^{235}U , ^{238}U and ^{232}Th to Earth's internal heating rate. As shown in the previous figure, radioactive heating is but a part of the total heat of Earth's interior. If the convective Urey ratio is about 0.38, what remains is gravitational heat including that left over from planetary accretion and latent heat of core crystallisation.

I love visiting France. You will often find me there, enjoying the genius of my French colleagues (which is certainly a special kind of epicurean way of doing things) and the lifestyle, the style, of the place. It is a different thing to live there, which can be quite alien, even discouraging. After some time at trying my hand in the French system, I had to return to the USA. My daughter was there and I wanted to be part of her early childhood. My Dean in Boulder looked at me knowingly upon my return, and despite my best efforts, I know that Lyon was disappointed that I did not stick with it. I gave it a chance, and I gave myself a chance. After many adventures internal and external, I came back from France to the USA to re-invent myself in Boulder, yet again.

That is not to say that reintegrating to academic life in the USA was all that easy after leaving Boulder for France and probably disappointing both institutions in the process. When I returned to Colorado, it was clear that my professional life choices caused some of my fellow faculty members to cast a dark eye in my direction. Let me be frank with you, it was, at times, uncomfortable. So, I put my head down and just got to work. The outcome of this was a new idea:

I wanted to unite the last two of the natural sciences that had yet to be conjoined – geology and astronomy – and develop a brand new research programme. This is geoastronomy.

It often comes to mind that comparative planetology (Earth-Mars-Venus) reveals a little something about the outgassed atmosphere of the Hadean Earth at the time of the origin of life. Let me just say that Venus and Mars provide only a small amount of guidance about Earth's earliest days. Each planet, Venus, Earth and Mars, has a separate history unique to that planet.

3.13.2 Building our Planet's Secondary Atmosphere from Outgassing

Earth's atmosphere and oceans are the product of degassing of the mantle (and crust), which for the most part was completed early in Earth history (*e.g.*, Gaillard and Scaillet, 2014). Carbon, hydrogen, nitrogen and their compounds, as well as the noble gases, are historically classified as atmophile as they are preferentially partitioned into the gas phase during geological processes. We include sulfur and the halogens since these can act as volatile elements in volcanic systems. The various atmophile elements are essential to the origin of life. The presence and abundance of atmophiles control many surface properties, such as climate and both the stability and chemistry of surface (liquid) waters. Atmophile elements are abundant at the surface, but the planetary interior is the dominant reservoir. Despite large uncertainties, these various reservoirs have been identified through their elemental and isotopic abundances (Marty, 2012). Venus has similar mass and geophysical properties to Earth. Evidence that degassing probably occurred in the magma ocean stage of Earth (and Venus) comes from the strikingly similar masses of C and N in the surficial reservoirs of both planets (Lécuyer *et al.*, 2000). Venus' carbon budget ($1.15 \pm 0.15 \times 10^{23}$ g) is about the same as Earth's, and its nitrogen budget is also similar ($5 \pm 0.1 \times 10^{21}$ g). Because Venus lacks surface water, its C and N are almost entirely partitioned into the atmosphere, whereas on Earth and Mars these are stored in the crust thanks to the interactions of crust with water (*e.g.*, Wordsworth, 2016). Other work has explored this topic further and invokes plate tectonics to explain Venus' nitrogen inventory (Weller *et al.*, 2023), although catastrophic early degassing could just as well be explained by the planet's magma ocean phase (Gaillard *et al.*, 2021). What were the sources of these atmophiles to the planets?

The post-primary (late) accretion contribution to Earth's volatile inventory from comets and other extraterrestrial materials that carried volatiles is probably small; less than ~10 % (Marty *et al.*, 2016) and maybe even less than <0.2 % (Cassata, 2025). The reason for this assessment is that the isotopic compositions of the cometary volatiles nitrogen and hydrogen (*e.g.*, $^{15}\text{N}/^{14}\text{N}$ vs. D/H) deviate strongly from terrestrial values, which means that the atmophiles are indigenous to Earth and probably derived from its planetary building blocks. Thus, on Earth,

Venus and Mars, the atmophiles (and, thus, the atmosphere) degassed from the mantle at the magma ocean stage and in all subsequent volcanism and other emanations.

Over the last century, there have been about 380 active volcanoes on Earth (Stoiber and Jepsen 1973; Textor *et al.*, 2004), with around 50 active in any particular year (Andres and Kasgnoc, 1998). Right now, more than 80 % of active volcanoes are oceanic (Sigurdsson, 2000). The abundance of gases released by volcanism varies considerably from volcano to volcano, with different kinds of volcanic activity and with different tectonic settings. Water vapour is consistently the most abundant volcanic gas, normally comprising more than 60 % of total emissions for any given area. Carbon dioxide typically accounts for 10 to 40 % of emissions. Most volcanism on Earth is centred at the 65,000 km long system of active volcanoes dubbed the mid-ocean ridges (MOR), which wrap around the planet at divergent plate boundaries in the ocean basins and occasionally reach the surface (*e.g.*, in Iceland). Volcanism also occurs at convergent plate boundaries where one plate is subducted beneath another (island or oceanic arcs and continental arcs) such as in the western Pacific (*e.g.*, the Japan arc) or the western margin of South America (the Andean arc); by plume volcanism at centres such as Hawai'i and Reunion islands (hot spots); or flood volcanism associated with Large Igneous Provinces (LIPs) on continents (*e.g.*, the Siberian Traps) or the oceans (*e.g.*, the Ontong Java plateau). Some volcanic centres are combinations of these (*e.g.*, the Icelandic plume situated at the northern Mid-Atlantic Ridge). Subordinate passive degassing also happens continuously from rocks (including sediments) in the crust, at fault and fracture zones, and around hydrothermal vent fields and fumaroles. The most important high temperature volatile components erupting out of volcanoes on Earth today from the different plate environments cited above are reported in Table 3.2 (Cadle, 1980; Gerlach, 2004). Note that these gaseous components are present for an oxygen fugacity of contemporary volcanic systems. Hadean and Archean (upper) mantle oxygen fugacities (the quantified value of magmatic redox conditions) are documented to be approximately the same as modern values (*e.g.*, Trail *et al.*, 2011) so that the composition of contemporary volcanic gas exhalations guides us regarding the kind of volatile species that were available for prebiotic chemistry from indigenous sources.

The most important volcanic gases are water vapour (H₂O), carbon dioxide (CO₂), sulfur either as sulfur dioxide (SO₂; high temperature) or hydrogen sulfide (H₂S; low temperature), hydrogen chloride (hydrochloric acid, HCl), hydrogen fluoride (hydrofluoric acid, HF) and carbon monoxide (CO). Further minor gases are nitrogen (N₂), argon (Ar), helium (He), neon (Ne), and trace oxygen (O₂) mostly entering these exhalations from contaminant ambient air. The most abundant metal in volcanic emanations is mercury (as Hg⁰ or Hg^{II}; Siegel and Siegel, 1984). It is important to note that volatile metal species have been detected in volcanic gases; among these are B, Mo, Cu, Cd and Zn (Rubin, 1997; Edmonds *et al.*, 2022). Note that modern terrestrial air contains 78 % N₂,

Table 3.2

Representative high temperature volcanic gas compositions expressed in mole %. Data compilation from Cadle (1980), Javoy *et al.* (1986), Chin and Davis (1993), Marty (1995), Halmer *et al.* (2002), Gerlach (2004), Elkins *et al.* (2006), Fischer (2008), Hoshyaripour *et al.* (2012), Self *et al.* (2014), Oppenheimer *et al.* (2018), and Melian *et al.* (2021).

	Hot spot (mantle plume)	Divergent (MOR)	Convergent (ARC)	Rift zone (flood volcanism) LIPs
T (°C)	768	1130	1140	1150
H ₂ O	91.9	75.1	75.7	63.6
CO ₂	4.6	13.1	3.2	20.6
H ₂	0.5	1.59	0.95	4.91
H ₂ S	0.67	1.01	0.16	0.91
SO ₂	1.44	7.84	19.4	9.49
HCl	0.76	0.42	0.17	n.d.
HF	0.061	0.42	0.18	n.d.
CO	0.03	0.6	0.09	0.92
OCS	0.01–0.0023	0.05	0.014	0.00071
N ₂ [†]	2.8×10 ⁻⁷ –1×10 ⁻⁵	0.105	~10 ⁻⁴ –0.2 (78.7)*	–
NH ₃ [‡]	–	–	0.017–0.411*	–
[CH ₃ Hg] ⁺	–	1.0396×10 ⁻⁷	–	–
Hg ⁰ or Hg ^{II}	6.94×10 ⁻⁵	2.32×10 ⁻¹⁰	1.67×10 ⁻⁴	>1.4×10 ⁻⁴

* low temperature (<300 °C) gas samples very strongly affected by air and sediment contamination

n.d. = not determined

[†] strongly affected by air contamination; [‡] likelihood of some sediment contamination

21 % O₂, 0.9 % Ar, 0.03 % CO₂, and 0.07 % of everything else including water vapour. The proportions coming from outgassing do not match the proportions in the contemporary atmosphere, the cause of which is strong modulation by geochemical interactions with the crust and oceans, and biology. On Venus, however, we might expect that the atmosphere is overwhelmingly volcanic and very likely (even, certain) to be abiotic. Venusian air contains 96.5 % CO₂, 3.5 % N₂, 150 ppm SO₂, 70 ppm Ar, 20 ppm H₂O, 17 ppm CO, 0.1–0.6 ppm HCl, 0.001–0.005 ppm HF, with the rest being noble gases (He, Ne). Notice the similarities between the atmospheric components of Venus and the volcanic gases on Earth. Interestingly, while we continue to wait for a venusian sample return, the catalogue of gases emanating from volcanoes on Earth may help to better understand Venus' atmosphere but not the other way around (Fig. 3.30).

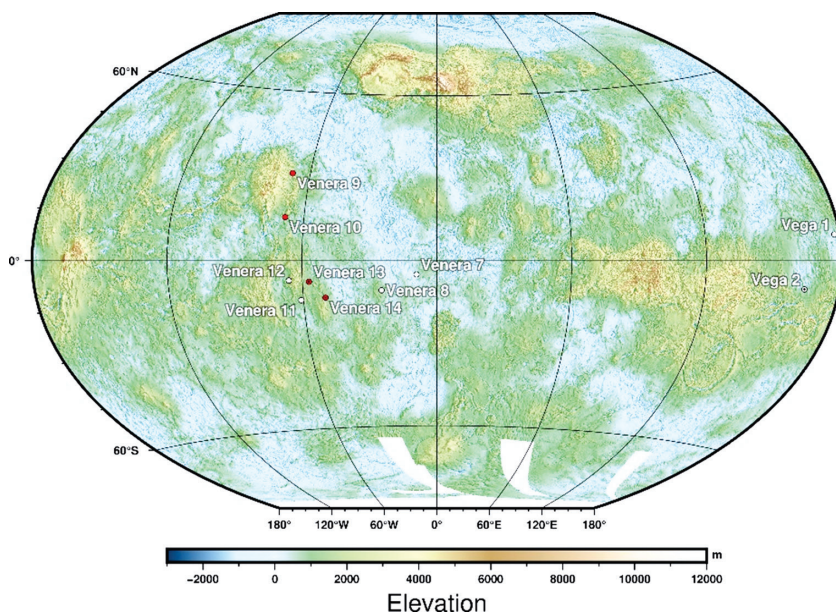


Figure 3.30

Fifty three miles west of Venus. Compilation map of Venus's surface features with the positions of Venera landing sites superimposed on combined Magellan/Pioneer/Venera topography data. Red dots denote sites with returned surface images; black central dots indicate sites of surface sampling analysis. Analysis shows the presence of at least 80,000 volcanic structures on the planet, some of which may be actively erupting now. From a combination of Public Domain data sources from Pioneer Venus Orbiter, Magellan and Venera 15/16; Wikimedia Commons.

After returning to Boulder, Colorado, from my very productive time in Lyon, France, I had my belongings, my vehicle, and an empty house to sell. When I say that my time in Lyon was productive, no less than a dozen publications came out of the science we did there together. Working also with the mountaineer Antoine Roth and the mathematically minded John Rudge, as well as the jovial deep thinker and talented field geologist Wouter Bleeker, I felt that I had reached some kind of pinnacle in my personal development as a metamorphic field petrologist.

This was a big time transition for me. It was tough, but it was also right in terms of opportunities to try something new. As mentioned, I had these talented students and research projects that were becoming progressively more astrophysical, which made a few of my geological colleagues in Boulder, confused. I remember one or two of them asking me: "Steve! How long are you going to continue publishing work in Astronomy journals?" (as if this was something bad). My reply: "For as long as the topic continues to interest me." There are those, like my geologist friend and long time deep thinker and conversationalist,

Boswell “Boz” Wing, who understood my point completely and immediately. Most people know that those of us who are serious about being academics work on that which we find the most interesting. We do not have to work on what has historically defined us, somehow, from what we did before.

3.13.3 Enriching the Secondary Atmosphere with more than just Carbon Dioxide

Nitrogen is an interesting case; it is generally of low abundance in volcanic gases, but Earth and Venus have about the same inventory in their respective atmospheres. Nitrogen has important chemistry relevant to biology such as an amine (-NH_2) group. Volcanic gases dominantly carry nitrogen in the molecular form (N_2), with small emissions of ammonia (NH_3) in low temperature hydrothermal gas (Uematsu *et al.*, 2004). Nitric acid (HNO_3) is also present in some volcanic gases (Delmelle and Stix, 2000; Mather *et al.*, 2004; Felix, 2024), as well as other forms of nitrogen from volcanic lightning or thermal processes that lead to NO_x formation (Navarro-González *et al.*, 1998).

