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VOLCANIC COLUMNS

There are many different kinds of volcanic flows in the world. Volcanic columns, the result of one particular kind of lava flow, have always attracted attention around the world because they give the appearance of being artificially constructed. The west of Canada underwent intervals of volcanic activity many times during the history of building the Rocky Mountains, with some of the most intense activity being during Paleogene time. The Okanagan Valley in the interior of British Columbia contains some of the best displays in North America of volcanic flows in which vertical joints form polygonal-shaped columns, as a result of rapid cooling, otherwise known as volcanic columns. Volcanic columns have intrigued me ever since, as a graduate student, I first saw them in the interior of British Columbia. It was hard for me to believe they represented natural formations because they looked to me to be too regular, well-formed and intricately positioned together to be the result of the chaotic geological processes of lava deposition and cooling. I was reminded of my earlier visits to the interior of British Columbia when I watched the spectacular film footage, shown during the opening ceremonies of the 2012 Summer Olympics in London, of the famous basalt columns of the Giant’s Causeway on the north coast of Ireland.

I decided we needed to have some volcanic columns in the Peter Russell Rock Garden, and where better to get some fine Canadian examples than from the Okanagan Valley of British Columbia.

I arranged to meet up with Don Sandberg in Kelowna, British Columbia. I was directed to him through inquiries that started with my colleague John Greenough, an igneous petrologist in the Earth Sciences Department at UBC Okanagan. Don is an amateur rock-hound, prospector and long-time resident of Kelowna, who knows the local geology like the back of his hand. Before meeting up in person, I explained to Don my interest in getting some volcanic columns for our Rock Garden.
I told him about the basalt columns I had seen decades earlier in the B.C. interior, my reading about dacite columns in the region, and the rhyolite and andesite columns on the famous Mount Boucherie in West Kelowna, a noteworthy landmark of an early Cenozoic composite volcano. He knew what I was talking about right away. Don and I arranged to link up at the end of June 2013. I met him at his home early in the morning. He showed me his personal rock collection in his backyard. He had many fine specimens including small hand samples of the opals he found in the Kelowna area (Church and Hora 1997). Don led me inside his home to introduce me to his wife Barbara and to show me the dacite column fireplace he built in his family room. Barbara packed both of us a lunch and sent us off for the day.

As a young lad in the 1930’s, Don’s family came to the Okanagan Valley from Alberta. He had always been fascinated by rocks and knew about the economic importance of geology in the interior of British Columbia. He learned his geology through reading and interacting with fellow members of the Kelowna Prospector’s Club; a Club with several serious novice and professional rock hounds and famous members such as Charles Fipke (of Ekati Diamond Mine fame). This interest led him to exploring and staking claims on several potentially important plots of land. He bought and sold many claims over the years, and still holds the rights to several properties. He knew several logging-truck drivers who reported to him when new outcrops were exposed during road construction, or when they saw some weird and wonderful rock outcrops along the back roads, especially those outcrops with perfectly shaped vertical columns. He owns the rights to a few sites with volcanic columns and sells the stone to landscape and building stone companies in Kelowna. He took me to two of his quarries.

We headed southeast of Kelowna towards Big White Ski Resort. Our first stop was an outcrop of basalt columns forming a solid wall along the logging road. The vertical jointed columns were towering over 20 m high in the outcrop and exhibited the classic sharp geometric shape, 4, 5 and 6-sides each, about 30-40 cm in diameter.

Even more spectacular were innumerable inclusions of small and large green olivine-dominated xenoliths. Don explained they would begin quarrying the columns for use as building and landscaping stone in the coming weeks. Getting some good pieces of the basalt columns suitable for the rock garden would not be a problem. I quickly put in my order.

Our second stop, later in the day, was a quarry a few kilometers away, where dacite columns were being collected for what the building stone industry refers to as splitstone. Splitstone is an industry term referring to rocks exhibiting platy characteristics as a result of bedding, flow banding or cleavage. The dacite columns are unusual because they exhibit horizontal iron-rich bands that can be split apart easily with a wide mason’s chisel. Don and I spent considerable time splitting dacite columns to expose the beautiful iron patterns on the rock surface. Dacite splitstone is a favoured building stone not only because of the beautiful dark iron patterns on the surface of the pale-coloured silica-rich dacite, but because it is much lighter in weight and less dense than other more traditional building stone materials, such as quartzite (Church and Hora 1979). Don was happy to provide some specimens of dacite columns for our rock garden too. Two types of volcanic columns in the Rock Garden would be a good opportunity for students to compare and contrast different kinds of volcanic rocks. Perhaps this will help students understand the purpose and need for QAPF (Quartz, Alkali feldspar, Plagioclase, Feldspathoid) diagrams for classifying igneous rocks based on mineralogical composition.

Our second day included a trip to Mount Boucherie in West Kelowna. The site is noted for its andesite and rhyolite columns and its particular pale colour when the sun hits it during sunset. It is also the home to the Mission Hill Winery, one of the largest wineries in the Okanagan. Mount Boucherie is a park and is surrounded by residential developments, all of which have spectacular views of Okanagan Lake. Unfortunately for us, this makes collecting volcanic columns impossible. Some beautiful pale mauve and pink rhyolite columns would have nicely

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rounded out our collection of volcanic columns. On the way home, we stopped at the Lake Okanagan Shopping Centre, part of new developments in West Kelowna. Don was proud to point out to me the dacite column splitstone on the faces of the stores in shopping centre. Proud so he should be, because the buildings were most attractive and unusual and unique to Kelowna.

I thank Don for the two wonderful days we spent together. It was fun to get out in the backcountry to explore and learn about not only the local geology, but also the history of the Okanagan and its people. Don was very enthusiastic about having examples of volcanic columns in the Peter Russell Rock Garden so visitors and future generations of geologists can learn more about these fascinating rock types and the geology of the Okanagan Valley. We thank Don for his donation and being a friend to the Department of Earth and Environmental Sciences.

