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The Central Role of Weathering in the Geosciences

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Abstract

Weathering is the chemical and physical alteration of rock at the surface of the Earth, but its importance is felt well beyond the rock itself. The repercussions of weathering echo throughout the geosciences, from ecology to climatology, geomorphology and geochemistry. This issue of *Elements* provides an overview of weathering and its consequences, including the evolution of scientific thinking about weathering, the human impact on weathering — to both good and bad effect, and speculating about future developments in the science of weathering, through computational, conceptual and methodological advances.

Keywords: weathering, earth system science, nutrient cycling, landforms, enhanced weathering, planetary habitability

Introduction

Weathering is the process by which rocks decompose at or near the Earth's surface. Together with erosion, it is the Earth's mechanism for redistribution of mass at the surface, and so is a central part of the Earth system: if petrology is the birth of rocks, weathering is their death. It is a death that enables life on Earth: solutes released during chemical weathering reactions provide nutrition to ecosystems and represent the starting point of the biogeochemical cycles of almost all elements. These reactions ultimately determine soil, river, groundwater and ocean chemistry. The removal of mass from rocks by chemical weathering alters their structure and susceptibility to physical weathering and erosion, and facilitates the formation of soils, with impacts on landscape

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evolution and hydrological and geomorphological processes. Weathering is also crucial for the habitability of the Earth – and perhaps planets beyond our solar system – because it acts as a long-term sink for the greenhouse gas CO_2. For this reason, weathering of silicate rocks can be thought of as a planetary thermostat. These are just a few of the ways in which weathering influences the flow of mass and energy across the thin 'skin' of Earth's rocky surface.

What is Weathering?

Weathering involves processes that span many orders of magnitude in spatial and temporal scales, from global geochemical budgets operating over billions of years, to sub-micrometre mineral fabrics and reactions (FIG. 1). Therefore 'weathering' means different things to different people (to the point that this familiar word may even impede discussions between scientific disciplines; Hall et al. 2012). One relatively simple and familiar way to define weathering is to categorise its various actions into either physical or chemical processes. Under this bipartite division, *physical weathering* causes mechanical disintegration of rock without compositional change, whereas *chemical weathering* involves the breaking of chemical bonds and a change in the chemistry and mineralogy of the rock.

Most definitions of weathering emphasise the thermodynamic instability of minerals to conditions at the Earth surface. For example, Viers and Oliva (2017) define weathering as the "*spontaneous* and *irreversible* thermodynamic process that causes degradation of the mineral phases under the prevailing environmental conditions at the surface of the Earth." This definition is a useful starting point and is applicable to a range of weathering reactions. For example, limestone precipitated from carbonate-saturated, high-pH seawater will dissolve (a simple form of chemical weathering) when exposed to carbonate under-saturated, low-pH rainwater. Silicate minerals in igneous and metamorphic rocks form at high temperatures and pressures, so many of them are not at thermodynamic equilibrium at the Earth's surface and will eventually transform to more stable phases. Elements such as iron that are sensitive to reduction or oxidation ('redox') are usually present in in igneous minerals in their reduced form (e.g. Fe(II)) and so are prone to oxidation in the O_2 rich surface environment. The fact that these weathering-sensitive minerals are found at the Earth surface reflects the relatively slow kinetics of the reactions that destroy them.

We can subdivide the effects of chemical weathering reactions into those that alter primary minerals through dissolution and those that form more stable secondary minerals through precipitation (FIG. 2). Dissolution is the solubilising and releasing of elements from minerals whereas precipitation is the formation of secondary minerals from the solubilised products of dissolution. These two aspects of chemical weathering are often (though not necessarily) coupled in space and time (e.g., Ruiz-Agudo et al. 2016), such that their combined effects can be written as net reactions transforming reactant minerals into dissolved ions and secondary mineral precipitates.

The hydrolysis of silicate minerals is a common example of coupled dissolution and precipitation, as in the transformation of K-feldspar into kaolinite:

$$KAlSi_3O_8 + H^+ + 0.5H_2O \rightarrow 0.5Al_2Si_2O_5(OH)_4 + K^+_{(aq)} + 2SiO_{2(aq)} \qquad (1).$$

where potassium and some of the silicon are released as dissolved species that can be transported away. Not all weathering reactions are associated with the formation of a secondary phase. For example, carbonate minerals typically weather congruently, with both the calcium cation and the carbonate anion removed from the weathering system in dissolved form:

$$CaCO_3 + 2H^+ \rightarrow Ca^{2+}_{(aq)} + H_2CO_{3(aq)} \qquad (2).$$

Weathering also encompasses a suite of processes that alter minerals with little mass loss or gain. Hydration reactions are a common example: serpentinisation is essentially the hydration of olivine (or other ultramafic rocks), and is associated with volume expansion, changes to rock mechanical properties and the production of hydrogen (H_2). Further examples include the hydration of anhydrite to gypsum, or the incorporation of water into inter-layer sites of clay minerals. Both of these examples of hydration reactions are also associated with volume expansion, which can lead to physical disintegration of the host rock. A second group of reactions that can alter minerals without necessarily requiring net mass loss are those associated with a redox change. For example, the in situ oxidation of Fe(II) to Fe(III) in the structures of Fe-bearing minerals (like biotite or pyroxene), is not associated with substantial mass loss from the system, but does build up elastic strain that can fracture rocks (Fletcher et al. 2006).