Sulfur gases can be a mix of SO_2 and H_2S depending on temperature and both are abundant. Other compounds detected in volcanic gases include carbonyl sulfide (OCS), carbon disulfide (CS_2), hydrogen bromide (HBr), sulfur hexafluoride (SF_6) and several organic compounds. Trace mercury (Hg) and a host of halocarbons, including many chlorofluorocarbons, have also been detected (Jordan, 2003). Some of these minor but interesting components deserve mention. For example, carbonyl sulfide is relatively insoluble (K_{H} (25 °C) $20.98\text{--}21.98 \times 10^{-3} \text{ mol dm}^{-3} \text{ atm}^{-1}$) and its lifetime in the atmosphere is a few years (Kjellström, 1998). Motivated by studies of Venus’ atmosphere, it was found that carbonyl sulfide forms in the thermochemical reaction of CO and SO_2 (Hong and Fegley, 1997). Belviso *et al.* (1986) showed that the ratio OCS/CO_2 tends to increase with increasing emission temperature of the gases. Carbon disulfide (CS_2) is somewhat less soluble than OCS (K_{H} (25 °C) $54.95 \times 10^{-3} \text{ mol dm}^{-3} \text{ atm}^{-1}$), and due to the production of OCS from photolysis of CS_2 and sink flux from OH, it tends to follow the concentration of OCS in various measurements (Chin and Davis, 1993), including volcanic degassing (Khalil and Rasmussen, 1984). Interestingly, the volatile organic sulfur compound dimethyl sulfide ($\text{CH}_3)_2\text{S}$: DMS has also been reported in volcanic gases (Stefels *et al.*, 2007; *cf.* Andraea, 1990)⁵⁸. Mercury (as Hg^0 or Hg^{II}) is a component of most volcanic emissions; Kilauea degases about $2.7 \times 10^5 \text{ kg a}^{-1}$ (Siegel and Siegel, 1987). For a review of incrustations, sublimates and condensates from volcanic vapours, I point to Symonds *et al.* (1987). For a review of volcanogenic organo-sulfur compounds, I further refer the reader to Watts (2000).

58. DMS has been in the exoplanet news a lot lately, of all places. It was proposed to be present in the atmosphere of a planet around another star, and that it was good evidence for biological activity. That it is also found in volcanic gases, rules it out as a biomarker in my mind.

The Mauna Loa caldera is in the Hawai'ian hotspot, which is the expression of a deep mantle plume perhaps starting from the core-mantle boundary (2900 km depth). Aside from methane, other organic gases such as methyl chloride (CH_3Cl), methyl iodide (CH_3I), and methyl bromide (CH_3Br) were reported from a newly formed fuming fissure at Mauna Loa (Cadle, 1980). Methyl mercury (CH_3Hg) is also documented to be volcanically outgassed (Grasby *et al.*, 2019). These are the only organic compounds thus far firmly established to come directly from magma degassing. There are likely many more organic gases and condensates captured in volcanic rocks and glasses that await further detailed analysis. For instance, it has long been known that carbonaceous residues attributed to condensates of volcanic gases are present in alkaline basalt xenoliths of mantle origin (Mathez, 1987; Tingle *et al.*, 1990). In my opinion, there is still much to learn about the organic geochemistry of volcanic systems. I wonder if any of this is important in some way to the first chemical systems leading to life?

Taking a step back for a moment, whatever it took to get life started here on our planet, we seem to be taking it supremely and tragically for granted as a species. Take, for example, the air we breathe and the water we drink. The fact that we expect it to always be there and available is borne out of blissful ignorance. Looking down at our feet (which we do almost all the time) is a lot different from looking up at the sky and considering the space beyond, where the threatening void is all around us in opposition to the nourishing Earth.

My trip to space was supposed to be a celebration; instead, it felt like a funeral.

Boldly Go: Reflections on a Life of Awe and Wonder (W. Shatner, 2022)

The above quote from the actor William Shatner (born March 22, 1931; age 94 years at the time of this writing) sums up for me how important it is to be grateful for what we have. In 2012, I was picking up the pieces of my personal and professional life, and it was time for me to build both back in Colorado after the productive and necessary time in Lyon. Even if my relationship with some of my immediate colleagues in Boulder was a bit weird owing in no small part to them wondering why I had galivanted off to France in the first place, my work continued to flourish with my clever collaborators down at the Department of Space Studies of the Southwest Research Institute (people call it "Swerie" for its acronym, SwRI). The people who I spoke the most with were Hal Levison, Bill Bottke and Simone Marchi. The latter was getting more into geodynamics and the effects of bombardments on early Earth. In those days you would often find me visiting SwRI for one of its seminars where they brought people from all over to talk about space related science. Whenever I went there, I felt totally welcome; everyone was friendly and curious about research. It is a delight to have what is basically a planetary think tank in Boulder in the form of SwRI. What has long been puzzling to me is why the University of Colorado people do not work more with them. For the next decade prior to moving back to Europe (2012–2021), I worked to develop myself into more transdisciplinary scientific directions. I wanted to unite disparate fields.

Still, when ruminating over the nature of the Hadean surface environment, we cannot ignore the early atmosphere. If it was dense, as most propose, then there had to be a way to get rid of a lot of it. Otherwise, we would have two Venuses in our Solar System. There are some good arguments that can be made that for terrestrial-type rocky planets the Venus-like case is the default physical state. We will not know, I think, until we find a bright pixel in the so-called Habitable Zone around a Main Sequence Sun-like (F, G, K) or even M star.

3.13.4 Early Greenhouse Atmosphere(s)

The massive early degassing of water vapour coupled with CO₂ means that the early Hadean Earth had a potential runaway greenhouse problem that required a solution to quickly remove this potent greenhouse gas, otherwise our planet would have met the fate of Venus (Zahnle *et al.*, 2007). Most workers on the problem of too much CO₂ in the Hadean atmosphere invoke strong sequestration in the presence of liquid water to form carbonates. This mechanism usually implies weathering of silicates from landmasses as the most effective abiotic means of atmospheric CO₂ drawdown, but submarine weathering and serpentinisation of peridotite also sequester carbonate (Alt *et al.*, 2013). Crustal processes, such as recycling by subduction of carbonate-bearing oceanic plates that also carry organic matter can recycle carbon as carbonate and/or graphite into the mantle (Kelemen and Manning, 2015). The ferrous carbonate siderite (Fe^{II}CO₃) is a good candidate phase for delivering carbonate to the mantle. When heated to temperatures of the Earth's geotherm at pressures to ~50 Gpa, equivalent to the mid-mantle, siderite partially dissociates to form iron oxides. Yet, at higher pressures it forms new structures that are stable at conditions along the entire geotherm to depths of at least 2,500 km (Cerantola *et al.* 2017). This shows that self-oxidation-reduction reactions can preserve carbonates from the surface to be stored in the Earth's mid-mantle *via* down-going crust.

Earth clearly escaped the hellish fate of Venus. This could mean that (i) our planet was sufficiently cool from the very beginning to avoid a moist runaway greenhouse and effectively maintain liquid water interacting with rocks at the surface (Hamano *et al.*, 2013), and (ii) transient subduction or some other process of recycling primordial crust and delivering it to the mantle operated extensively on Hadean Earth (Stern and Gerya, 2018; Gerya, 2022).

As I mentioned above, if the composition of contemporary volcanic gases is any guide, the chemistry of hydrothermal fluids coming out into shallow lacustrine environments associated with fumaroles on landmasses on the early Earth was rich with potential for a huge variety of prebiotic reactions. Yet, what are some aspects that I think more of us ought to be aware of in the context of the Hadean crust-atmosphere-ocean interface? I will come to this a little later.



Figure 3.31 Steve's Angels. Charlie's Angels was a mildly entertaining American crime drama television series that aired from 1976 to 1981. One could say that our show followed the scientific adventures of three women (Hopkins-Frank-Maier) working at the University of Colorado in Boulder.

My graduate students in 2012, Michelle Hopkins, Elizabeth Frank and Analisa Maier referred to themselves as “Steve’s Angels” (Fig. 3.31) after the popular (but not “cult”) late 1970s television show.⁵⁹ Of course, I thought this was hilarious; they were great students! Michelle, who as mentioned earlier had done a Master’s degree with Mark Harrison and Craig Manning (and published her M.Sc. work in *Nature*!) wrote important work for her Ph.D. on the evidence for late accretion to asteroid 4Vesta from geochronological analysis and thermal modelling of eucrite zircons (Hopkins and Mojzsis, 2015). She also set out to decipher the impact history of the ancient lunar crust from analysis of Apollo 14 samples (Hopkins *et al.*, 2015). Analisa Maier, a Colorado native who excelled in my introductory geology courses; and who I initially hired as a laboratory assistant, prepared her Master’s thesis on the occurrence of Hadean zircons in the Beartooth Mountain outcrops in southern Montana (Maier *et al.*, 2012) before moving on to becoming an exploration geologist. Elizabeth came to Boulder with full support to create her own research programme. While 2/3 of “Steve’s Angels” were directly involved with the CLOE project we participated in with people from SwRI, Elizabeth wanted to go further. When we discussed ideas for projects, it came to mind that this would be an excellent time to ask the question:

59. https://en.wikipedia.org/wiki/Charlie%27s_Angels

“What can the chemical evolution of the Galaxy tell us about the evolution of rocky planets around Sun-like stars?”

That moment, in the summer of 2012, was when geoastronomy began. The germination of the idea was the result of being at the right place at the right time. I was ready to try something very new, and here was an energetic student who could do it all. She was a talented writer, an enthusiastic mathematician and an eager physicist who had learned geology from Bruce Watson and Frank Spear at RPI. An early paper we wrote together with the worldly Wolfgang Maier (no relation to Analisa), however, was not on geoastronomy but concerned with tracing evidence for the late veneer on Earth using the highly siderophile elements Pd, Ru and Pt values in the oldest rocks of komatiite protolith. Some of those data were used in Figure 3.28 to expand the analysis of the evolution of heat production in Section 3.13.1.

That the early Earth’s mantle was significantly hotter than at present is in little doubt, but what this means for the origin of life remains to be developed much further.

3.13.5 Early Earth’s Internal Heat Modulated the Crust and the Origin of Life

As pointed out previously, models for the early Earth must take into account the peculiarities of the Hadean-Archean environment, including mantle potential temperatures about 300 K hotter at *ca.* 3.45 Ga compared to present day values of about 1700 K (Bickle, 1986; Richter, 1988; Nisbet *et al.*, 1993; Herzberg *et al.*, 2007), thicker basaltic and basaltic-komatiite oceanic crust (Sleep and Windley, 1982; Vlaar, 1986) and overall enhanced radioactive heating of the mantle and crust at that time (Mareschal and Jaupart, 2006).

With a mass ratio of 81.25, the Earth and Moon closely approximate a double planet. Interestingly, the next largest mass ratio (primary:satellite) is for Pluto:Charon of 8.2, and the range of estimated mass ratios for primary-satellite pairs in the Trans-Neptunian region ranges from 10 to 1000, thus encompassing the Moon to Earth mass ratio (Arakawa *et al.*, 2019). The prevailing view is that the Earth-Moon system sprang from a Giant Impact (Hartmann and Davis, 1975) when two proto-planets with a mass ratio ranging from ~1 to 20 (Canup and Asphaug, 2001; Čuk and Stewart, 2012; Hopp *et al.*, 2015) collided approximately 30–60 Myr into Solar System history or by *ca.* 4.51 Ga (Yin *et al.*, 2002; Barboni *et al.* 2017; Greer *et al.*, 2023). The kinetic energy of this collision translated into thermal energy and led to a global Magma Vapour atmosphere (MVA) where the atmosphere and surface had an effective radiative temperature of around 2300 K (Sleep *et al.* 2001). At such temperatures, the black body radiation of the cooling post-Giant Impact Earth ought to have shone like an orangish sub-stellar object akin to an L-dwarf (a.k.a. Brown dwarf, a celestial object intermediate in size between a giant planet and a small star; *e.g.*, Smart *et al.*, 2018) for a few thousand years in the near-solar system region. The glowing Earth was nevertheless

relatively dim; luminosity is proportional to its effective temperature to the fourth power and its radius squared, and Earth's radius is <10 % of a typical L-dwarf. Such planet to planet impact events of protean calamity are probably common, especially in young systems where leftovers of planet formation continue to persist for millions of years (Brasser *et al.*, 2021). In fact, the throes of a particular colossal impact of Neptune mass planets were witnessed in a planet forming region around the nearby solar-type (G2) star ASASSN-21qj (Kenworthy *et al.*, 2023). After MVA collapse and when the atmosphere could become transparent to heat transfer from molten rock to air to space, a mechanically flimsy layer of olivine mush is expected to have formed when the magma ocean-atmosphere interface cooled to about 2073 K (Holland *et al.*, 2018). This is the temperature in the phase diagram of mantle compositions at which the low pressure (<100 bar) mantle peridotite liquidus crosses into the olivine + pyroxene(solids) + liquid field (Takahashi, 1986). Thus, by argument of initial conditions, the Hadean crust was derived from high degrees of partial melting of the mantle leading to komatiite basalt. Based on the accumulated evidence from terrestrial Hadean zircons up to 4.4 Gyr old (Valley *et al.*, 2014) the surface cooled sufficiently in <120 Myr after the Moon forming event that whatever solid crust was present included some rocks of granitic composition probably in a watery milieu. Such a rapid cooling timescale is in broad agreement with theoretical models of Earth's growth. Local or regional re-melting of the Hadean crust is expected to have occurred with the occasional large (>100 km diameter) impactor from the leftovers of accretion. This primordial environment was the natural laboratory for the first life where either mixed mafic-ultramafic volcanic edifices made it to the ocean surface or were present in shallow areas of the seas (Fig. 3.32). Putting these ideas together, it makes sense that geology can be used to guide prebiotic chemistry.