The Water Rights Act (En. S.M. 1959 2nd Session c. 4 a. 47). The Provinces of Manitoba and Saskatchewan were the first to apply water allocation law to groundwater in Canada. This year will mark the 120th anniversary of surface water allocation and the 55th anniversary of groundwater allocation in Manitoba.

Date licensing was applied to groundwater in Canada
(after Nowlan 2005 in Anderson 2009)
\(»\) **TAKE A DEEP BREATH!**

This simple act provides your body with life-giving oxygen and removes waste carbon dioxide. It is part of what we call respiration, in which the chemical energy of organic molecules (derived from the food we eat) is released during a reaction that consumes oxygen and liberates water and carbon dioxide. During a single day, an adult will take about 20,000 breaths. Although essential for our survival, we routinely take each breath for granted as we proceed with our busy lives. Have you ever wondered when and why oxygen became so prevalent on Earth? Or how Earth surface’s oxygenation is intertwined with the evolution of life?

Why do we care about the past distribution of oxygen on Earth’s surface? Human activities, including fossil fuel burning and deforestation, are pumping greenhouse gases like carbon dioxide into the atmosphere. The Earth is getting warmer. What are the future consequences? We can expect a decline in ocean oxygen concentrations. Oxygen solubility in water decreases with increasing temperature. Continental weathering accelerates on a warmer Earth, delivering more nutrients (e.g., phosphorus) to the coastal oceans. Adding to this nutrient load is fertilizer runoff. These extra nutrients enhance the growth of primary producers and after these organisms die, oxygen becomes depleted.

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**FIGURE 1**

Earth’s surface oxygenation through time and its relationship to significant steps in biological evolution. The upper panel shows atmospheric oxygen abundances in % relative to present atmospheric levels (PAL). The lower panel shows the relative distribution of oxygen- (\(O_2\)), sulfide- (\(H_2S\)), and iron-rich (\(Fe^{2+}\)) waters in the shallow and deep oceans. Light gray shading indicates lower dissolved \(O_2\) levels. Lightest gray shading means less \(H_2S\) and more \(Fe^{2+}\).
the decay of their organic matter consumes oxygen. Declining ocean oxygen levels threaten to decimate the coastal marine biosphere, including fisheries — the main source of protein to many countries.

Warm-season “dead zones”, which contain too little O$_2$ (< 2 mg/L) to support large fauna, are expanding. To understand and manage this threat, we are motivated to learn the lessons of the past by “reading the rock record” about the history of ocean oxygenation. On a more positive note, astronomers have discovered hundreds of planets outside our solar system. The search for Earth-sized planets in the “habitable zone” — the region around a star where liquid water might exist on a planet’s surface — has commenced in earnest (e.g., NASA’s Kepler mission). Such planets could potentially support complex life. How might the geological history and the course of biological evolution on other habitable planets be different from our own? Of course, the big motivator driving us is the search for intelligent life elsewhere in the universe. Oxygen is thought to be a pre-requisite for the evolution of complex animal and intelligent life. A logical step for us is to search for oxygen-rich worlds. To guide our efforts, we seek to understand the co-evolution of life and environment on Earth. Today, the Earth’s atmosphere contains 21% oxygen and most of the oceans are well-oxygenated. However, for most of our planet’s 4.567 million year (Myr) long history, it was not this way. Our reading of the rock record paints a picture of protracted oxygenation of the atmosphere and oceans (Figure 1). For more than 2,000 million years (Myr) after Earth’s formation, free O$_2$ was almost non-existent at the Earth’s surface and the oceans were predominantly Fe$^{2+}$-rich. Oxygen did not begin to accumulate in the atmosphere until 2,400-2,100 Myr ago — a time interval called the “Great Oxidation Event”.

During this event, it is estimated that atmospheric O$_2$ concentrations rose to a level equivalent to about 1-10% of today. What triggered atmospheric oxygenation? The evolution of oxygenic photosynthesis was undoubtedly a pre-requisite because this is the single most important source of O$_2$ to Earth’s surface. However, it was probably not the only factor. There is growing evidence for photosynthetic O$_2$ production and accumulation in surface waters along some coastal regions (“oxygen oases”) at least a few hundred million years before the Great Oxidation Event. These oxygen oases may have even hosted the first O$_2$-respiring eukaryotes. Why then did the Great Oxidation Event take so long to occur? Oxygen had to first overwhelm the flux of reductants (e.g., H$_2$, CH$_4$) before it could accumulate in the atmosphere. Photosynthetic O$_2$ accumulation in the surface oceans may have started off slowly. The Great Oxidation Event led to widespread oxygenation of the surface oceans. However, atmospheric O$_2$ levels were not high enough to oxygenate the deep oceans. Instead, the Earth’s oceans became stratified, with oxygenated surface waters, anoxic and H$_2$S-rich (sulfidic) middle waters, and anoxic and Fe$^{2+}$-bearing (ferruginous) deep waters. How did the sulfidic conditions originate? In the presence of O$_2$, sulfide minerals exposed on land would be oxidized to sulfate, which was then delivered to the oceans by rivers. The Great Oxidation Event led to widespread oxygenation of the surface oceans. However, atmospheric O$_2$ levels were not high enough to oxygenate the deep oceans. Instead, the Earth’s oceans became stratified, with oxygenated surface waters, anoxic and H$_2$S-rich (sulfidic) middle waters, and anoxic and Fe$^{2+}$-bearing (ferruginous) deep waters. How did the sulfidic conditions originate? In the presence of O$_2$, sulfide minerals exposed on land would be oxidized.
to sulfate, which was then delivered to the oceans by rivers. In coastal regions where large amounts of dead organic matter from primary producers were sinking from the surface ocean, bacteria obtained energy by oxidizing the organic matter while reducing sulfate to sulfide. Sulfidic conditions then arose when enough H$_2$S was produced to consume all O$_2$ in the middle water column.

