Reflections on Earth surface research

Irasema Alcántara-Ayala[1†], Asmeret Asefaw Berhe[2†], Louis Derry[3,4†], Vamsi Ganti[5,6†], Alice A. Horton[7†], & Min Sub Sim[8†]

†email: ialcantara@igg.unam.mx

email: aaberhe@ucmerced.edu

email: derry@cornell.edu

email: vganti@ucsb.edu

email: alihort@noc.ac.uk

email: mssim@snu.ac.kr

Standfirst

To celebrate the first anniversary of Nature Reviews Earth & Environment, we asked 6 researchers investigating Earth surface processes to outline notable developments within their discipline and provide thoughts on important work yet to be done.

Main text

Broadly, what are some of the key advances and exciting future prospects in your discipline within surface processes research?

Irasema Alcántara-Ayala: The current pace of global environmental change mirrors an era in which landscape domains are inseparable from humankind, and anthropogenic intervention influences surface processes. Landslides, driven by the force of gravity, involve pre-failure deformations, failure and post-failure displacements controlled by geodynamic processes. Yet, in addition to landslides as natural processes, their frequent occurrence is induced by socio-environmental stresses or changes that influence or increase the instability of hillslopes. This relationship clearly reveals the importance of understanding their socio-natural essence[1]. Thus, defining landslides—and other hazards—exclusively as natural hazards *per se,* pressures us to leave aside conjecture and facts about what has been involved in causality and challenges existing disaster risk management frameworks.

Socio-natural hazards are produced or exacerbated by human intervention in nature, and are repeatedly confused with extreme natural events. The asymmetric relationship between spatial dimensions of causality and the spatial dimension of impact of socio-natural hazards presupposes a differential ownership for their occurrence and jurisdiction for mitigation options. If hazards are defined as acts of nature, preventive measures can be neglected. Lacking a proper understanding of causality and of responsibility leads to the focus efforts on emergency response and mitigation in the aftermath of disaster, not the need to manage disaster risk. Ergo, processes taking place across broad scales, often at catchment or regional levels (for example, deforestation), with no correspondence with political or administrative limits would defy institutional disaster risk management structures and accountability.

One clear message is that since the last half of the twentieth century, in consonance with the character of the Anthropocene, phenomena that appeared to have been natural are seen and understood as processes shaped by human actions. These actions are entrenched in a series of historical interlinkages of social, economic, political, cultural, institutional and environmental character, on which unsustainable development has been prioritized over the rational and harmonic equilibrium with nature. Accordingly, the key point made in disaster risk research is that disasters cannot be recognized in the absence of understanding their dimension of social construct, which is shaped by the interaction of diverse spheres of vulnerability and exposure to hazards (as in the FORIN assessment [http://www.irdrinternational.org/wp-content/uploads/2016/01/FORIN-2-29022016.pdf]). Over and above natural processes of the Earth's surface, the main emerging issue of landsliding is the social mosaic onto which landslide disaster risk is constructed. Population growth, large urbanisation rates, pressures on land use and land cover leading to deterioration of the environment, together with inequality and climate change, pose great challenges for research, policy making and practice inasmuch as landforms are continuously transformed.

The list of key recent advances of surface process research from a landslide hazard perspective could be expanded *ad libitum*. The comprehension of landslide dynamics has benefitted from the betterment of landslide instrumentation, monitoring, mapping, modelling, field tests and laboratory measurements, more accurate ground and remote sensing tools and methods for terrain observations and visual interpretation, along with technical development of early warning systems. Nonetheless, in contrast with such continued success and progress, we have witnessed that landslide research has failed to make its mark in the disaster risk management arena. Perhaps one of the clearest signs of landslide research's lack of influence within the disaster risk management sphere, and thus in disaster risk reduction, is the relative absence of transdisciplinary alliances. Partly catalysed by mono and multidisciplinary approaches, investigations have been focused upon the understanding of landslides as natural hazards, neglecting social underlying and driving processes.

As in the case of other types of hazards, the new direction of landslide disaster risk research requires integrated science-based policymaking to be designed and implemented[2]. Co-production of knowledge and co-decision making, notably in the form of integrated disaster risk reduction and its domain of praxis, thus should play a cardinal role in shaping the future prospects in surface processes landslide related research. It would of course be inaccurate to overemphasise the potential influence of science in policymaking without having examined the skills and capability of disaster risk stakeholders to develop effective application of knowledge, and most importantly without any thoughts on the convoluted inherent hindrances of disaster risk governance.