Based on extrapolation from remote, *in situ*, returned samples and meteorite analyses of the other rocky objects in our Solar System, namely Mars, Moon, Venus, Mercury, Vesta, and the igneous achondrite meteorites (*e.g.*, angrites), it is thought that Earth's proto-crust was mostly basaltic to komatiitic in composition with some fraction of more felsic components such as andesite. This is the expected composition from high degrees of partial melting of a generally peridotitic mantle composition. Komatiites have been proposed as an analogue for high Mg and Fe basalts from Gusev Crater on Mars (Bost *et al.*, 2012), as well as what is erupting from volcanoes on the jovian moon, Io (Williams *et al.*, 2000), and are documented to be associated with ultramafic crustal domains on Mercury (Mojzsis *et al.*, 2018). Interestingly, a "lunar komatiite" was calculated from compositional end member mixing models of an Apollo 16 highland breccia (Ringwood *et al.*, 1986).

Before getting into the geoastronomy themes that bring us to the end of the memoir, I want to share some thoughts about private foundation support. Mr. Lucky strikes again! If it was not for support at a crucial time in the transition I was experiencing from one kind of science to another, probably none of the following would have happened. Timing, as they say, is everything. All of my students graduated at once! "Steve's Angels" all moved on to other things

(industry, research centres, universities). Nicole Cates was now a postdoctoral fellow in my group, Oleg Abramov moved to the illustrious Lunar and Planetary Institute in Texas before taking up a staff position at the United States Geological Survey in Flagstaff, Arizona, at their Astrogeology Branch (established by the influential Eugene “Gene” Merle Shoemaker⁶⁰). I never met Shoemaker, or his famous wife Carolyn Jean Spellmann Shoemaker, but only ever heard great things about these people from many of my colleagues. Later on, Nicole Cates decided that it was also time for her to find new paths, and she moved from Boulder back to Canada. It was getting time to recruit more people; they say that we all train our best competition. I do not ascribe to that perspective so much as I think we ought to train our best future colleagues. When the time comes when you meet the students of your student’s students, then you will have concrete evidence of your success. Make it a casual sociological experiment to see if there are any echoes of your teaching in the style of these “grandstudents” and beyond. I have found it to be an eye opening experience to sit back and observe like an anthropologist.

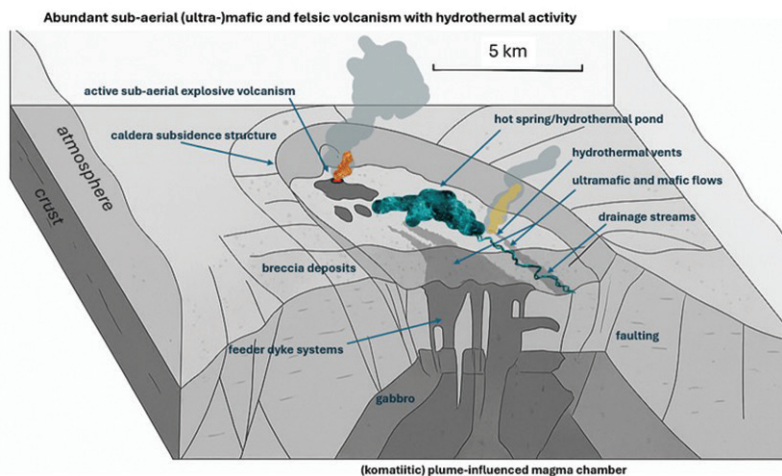


Figure 3.32

Archetypal crucible. The lava of komatiites was of low viscosity, perhaps 1 Pa s. Komatiite eruptions formed sheet flows that mixed with rocks of other compositions ranging from mafic to felsic on the surface of the Hadean Earth. Assuming this was a time of intense mantle plume activity, volcanism created numerous ocean islands. Such areas would serve as useful melting pots for prebiotic chemistry. Nick Arndt reminds me that Hadean/Archean oceanic crust was probably differentiated with basalt at the surface and cumulates deeper down, much like modern oceanic crust and oceanic plateaux. It could be that komatiite was less common on the surface than basalt. Here is my take on these origins of life scenarios as a geological diorama perhaps useful to prebiotic chemists to parameterise.

60. https://en.wikipedia.org/wiki/Eugene_Merle_Shoemaker

Now, rebuilding a group requires recruitment of people and raising money. These two objectives are hair raising. I was getting increasingly interested in better understanding the nature and tempo of late accretion. While models were and are useful for trying to explain observations, there were predictions to be made. To test predictions, you create schemes for measurements. In the case of late accretion there are two paths to follow: investigate lunar samples for thermal records of bombardment or take the geochronology of asteroidal meteorites that transcend the geological histories of Earth, Mars and the Moon to refine our understanding of the mass production function of impactors *vs.* time in the first half billion years. Of course, I decided to do both.

Back at CU Boulder, my department colleague, the stalwart Rebecca “Becky” Flowers, had established a very nice laboratory to measure the U-Th/He values of various minerals, including zircon and apatite, to decipher thermal histories of rocks. This seemed to me to be a perfect tool to study lunar zircons and apatites from the Apollo samples. We wrote a proposal to NASA and it was funded! After the celebrations, she and I thought about the next problem: who to recruit to work on this? Fortunately for us, the encyclopedist Nigel M. Kelly was up to the task and we were successfully able to lure him to Boulder to work on the project (Kelly *et al.*, 2018). At about the same time, the clever Jennika Greer joined my group after rising up through the ranks of our talented undergraduate students in Geological Sciences. She went on to write a fabulous Master’s thesis on the extended geology of the Nuvvuagittuq Supracrustal Belt in northern Quebec, with Guillaume Caro, Wouter Bleeker and others. Jennika went on to the University of Chicago to work with the noble gas specialist and big thinker Phillip Heck. She is now at the University of Glasgow as a postdoctoral researcher, and recently published the oldest age for a lunar zircon, 4.47 Ga, thus putting any further debates over a relatively young age of formation of the Moon to rest. My students are truly amazing people.

Then came the modelling aspects. Who was “out there” in the field of planetary dynamics that was open to asking questions and finding answers to problems that united the compositions of impactors to the target planets. It was my luck in 2015 to be invited to participate in a workshop at the newly established Earth-Life Science Institute (ELSI) as part of the Tokyo Institute of Technology in Japan. It was at that workshop, which concerned the chemical thermodynamic origins of life (and attended by the world renowned Michael Russell and Laurie Barge, among many luminaries) that I met the energetic Ramon Brasser. I remember the moment well. He and I were in front of a whiteboard with eraser markers in hand, debating over different ways to make the terrestrial planets (hierarchical accretion by planetesimals, Grand Tack scenario, pebble accretion, *etc.*) when I turned to him and said: “Why is Mars so different from Earth?” Its multiple oxygen isotopic composition is very different, as well as other nucleosynthetic tracers such as ^{54}Cr , ^{50}Ti and ^{62}Ni . If this sounds pretty far afield from the kind of things that I was doing before, you are exactly right. The time was ripe to try something very new for me. Ramon turned to me and said: “Let’s find out!” This began a very productive ~7 years of collaborative work that

culminated in Budapest. More about that later, but by working together Ramon and I began to put together a vision for something larger than a typical NASA or Japanese grant. This is when I started to look around at private foundation funding.

There are not a lot of private foundations that will accept proposals from a call for proposals, and it seems that aside from the Carlsberg Foundation (Denmark) and the Volkswagen Foundation (Germany), most of the rest are in the United States. The ones that we targeted for further inquiry were the John Templeton Foundation and the Simons Foundation. There are many others, but at that time Templeton and Simons seemed to be our best bet for trying to pull together a trans-disciplinary group to tackle the problem as stated: What is the nature and tempo of late accretion? And we also wanted to know what this could tell us about the conditions for the origin of life. While we were ultimately unsuccessful in gaining the interest of the Simons Foundation – even though they supported a Collaborative on the Origins of Life over the course of a decade – we had traction with the Templeton Foundation. Our fantastically creative and out of the box thinker colleague Steven Benner was the principal investigator of a new Templeton Foundation effort on the origins of life! Working furiously, I put together a proposal to create a centre we dubbed “CRiO”: the Collaborative for Research in Origins. Although the length of time that we had the funding was abnormally brief (3 years), we viewed this as a great chance and challenge to really try something new. With CRiO, we could merge planetary dynamics with cosmochemistry and origins of life research. By this time (late 2017), I was remarried to the amazing Kathleen Ebert and we were blessed with two sons, James and John, the brothers of my beautiful daughter, Anna. My personal life was completely back on track, my family was young and growing, and I was not getting any younger. I was already 50 years old when our youngest son was born. Consequently, there is/was/will be no time to lose. Now that CRiO was up and running, what were we going to do with it?

Ramon and Nigel and I immediately set out to combine all published ages for asteroidal meteorites of different classes (carbonaceous and non-carbonaceous, chondritic and non-chondritic, irons, *etc.*) from different chronometers with different closure temperatures. Having done this, which took about half a year(!), we, in parallel, began to construct new models of the formation of planets to account for the observations. This work was later published (Mojzsis *et al.*, 2019) to show that there had indeed been a “heavy bombardment”, but that it probably happened associated with giant planet migration **much** earlier than previously thought with the LHB, back to around 4.45 Ga or so. In subsequent papers led by Ramon (Brasser *et al.*, 2021) this idea was fleshed out further and now appears to be one of the established standards with which to define late accretion to the planets. There was no late heavy bombardment after all. It was an early heavy bombardment.

There were several big outcomes of the CRiO project that the readership may or may not be aware of, but that I take great pride in from a project that lasted only 3 years.

These results:

- 1) Show that mass-production functions derived for our new late accretion bombardment scenarios place useful constraints on the time when a biosphere could begin on our planet (Benner *et al.*, 2020). The result has also been used extensively since then to make sense of molecular clocks that place the LUCA (last universal common ancestor population of all life) at about 4.2 Ga or perhaps earlier (Moody *et al.*, 2024).
- 2) Can explain the highly siderophile element abundances on Earth, Moon and Mars that require a “Late Veneer” (LV) after the formation of the Moon. Simulations of the LV impactor aftermath show that transient hydrogen atmospheres are produced under certain conditions (Genda *et al.*, 2017) with variable lifetimes of atmosphere retention depending on the activity of the young Sun. Many groups are now advocating for such short lived “Miller-Urey type atmospheres” to overcome the problem of incorrect redox in prebiotic chemical production (Citron and Stewart, 2022). Some have recently claimed that LV events are a requirement for starting life. It may also be the case that the Late Veneer will go the same way as the late heavy bombardment (LHB): into oblivion. Time will tell as data accumulate.
- 3) Hint that the inner planets formed in local feeding zones, which we used to argue for the presence of disk sub-structures (“rings”) that can also account for the nucleosynthetic anomaly dichotomy of the inner (non-carbonaceous; NC) and outer (carbonaceous chondrite; CC) Solar System (Brasser and Mojzsis, 2020) seen in the isotopes of Ti, Ni, Cr and others. The most recent manifestation of this model is the “ring models” advocated by the ever productive and creative Alessandro Morbidelli and co-workers.

As you can read herein, I was beginning to move father away from projects based on field studies, geochemistry and geochronology, and more into astrophysics. There are many unanswered questions in my mind, of course, about the nature of the Hadean Earth. These are questions that will remain long after me and are for others to answer. As I wrap up these last few bits, I share with you some thoughts about challenges raised against the interpretations of the Hadean zircons, before I switch gears into astrophysical things.

3.14 Veracity of the Barely-There Hadean Record from Old Zircons

*It was like a bird of rarest-spun heaven metal or like silvery wine flowing
in a spaceship, gravity all nonsense now.*

Anthony Burgess, *A Clockwork Orange* (1961)⁶¹

Water and carbon dioxide are the most abundant volatiles released from degassing. They are strong atmophiles which prefer to remain in the atmosphere, but at the same time are reactive with rocks to make hydrates and carbonates.

Here is a thought experiment for what the degassed atmosphere would be like above a magma ocean (Sossi *et al.*, 2020; Gaillard *et al.*, 2021): If all carbonate and organic carbon now stored in the crust was converted back to CO₂ and all the liquid water in the hydrosphere was converted into steam, Earth would have an atmospheric pressure of about 160 bar and a moist greenhouse (Holland, 1984). Yet, such gas pressures (equivalent to ~16 MPa) do not reach the critical point of water, which is the temperature at which the phase boundary between liquid and gas terminates. Doing so would require increasing the gas pressure to ~20 MPa and bringing the temperature up to 647 K; these should go hand in hand because the vapour pressure of water at 647 K is 21.5 MPa (217 bar; 214 atm). Once the critical point is breached, the planet can go into a runaway mode and heat up to 1500 K, which would lead to melting of its crust (Zahnle *et al.*, 1988; Abe, 1993; Hamano *et al.*, 2013). Such conditions could, in principle, be generated during the most intense interval of accretion bombardment (≥ 4.48 Ga) for a time. But as shown above, on Earth there does not seem to be enough intrinsic gas pressure to achieve critical point conditions for water in the atmosphere over any significant length of time. If this analysis is correct, critical atmospheres are irrelevant to the crustal environment in which the Hadean zircons formed.

For about 25 years, I was engaged closely with figuring out the “Early Earth”. Indeed, as my friend the fantastic geobiologist Kurt Konhauser once said to me: “Steve, you are my go to guy when it comes to the Hadean Earth!” I am very grateful for the “run”. A quarter century of work is not something to sniff at, but it was time to go on to other things. Many fine people are working on the Hadean zircon story now, including the famous Nadja Drabon who is making good progress with studies of the Green Sandstone Bed zircons from South Africa, and of course Dustin Trail. Many questions remain about what Mark Harrison and I used to call “the Ambassadors from the Hadean”. For instance, there are some who have raised doubts about the interpretation of the oxygen isotopes in the Hadean zircons, which I now take time with.

61. Brilliantly and disturbingly visualised in the 1971 Stanley Kubrick film starring the brilliant Malcolm McDowell as the lead anti-hero Alex; the famous critic Rex Reed described it as “... one of the few perfect movies I have seen in my lifetime.”