Weathering as a part of the Earth system

Weathering is one of several interconnected processes that work together to govern the form and function of the Earth's surface. These processes, which include erosion, water flow, and biological activity, interact with weathering and climate through multidirectional, time-varying feedbacks (FIG. 3). For example, chemical weathering, physical erosion, and vegetation coverage all vary non-linearly with climate. The type and amount of vegetation controls sediment export by modifying the relationship between precipitation and erosion. Vegetation also alters subsurface soil and solute chemistry, physical structure, and hydrology, and thus affects chemical and physical weathering rates. In turn, weathering affects ecosystem health via the supply of mineral nutrients. Weathering is also coupled to erosion: weathering drives erosion by helping to fracture and disaggregate bedrock, and erosion drives weathering by supplying fresh mineral surfaces to reactive fluids. Coming full circle, erosion rates regulate soil thickness and development, and thus ecosystem structure. Yet more complexity is added on longer timescales by the tectonic control on mineral supply, and the feedbacks weathering has on global climate. Weathering thus sits at the centre of a web of interconnected processes (FIG. 3) that together determine the world we live in.

The Significance of Weathering

The influence of weathering can be felt across nearly all Earth science disciplines; in fact, most Earth scientists study some aspect of weathering (FIG. 4). The articles in this issue of *Elements* emphasise why we see weathering as a central, unifying process in the geosciences. This issue uses the process of weathering as a window onto different geoscience sub-disciplines (FIG. 4), and focuses in particular on the consequences of weathering, rather than the mechanisms (which are well described in existing reviews; e.g., Brantley 2003).

Nutrient Cycling

At the spatial and temporal scales considered by ecology (FIG. 4), weathering reactions create porosity, help form soil, and release biologically essential mineral nutrients. These nutrients encompass essentially everything biology needs except nitrogen and inorganic carbon (which are atmospherically derived – but note weathering can even be an important source of nitrogen; e.g., Houlton et al. 2018). The most crucial mineral nutrient is phosphorus, which is involved in all cellular energy transfers; phosphorus limitation can arise in old ecosystems that are physically isolated from underlying bedrock. Furthermore, macronutrients (e.g., potassium, magnesium, calcium) and the non-essential, but under-appreciated, silicon are also supplied solely by weathering. Writing in this issue, Porder (2019) describes the strategies plants have evolved to enhance the weathering process to their own benefit, and how ecosystems are forced to shift towards tighter recycling strategies when the supply of nutrients from rock weathering is low.

Weathering also supplies micronutrients like iron, boron, zinc, molybdenum, or nickel. These elements play crucial biochemical roles, typically in the facilitation of metabolic pathways or as enzyme cofactors. One of the purposes of agricultural fertilizers is to provide macro- and micronutrients in easily accessible forms, allowing plant growth to outstrip what would be possible from ‘natural’ nutrient acquisition and recycling. The relationship between mineral nutrition and weathering is receiving growing attention in agricultural research, particularly with the realisation that even though crop yields have increased in recent years, their nutrient content may have declined (e.g., Davis et al. 2004). As a consequence, almost three billion people suffer from “hidden hunger” – some form of micronutrient deficiency (as do many animals). Tackling this problem in the years ahead will require a better understanding of weathering as the ultimate source of these elements.

Weathering also has implications for aquatic ecosystems and Earth-surface water fluxes. The chemistry of surface waters can be seen as the net result of weathering reactions. These reactions, together with biological activity (and often pollution) are the key determinants of freshwater chemistry, thereby governing several ecologically relevant variables, including water pH and nutrient status, and ultimately the type of aquatic ecosystem that can develop.

Water Flow and Landforms

The flow of water at the Earth surface – i.e. the field of hydrology – is also influenced by weathering reactions at a range of scales. At soil-profile scales, primary mineral dissolution and secondary clay precipitation govern the porosity and permeability of the soil matrix that water moves through, especially in the near-surface. Deeper in the subsurface, preferential flow-paths (e.g., rock fractures) can be created, enlarged or filled by weathering reactions. We are also learning that water residence time is a key control on the efficiency of weathering reactions (e.g., Maher 2011). Eventually, surface- and ground water transport weathering products to the oceans where they provide nutrients for marine life as well as the building blocks (Ca^{2+}, CO_3^{2-}) for forming carbonate rock, which sequesters atmospheric CO_2.