Widespread ocean redox stratification likely persisted for more than 1,500 Myr of Earth’s middle age. However, this period of time was not entirely monotonic. The younger part of the Great Oxidation Event features a transient rise in atmospheric O$_2$ levels 2,200-2,100 Myr ago. A possible explanation is that the onset of global oxidative continental weathering delivered a large load of phosphorus to the oceans, triggering massive primary productivity and burial of organic matter in sediments. By contrast, a temporary fall in ocean O$_2$ levels occurred 1,900 Myr ago because intense volcanism released large amounts of Fe$^{2+}$ and other reductants. Afterwards, there appears to have been relatively little change in atmosphere-ocean oxygenation for a long time. During this “boring” billion-year-long interval, eukaryotic evolution proceeded very slowly.

In stark contrast, the interval between 800 and 500 Myr ago was marked by dramatic changes, specifically a major oxygenation event, breakup of a supercontinent, at least two severe glaciations, and major eukaryotic diversification. Formation and breakup of a tropical supercontinent supplies abundant nutrients to the oceans and may have led to high rates of primary productivity and organic matter burial. Newly evolved marine eukaryotes with organic body parts more resistant to degradation could also have allowed more efficient organic matter burial. However, the greatest driving force for change may have been the glaciations (Figure 3). In the wake of the youngest global glaciation 635 Myr ago (a “Snowball Earth”), a hot climate likely promoted elevated primary productivity and organic matter burial. A significant increase in ocean oxygenation followed shortly after the glaciation. For the first time in Earth’s history, the oceans contained enough dissolved O$_2$ to support large complex animal life. Shortly after the end of the Snowball glaciation and the increase in ocean oxygenation, the first large complex animals appear in the rock record, including those that could move and prey on other organisms. A series of dizzyingly rapid evolutionary innovations driven by environmental, genetic, and ecological factors then culminated in a “Cambrian Explosion” (named for the Cambrian Period in which it occurs) of skeletal animal life some 540 to 520 Myr ago.

Conventional thinking is that the Earth’s atmosphere and oceans have been well-oxygenated since then. However, recent findings suggest lower atmospheric O$_2$ levels and large oscillations in oceanic O$_2$ levels between 635 and 400 Myr ago. Another O$_2$ boost may have been triggered by the diversification of land plants 400 Myr ago. Land plants enable more efficient organic matter burial by accelerating the rate of continental weathering. Organic plant material can also be highly resistant to degradation and be buried more easily.
The resulting increase in O₂ levels may have stimulated the evolution of large predatory fish. Diversification of land plants and formation of the supercontinent Pangaea likely played major roles in burying enough organic matter to generate the highest atmospheric O₂ levels in Earth’s history 300-275 Myr ago. Although the Earth’s oceans were predominantly oxygenated during the past 400 Myr, there were brief intervals called “ocean anoxic events” that were accompanied by a mass extinction of life. Ocean deoxygenation was typically caused by a warm climate (high atmospheric CO₂) and poor ocean circulation. During the anoxic event, higher rates of organic matter burial and continental weathering consumed the excess atmospheric CO₂. The drop in CO₂ promoted a return to colder oceans (favoring greater oxygen solubility and ocean circulation) and lower nutrient inventories for primary producers (less consumption of O₂ by decay of organic matter). Together with the preceding organic matter burial (O₂ release), these changes allowed the re-establishment of oxygenated oceans. The Earth’s worst mass extinction was suffered during an ocean anoxic event 250 million years ago. Geoscientists scrutinize these events closely to better predict the future extent of ocean deoxygenation and its impact on human civilization. Finally, how do geoscientists reconstruct the history of Earth’s surface oxygenation? Our clues come from sediments deposited in Earth’s ancient oceans, now preserved as layers of sedimentary rock. We can sample these rocks at the Earth’s surface where they have been exposed by erosion (outcrops) or by human activities (mines, road cuts). Alternatively, we can obtain samples by drilling deep below the surface (Figure 4).

Geoscientists prefer drill cores because the recovered rocks have not been affected by weathering reactions at Earth’s surface. Our preferred method for reconstructing the story of atmosphere and ocean oxygenation is to study the distribution of oxygen-sensitive elements and minerals in sedimentary rocks. One example is the massive iron formations (the major source of industrial iron ore) deposited before the Great Oxidation Event and during the volcanic episode 1,900 Myr ago (Figure 5). Their formation requires that large amounts of dissolved Fe²⁺ accumulate in predominantly oxygen- and sulfur-free oceans. Another example is the abundance of redox-sensitive metals like molybdenum (Mo) and vanadium (V) in organic-rich sediments (Figure 6). In the presence of O₂, these metals are weathered from the continents and transported by rivers to the oceans where they accumulate in oxygenated seawater.

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**FIGURE 3**
Glacial sediments deposited ~670 million years ago in an ocean basin. This type of rock is called diamictite, and consists of a poorly sorted mixture of large and small clasts surrounded by a finer-grained sediment matrix. Note the coin for scale. Areyonga Formation, Amadeus Basin, central Australia. PHOTO CREDIT: R.A. CREASER

**FIGURE 4**
Organic-rich black shale deposited ~2,500 million years ago in deep ocean waters. Shale is composed of fine-grained sediment (<0.0625 mm particle size) and is fissile (split easily into thin paper-like sheets). Also visible are thin laminations and nodules of metallic brass-yellow pyrite (“fool’s gold”). Mt. McRae Shale, Hamersley Basin, Western Australia. PHOTO CREDIT: B. KENDALL
Abundance of iron formations through time. Most iron formation was deposited early in Earth’s history when the oceans were predominantly anoxic and Fe$^{2+}$-rich. As a consequence of the Great Oxidation Event, the amount of dissolved Fe$^{2+}$ in the oceans was significantly reduced by reaction with oxygen, sulfate, and sulfide, thus largely preventing further deposition of iron formation. An exception occurred about 1,900 million years ago, when intense volcanism supplied large amounts of Fe$^{3+}$ to the oceans. After this time, iron formation is scarce in the rock record. Modified from Rasmussen et al. (2012).