3.14.1 Distrust about the Hadean Zircons

Objections have been expressed that the oxygen isotopic composition of the oldest zircons provides “unique evidence”⁶² for stable liquid water on Hadean Earth (Kasting and Ono, 2006). Some claim that the Hadean zircon oxygen isotope data could just as well point to an ultra-dense steam atmosphere or an atmosphere comprising critical point water that interacted with the Hadean proto-crust (e.g., Kasting and Howard, 2006). As far as I can tell, the arguments raised – by experts in atmospheric physics, isotope geochemistry and modelling – do not challenge any of the other data presented for Hadean zircons such as mineral inclusions, REE partitioning and so forth. How about we look at this more closely. At 30 bar the boiling point of water is 507 K. Putting aside for the moment the physical challenge of reaching critical point conditions in the whole of Earth’s atmosphere, I note that equilibrium isotope fractionation between different oxygen hosting substances varies with temperature. What is high *vs.* low temperature depends on the vibrational frequencies of the isotopically substituted molecule, but for all chemically reactive nuclides (apart from hydrogen), temperatures of 300 K and above can be considered “high”. Since temperature is the single most important variable for determining isotopic fractionation behaviour, at the critical point temperatures and pressures cited above there should be no mass distinction between the oxygen isotope substituted molecules. Theory, experiments and observation of natural samples show that the oxygen isotopic composition of hot water in reaction with rocks to make clays would yield the same ¹⁸O/¹⁶O water:clay ratio; this is because the fractionation factor (α) between water and clay sharply declines at temperatures above about 300 °C (Delgado and Reyes, 1996; Fig. 3.33).

Clays can form in four ways, all by water-rock interaction and the end product depends on the source rock being altered (Fig. 3.34). These are (i) weathering either subaerially or sub-aqueously, (ii) precipitation from concentrated solutions such as in saline lakes and closed marine basins, (iii) burial diagenesis from the effects of chemical and thermal changes, and (iv) hydrothermal alteration. The range of conditions for clay formation extends from the land-air or rock-water interface, which gives minimum temperatures of 2 °C for ocean bottom formation and maximum temperatures near 200 °C where clay minerals are found. Burial depths for the formation of clays are usually not greater than 6–7 km and they mostly form within the surface zone (Velde, 1992). The existing oxygen data for Hadean zircons do not provide absolute temperatures of the weathering products (clays) that ultimately contaminated some Hadean magmas. Generally speaking, rocks with abundant aluminosilicate minerals tend to produce kaolinite and illite clays, whereas smectite tends to form from basaltic and ultramafic rocks.

62. While demanding “extraordinary evidence” for “extraordinary claims” is considered a sound principle of critical thinking (the Sagan Standard), demanding evidence that is physically impossible or irrelevant to the claim being discussed is classified as Special Pleading.

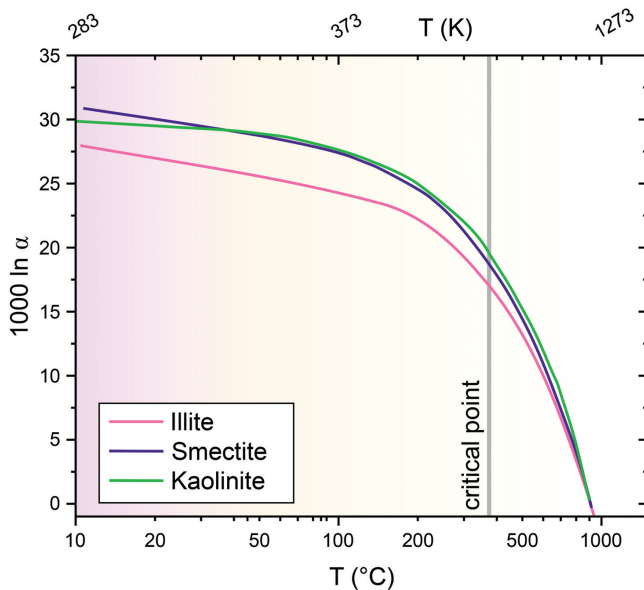


Figure 3.33 Feet of clay. Estimates of the oxygen isotopic fractionation (expressed as $1000 \ln \alpha$) between three clays: illite, smectite, kaolinite and water as a function of temperature. Modified from Savin and Lee (1988).

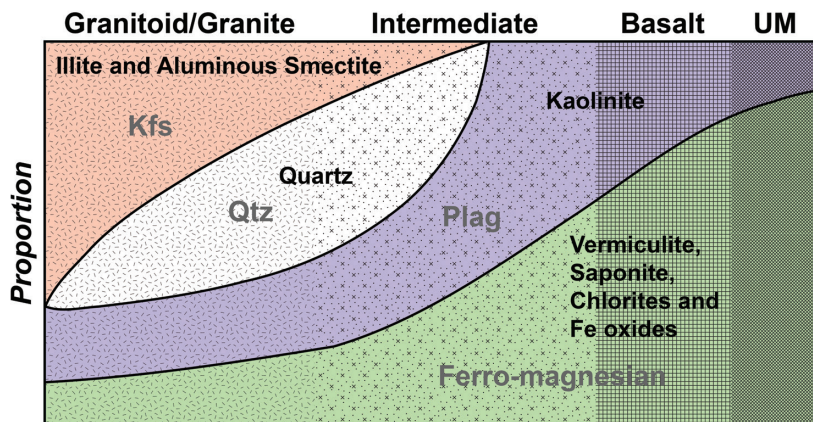


Figure 3.34 Clay origins, now and then. Compilation diagram of the proportional change of different minerals as rocks weather by hydration. The vertical axis is the proportion of minerals, and the horizontal axis shows the progression from more silicic to more mafic and ultramafic sources of the clays. Granitoids/

granite typically weather to illite and aluminous smectite from parent minerals K feldspar (Kfs), quartz (Qtz), plagioclase (Plag) and ferro-magnesian minerals. Mafic and ultramafic rocks typically yield kaolinite and others as listed.

Thus, evidence appears to point to atmospheric conditions sustained on Earth's surface since around 4.4 Ga that have been far away from the critical point water. The oxygen isotopic compositions for a significant percentage of Hadean zircons show evidence for ^{18}O -enriched (Harrison, 2009) and depleted (Gamaleldian *et al.*, 2024) source materials which contributed to the contamination of Hadean magmas. The most likely source of the isotopically heavy (^{18}O -enriched) materials are clays and their metamorphic equivalents, pelitic schists. The precursor clays to the rocks which contaminated Hadean magma chambers crystallising zircon had values of $\delta^{18}\text{O}$ up to around +30 ‰, much like now.

It never ceases to amaze me that the more we learn about the “Early Earth”, the more our dire preconceptions for how terrible it was, are consistently dashed by the accumulated evidence.

Caught a handle on the rising Sun. Took a day to rise and fall. At the end of the trail I was scarred and burned, but felt no pain at all.

Henry Rollins and Kira Roessler, I'm the One, Black Flag (Loose Nut, 1985)

Welcome to the last part of this volume. Starting back in 2013 in Boulder, Elizabeth Frank and I put together a manuscript that attempted to analytically model the evolution of uranium and thorium in the Galaxy (Frank *et al.*, 2014). We sent the paper to *Proceedings of the National Academy of Sciences* for their consideration. Interestingly, it was sent out for review, and although the work was ultimately rejected, we got great positive feedback. So much so that one of the reviewers of our original work, the brilliant Bradley “Brad” Myer, ended up inviting Elizabeth to Clemson University to work with him on the problem more thoroughly using a code he had developed with the legendary Donald Clayton. Don Clayton (not to be confused with the equally legendary Robert “Bob” Clayton at the University of Chicago), predicted the nature of presolar grains in meteorites before they were discovered, among many achievements. The result was a paper in the journal *Icarus* on estimates of the rock forming inventories and heat producing elements for planets over galactic time. This was, for me, the first geoastronomy paper. The concept for geoastronomy was drawn from historical precedent: geo-chemistry, geo-physics, geo-biology all united the Natural Sciences together – it was time to do the same with Astronomy. The concept is to blend geology and astronomy to study the composition, structure, and evolution of rocky planets in a cosmic context. By bringing together the principles of Earth sciences and astrophysics, geoastronomy aims to better understand both our home planet and distant exoplanets.

You see, I thought it made sense to search for the chemical foundations of exoplanets by using insights like those Brad provided from Galactic Chemical Evolution (GCE) to predict and understand the chemical nature of rocky exoplanets by extrapolating the compositions of their host stars. What continues to set our work apart is just how the elemental and isotopic makeup of a planet can differ depending on when and where it formed in the Galaxy. I refer to Figures 3.8 and 3.9. Such observations continue to be the inspiration for this kind of study and I am confident that this will be the case for centuries to come.

We are standing on a shore – our small and beautiful planet – looking out over a vast ocean of something that is neither nothingness nor is it entirely unknowable. I have the strong suspicion that the complexity of the universe is so great that our brains will be unable to grasp it except in the most rudimentary terms. We will most probably have to have it explained to us by something better able to do this such as an artificial super intelligence. Yep, you read that right, we will almost certainly need AI to make significant progress in understanding nature.

4.1 Planets Around Other Stars – Exploring the Zoo

And now, Socrates, as you rebuked the vulgar manner in which I praised astronomy before, my praise shall be given in your own spirit. For everyone, as I think, must see that astronomy compels the soul to look upwards and leads us from this world to another.

The Republic, Book VII (Πλάτων - Plato, 360 B.C.E.)⁶³

At the current pace of discovery, we will have confirmed the existence of 10,000 exoplanets – worlds around other stars – before the end of this decade. It is widely regarded as fact (but not substantiated by observation *per se*) that most Sun-like stars (those of spectral types F, G, K and M) in our Galaxy host planetary systems. The huge drawback to any research of these objects is that their chemical and physical attributes are barely known, especially for those composed of rocky material. Such planets are difficult to observe, being tiny, far away, and faint. What little we know about these objects is confined mostly to mass-radius-density, and orbital parameters (Fig. 4.1). Space telescopes used to search for exoplanets were designed before it was realised that they could also be used to study exoplanet atmospheres (e.g., Hubble Space Telescope) and hence were not optimised for this challenge. Consequently, up until very recently, we have been limited in our ability to understand even the basic physical-chemical properties of rocky exoplanets. It seems that every day, there is a new exoplanet discovery. Yet, beyond mass and radius, how do they function? How do their attributes depend on age and composition? Why is the observed continuum of exoplanet sizes and densities between Earth and Neptune absent from our Solar System?

We will never have actual samples from an exoplanet, other than photons in our collectors. Therefore, an exoplanet's geologic history will never be decoded remotely except through whatever expression of its geology can be found in its atmosphere, and reflected surface features. What is the chemistry of exoplanet atmospheres? As we retrieve spectra for rocky exoplanet atmospheres later this century, what will they tell us about their interiors and geologic histories? Such a task is formidable because data indicate a full range of planetary types from metal dominated to fluid dominated, and in between metal-silicate-fluid. A way to achieve such an aim is to use the compositions of stars to place plausible constraints on the bulk compositions of the building blocks of exoplanets and, eventually, of the exoplanets themselves.

*To say that exoplanet science is in a **revolution** is something of an understatement.*

63. Plato's real name was Aristocles (Αριστοκλῆς). It seems that "Plato" was originally a nickname that stuck.

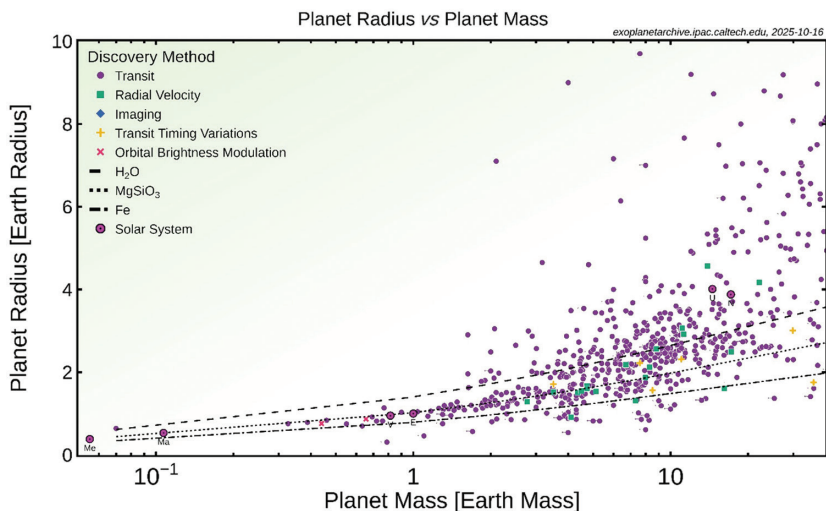


Figure 4.1

Out there. The values plotted are detected exoplanets grouped by discovery method (see legend). This Radius vs. Planet Mass plot is relative to Earth values and shows planet masses in the range 0.05 to 40 Earth Masses and planet radii between 0 and 10 Earth Radii, with addition of H₂O, MgSiO₃ (the pyroxene end member, enstatite) and Fe (metal) density curves for reference. Also included are data points for the Solar System planets (Me = Mercury; Ma = Mars; V = Venus; E = Earth; U = Uranus; N = Neptune). From <https://exoplanetarchive.ipac.caltech.edu>.

The James Webb Space Telescope (JWST; Fig. 4.2) is directly constraining the atmospheric chemistry of Super Earths (between 1 and 1.6 Earth radii) and sub-Neptunes (between 1.6 and about 4 Earth radii). The reason for this separation of radius for the two classes of planets is that when a rocky planet – basically a world composed of silicates + metal ± fluid – begins to approach something like 6× Earth’s mass (anything much larger than Earth that is still Earth-like, is referred to as a “Super Earth”, or when it is also ultradense, a “Mega Earth”), it collects gas and becomes a sub-Neptune and geophysically speaking leaves the category of a rocky planet.⁶⁴ Soon, in 2026, the European Space Agency’s (ESA) PLATO mission will launch⁶⁵ with the explicit task of finding terrestrial planets. This spacecraft will survey up to a million bright Sun-like stars to search for transiting Earth sized planets and enable better stellar age measurements *via* asteroseismology⁶⁶. The asteroseismology

64. Neptune is 17 times more massive than Earth. Thus, a sub-Neptune is something smaller than this that still has the gross properties of an ice giant.