Moving towards larger scales, geomorphology – the study of landforms and landscapes – is fundamentally about the redistribution of material at the Earth surface. Weathering prepares rock for mass-wasting processes at the surface, and because weathering is climate dependent, similar rock types can produce different landscapes in different regional climatic settings. It is not uncommon that more than 50% of mass-loss from a landscape is accomplished chemically (Dixon and von Blanckenburg 2012). The resulting landscapes are thus the product of chemical weathering. Karst landscapes, where almost 100% of mass loss can be achieved chemically, are particularly spectacular examples. Even in rapidly eroding, mountainous systems where most mass-loss is via physical erosion, chemical weathering rates are typically higher than more gently sloping regions, simply because the supply of reactive surface areas is so great. However, there appears to be an upper limit to weathering rate — the weathering "speed limit" (of about 150 t km^{-2} y^{-1} for silicate lithologies; Dixon and von Blanckenburg 2012), which is governed by the maximum rate of tectonic supply of rock and mineral dissolution kinetics.

Landscapes ultimately arise as the integrated result of processes that act at the mineral-grain scale. At these small scales, the mechanical disintegration of rock under typical Earth surface conditions often proceeds by *subcritical cracking* (Eppes and Keanini 2017). This refers to slow-speed fracturing of material at much lower applied stresses than the 'critical stress' required for catastrophic failure. Subcritical cracking is a process that involves bond breaking and so is fundamentally physio-chemical in nature (Eppes and Keanini 2017). There is evidence that weathering reaction rates (and thus the susceptibility of rocks to fracture) increase in the presence of stress (e.g., Schott et al. 1989). In other words, the binary division between physical and chemical weathering processes is becoming increasingly blurred. Anderson (2019 this issue) reviews a suite of processes that generate subcritical cracking, and what this means for the shaping and sculpting of the Earth's surface.

Climate Regulation

At still larger spatial and temporal scales, weathering provides a *planetary homeostasis* mechanism. As described by Kasting (2019 this volume), the hydrolysis of silicates by carbonic acid produces cations and bicarbonate ions that later recombine as marine carbonates, constituting a sink in the long-term carbon cycle that balances the carbon emitted by volcanoes and mid-ocean ridges. Because the weathering reactions proceed at a climate-dependent rate, and climate depends to a first order on atmospheric $p\mathrm{CO}_2$, then silicate weathering is the best candidate for a stabilising ('negative') feedback in the Earth's climate system. In other words, without silicate weathering, the Earth would likely have become a runaway greenhouse with an inhabitable climate.

The operation of the weathering thermostat thus plays a fundamental role in how we understand palaeoclimate and ocean chemistry over million-year-timescales. How the thermostat interacts with tectonics and solar physics is central in the emerging field of exoplanet habitability. And because a stable planetary climate is presumably a necessary precursor for the persistence of complex life, the weathering thermostat also bears on some of the most profound questions in biology, including the origin of life. Kasting (2019 this issue) reviews the operation of the silicate-weathering feedback and many of the emerging nuances that govern the stability (or lack thereof!) of climate on Earth and other planets. Also in this issue, Frings (2019 this issue) summarises the progress being made towards identifying and quantifying weathering rate changes in the past – a crucial step if we are to properly understand how the thermostat works.

Economic Resources

Weathering also has economic repercussions. For example, the suite of processes that make up the phenomenon of *supergene enrichment* are essentially weathering reactions. Supergene enrichment refers to the concentration of metals near the Earth surface above lower-grade ore deposits. These metals commonly have a high industrial or societal demand and low crustal abundance in near-Earth surface layers, so supergene enrichment can thus create economically viable ore deposits. Through a complex series of redox-sensitive dissolution, transport and re-precipitation mechanisms, enrichments of 10x or more in metal grade can be achieved. Supergene ores are often central to determining the overall viability of a deposit, but typically are only accessible through open-pit mining. Understanding weathering's role in supergene ore enrichment thus takes on economic and societal significance (recently reviewed in Reich and Vasconcelos 2015).