Abundance of molybdenum (Mo) and vanadium (V) in black shales through time. The abundances are reported as parts per million (p.p.m.), where 1 p.p.m. means $1 \times 10^{-6}$ gram of Mo (or V) per gram of shale. Metal concentrations are also divided (or “normalized”) to total organic carbon content (TOC; given as weight % of the shale) to correct for variable amounts of organic matter in the sediment. It can be seen that Mo and V concentrations in black shales have increased through time, reflecting the growth of the oceanic inventory of these metals in response to ocean oxygenation. Major increases in metal concentration are observed in response to the Great Oxidation Event (2,400-2,100 million years ago) and shortly after a “Snowball Earth” glaciation 635 million years ago. Modified from Sahoo et al. (2012).
Upon encountering anoxic conditions, Mo and V are removed from seawater to sediments. Metal abundances in the sediments (now black shales) can be used to infer ancient seawater metal concentrations and the extent of oxygenation. High amounts of Mo and V in black shales indicate a large metal inventory in widely oxygenated oceans. By contrast, low amounts of Mo and V in black shales point to negligible oxidative weathering or O₂-deficient oceans (which favors high rates of metal burial in sediments). Armed with these tools, geoscientists will continue to probe the Earth’s rock record and provide us with the necessary knowledge to ensure that we are best equipped to deal with the environmental threats facing us, and to guide us on the search for life elsewhere in the cosmos. The story of oxygen on Earth is one aspect of the rapidly emerging field of astrobiology — which studies the origin, evolution, and distribution of life in the universe.

References:
I had my first geeky moment in Germany when I saw the gneissic countertop in the hotel washroom, its foliation marked by striking, mafic-rimmed leucocratic blebs. I confess that I may have spent a few minutes too long brushing my teeth on certain mornings searching for euhedral K-feldspar crystals. But such impromptu petrographic examinations seem less of a deal compared to the hunt for crinoid and gastropod fragments on the black marble baptismal font at the altar of the famed Thomaskirche a few days later. All those aside, one of the greatest things Germany — with most of Europe, I am sure — has to offer geology enthusiasts is the incredible ease with which you can find a prominent outcrop, without having to travel too far off the roads. Slumping Triassic sequences stare at you right in the face through the window as the train unloads passengers on an afternoon commute. Devonian slate outcrops are a common sight on an evening stroll in a hillside neighbourhood. A wall of columnar basalt looms over the Elbe valley en route from Dresden to Prague, much as the Escarpment looks over the 401 between Waterloo and Toronto. The compact nature of Europe extends even to its geology — as far as the geographic heart of Germany is concerned, at least. The Harz Mountains sit at the junction of the regions of Saxon-Anhalt, Lower Saxony and Thuringia.

Rising over 500 metres above surrounding plains, the massif resembles an island in a sea of crop fields. Formed during the Hercynian (Variscan) orogeny in the late Paleozoic, it records the collision between Euramerica and Gondwana to form Pangaea. Since the earliest medieval times, its economic resources have played an indispensible role in the region’s prosperity and the rise of German sovereigns. The densely wooded hills and valleys are only part of the untamed nature that...
has given rise to many folklores and legends over the ages. Traveling from the northeast, my first stop was the small town of Thale at the mouth of Bodetal, one of the numerous gorges carved out by narrow streams. A cable lift takes one to the top of the Rosstrappe, a 403 m high granite crag, which offers an incredible view of raw, defiant cliffs piercing through the green coat of the woods. The path to the vantage point is lined with oddly-shaped blocks and tors, jointed by hydrothermal fluids and further rounded by weathering. With the intangible forces of nature manifested so wonderfully before one’s eyes, it is not difficult to understand why the place was a ritual site in pagan times. Facing the Rosstrappe on other side of the gorge sits the Hexentanzplatz, the so-called ‘Witches’ Dancing Place’, immortalized in Goethe’s Faust. Not an aficionado of Romantic literature myself, I was overjoyed enough to be roaming over barren granite. True to my geological training, I spent a good part of the hour measuring quartz veins, peering at weathered granite fragments through a hand lens and diligently noting crystal sizes in my notebook.

What better way to commemorate a visit than a short petrographic description? Geologist or not, another feature rarely missed by tourists coming in and out of Thale is the long, jagged ridge of broken sandstone poking out of the nearby farm fields. Ghastly brown, like ruins of a Gothic edifice, the Teufelsmauer, or ‘Devil’s Wall’, stretches across the northeastern boundary of the Harz Mountains in several segments. Fabled as the artefact of a lost wager between Satan and God, the formation was in actual fact created when sedimentary strata in the Paleozoic marine basin became tilted and folded with the uplift of the Harz Mountains. The tectonism was vigorous enough in several places that the strata actually overturned, resulting in the walls dipping slightly towards the mountains. Differential erosion took care of the rest and the vertical sandstone ridges now stand as a reminder of the violent forces at work in this region some 300 million years ago.