65. https://www.esa.int/Science_Exploration/Space_Science/Plato

66. <https://en.wikipedia.org/wiki/Asteroseismology>



Figure 4.2 Sky eye, fully deployed. The James Webb Space Telescope (sometimes called JWST or Webb) is an orbiting infrared observatory. The human figure displayed next to it for scale gives a sense of how large it is. JWST image by NASA.

technique is considered the most robust means for determining stellar ages. Another European project on the horizon is the Extremely Large Telescope (ELT), expected in 2028. This instrument will perform unrivalled high resolution spectroscopy of exoplanet atmospheres and may directly image small exoplanets around the nearest stars. Yet another ESA mission dubbed ARIEL is planned to launch in 2029. This spacecraft will be dedicated to atmospheric spectroscopy⁶⁷. These powerful capabilities are forthcoming within the decade, with a lot of the drive provided by European science.

The European Association of Geochemistry (EAG), publisher of these *Geochemical Perspectives*, has a lot to gain by aligning itself with these initiatives.

We will soon see the discovery of thousands of new exoplanets, for many of which atmospheric chemistry will be accessible. It will require trained geochemists to help make sense of the data coming in if we are to understand anything about exoplanet properties such as differentiation, core formation, and the mantle-crust-atmosphere: Magma lurks behind the formation of the envelopes and gases are partitioned between them. Hence, the key to understanding the geodynamics of exoplanets is to analyse their atmospheres. If only we did not get interrupted in the quest due to changes in funding profiles, political actions, or surprise global events such as war or pandemic.

67. https://www.esa.int/Science_Exploration/Space_Science/Ariel

4.2 The COVID Contagion Changed the World

On December 31, 2019, the government of China announced the discovery of a cluster of serious pneumonia cases in Wuhan with a high fatality rate. Wuhan is the capital of Hubei province and the most populous city in Central China, with a population of over 12 million. It serves as a critical political, financial, and transportation hub, and as such the world can feel the effects of events in Wuhan. The first American case of COVID-19 was reported on January 20, and a public health emergency was declared in the United States on January 31. The timing was terrible because the US government at the time was headed by people who did not take the threat seriously. Some people do not know what COVID-19 means, except for an acronym for annoyance and death: CO stands for coronavirus, VI for virus, and D stands for disease, while 19 stands for the year, 2019, that the outbreak was first detected. Hence, there was no COVID-1 through 18! Contrary to popular opinion, the fatality rate of COVID-19 was far lower than that of historical catastrophes like the Black Death and Smallpox, but significantly higher than recent influenza pandemics such as the 2009 H1N1 “Swine Flu”. Perversely, I put together a comparison of morbidities in Table 4.1 to underscore this fact. It is evident when doing so that comparing fatality rates across centuries is complex due to vast differences in medical technology, public health responses, global population size and availability of data.

When I write that it was time for a change, I really meant it, at least with me. Kathleen and I were home with two small children (ages 5 and 6), in lockdown conditions like hundreds of millions of other families around the world. Our big and spacious house in the Front Range of the Rocky Mountains above Boulder, Colorado, felt isolated and became a lonely bastion, even if the views of Long’s Peak (4346 m) were breathtaking. As an aside, I resolved to climb this mountain in 2020 (at age 55) around COVID time, which worked out well because it was within the quarantine guidelines. The climb up the mountain and back to the trailhead took 14 hours. All the while, I thought of how marvelous my children Anna, James and John are.

Our family made the best of the COVID time and threw regular “ZOOM Parties”, but the world changed. During that interval, I resolved to redouble my efforts to get closer to our extended family in Central Europe (which paid off, see below). It also became abundantly clear to me that large parts of the government in my birth country no longer cared for the welfare of the majority of its citizens, and was fatally drifting into kleptocracy, nepotism and oligarchy. To say that I was concerned about the direction the US was taking with choosing the kind of leadership it embraced, is a big understatement. You might say that I could see the writing on the wall, and decided it was time to go. Hope for a change keeps us from making a change. Hope is nice, but it has its limits, and we had reached ours.

Table 4.1

The COVID-19 contagion compared to other pandemics. Information from Wikipedia.

Pandemic	Years	Agent	Fatality (%)	COVID-19 comparison
Black Death	1346–1353	Bubonic Plague (bacteria)	50–100 %	A vastly more lethal pandemic, killing a much larger percentage of the global population at the time.
Smallpox	Early 16th century onwards	Variola major (virus)	20–60 %	In areas with no prior immunity, like the New World, it was devastating, killing up to 90 % of the indigenous population.
Ebola	2014–2016 epidemic	Ebola virus	~50 %	Ebola's fatality rate is much higher, but its lower transmissibility and more contained outbreaks resulted in fewer overall cases compared to COVID-19.
MERS	2015–present	MERS-CoV (coronavirus)	~34 %	MERS was far more lethal but much less contagious than COVID-19, leading to significantly fewer overall cases and deaths.
SARS	2002–2003	SARS-CoV (coronavirus)	~15 %	SARS had a higher fatality rate but, like MERS, was less transmissible, limiting its global spread compared to COVID-19.
1918 Spanish Flu	1918–1920	H1N1 influenza (virus)	2–3 %	The Spanish Flu was more lethal on a per-infection basis and killed a disproportionate number of young, healthy adults. A much smaller global population at the time meant a lower overall number of infections but a higher relative mortality rate.
COVID-19	2019–present	SARS-CoV-2 (coronavirus)	0.25–3.0 %	While fatality ranges for COVID-19 are comparable to the Spanish Flu, the effect on a much larger global population, combined with high transmissibility, led to a high absolute death toll. The virus was also deadliest for the elderly and those with comorbidities.

When all seemed lost and my various attempts to build a group dedicated to Origins studies in the USA was stone walled again by repeated denial of funding from NASA, NSF or anywhere else, things suddenly changed. Before this change, many leads for what looked like promising possibilities to move

my operation abroad failed. Either this shortfall was due to lack of interest or pre-determined strategic decisions, or something else that I will never know the facts about. It is amazing how rapidly change can happen. I was just coming off a big service activity at the University of Colorado as the Chair of the College of Arts and Sciences' Council after three years. It was a deeply fulfilling experience, and my colleagues seemed to be happy with my performance even if the (former interim) Provost and his so-called "Interim Dean" did not appreciate my sticking up for the faculty and staff so much. Indeed, can you really call someone "Interim" if they are around for 3 or 4 years in the role? In any event, I was itching for new challenge, COVID was in full swing, and we were ready to go.

My inquiries in Europe started to pay off. In November 2020, I was on the receiving end of a Lazarus Experience⁶⁸. But, as usual, I digress.

4.3 Will Any of Us Be Remembered 100 Years from Now? 500 Years from Now?

By now you realise how fond I am of pulling together wild ideas from here and there. Have you ever heard of Sturgeon's Law? Editor and writer (especially of science fiction) Theodore Sturgeon⁶⁹ was at a seminar in the 1950s about science fiction, his genre, when a heckler loudly jeered: "Isn't it true that 90 % of all science fiction is just crap?" Sturgeon responded:

"Sure! But 90 % of everything is crud. If you're going to judge everything - art, literature, music, food - by the 90 % that's crud you're going to miss everything that's good in life and everything is going to look like crud to you. You judge everything by the 10 % (or 5 % or 1 %) that's not crud, and things look pretty good."

Or words to that effect. The thing is, just like literature and any other art form, many things in science were viewed as "ground breaking" or "revolutionary" once. Time and the community have curated what has survived. Do you think the 1960s (or '70s, or whatever) were a golden age for music or geochemistry? Do you like to play oldies from your collection of "Greatest Hits of the '70s" because it is great, or because you are smitten with nostalgia? Not everything that is published is worth listening to or worth reading, not even your own stuff. For example, sometimes we are wrong about something (like I was about the late heavy bombardment), but many of us stubbornly do not want to

68. The term "Lazarus experience" refers to the biblical story of Lazarus of Bethany (New Testament, John 11), who was raised from the dead by Jesus after four days in the tomb. In my context, I use it as a metaphor for renewal or rebirth.

69. https://en.wikipedia.org/wiki/Theodore_Sturgeon. In his "Law", he originally used the word crud, which has since been substituted with the word "crap". The meaning is distinctly different, even if the sense is similar.

give up on the idea because so much has already been invested in it. Our money, and most valuable of all, our time and reputation, are perceived to be on the line if we fail to keep “defending the edifice”.

*Deyr fé, deyjja frændr,
deyr sjalfr it sama,
ek veit einn, at aldrei deyr:
dómr um dauðan hvern.*⁷⁰

The Poetic Edda, Hávamál 77 (800-1050 C.E.)

Such irrational behaviour is related to the Sunk Cost Fallacy, a very common psychological phenomenon whereby a person is unwilling to give up on an idea (usually based on belief rather than understanding) because they have invested heavily in it. Many of us hold on to that which is incorrect even when abandonment would be more beneficial. Back to the music analogy: Think about the enormous quantity of music generated in your favourite decade that has never been heard since then. Most of it was junk and it is not just because taste changed. Unlike science, time is generally your friend in the arts like music, painting, sculpture, literature, and so forth. It is hard to argue which is closer to the truth: Picasso or Mondrian.

The method of science curates itself as we go about our business collecting new data and modifying (or, God forbid, abandoning...haha) theories to fit the new reality. So, you might tour a contemporary art museum and find yourself covering your eyes much of the time (I do) and shaking your head in wonderment at the choices curators have made. Yet, what about that 5 or 10 % which is out there that is good? It will be around for a while.

Text Box 4.1 – The Rate of Scientific Output Has Been Increasing for Decades, but Has the Quality or Discovery Potential?

For example, Web of Science reports that the number of papers has doubled approximately every nine years since the 1970s. Over 5 million academic articles⁷¹ were published in 2022. There is no exact number for scientific journals but estimates from around the year 2010 (e.g., Larsen and von Ins, 2010) and extrapolated to today suggest there currently are around 30,000 to 40,000 peer reviewed journals globally. Some years ago, it was pointed out that around half of all scientific papers are only read by the author(s), editor(s) and reviewer(s) and that only one in ten has a citation (Hamilton, 1990, 1991). This is sobering news and brings me back to my earlier point with Sayre’s Law. It may also be a flawed analysis and more papers are cited than urban legend permits (Pendlebury, 1991).

70. Cattle die, | and kinsmen die,
And so one dies one’s self;
One thing now | that never dies,
The fame of a dead man’s deeds.

71. <https://wordsrated.com/number-of-academic-papers-published-per-year/>

4.4 Break on through to the Other Side (of the Atlantic)

In November 2020, I was sitting in my home office and minding my own business. Then I got a message in my email Inbox from the Alexander von Humboldt Foundation in Germany. They were going to award me the Humboldt Research Prize! I was nominated by the proficient Christoph Heubeck at the University of Jena (in eastern Germany) whom I have long admired for his work on the sedimentology of Paleoproterozoic rocks mostly from South Africa. A day later, I got another message, this time from the Faculty of Earth Sciences, Geography and Astronomy at the University of Vienna, that I was one of the new visiting Ida Pfeiffer Professors! One of us was a geologist (me), while the other recipient was an astronomer (the adept Eric Gaidos from the University of Hawai'i). My friends and colleagues, the brilliant Christian Koeberl, João Alves and Manuel Güdel at the University of Vienna were now going to be in my proximity. Things were beginning to look very bright at this point and Kathleen and I began to discuss how we were going to make a move to Europe happen, with the children in school, the house we were renovating, the new cars, and our extensive belongings to consider, and beyond that all our professional stuff. The answer came the next day. I received a call from the Director General of the Research Center for Astronomy and Earth Sciences⁷² (RCAES) of the Hungarian Academy of Sciences in Budapest, the ingenious and savvy astronomer Laszlo Kiss. For the past several months, he and I, along with the proficient geochemist Attila Demény and the world renowned theoretical biologist Eörs Szathmáry, had been holding discussions over the possibility of me starting a geoastronomy group in Budapest. They shared with me that it would happen! The initial joy and excitement gradually gave way to the cold reality that we were leaving what we had built in Boulder, Colorado, for over twenty years. The result was the decision to move to Vienna for half a year, then to make a home in Budapest. Sixty five years later, the son of the man who left his homeland was bringing the family back to the Old Country.

4.5 Planet-Forming Nuclides and their Expression in Terrestrial Exoplanets

The geochemical and cosmochemical underpinnings of planets are as important – if not more so – to their ‘habitable potential’ as proximity to their host star. Studies that elucidate the origin of the elements in the early Universe and in massive stars make use of codes that are built to track nucleosynthetic pathways or networks under different extreme conditions. Such nucleosynthesis studies must have an accurate, physically motivated explanation for the pattern of abundances found in nature. These sources of information come from the Solar

72. Csillagászati és Földtudományi Kutatóközpont in Hungarian, or simply, CSFK.

System (*i.e.* the Sun) and other locations in the cosmos such as other stars, the interstellar medium, cosmic rays, the intergalactic medium, and other galaxies including the satellite galaxies of our Milky Way. The key is accurate information on the bulk composition and pattern of relative abundances of the nuclides in the Sun. For solar abundances, the main sources of information are Earth and the sampled bodies of the Solar System, namely the solar spectrum and primitive meteorites that broadly represent the devolatilised composition of the Sun. As I have written about elsewhere (Mojzsis, 2022⁷³), these are not new ideas even if the way they are implemented may be novel. For instance, Harkins and Hall (1916) presciently argued that the cosmic abundances of the elements are reflected in the composition of meteorites, which ought to follow the values for the Sun owing to the fact that this object comprises >98.5 % of the mass of our Solar System. Somewhat later, the father of geochemistry the immortal V.M. Goldschmidt (1929) proposed that primitive meteorites should lend insight to Earth's bulk chemical makeup of the rock forming elements. These ideas were not fully validated until the 1960s. Compilations of stellar photosphere abundances against the most "solar" CI group of meteorites (*e.g.*, Anders and Grevesse, 1989; Lodders, 2003) provide very strong support for the inverse idea that the composition of the building blocks of the planets can be estimated from the composition of the Sun. Over forty elements have a Si normalised photospheric/CI chondrite abundance ratio between 0.9 and 1.1. The relative elemental abundances of refractory and moderately refractory elements such as Fe, Mg, and Si are similar among the Sun, Earth, Mars, the Moon and meteorites (Fig. 4.3).