Other Impacts of Weathering

The impact of weathering reverberates, directly or indirectly, through many other geoscience fields. The storage or remediation of pollutants (including nuclear waste) can be thought of as forms of weathering reactions. Weathering influences risks due to several natural hazards, including floods, earthquakes, or landslides, primarily through its influence on soil development and subsurface properties. About three-quarters of the terrestrial surface is covered by sedimentary rocks formed during past cycles of weathering, erosion and deposition. The differences in composition, strength and susceptibility to weathering and erosion among these rock types exert controls on landscape form and how sediment is routed from its source to its ultimate sink at the seafloor. The amount and nature of sediment delivered to subduction zones influences the lubrication of the descending plate (Sobolev and Brown 2019). This implies the existence of connections between weathering and erosion that supply sediment, and plate velocities, earthquake genesis, and melt generation. Ultimately, these interactions may even shape orogenesis and continental growth. The subduction of weathered material influences the composition and rheology of crustal melts, for example leading to compositional differences between “S” type granites (Sedimentary, depleted in Na, Ca and Sr) and “I” (Igneous) type granites, which differ in susceptibility to weathering and erosion, and in mineral nutrient content. Modern isotope geochemical tools allow us to distinguish between different melts even in the ancient Earth (Trail et al. 2018), letting us document the feedbacks between weathering and igneous petrogenesis in the distant past. Some of these connections with weathering might seem tenuous, but they exist nonetheless: For these reasons we suggest that weathering is the strongest link between Earth surface processes and solid Earth dynamics.

Historical Development of Weathering Research

As a topic of scientific investigation, weathering has a long history. It is often surprising how much of what we consider as modern science was actually sketched out by workers in the 19th century or earlier. For example, the concept that acids, including carbonic acid, react with minerals was known in the 1700s and by the early 1800s, dissolution experiments with various minerals were being conducted on both sides of the Atlantic Ocean (Bischof 1847; Rogers and Rogers 1848). This approach remains central to quantifying and understanding weathering to this day. Early workers recognized both the neutralisation of carbonic acid by silicate-hosted alkali elements, that the decomposition of minerals releases elements essential to plant growth, and that plants may actively obtain nutrition from ‘mining’ solids (von Liebig 1859).

Much of the pioneering work on landscape evolution had a tendency to attribute observations simply to the physical disaggregation of rocks and transport of the resulting clastic sediments. For example, in the late 1800’s, American geologist, G.K. Gilbert, identified that landscape evolution was driven by soil production (Gilbert 1877). However, in 1879, British geologist Thomas Mellard Reade proposed that chemical denudation can be an important part of landscape development. Also in the 19th century, there was interest in mapping and describing soil profiles – the precursor to modern soil science. Friedrich Fallou, a German lawyer, realized that soils are chemically as well as physically different from the bedrock from which they derive (Fallou 1862) and the famous British naturalist, Charles Darwin, noted the influence of earthworms on rock weathering rates and soil formation (Darwin 1881).

Perhaps most impressively, by the 1840s the importance of weathering in the long-term carbon cycle had been established. In 1845, the French mining engineer Jacques Ébelmen presented a remarkably complete picture of the processes governing atmospheric $p\mathrm{CO_2}$ – over a century ahead of his time, and only recently has been properly appreciated (Berner and Maasch 1996). Working simultaneously and apparently independently, the German chemist Gustav Bischof published in 1847 the first volume of a series that would eventually be recognised as defining the new field of geochemistry. Both Ébelmen and Bischof realised that there must be mass-balance in the long-term carbon cycle: *"If the formation of carbonates were to take place at the expense of the silicates only by means of atmospheric carbonic acid, then this component of the atmosphere would continuously decrease and the balance so necessary in Nature's household would be disturbed ... It is a necessity that the CO_2 consumed by the weathering process, constantly emerges from the interior of the Earth"* (Bischof, 1847). It was not until 1952 that this issue was revisited by Harold Urey, who suggested that a relatively constant partial pressure of atmospheric CO_2 is maintained by the tendency towards thermodynamic equilibrium of what has since become known as the "Urey reaction":

$$CaSiO_3 + CO_2 \rightleftharpoons CaCO_3 + SiO_2 \qquad (3).$$

The idea of a purely equilibrium control never gained much traction, and in the early 1980s, the concept of a kinetic control on silicate weathering rates forming the basis of a planetary thermostat was introduced; this remains the favoured explanation to this day (Walker et al. 1981). Kasting (2019 this issue) provides an overview of the principles, nuances and intrigues in the silicate-weathering feedback. In the years that followed the presentation of the modern formulation of the weathering thermostat, we have come to recognize periods in Earth history when it worked differently or not at all — e.g., Snowball Earth episodes, or Cenozoic cooling. It has become widely accepted that these excursions in Earth's climate might be related to the enhancement or diminution of weathering rates or efficiencies, though we are still fitting together the pieces of these puzzles.