Ten minutes north of Thale is the medieval town of Quedlinburg, which soared to historic prominence after the first German king, Heinrich I, was buried here. The royal complex, with modest, reserved Romanesque proportions, was built on top of a sandstone promontory overlooking the town. ere, the quartz-dominated Cretaceous sandstones are part of the Quedlinburg anticline, created by salt dome movement with a dip of 25°-30° to the southwest. gh porosity (30%) and a low degree of cementation, combined with overcrowding...
of buildings on the promontory, have led to numerous structural problems over the ages. The impressive collegiate church, in particular, suffers numerous masonry damages that continue to appear despite constant repair. Settling also poses danger to some of the picturesque half-timbered houses across the UNESCO-listed old town. A testimony to this is the narrow street known as ‘Steinbrück’, or ‘Stone Bridge’, which once consisted of an eponymous structure crossing a marsh. The piers of the bridge have long sunk below ground, their positions marked today only by a red tile pavement. With support from the German government, extensive geotechnical work is being done to protect these historical monuments.

Travelling west, crossing the former Iron Curtain which once divided the mountains, I entered the Upper Harz, whose former bustling mining industry gave the Harz a lasting place in the history of the German economy. The best example of this is the city of Goslar, which was made an imperial residence after the discovery of silver in the 10th century.

Located in the Rammelsberg hills south of the medieval town centre, the rich sedimentary-exhalative (SEDEX) deposit was formed by hydrothermal fluid cycling beneath the Devonian seafloor, and subsequently folded and brought to the surface by the uplift of the Harz. Containing high grades of zinc, lead, silver, copper and gold, the deposit helped Goslar establish itself as an important trade centre throughout the medieval and early modern times. Although mining operations ceased in 1988, after 1,020 years of continuous production and 30 Mt of extracted ore, its far-reaching economic impact is seen in the town’s richly-decorated wooden houses, fortified walls and abundance of churches. The Rammelsberg mine is today a museum. At the foot of the imposing, multi-level complex that scales the hill, rusting giant machines, left in their original positions, are accompanied by audio guides explaining the ore refining process in detail. Poolsized rotating vats, for example, were used to thicken the water-ore powder mixture by means of centrifugal force. The nearby ore specimen collection is enough to tickle the fancy of anyone who has taken the Exploration Geology course. Even though the labels were in German only, it does not take long to find out what words like ‘Bändererz’ and ‘Schiefer’ mean (banded ore and slate). A separate exhibition is dedicated to the lives of mine workers against the backdrop of over a millennium of history.
From silver coins, pickaxes, lamps, to uniforms, jack hammers and regulatory signs, the vast collection of artifacts illustrates everything from the struggle for mining rights between townsfolk and nobility, to the ambitious expansions by Nazi Germany, and the ultimate exhaustion under Preussag. No trip to the Rammelsberg is complete without a visit underground. Being the only English-speaking visitor of the afternoon, I enjoyed an exclusive one-person guided tour of the stunning 19th century hydraulic works. A system of underground channels and waterwheels was constructed to power the removal of ores some 80 m through the mine shaft. Sitting in dark grottos, the main waterwheels, each measuring 7-8 m in diameter and weighting 20 tons, were powered by water from an 16th-century artificial lake. The wheels can be turned both ways via an ingenious mechanism of wooden rods controlled from the mine level.

The former waterways have been empty for more than a century. The damp, arched walls of wildly dipping slate sometimes show a snakeing calcite vein, or patches of fine green moss that lives on the dim yellow lights. Sulfate-rich groundwater seeping into the tunnels has created an abundance of vitriols, as ghastly stalactites hanging from the roof or mini-terraces painting the walls blue (copper), white (zinc), red (iron) and black (manganese). As I beheld the bizarre geochemical graffiti, my guide explained its economic uses: paint, skin remedy, leather staining, etc. Miners over the ages would bring vitriols home to sell for some extra income. Although the ore itself was nowhere to be seen on the tour, observing rocks and minerals in their natural setting in the cold, damp underground was a thrilling experience.

Before catching the afternoon train back to Leipzig, I came across a boulder of massive sulfide by the station. The imprint of a hand was carved into the polished top. Nine other such monuments are scattered across the city, paying homage to its millennium of mining legacy. Indeed, wrought by hundreds of millions of years of geologic processes, the richness of the Harz, alongside its awe-inspiring beauty, have earned itself a lasting place in German history.

And if, by chance, you are still wondering why the name sounds so familiar, the first station eastwards from Goslar is Bad Harzburg, the very namesake and locality of the ultramafic rock.
Dr. Wu specializes in low-temperature geochemistry, geomicrobiology, and isotope geochemistry, combining fieldwork, laboratory experiments, and geochemical modeling, to understand how inorganic and biologically-mediated processes shape the geochemistry of the Earth’s surface. The overall theme of her research is to quantify the biogeochemical cycling of elements, including carbon, phosphorus, nitrogen, base cations, and metals, in both modern and ancient environments. She focuses on chemical weathering reactions that control the chemistry of the Earth’s hydrosphere and atmosphere, and produce the basic constituents of soils. Of particular interest are microbe-rock interactions, which have likely contributed to the environmental evolution of the Earth’s surface throughout geologic time. Since the origin of life, microbial metabolism has fundamentally altered geochemical cycles operating at the Earth’s surface. Microbes impact their environment, and in turn, the environment shapes microbial communities. Specifically, microorganisms influence the chemistry of aquatic systems either directly through the acquisition of energy released from redox reactions and/or limiting nutrients such as phosphorus, nitrogen required for biomass synthesis, or indirectly through the release of metabolites that lower pH, complex cations, and/or change mineral saturation states.