To make sense of this insight, we need to continue to foster the tradition of combining fields in the Natural Sciences (Fig. 4.4). Before World War 2 (1939–1945 C.E.), the fields of science concerned with the study of the natural world through observation and experimentation, focusing on physical and natural phenomena, were parochial. Natural science's main branches are physical sciences (chemistry, physics, astronomy), life sciences (biology), and earth sciences (geology). The common goal of these five is to understand the fundamental principles, laws, and processes that govern the universe, living organisms, and Earth's systems. Geology got together with physics to create geophysics, which gave us such discoveries as plate tectonic theory. Geology and chemistry combined to form geochemistry that led to many insights such as the age of the Earth. Geology and biology have more recently merged to yield geobiology, which is a hot topic that investigates the interaction of the geosphere with the biosphere at all scales. We are now witnessing the combination of geology and astronomy into geoastronomy:

73. I encourage you to have a look at this paper. If you have trouble finding a copy of it, just email me (smojzsis@gmail.com) and I will happily send you the pdf.

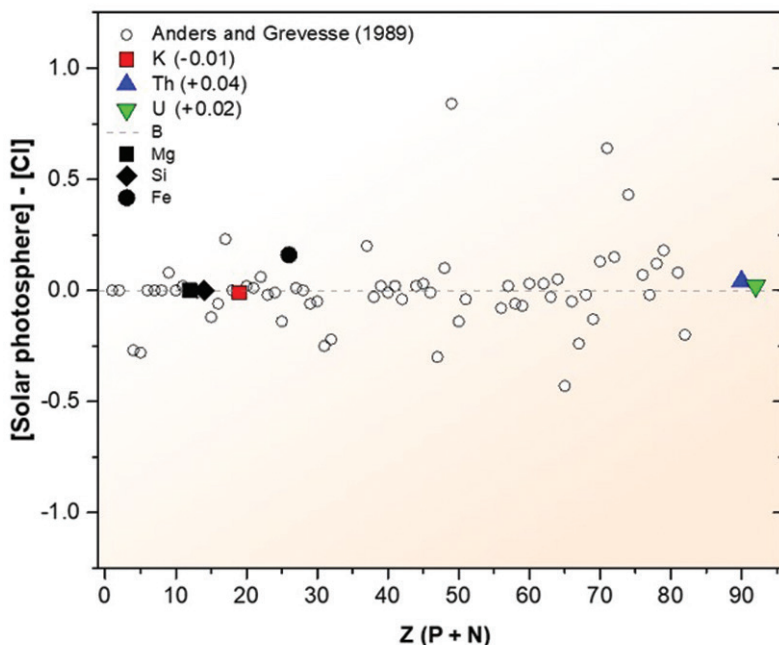


Figure 4.3

Know thy star, know thy planet. Shown here are data from Anders and Grevesse (1989) of different nuclides (Z) expressed as the sums of the proton (P) and neutron (N) number, normalised to the solar photosphere and CI chondrite. Note that there are many other data sources but they generally show the same thing. The correspondence between low atomic number elements and the principal long lived radioactive heat source (K , Th , U) is imperfect but evident.

Different stars have different compositions from our Sun, which means that the planets forming around them are expected to reflect these differences in their geodynamic properties.

Already well before arriving in Budapest, I began to formulate my long term strategy to make geoastronomy a reality. The first person I met with to bring on board was the astounding Kevin Heng, who was at the University of Bern in Switzerland at the time. Over a cup of coffee in a small café in central Bern, Kevin and I talked about what we found to be of mutual interest and I made the pitch to him. He was immediately in agreement with me and we put together a plan to write a large, multi-year proposal to the European Research Council (ERC) Synergy grant scheme. This is the crown jewel of the ERC, and a very high bar to shoot for, but we wanted to try. Not long after our meeting, Kevin moved from Bern to take up a new Chair of Exoplanet Astronomy at the

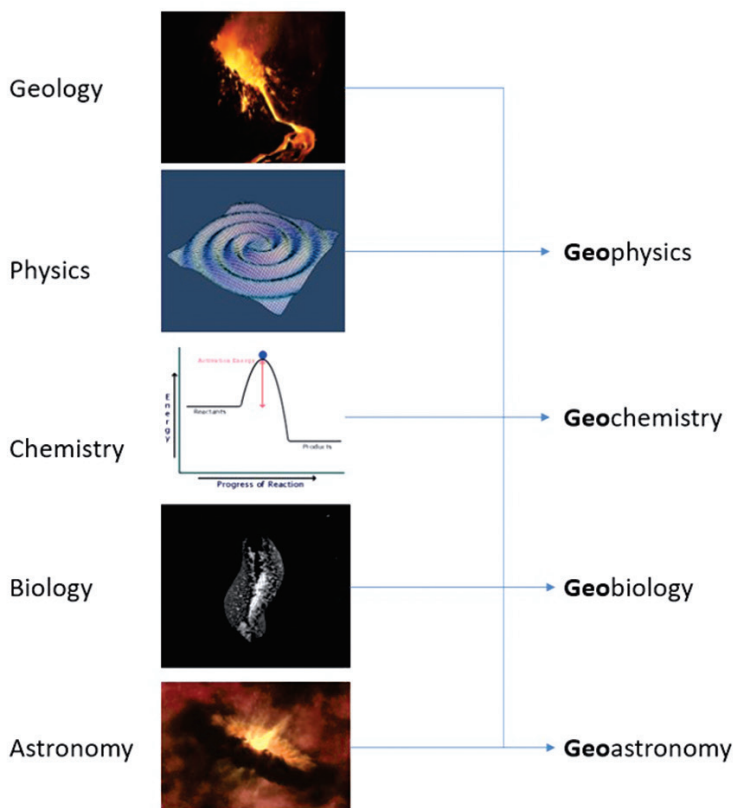


Figure 4.4 Blending and multi-disciplinarity. Geology is an enthusiastic consort with the other natural sciences. This promiscuous scientific network reminds me of a common saying of the magnificent Kevin Burke: “Geochemists make excellent servants, but terrible masters”.

Ludwig-Maximilians University of Munich. This change also meant that he could devote considerable resources from his side of the equation to help bring the geoastronomy project from the status of dream to reality. Meanwhile, following my extremely nice stint as Ida Pfeiffer Professor in Vienna, I set up shop at the venerable Konkoly Observatory of the CSFK on a wooded hill above Budapest completely infested by the European wild boar (*Sus scrofa*)⁷⁴. For almost the entire

74. The wild boar has a long history of association with humans, having been the ancestor of most domestic pig breeds. Anecdotally, Saint Emeric of Hungary (Szent Imre) died in 1031 C.E. from injuries sustained during a hunting accident where he was attacked by a wild boar. He was the crown prince, the son of King Stephen I, and was killed at the age of 24 while hunting in Transylvania.

time I was at CSFK, my mind was laser focused on writing the ERC grant. The directorship of CSFK was wonderfully supportive of my endeavour, even after the first two attempts failed. By the third attempt, in 2023 with the interview at ERC headquarters in Brussels in 2024, we, the three principal investigators, had learned how to enhance the competitiveness of our proposal and were delighted to learn the news of its acceptance. As I mentioned, Kevin Heng was one of these, while the other is the convivial Fabrice Gaillard in Orléans, France. I thank my lucky stars for working with such a talented team.

4.6 Life in Budapest

Hungary is my *heimat*. As someone with feet in both America and Europe, it was the first place I felt at home. Although my language skills in Hungarian could be a lot better and I will never lose my American accent no matter how hard I try, it nevertheless feels like I am with “my people” when I am there. As you learned from an earlier section of this *GP* from my father’s history, Hungary was under the Soviet boot for more than 40 years. This occupation and dominance by a foreign power of that strength had a profound negative effect on the psyche of the nation that it might take another generation or two to erase. On top of that, the loss of territories and isolation of minority communities in neighbouring countries, continues to fuel resentment in some people. For me and many people I know, we shrug our shoulders and ask: “Aren’t we all friends now?” Living in Budapest allowed me to rekindle connections with cousins from the countryside, to make many new friends and to be surprised out of my mind with a voice from the old times, from my wild and wandering youth. Before reading further, go back to Figures 2.6 and 2.13. Now read this:

Around Spring 2022, I was on a business trip and called home to Budapest. My wife answered that she and our sons had just returned from a birthday party for one of James’ classmates in the Austrian-Hungarian Europa School (a bi-lingual German-Hungarian grammar school on the Buda side of Budapest). The party took place in a park and was for a little girl Josie who was quite fond of James. Kathleen told me that she had met the parents of this little girl, who were a German woman from Bautzen (a small city not very far from where Kathleen grew up in East Germany) and an American man; both of them had lived in Budapest for many years. I did not think much of this story (I missed the party, remember), but was pleased that everyone seemed to have had a good time. A few months later, we decided to invite the mother and daughter over for dinner and board games. That was when I learned that the father of Josie, who was the same age as James, in the same school, and in the same classroom, was none other than the nonpareil Mark Richards (Fig. 2.6). The last time I saw this man was in 1992 when we worked together at a language school. Here we were again 30+ years later, having come full circle, and he was in Budapest and spoke beautiful Hungarian.

Anybody who is in the know will tell you that the Hungarian language is difficult to grasp, especially for Indo-European speakers. It is one of the 24 official languages of Europe, and consistently considered the most difficult owing to its 18 (or 22, depending on how strictly you define them) noun cases and fundamental Ugric language family roots (Fig. 4.5). As an agglutinative language, it forms words by joining multiple morphemes (meaningful parts) in a linear sequence, with each morpheme retaining its original form and meaning. Other examples of this genus include Turkish, Finnish, Korean, and Japanese, which often form complex words or even entire sentences with a single long word. A favorite example I like to use to illustrate this point is the word *élem*. This one word can be translated as: “Away from in front of me”. You might say that my own interest in languages is something of an obsession (I can have conversations with people in American English, High German, Hungarian, and after two or three glasses of wine, French-Spanish-Italian all mixed up).

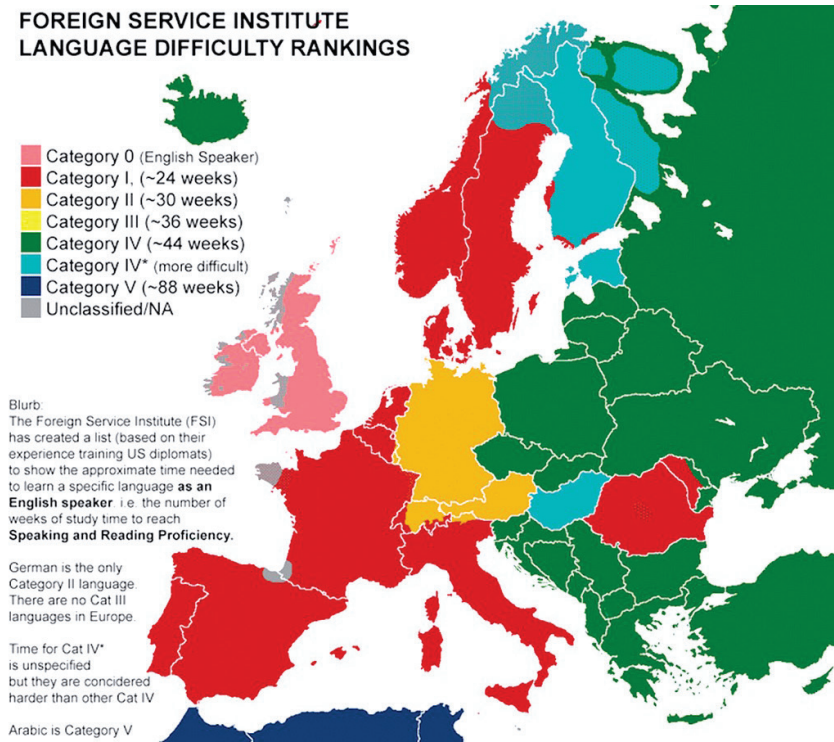


Figure 4.5 The irony of it. Although English is classified as a Germanic language (with strong Latin influences), ironically German is the most difficult of the Germanic languages for an English speaker to pick up. Note the position of Hungarian and its distant linguistic relatives, Finnish and Estonian. I moved from Category 0 to Category I to Category II, and then skipped to Category IV. From the Foreign Service Institute.

My experiences are not unique to anyone who has decided that there are times when one must move from one country to another, and even from one continent to another. I have lived (more than 2 months) in New York City, northern New Jersey, Boston, Houston, Budapest, San Diego, Los Angeles, Boulder, Nancy, Lyon, Tokyo, Vienna, Jena, and Bayreuth.

For human history up to very recently, almost everyone lived within a day's walk of where they were born. Aside from war/invasion and famine, people stayed where they were. For most, it is intimidating to go someplace where customs are foreign and the language is (at first) unintelligible and the food is unfamiliar. As my wife Kathleen often points out:

*Moving is Living.*⁷⁵

As we extend our gaze to other Solar Systems, what can we learn about the uniqueness of ours?