Human Alterations to Rock Weathering

Human influence is visible on ecosystems from the Marianas trench to Siberian permafrost, and is just as clearly changing natural weathering. There is direct observational evidence of an increase in solute export fluxes at the catchment scale following the warming of the last decades (Eiriksdottir et al. 2015). Yet it is unclear how weathering processes are being affected, and several mechanisms could be at play. The direct effect of temperature increases on reaction kinetics is certainly part of the story, but other processes might be just as significant. Deforestation or other land-use changes might have induced a change in how ecosystems store and recycle nutrients, which can be manifest as a transient increase in solute export. As Porder (2019 this issue) notes, we can see the industrial mining of nutrient deposits as a kind of accelerated weathering that may have long-lasting ecological implications. Changes to hydrology associated with water extraction, damming and urbanisation have the potential to alter groundwater levels and flow regimes. This can influence weathering by altering water-rock interaction times, which we know is a key control on how efficiently weathering proceeds. Globally, the same concept holds true: the magnitude, seasonality and geographic distribution of rainfall are all predicted to change in a warmer climate. Human activity can also impact weathering via acid rain. Burning of fossil fuels releases nitrogen and sulfur compounds that later form nitric and sulfuric acids in rainwater. These are stronger acids than carbonic acid, and accelerate rock dissolution and negatively impact ecosystems. This is a particular problem for weathering of the 'built environment' – monuments and architecture – as well as in the natural environment.

Might there also be a positive side to human perturbations to weathering processes? Various geo-engineering schemes, grouped under the heading of "carbon capture and storage", aim to remove CO_2 from the atmosphere. Some of the most promising are those that short-circuit the natural weathering processes. One example is the injection of CO_2 charged water into Icelandic basalts to form new carbonate minerals (Matter et al. 2016). A slightly less dramatic carbon sequestration strategy is simply to enhance the natural weathering process at the Earth surface. Andrews and Taylor (2019 this issue) review the progress made towards using so-called 'Enhanced Weathering' as a geoengineering tool to sequester carbon from the atmosphere. By distributing finely ground, highly weatherable rocks (e.g., andesites or basalts) on tropical land surfaces, natural weathering rates might be increased, removing CO_2 from the atmosphere. Potential bonuses could include the partial amelioration of ocean acidification and improved cropland fertility. Andrews and Taylor (2019 this issue) emphasise that although the way we think about enhanced weathering has its roots in studies of "natural" weathering processes, it actually differs in important ways. If we want to harness the power of weathering as a carbon capture and storage tool, the challenge is to understand these differences and scale-up from the pot- or plot- scale of experiments to the catchment scale needed for implementation.

Whither Weathering – Future Directions in Weathering Studies

There are long-standing questions about weathering that remain unsolved. For example, it has been observed for decades that there is a substantial discrepancy between weathering rates measured in the lab relative to those measured in the field, which are often several orders of magnitude slower (Brantley 2003). Several mechanisms have been suggested to be responsible for this difference, but no consensus has emerged. Similarly, the extent to which biological activity enhances weathering rates is also unclear. Though several mechanisms have been described by which plant or microbial life should speed up weathering reactions (see Porder, 2019 this issue), the actual enhancement beyond an abiotic control is hard to quantify, simply because no control sites exist on Earth today. The relationship between biology and weathering reactions is further complicated by the fact that biological processes can work to either speed up or slow down weathering (e.g., tree root growth reduces erosion, which may slow weathering). Solving these problems will require identifying and disentangling the overlapping and competing processes and feedbacks on multiple scales (FIG. 3), a daunting task that will require interdisciplinary teams and combined approaches (e.g., critical zone science) utilizing experimental and field data to inform numerical models.

At global scales, it is unclear whether seafloor weathering or continental weathering govern the silicate-weathering thermostat (see Kasting 2019 this issue). The role of reverse-weathering – the formation of new minerals in marine environments via CO_2-producing reactions – in the long-term carbon cycle in the present and past Earth is debated. The increased interest in astrobiology and planetary habitability provides a pressing motivation for advancing understanding of these issues.

As the science we do becomes progressively more interdisciplinary, the interfaces of weathering with various geoscience fields will become more obvious. We anticipate that our ability to 'Earthcast' — to predict material and energy fluxes at the Earth surface — will improve along with our abilities to numerically model the Earth system and to understanding mechanistic physical and chemical weathering processes. Earthcasting efforts are beginning to explicitly consider weathering processes, rather than treating them as prescribed boundary conditions (Sullivan et al. 2019). We expect deep subsurface weathering to also be increasingly important to the study the deep biosphere and landscape evolution. Microbial ecosystems have been found to thrive essentially everywhere in the upper few hundred metres of the Earth's crust, and they clearly gain energy and/or mineral nutrients from the rocks in which they live. Yet we are only beginning to sketch out the linkages between the deep microbial biosphere, 'deep' weathering, and what this means for rocks at the Earth surface. Finally, the intersection of weathering with human needs will surely emerge as a focal point of research. To feed a growing human population and simultaneously avoid the problems of hidden hunger (i.e. micronutrient deficiency), a sustainable agricultural strategy will have to account for the supply of nutrients from bedrock. Other issues with particular societal implications that will require understanding of mineral alteration include the formation and exploration of ores containing the rare metals increasingly demanded in electronic goods, waste storage, and the environmental impacts of hydraulic fracturing (i.e. fracking).