Dr. Wu’s current research focuses on investigating stable Fe isotope fractionations during interactions between Fe(II) and Fe-bearing phyllosilicates, in both biological and abiological experimental systems. The Fe-bearing phyllosilicates are wide-spread in subsurface environments and have been recognized as an important terminal electron acceptor by a group of microorganisms called dissimilatory iron reducing bacteria (DIRB). A solid understanding of stable Fe isotope fractionations during redox transformations of Fe(III) oxides has been achieved in the last decade, through both experimental and field work. As a contrast, much has yet to be learned about what occurs during microbial reduction of Fe-bearing phyllosilicates. This project investigates the stable Fe isotope fractionations during interactions between ferrous iron and Fe-bearing clays, in both biological

### FIGURE 1

A cartoon illustrating the long-term (greater than million-year) carbon cycle between atmosphere, hydrosphere, geosphere, and biosphere. Similar cycles also exist for other elements.
and abiological systems. The goal is to understand the mechanism and fractionation factor for isotopic exchange during these processes, which can then be applied to interpret Fe isotope data in natural systems. Field work will characterize the Fe isotope signature in lake sediments, aiming at a better understanding of coupled Fe and P cycling. Future effort will be devoted to probing the nature and reactivity of surface phases during coupled Fe oxidation and Cr reduction using both Fe and Cr isotopes. Microbial dissimilatory iron reduction produces ferrous iron, which is a very efficient reducing agent in the presence of mineral surfaces. It can reduce Cr(VI), which is highly soluble, mobile and toxic, to insoluble Cr(III) that readily absorbs onto mineral surfaces and is less toxic.

A variety of Fe oxyhydroxide substrates including hematite, goethite, and poorly crystalline ferrihydrite will be examined to probe the nature and reactivity of surface phases formed during this coupled process using Fe isotope fractionations. As a second stage of this project, Cr isotope fractionations will be investigated. This system is largely underexplored compared with the Fe isotope system. Another project will examine the impact of microbial N utilization from rocks on chemical weathering. This project quantifies how and to what extent microorganisms affect chemical weathering rates when they utilize N-bearing rocks. Minerals comprising sedimentary rocks, such as feldspars and clays, contain ammonium as a substitute for potassium. Traditional models of the N cycle emphasize nitrogen fixation from atmospheric N and uptake of N from soil organic matter but do not consider microbial utilization of N in rocks. This could have a significant influence on chemical weathering rates and consequently the evolution of atmospheric CO₂. This could shed new light on the terrestrial N cycle.

Since the origin of life, microbial metabolism has fundamentally altered geochemical cycles operating at the Earth’s surface.

Since the origin of life, microbial metabolism has fundamentally altered geochemical cycles operating at the Earth’s surface.

![Burkholderia fungorum](image1.png) (a gram-negative, heterotrophic bacterium) colonizing a basalt particle.

![Burkholderia fungorum](image2.png) excretes EPS (extracellular polymeric substances) in order to stick on the surface of basalt.

A sealed, hematite (an iron (III) oxide) reactor containing iron-reducing bacteria *Geobacter sulfurreducens*.
In late 2013, I submitted a detailed application outlining my reasons for wishing to attend the two-week Student-Industry Mineral Exploration Workshop (S-IMEW), which is hosted annually by the Prospectors & Development Association of Canada (PDAC) in the greater Sudbury area in northern Ontario. To provide some background, the PDAC was established in 1932 to represent the interests of the Canadian mineral exploration and development industry and in 2007, as part of their strategic plan to attract new people to the exploration industry, the first annual S-IMEW was held. S-IMEW is a two-week, all-expense paid workshop that is intended to expose 26 upper-year geoscience students from 26 Canadian universities to the field, technical and business sides of the mineral exploration industry. As a 3rd-year Earth Sciences student specializing in Geology, and knowing that I want to begin my career in the mineral exploration industry upon graduation, I felt this workshop was right for me. When I was selected in February by the University of Waterloo’s Earth and Environmental Sciences Department and the S-IMEW committee to participate and represent Waterloo at the upcoming 8th annual workshop, I was honoured and excited for the opportunity.

A few weeks, after completing this workshop, I realized that not only did it teach students about the many practical aspects of this industry, it also provided a setting to network with knowledgeable industry leaders and highly motivated students, some of which I’m sure will become lifelong friends and career connections. In early May, fellow like-minded students travelled from across Canada to gather at the Toronto airport before embarking by van to reach our final destination in Sudbury. Our home base for the next two weeks would be at Collège Boréal and it was here that S-IMEW’s Student Program Manager, Krishana Michaud, reviewed the intense itinerary that usually began with breakfast.
at 7 a.m. and often ended with a social networking opportunity by 10 p.m. Each day was typically dedicated to a main topic such as career development, mineral exploration and development, government mapping, the Sudbury Basin, exploration geophysics, Sudbury Integrated Nickel Operations, geochemistry, exploration mapping, and during the final week a 4-day field trip to Val d’Or and Rouyn-Noranda was also planned. After reading over the schedule it was clear that each day would be filled with back-to-back activities from presentations by industry speakers with a high-level of expertise, to field mapping activities, drill rig visits, core shack tours, lake sediment sampling and even tours of operating smelters and open pit gold mines to name a few. One day was dedicated to touring the Sudbury Basin where we traversed across the basin and learned about the history of the Sudbury impact and how it formed each geologic formation as we encountered them. Another day we were exposed to the mapping techniques used by the Ontario Geological Survey (OGS) for government mapping by traversing and drawing maps, and a few days later, we were introduced to mapping techniques used by exploration companies at a property owned by Wallbridge Mining. After dinner each evening there were presentations/talks by industry professionals and afterwards we often had the opportunity to network with them on a one-on-one basis to ask additional questions or learn how their individual career paths eventually led them to their current positions. Mining is a large industry in Canada but I quickly discovered that within this industry there’s some truth to the saying “it’s a small world”. A few weeks prior to attending S-IMEW I was successful in securing a summer job with OGS as a Field Mapping Assistant through a phone interview. During S-IMEW’s government mapping day we were split into small groups and I was surprised to discover that it was my future OGS boss who was leading my group. This was the first time we met in person and proved that the connections students make at S-IMEW could easily lead to future meetings and opportunities within this industry. During the final week we embarked on a 4-day field trip to tour the Superior Province and travelled to Val d’Or, Rouyn-Noranda and Cobalt. Along the way we stopped at numerous outcrops to understand the area’s geology and with each stop experience and confidence was gained. In Val d’Or we visited Osisko’s Malarctic Mine, an operating open pit gold mine, and for many S-IMEW participants, this was their first time in an open pit mine. The massive scale of the complex operation awed many of the students. In 2013 I experienced two co-op work terms at Agnico-Eagle’s Meadowbank open pit gold mine site in Nunavut and it was interesting to see the similarities and differences between the two operations. In the Rouyn-Noranda area, we explored a number of outcrops to discuss the geologic history and mineral potential. The next day a detailed outcrop scale mapping project was completed and on route back to Sudbury we toured the old mining town of Cobalt where abandoned mine shafts littered the landscape. The stop in Cobalt made me realize the importance of having a proper reclamation plan in place after mining operations come to an end and prompted an in-depth discussion later that evening amongst some of the students. These were only a few of the hands-on field activities that our group participated in and, combined with the numerous