4.7 How Unique is our Solar System?

This is a question that I like to answer in a Socratic way, and I do not profess to know the answers to these questions. We have already documented thousands of times over that there are many instances where exoplanetary systems are very different from our own. Did our system experience fewer or less dramatic planetary migration than is typical? Is our system cosmochemically typical? (Is there even such a thing?). At present, small, rocky terrestrial planets are hard to get details on, even if they are abundant. According to what we have seen in Figures 2.9 and 3.1, we will have to wait for the information we need to know this.

What, for example, determines planetary diversity? I would say that the answer comes down to:

- 1) It must be stable (can survive for a long time – many millions to billions of years).
- 2) It is cosmochemically plausible (starting components are available in the universe).
- 3) A dynamical path exists that can lead to such a planet (it has a credible origin).

Stability considerations exclude a wide range of objects or characteristics that cannot persist. For example, a self-gravitating, one Earth-mass body of hydrogen and helium with the entropy of Jupiter could not exist in Earth's orbit. It would literally disassemble by tidal action and the action of external UV radiation from the Sun. Somewhat less dramatically, stability considerations

75. This quote was something she read from the label on a Yogi Tea bag; a hilarious example of profundity wrapped in the mundane.

also preclude small bodies close to the parent star from retaining substantial atmospheres. Stability should be regarded as a strong constraint on hypothetical planets because the physical considerations are firmly based and well understood. Of course, it is usually much easier to prove that something is unstable than to prove it is stable, so even this consideration has its limitations.

Cosmochemical plausibility means that we can expect that there are no planets formed entirely of gold, or lead, nor are there worlds out there that are hundreds or thousands of times enriched in long lived radioactive elements. Beyond ^{40}K , the other long lived radioactive heating sources for rocky planet interiors, ^{232}Th and $^{235-238}\text{U}$, are only produced by the rapid neutron capture (r-)process. Common core-collapse supernovae (CCSNe) cannot produce the required neutron densities for the r-process (e.g., Roberts *et al.*, 2017; Kilpatrick *et al.*, 2017; Watson *et al.*, 2019). Rare magneto-rotational CCSNe specifically associated with high rotation and jets are also possible r-process sources, but these are debated (Cowan *et al.*, 2021). Observational surveys, such as the Hamburg/ESO R-process Enhanced Star survey (Christlieb *et al.*, 2004) are making models more robust. Some stars even show an ‘actinide boost’ wherein excess Th and U exist with an unclear origin (Holmbeck *et al.*, 2018). Unfortunately, the abundances of the long lived heat-producing isotopes ^{40}K , ^{238}U and ^{235}U cannot yet be observed or even computed for stars. This is an active area of research in our geoastronomy project.

4.8 How do we Classify Planets?

*Romantically, you could say that we are all made of stardust,
but the truth is also, that we're all just nuclear waste.*

Jim Al-Khalili (fyp-science.com)

There exists no Hertzsprung-Russell (HR) diagram for planets as there is for stars. The predominance of hydrogen (and helium) and the simplicity of its material properties allow astronomers to collapse most of the behaviour of stars into a two dimensional plot, the Hertzsprung–Russell (H–R) diagram of colour *versus* brightness. And most stars fall along the main sequence of that diagram (Fig. 4.6). The richness of planets such as the zoo of possibilities that exists just in our own Solar System, much less exoplanetary systems, arises from imperfection and from chemistry. I define that to embrace the range of behaviours that can occur when materials are alloys or physical mixtures.

Planets lack the equivalent of the low dimensional H–R diagram owing to their complexity.

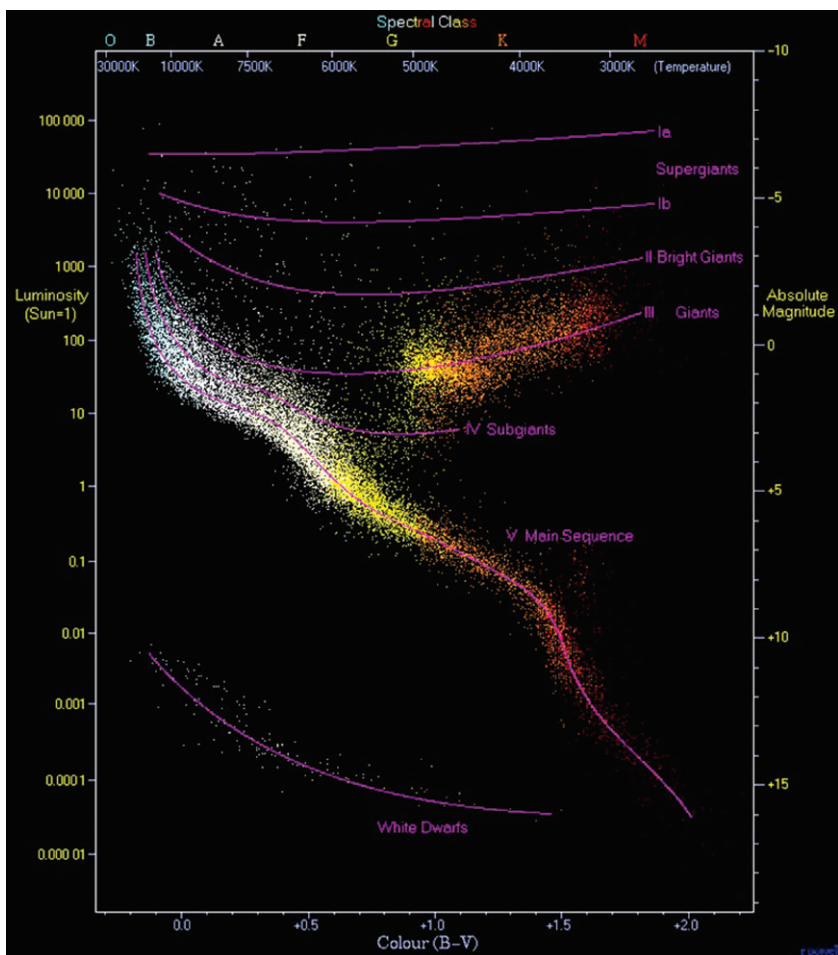


Figure 4.6

Mapping stars. Hertzsprung–Russell diagram. A plot of luminosity (L ; absolute magnitude) against the colour of the stars ranging from the high temperature blue-white stars on the left side of the diagram to the low temperature red stars on the right side. This diagram is a plot of 22,000 stars from the Hipparcos Catalogue together with 1000 low luminosity stars (red and white dwarfs) from the Gliese Catalogue of Nearby Stars. The ordinary hydrogen-burning dwarf stars like the Sun are found in a band running from top left to bottom right called the Main Sequence. Giant stars form their own clump on the upper right side of the diagram. Above them lie the much rarer bright giants and supergiants. At the lower left is the band of white dwarfs – these are the dead cores of old stars which have no internal energy source and over billions of years slowly cool down towards the bottom-right of the diagram. From <http://www.atlasoftheuniverse.com/me.html>; Richard Pyle; Wikipedia.

Yet, the diversity of planet types also arises from the remarkable range of patterns in which they form and interact. The output of planet formation is determined in large part by initial conditions such as the mass, composition and temperature of the protoplanetary disk, as well as by variations induced by later effects up to the final stages of planet formation. Our own Solar System is comprised of rocky planets, gas giants, and lots (perhaps hundreds) of dwarf planets (including asteroids 1Ceres, 4Vesta and 6Pallas) and the trans-neptunian objects. What we do not have in our Solar System, oddly, are planets well represented elsewhere in our stellar neighbourhood: Super Earths with masses up to 6× that of our planet, and sub-Neptunes. The latter are planets that are somewhat smaller than Neptune and shrouded in gaseous (±ice) envelopes. We do not understand these worlds because we have no experience with them.

Six variables exist in our current catalogue of exoplanet observations: (i) location around the star, (ii) planet mass (sometimes), (iii) planet radius (sometimes), (iv) atmosphere and clouds (very small data set), (v) age (of the host star; uncertain), and (vi) inferred temperature, luminosity and albedo (sometimes). This is not a lot to work with, especially since what we really want to find are terrestrial planets.

What is the definition of a terrestrial planet? I propose that a terrestrial planet is one that has at least the mass of Mars up to about 6 Earth masses (e.g., Weiss and Marcy, 2014). Rocky worlds smaller than Mars (0.107 Earth) becomes thermally moribund rather quickly, whereas something much above a Super Earth (>6 Earth masses) starts to look like a “sub-Neptune” or, as it is sometimes called, an “Ice Dwarf” (Fig. 4.7).

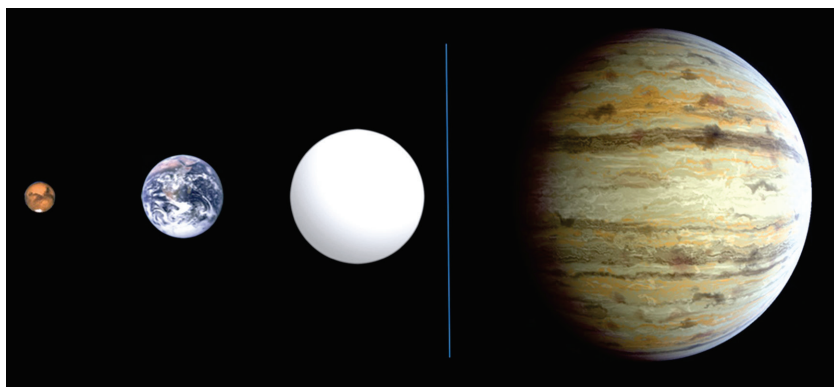


Figure 4.7

Terrestrials and not. The planets shown in this image span a range of almost three orders of magnitude in mass. On the low mass end (around 6×10^{23} kg), the range extends roughly to a point at which the effects of gravity and insulation allow the inside of a body to be different from the outside. This is arbitrary because comets and asteroids can be different outside-in. The high mass end (1×10^{26} kg) extends roughly to a point at which the atmosphere and any rocky core material probably blend with one another.

Given the parameters I provide above, what determines rocky planetary diversity and how can we begin to classify such things? As I have mentioned, cosmochemistry is the legacy of thermonuclear synthesis from the beginnings of the universe to the end games of today's massive stars. It varies with time and location, but the broad consequences are the same. The products of this evolution can be divided into three classes on the basis of nuclear physics and physical chemistry: gases, ices, and rocks (Fig. 4.8).

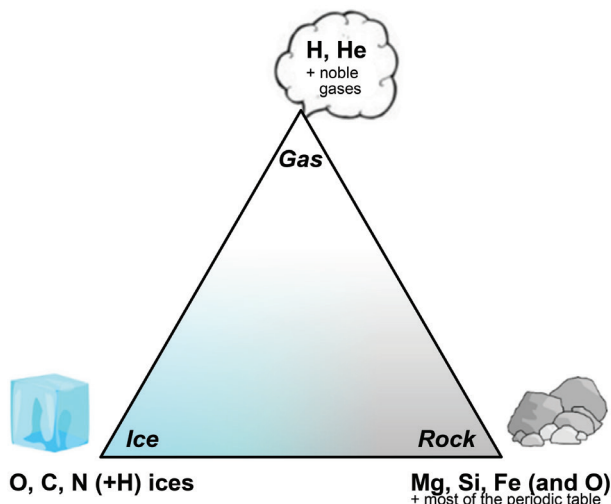


Figure 4.8

A simple ternary diagram for planets. This is a convenient start for a classification scheme. Gas refers primarily to hydrogen and helium, the most abundant baryonic elements in the universe. These elements also happen to comprise molecules that do not condense as solids or liquids under conditions that are encountered during planet formation. The classification that follows is restricted to rocky planets up to about 6 Earth masses. Adapted from Stevenson (2004).

Now, what if we take the diagram that the far famed David J. Stevenson proposed in 2004 for classifying planets and add some extra dimensions? Specifically, I want to include mass to this framework. Figure 4.9 is what comes from that exercise. I call this a Toblerone Diagram owing to its obvious gustatorial associations and resemblance to a popular (albeit formerly implicated as Swiss) chocolate.

The Toblerone diagram requires some explanation. Whereas the axes of the ternary plot are the same, an additional axis tracks masses from approximately that of Mars to Earth to a terrestrial planet somewhat more massive than Earth.

This thought experiment is useful because it challenges us to consider what are forbidden regions for the kinds of planets that exist. The diagram is necessarily empty and in need of development. I invite you to try your hand at it.

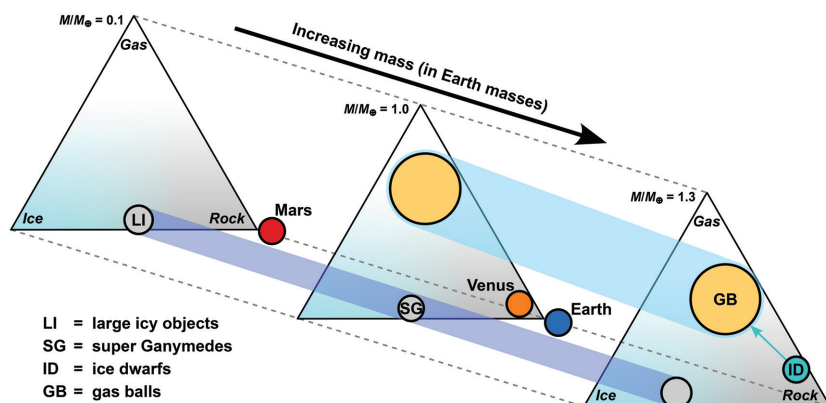


Figure 4.9 Toblerone diagram for low mass terrestrial planets. Here, I attempt to place some very rough boundary conditions on the classification of rocky exoplanets composed of metal, rock and fluid.