The big challenge is the integration of weathering across disciplines and across temporal and spatial scales (FIG. 4). Geoscientists are helping to push the development of unique tools, from reactive transport models, to isotope geochemical tracers, to instrumentation to probe samples at the nanometre scale. These developments will help address the many problems of weathering science and help cement weathering as a central process across the different fields of the Earth sciences.

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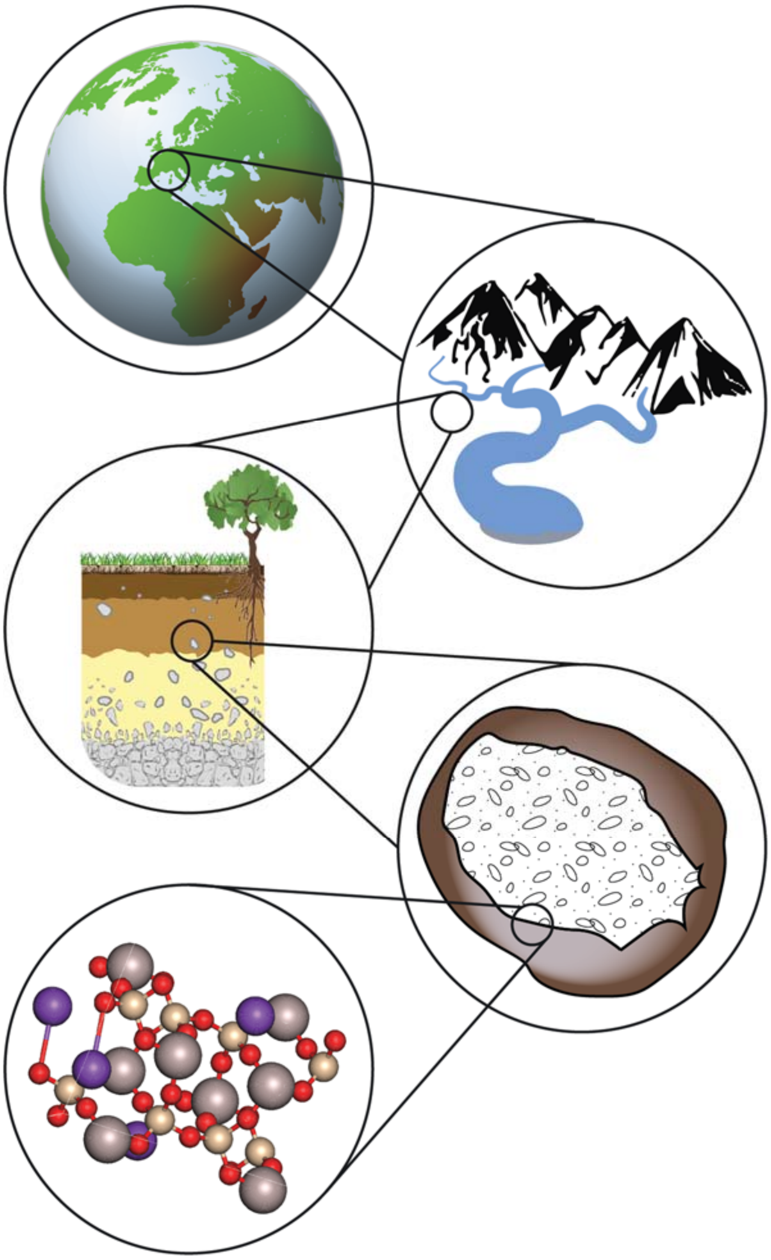
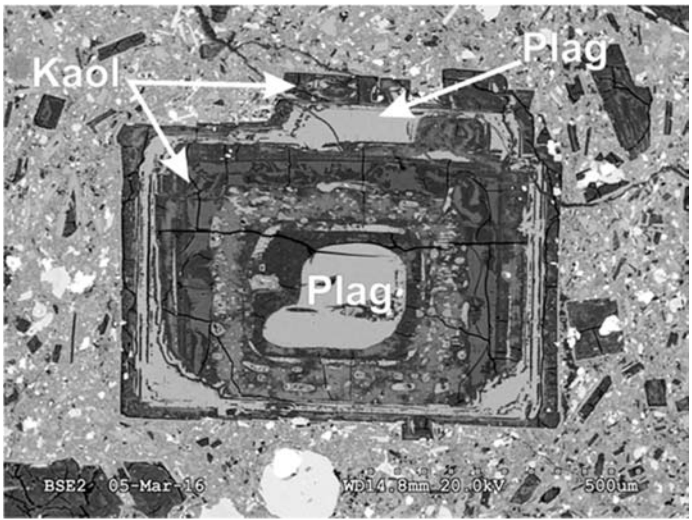
Figure 1: Weathering happens as a chemical reaction at mineral surfaces, but it can be observed, investigated and quantified across a huge range of spatial scales, including A: in regional to global element budgets (typical length scale ≈ 10^3 km); B: in catchment solute fluxes (typical length scale ≈ 10^3 m); C: in soil/saprolite geochemical and mineralogical profiles (typical length scale ≈ 1 cm - 10 m); D: on individual rocks, grains or minerals (typical length scale ≈ 1 μm – 1 cm), and E: as a molecular scale process (typical length scale < 1 μm).