The connections students make at S-IMEW could easily lead to future meetings and opportunities within this industry.

Tyler Ciufò pointing out a clast in an outcrop
presentations and discussions, the wealth of knowledge and experience that I personally obtained during these two weeks was simply invaluable. What struck me most however, was the passion that was demonstrated for this industry by everyone including the organizers, speakers, volunteers and sponsors. So many people who are very busy with their own careers and families still donated their time to 26 students they didn’t know in an effort to recruit young adults into the mineral exploration industry, and to me, this spoke volumes.

During the final dinner and cocktail reception in Vale Cavern at Science North, we watched a slide show summarizing the many activities we participated in during S-IMEW and afterwards expressed our gratitude to ALL sponsors and individuals who gave their time, resources, staff, facilities, and even opened up their home to make this unique event possible for students, like myself, who truly have a growing passion for this fascinating industry. To see this enthusiasm amongst industry leaders only fueled my passion and desire to learn as much as possible about the many aspects of the mineral exploration industry, and this was exactly what I was hoping and did gain through the S-IMEW experience. All the people I met, including fellow students and industry staff, and the hands-on knowledge obtained about the mining industry at this well-rounded workshop, immensely added to what I’m learning through my co-op work terms and studies at the University of Waterloo. In appreciation, one of my goals is to one day give back by encouraging and instilling this same desire in future geoscience students. After the closing dinner celebrations came to an end at Vale Cavern, all the students, who by this time knew each other very well, went out to enjoy the “legendary” Sudbury night life and our final evening together.

It was not until after the workshop, when I had time to reflect, that I truly recognized the extent of the knowledge and experience that I gained in just two short weeks. It was a fun and informative learning experience that I would highly recommend to any upper year Earth Sciences student who wishes to pursue a career in the mineral exploration field. If, by chance, you’re a high school student who is still not sure of what you want “to do”, but enjoy the outdoors and are interested in
Canada is a **world leader** in mineral exploration and I am looking forward to beginning my career and contributing to this industry.

the earth, this is your chance to look into studying Earth Sciences and perhaps, one day, attend S-IMEW and eventually become a part of this fascinating industry.

Canada is a world leader in Mineral Exploration and I am looking forward to beginning my career, contributing to this industry, and perhaps one day working with some of the students I met at S-IMEW 2014.
Last winter I visited Jim and Ellen’s Rock Shop in Cottonwood, Arizona and purchased a large piece of charcoal, 15 cm x 19 cm x 10 cm, which someone had carefully collected. It is mainly a web of quartz holding together charcoal: a wonderful, rarely collected specimen from near the Petrified Forest National Park. We are all familiar with the petrified wood logs, preserved with silica of many colours, from the Petrified Forest area. Charcoal must be more common than it appears, although you have to be lucky to find it, as pieces break down easily. Occasionally, small pieces were washed down the Triassic rivers and have to be extracted from the sediment to be studied. Odd larger pieces are found. One large specimen was found at the Ghost Ranch area of New Mexico in the same upper Triassic deposits. The presence of charcoal indicates that there were occasional fires started by lightning.

Most of the charcoal was transported out of the area, as crumbs and larger pieces, by heavy rains following the fires. Some pieces were preserved when the burned logs were rapidly covered with sediment. The interesting thing about charcoal is that it is inert in this environment and doesn’t interact with minerals as they form, and seems to repel them. As silica dissolved in the water from volcanic ash gradually converted logs to stone, cracks around charcoal in burned parts of the logs were filled with quartz, preserving the charcoal. This specimen has to be gently handled so that the charcoal doesn’t fall apart.

Reference:
Late Triassic charcoal from the Petrified Forest National Park, Arizona, USA.
sciencedirect.com/science/article/pii/S0031018202005497
The colourful sediments containing petrified wood and other fossils in the Petrified Forest and Painted Desert are rich in swelling clay (bentonite), which is is formed of the clay mineral montmorillonite. Weathering of volcanic ash, in the tropical humid environment, produced the bentonite clay. Clay minerals are formed of layers of silica and elements, such as magnesium, forming a sheet structure of connecting rings, like chainmail. Two sheets of these layers attract water like a sponge and expand seven to eight times the dry volume. Clay minerals are members of the phyllosilicate family. The name comes from the Greek name for leaf phyllo. Phyllo pastry is also made in thin sheets. Swelling clay is used for kitty litter, drilling mud, as a bulk laxative and many other purposes. Stone Tree House was built in the 1920’s and purchased by the National Parks Service in 1936 and renamed The Painted Desert Inn.