4.9 Homecoming

At CSFK in Budapest, it was my sincere pleasure to be awarded an honorary professor at the flagship university of Hungary: Eötvös Loránd Tudományegyetem (ELTE), or the Eötvös Loránd University. My excellent colleagues there, including the volcanologist pair Szabolcs Harangi and Reka Lukács were always ready to meet and talk with me about geology. It was also at ELTE that I recruited my clever Ph.D. student Anna Medvegy in the Department of Plant Systematics, Ecology and Theoretical Biology. She and I are working together on the nature of the transition from the postulated RNA World in the early Hadean to the contemporary DNA + peptide World since the origin of the Last Universal Common Ancestors. It was also around 2 months after I arrived in Budapest to move to the CSFK that the talented planetary dynamicist Ramon R. Brasser moved from the Tokyo Institute of Technology's Earth-Life Science Institute (ELSI) to join us at Konkoly Observatory. At the present time, Ramon is building an independent research group there by combining principles of planetary dynamics with constraints placed by cosmochemical tracers such a nucleosynthetic anomalies, in close collaboration with the proficient Audrey Bouvier at the Bavarian Geoinstitute (BGI) in Bayreuth, and the adroit Mario Fischer-Gödde at the University of Cologne, both in Germany.

The life in Budapest was marvelous and seemed to reach a metastable equilibrium, until of course, everything changed. Again! Our professional and social lives were enriching, with such excellent friends and colleagues as Robert Szabó, Laszlo Kiss, Attila Demény, Péter Némét, Maria Lugaro, Marco Pignatari, Thomas Truem, Lorenzo Roberti and many others too numerous to name. Yet, as usual with major outcomes, we found ourselves on the move yet again. The European Research Council came calling and, after much effort and three attempts, awarded Kevin Heng, Fabrice Gaillard and myself the Synergy grant in late 2024 (Fig. 4.10).



Figure 4.10

Geoastronomy trio. Here, three overly handsome gentlemen that also happen to be the principal investigators of the ERC Geoastronomy project (R-L: Fabrice Gaillard, Kevin Heng and the author) enjoy a celebratory evening in downtown Helsinki prior to the 2025 Europlanet Science Conference.

This was, for me, a tremendous vindication and without question a dream come true. While I often felt that I was swimming against a strong counter current that at times seemed to try to prevent us from realising the unification of Geology with Astronomy, there was never a doubt in my mind that this was the future of exoplanetary science. I had been trying to put together a programme on this topic since 2014! Talk about being stubborn about it, I count no less than 5 funding agencies that turned this idea down! As my colleague, the planetary biologist Barbara Kremer at the Polish Academy of Science likes to say: “Nobody knows what the future will bring.” This is an inarguable truth. In the summer of 2025, I celebrated my 60th birthday. Leading up to this momentous occasion, I was confronted with what can only be described as a Deep Reckoning. Where will we raise our children? Where would I spend the last years of my productive professional life? Not to be too morbid about it, but it is not like I had another

twenty years ahead of me as a professor somewhere. My wife Kathleen and our boys pushed for Germany as our ultimate destination. Maybe you think there is no competition: Germany or Hungary? But for me, this was a heartbreaking decision. My heritage site is in the region of the Pannonian Basin, and it will always be there no matter where I am. This, dear reader, is the most personal part of my *GP* so far. There are no words to describe how hard it was to share the news with my Hungarian colleagues that we were leaving. They had always been supportive of me, but a hard decision needed to be made, also considering political and economic considerations. Uncomfortable as this has been, we all keep sailing on no matter what. It was a big move, and an excellent and opportune one at that, when I took my Geoastronomy research programme to grow roots at the BGI of the University of Bayreuth. That is where you will find me, amongst world class experimental petrologists (e.g., Hans Keppler, Tony Withers), geodynamicists (Gregor Golabek), geochemists (e.g., Dan Frost) and cosmochemists (Audrey Bouvier). There are many people I can now work with at BGI, and I am just beginning to learn about this corner of Franconia, north of Bavaria. It is home for us now. Owing to the unfortunate political and economic developments unravelling elsewhere, it seems like I made a good choice to move here. We all hope that truth and justice and tolerance prevail.

In challenging moral relativism, Bertrand Russell might have put it this way to combat the disease of relativism: *If you think there are no wrong answers, it also means that there are no right answers. This would deny truth.*

L'Amor che move il Sole e l'altre Stelle.

La Divina Commedia, Dante Alighieri (1472)

If you read this far you know something about my personal and professional journey up to now. It was interspersed with vignettes on various topics in the kinds of science that have captured my interest. The guiding light has been to gain a better understanding of the origins of the natural world, even if this seems to happen mostly in small steps. My personal historical lesson is necessarily fragmented and unfinished. It was also edited for a G rating so to say.

In parallel with various personal stories, I divided my journey into two major themes, Bio- and Geo-, with a healthy dose of Astro- for both. These themes are not meant in any way to be mutually exclusive. My argument is that you cannot talk about one and ignore the other, especially when attempting to make sense of how our planet functions. Consequently, the overall narrative of this work weaved from one theme to the other and back. I hope that you saw how these broadly tied together in a common thread by the end.

The first theme touched on my fascination with understanding the nature of the transition from the non-living to living world by using Earth as a natural laboratory. This transition is termed abiogenesis. Together with my many talented students and colleagues, I have had the satisfaction of overturning some old paradigms. My work gradually showed that rather than being an uninteresting slag heap in its first 500 Myr (*q.v.* Hadean eon), Earth's crust evidently co-existed with liquid water from almost the very beginning. Not a lot of people believed this before about the year 2000, apart from the foresighted Yutaka Abe. This early crust was affected by late accretion bombardments and almost certainly harboured chemically diverse hydrothermal systems at the regional scale. Globally active volcanism powered by a hotter mantle, impact generated topography and inherent differential buoyancy of the crust means that scattered emergent land masses must have existed irrespective of different estimates for plausible Hadean ocean volumes. Let me be clear about this: Earth was never without dry land somewhere, even if only in small expanses. That is the inevitable consequence of planetary cooling. Oceanic islands, island arcs, microcontinents, you name it. They were there. Any time water interacts with hot rocks you get disequilibrium chemistry which can drive metabolism. I have long argued, as have others such as the talented Jun Korenaga, that land surfaces in the first few hundred million years with diverse subaerial and (sub-)aqueous environments brought prebiotic chemical ingredients to reactive concentration. A lot of people see it this way too. Disequilibrium is what makes this chemistry more interesting, and dilute solutions in places like the ocean tend to break

chemical bonds, not facilitate them. Logically, this kind of concentrated active chemistry enabled the first life at the hydrosphere-atmosphere-geosphere interface. Dilute mixtures are not procreative.

What is often ignored is that the inferred complexity for even the minimum biological entity probably means that both operative and persistent biology in a planetary environment is the most difficult developmental stage to reach. Contrary to prevailing thought, I argued that Earth's surface had the capacity to host fully fledged biochemistry since soon after its formation. Taken together, studies of the interdependence of the geosphere and biosphere have collectively come to be called Biogeodynamics (Zerkle, 2018). We may never know whether any particular Hadean environment was ideally suited, or merely good enough, to facilitate life's emergence. Geologists should be more closely involved with origins of life research because we have a lot to offer to synthetic organic chemists and biophysicists. It was long promulgated by certain "experts" that life had to wait a long time to get started for one reason or another. Nobody knows if this is true and anyone who tells you with certainty that they know, is insincere.

On another note, in the last dozen years, I have further argued that we cannot neglect what we have gleaned from Earth geology to the field of exoplanet science. This does not mean that everyone bothers to listen to me when I say so, but it seems that the idea is finally catching on that geologists also have a role in the game of astrophysics. Understanding the origin of our Solar System and of planets around other stars must include principles of planetary geochemistry, as my close colleagues Kevin Heng and Fabrice Gaillard will tell you. Should we just leave exoplanets to the astronomers? No, there is too much fun to be had! Space is all around us and closer than most people think, just point upwards and look. The second theme of this monograph touches on natural phenomena of planets beyond Earth. Why bother about this now? It is because trans-disciplinary science is finally having its day.

The way we do science is changing rapidly. A hundred years ago (or less), what we call the Natural Sciences were locked in a parochial attitude and almost nobody looked outside their chosen discipline. Exceptional individuals like Alfred Wegener and Svante Arrhenius faced ridicule in stepping out of their respective fields. This attitude began to change when geology teamed up with the other empirical sciences to give us geophysics, geochemistry, and geobiology. These disciplines provided marvelous discoveries from plate tectonics to the age of the Earth to the deep biosphere. Over the course of my career, I have worked in each of these disciplines to different degrees. What really captures my imagination now is the emerging discipline of Geoastronomy. Many thousands of planets orbiting other stars are documented.⁷⁶ Despite the fact that a large

76. Check this out for yourself: <https://exoplanetarchive.ipac.caltech.edu/>

fraction of Sun-like stars (of spectral type F-G-K)⁷⁷ in our Galaxy are thought to host planetary systems, their chemical and physical attributes are barely known, especially for those composed of rocky material. Any competent astronomer will remind you that such planets are difficult to observe, being tiny, far away, and faint. What little we do know is mostly confined to mass-radius-density (M-r- ρ) and orbital parameters. This parameter space is very limited, but that has not prevented elaborate speculation and the construction of dizzyingly complex diagrams based simply on M-r- ρ . Space telescopes (*e.g.*, Hubble) used to search for exoplanets were designed before it was realised that they could also be used to study exoplanet atmospheres and hence were not optimised for this challenge. We are limited at present in our ability to understand even the most basic physical chemical properties of rocky exoplanets. It seems that every day, much like the latest sensationalist breakthrough touted in origins of life, a news story reports the latest exoplanet discovery and claims its “Earth-like” characteristics, “habitability” or even that it sports “biomarker molecules”.

How can we understand what is habitable if we do not understand how life began? We should study planets first in my humble opinion, at least for the sake of understanding how they function and perhaps we can come up with an idea of what is “biocompatible”. Yet, beyond observing mass and radius, how do exoplanets function? How do their attributes depend on age and composition? Why is there a continuum of exoplanet sizes and densities between Earth and Neptune that is not represented in our Solar System? The talented and growing cohort of people with whom I am working on these problems is confronted with the challenge of building the chemical foundations for rocky exoplanets from the core to the mantle and crust, and into the atmosphere. We are challenged to make sense of observations, but the task is formidable because exoplanet data indicate a full range of planet types from metal-dominated to fluid-dominated, and in between metal $\pm$ silicate $\pm$ fluid. One way to achieve this aim is to use the compositions of stars tied to galactic chemical evolution and principles of nuclear astrophysics to place plausible constraints on the bulk compositions of the fully formed planets that orbit them. This knowledge helps guide laboratory experiments on different mantle compositions based on derived compositional constraints, track outgassing, and investigate transformations of atmospheric gases. The approach absolutely requires a multifaceted strategy to further motivate the next generation of ground and space based observations of alien worlds. We ought not be at all surprised to discover an increasingly bizarre collection of terrestrial-type planets in the coming century. With such an

77. These stars are close enough to our Sun (G-star) in mass and composition that we have a good understanding of them.

unimaginably huge parameter space, we are unlikely to find the idiomatic “Earth 2.0”. We ought not to be so naïve to expect to find it, nor feel confounded when we fail. As the saying goes: never tell Nature what to do.⁷⁸

Most workers in the various sub-fields I touch on in this work share a few of the views that I espouse. Looking back thirty years, the progress is astonishing. Nevertheless, I believe (rightly) that the consensus is that, first, the origin of life remains one of the greatest mysteries of science. Second, no forward model successfully reproduces the Solar System we have so we must be like detectives and figure out how the observed planets here and around other stars came to be.

Nature produced life-giving planets in our universe; the great challenge is to understand how.

78. I first heard my friend Kevin McKeegan make this statement during a particularly heated QandA at a SIMS workshop in the late 1990s when a famous geochemist colleague from the Australian National University challenged data *vs.* mythology (in this business, we run into that issue a lot). I later discovered that the turn of phrase was a more succinctly rendered version of a quote that originated from Richard Feynmann: “The imagination of Nature is far, far greater than the imagination of man.” I never met Dick Feynman in person (he died in 1988) but I heard some good stories about him from my Ph.D. advisor, Gustaf Arrhenius. You can find more juicy and oftentimes amusing quotes from Feynman, here: https://en.wikiquote.org/wiki/Richard_Feynman

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STEPHEN MOJZSIS studied geology at Boston University before moving to the University of California, San Diego to take up geochemistry and solid state physics at the Scripps Institution of Oceanography. Following his doctoral degree at UCSD on tracing the earliest chemical and isotopic evidence of life in the oldest sediments on Earth, as well as modelling environments for prebiotic chemistry, he moved to Los Angeles for three years as a postdoctoral scholar at UCLA. While there, he pursued research in U-Pb zircon geochronology, metamorphic field petrology and stable isotope geochemistry; this work led to the discovery of terrestrial Hadean zircons with characteristic compositions consistent with a dynamic early crust interacting with a liquid water ocean. After taking up a tenure track position at the University of Colorado, Boulder, he expanded his field and geochronological studies of the oldest rocks, and developed new projects in meteoritics, lunar science, and the geobiology of sulfur, nitrogen, chromium and cobalt. During his time at CU his interest in nuclear astrophysics continued to grow, and the idea of developing geoastronomy (Geology + Astronomy) and biogeodynamics (Geodynamics + Geobiology) as new fields of science became an obsession. He was promoted to Full Professor in 2014. After leaving Boulder in 2021, he held visiting professorships at the University of Jena (Germany) and the University of Vienna (Austria) and became a Senior Research Associate in Budapest, Hungary at the CSFK. In 2025, he moved to the Bavarian Geoinstitute (BGI) in Bayreuth, Germany, to direct the ERC funded Geoastronomy programme.

Stephen Mojzsis' research interests broadly follow questions about the origins of rocky planets in our solar system and beyond (exoplanets), the early timeline of life's emergence on Earth, origin of metabolism, appearance of photosynthesis, and how we can use galactic chemical evolution to understand the diversity of planet types as a function of time in the galaxy.

In his personal time, he enjoys adventures with his family, playing and listening to unconventional music, and engaging in charity work.

Stephen Mojzsis is a Member of the Hungarian Academy of Sciences, the Academia Europae and a proud member of the European Association of Geochemistry.