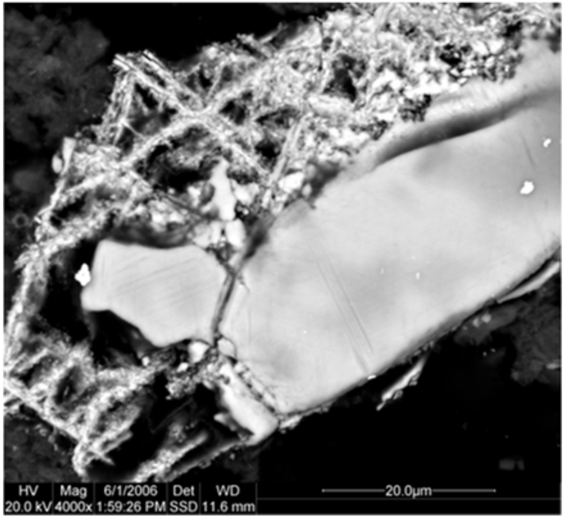
Figure 2. Backscattered electron images of dissolution-precipitation mineral weathering. A) The Ca-rich parts of zoned plagioclase crystals dissolve preferentially, with kaolinite precipitating in the pore space. Image courtesy of O.W. Moore, University of Leeds. B) Primary hematite dissolving along the edges of the crystal are replaced by a hydrous Fe(III) oxide secondary mineral precipitate with a porous, 'boxwork' texture. Image courtesy of H.L. Buss.

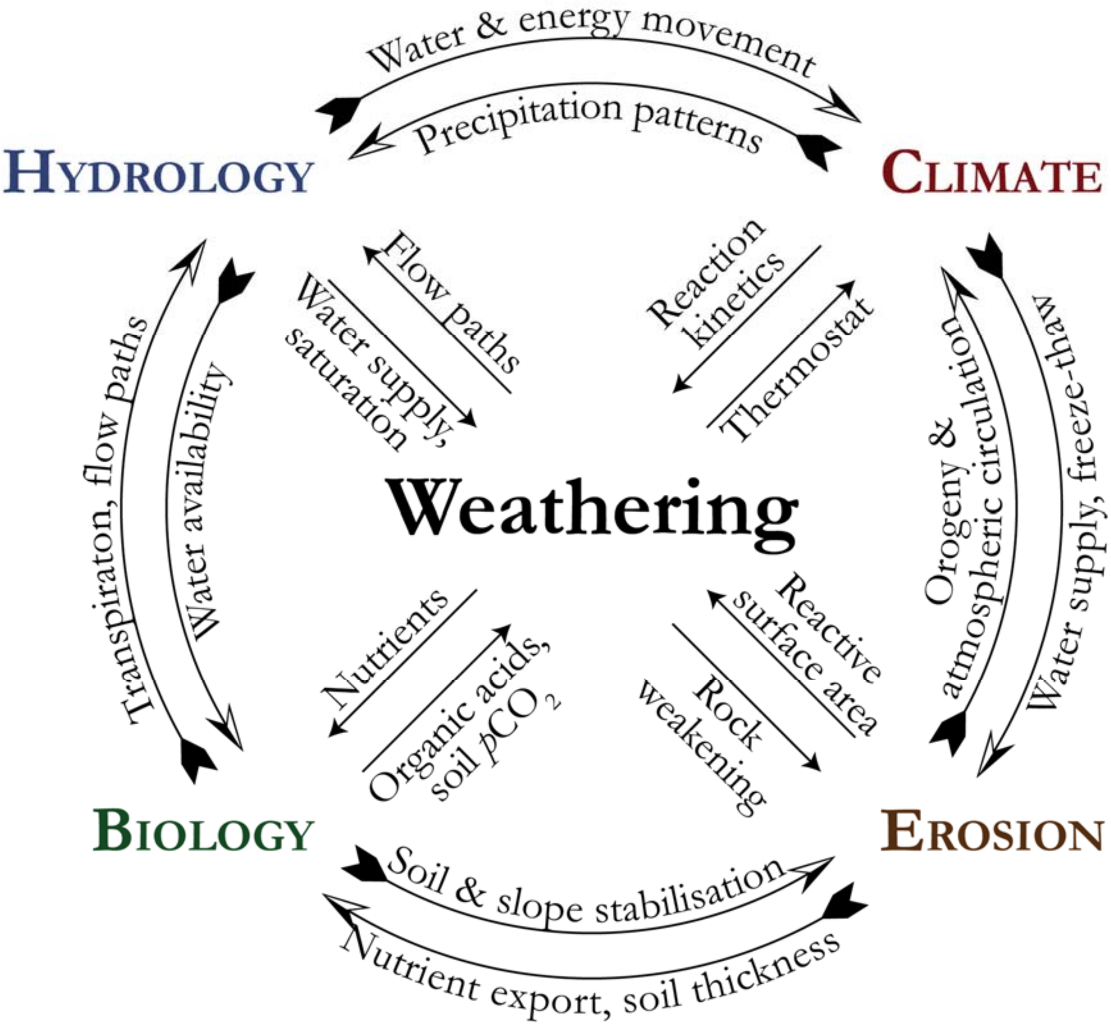
Figure 2: Weathering sits at the centre of a web of interconnected processes that together govern the form and function of the Earth surface. The interactions in this web form a series of positive and negative feedback loops and span from the quick (e.g. mass-wasting events exposing new rock to weathering) to the very slow (e.g. the feedbacks between tectonic supply of rock and its removal by erosion and weathering).