The building was closed in 1963. Public opposition saved the structure from being torn down and, in 1975, it was designated a National Historic Landmark. The Painted Desert Inn was built on swelling clay, which caused lots of problems keeping the place intact. When I visited in 2003 with a group of students, tests were being carried out to measure the amount of damage to the structure that was being caused by the swelling clay. In 2006 the building opened again, after extensive renovations, and is now a museum and bookstore. Another building, which was plagued with problems from swelling clay, soon after it opened in 1957, is the Dinosaur Quarry Building in Dinosaur National Monument in Colorado, which closed in 2006. In 2009 a 13.1 million dollar grant allowed rebuilding of the Dinosaur Quarry Building, extending the steel columns below the swelling clay to bedrock below. The building reopened in 2011.
RELIC HUNTER

PHOTO: View from the Burgess Shale Quarry in Kootenay National Park, British Columbia

THE HUNT FOR CAMBRIAN FOSSILS

The following report comes from Manuel Arab, 4th year student in the University of Waterloo’s Earth & Environmental Sciences Department studying geology and minoring in classical studies. During the summer of 2014, Manuel was invited to work with Dr. Jean-Bernard Caron from the Royal Ontario Museum and his team to uncover fresh fossils from a new Burgess Shale site in British Columbia. This is one of his experiences.

The view from up here is amazing, isn’t it?” I ask excitedly as my colleague nods. “The mountains are majestic and they make you feel small, like your problems don’t matter.” I’m gazing at the vista that is Marble Canyon in Kootenay National Park, my home and field site for part of the summer of 2014. I wasn’t expecting my archaeological experience from Jordan to be so essential to understanding how paleontological methodology works. Minus the medium being solid shale, I am surprised at the similarities in the recording process: A yell of “Five Haplophrentis, 236!” is directed at our recorder, who duly notes the presence of five of the little aquatic creatures 236 centimetres below the datum point established on-site. Back at camp that evening, he will incorporate this data into a spreadsheet as part of his thesis on paleo-communities. I focus on the rock I have in my hand, trying to imagine the lines of weakness in the shale. It is a piece of stone we jackhammered off the side of a massive rock earlier that day: a part of the Stephen Formation that the famous Burgess Shale came from. It had lain undisturbed for 500 million years and I was about to take a geological hammer to it.

I carefully place the chisel along the thin line I can see on the flat edge of the shale. It marks a turbidite event (deposition from a storm event lasting anywhere from a few hours to a few days in the ancient past) on the continental shelf of a supercontinent that no longer exists, and would be pushed up into the mountain range by orogenic processes millions of years later. I hit hard and, four blows later, there is a crack along...
the middle of the shale, trailing off to the edge. “Poor Cambrian rock, it never stood a chance,” I think to myself. It is easier to manipulate the crack’s direction and make it grow, rather than try to split the whole rock from only one spot. After a few hits along the edge with the hammer, to redirect the crack as much down the middle as possible, I give a final, sharp rap and the rock splits open. I hold the rock up to the light and look for the telltale signs of a fossil — coal black colour, an unusual shape, a distinct magnetite-like shine — and find ... nothing. I shrug: “You win some, you lose some.” I muse to myself. I give it a sharp rap in the centre to split it into smaller pieces, checking one last time for any traces of a fossil before throwing the fragments off the side of the mountain. If I find something different I will call someone over for an expert opinion, but if it’s part of the usual crowd of species that swam the local waters here millions of years ago, then it gets the same treatment as a barren sample. The same goes for pieces of a fossil rather than the whole thing. Most of the fossils I find are small black lines on the smoky gray of the shale. They might have been an acorn worm or even a Haplophrentis, but it is purely a guess and the rock won’t divulge any more details without ruining the fossil beyond recognition, thanks to the shale’s tendency to fracture conchoidally due to its carbonate content. If we get lucky, we might come across a section of shale that is untainted by carbonate but, generally, if the layer is going to fracture it is either on a depositional layer or it is going to break into small circular pieces. I observe the ever-growing mound of circular fragmented pieces that lay in a pile to my left. Shale normally doesn’t fragment quite this way, but I attribute it to stronger bonds between the depositional layers due to the presence of calcite between the little silt particles. Working on another rock I quietly curse the carbonate layer I’m trying to crack, despite its increased resistance to my hammer blows. I feel the rock shift and a fragment breaks off along a layer I suspect was weathered by water more recently than the rest of the rock. Holding it up to the sunlight, I hold my breath as my eyes search for signs of something ancient lying in wait in the stone. I stumble across something big and shiny. It is clearly something noteworthy, but I have never seen it before. Excitedly, I get up and ask one of the PhD students about my sample. He looks at me, and looks at the slab I place in his hands and exclaims that I have found a Sidneyia, an extinct species of arthropod. Some of my colleagues get up so they can have a look at the massive, albeit decayed segmented arthropod I have uncovered. I pass the fossil around so everyone has the chance to see it, along with its counterpart. I pass it up to the recorder, since he has to pack the specimens that we are keeping to bring back to the Royal Ontario Museum and pose the all-important question: “Are we keeping it?” I ask nervously. He looks up from his work and he says “yes,” resulting in a sigh of relief.

“I hold my breath as my eyes search for signs of something ancient lying in wait in the stone.”

The Burgess Shale Quarry in Kootenay National Park, British Columbia
Bringing the science of planet Earth into the lives and careers of all by sharing knowledge and raising awareness for the Earth, its history, its resources, and the environmental issues facing society.

The museum, through its collections, displays and programs aims to foster a broad and diverse appreciation for all features and processes of planet Earth for all ages, both within and outside the university community.

uwaterloo.ca/earth-sciences-museum