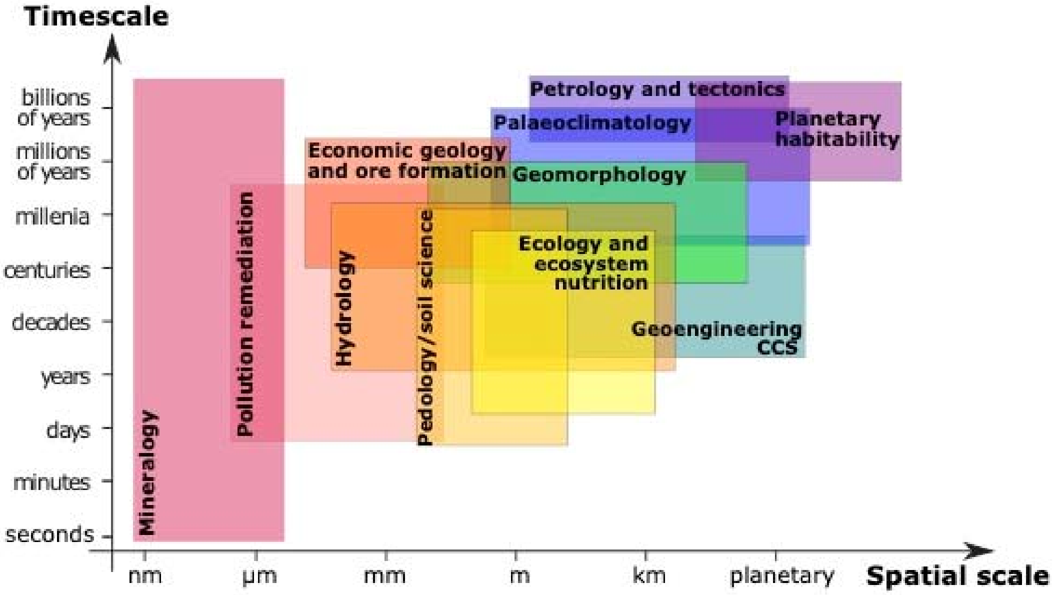
Figure 3: Examples of the spatial and temporal scales over which different Earth science disciplines are influenced by weathering. By providing a link between disciplines and between Earth surface processes and solid Earth dynamics, weath- ering should be seen as a unifying process across the Earth sciences. Abbreviation: CCS = carbon capture and storage




Kaol
Plag
Plag
BSE2 05-Mar-16
WD14.8mm 20.0kV
500um


HV
20.0 kV
Mag
4000x
6/1/2006
1:59:26 PM
Det
SSD
WD
11.6 mm
20.0μm


HYDROLOGY
CLIMATE
BIOLOGY
EROSION
Weathering
Water & energy movement
Precipitation patterns
Transpiraton, flow paths
Water availability
Orogeny & atmospheric circulation
Water supply, freeze-thaw
Soil & slope stabilisation
Nutrient export, soil thickness
Flow paths
Water supply, saturation
Reaction kinetics
Thermostat
Nutrients
Organic acids, soil pCO$_2$
Reactive surface area
Rock weakening


Timescale
billions of years
millions of years
millenia
centuries
decades
years
days
minutes
seconds
nm
µm
mm
m
km
planetary
Spatial scale
Mineralogy
Pollution remediation
Economic geology and ore formation
Hydrology
Pedology/soil science
Petrology and tectonics
Palaeoclimatology
Planetary habitability
Geomorphology
Ecology and ecosystem nutrition
Geoengineering CCS