At the end of the day, there remains the task of engaging into transdisciplinary efforts that rotate around the spatial-temporal new imperative flavour of surface processes research. Such transdisciplinary orientation must be thought of as a collaborative cross-cutting process tailored by the union of academic and non-academic stakeholders, and directed to guide convergences between science and practice through participatory and multi-methodological approaches. At the heart of these aspirational transdisciplinary endeavours, the co-production of knowledge and the ability to transfer it to politics and practice in the light of the integration and coordination of differentiated territorial levels, provide an opportunity to address societal concerns, but also pose a grand challenge to sustainable and egalitarian development.

Asmeret Asefaw Berhe. Early soil science research was largely focused on the role of soils in supporting plant growth in agricultural systems. Over the last five or so decades, the field of soil science has seen renewed interest in the role of soils in mediating key bio(geo)-chemical and -physical processes. Part of this renewed attention is driven by our improved ability to quantify and model dynamic soil surface processes that have important implications for the amount and nature of soil covering the earth's surface; and the two-way relationship between soil and human communities.

Advances in our ability to observe and model the role of soils as biogeochemical reactors where multi-phase processes take place have aided in expanding the knowledge base in numerous directions, including two major environmental issues of our times: climate change and land degradation.

First, a large and growing number of studies are demonstrating that soil can be part of the solution or problem concerning greenhouse gas fluxes between land and atmosphere. Better quantification for how much, and expanded understanding of why and for how long carbon persists in the soil system has led to growing interest in soil's contribution towards terrestrial sequestration of atmospheric carbon dioxide (CO_2) and climate change mitigation. Incorporating climate-smart management of soil as part of a comprehensive strategy that primarily includes reducing fossil fuel emissions has now been shown to offer powerful solutions that can offset up to a third of the fossil fuel emissions that are currently released to the atmosphere from human activities[3]. Moreover, soil surface processes have emerged as key for parameterization of global climate models.

Second, land degradation that now affects about a third of the world's soils[4] has led to a marked decline in soil's health—its ability to support plant productivity; maintain soil structural stability, withstand erosion, regulate water status and nutrient cycling, filter contaminants and buffer against plant diseases. Tillage continues to be a major soil destabilizer that has accelerated near-surface mixing, weathering, organic matter mineralization, erosion, and more. Along with conventional tillage, human use, overuse, and abuse of soil in intensive agricultural production systems (as a result of deforestation, overgrazing, and more) has led to 1-3 orders of magnitude increase in rates of soil erosion globally[4], pushing the world's soils, key processes that they mediate, and adjacent aquatic system's health to the brink. Climate-smart land management practices have been highlighted for their potential to simultaneously address climate change and land degradation, both of which are key for ensuring food and nutritional security of the growing human population.

In recognition of the fact that more than half of the earth surface is dominated by sloping landscapes, studies over the last three decades examined the role of soil erosion on biogeochemical cycling of essential elements on eroding and depositional landforms[5]. As we expanded our understanding of climatic, geomorphic, and anthropogenic activities controlling the rate and nature of soil erosion, studies showed that there is significant erosion occurring in flat lands[6] and that post-fire erosion has the potential to mobilize a large amount of mass and can alter key soil processes in fire-adapted ecosystems. Further works highlighted the yet poorly quantified magnitude and distribution of wind erosion globally, along with the role of dust deposition on critical biogeochemical processes on land and oceans globally[5].

In the context of climate change, discussions on soil surface processes have directed considerable attention to the role of extreme climatic conditions, in particular those that have to do with increasing atmospheric temperatures and (de)intensification of the hydrologic cycle. Increased atmospheric temperatures are leading to fundamental transformation of surface processes in circumpolar soils that continue to experience rapid, and large-scale thawing of permafrost and associated thermal erosion, loss of greenhouse gases, and major alterations of their regional biogeochemical cycles. At lower latitudes, extreme drought continues to lead to expansion of drylands towards desertification, and causing soil drying while desiccation due to extreme withdrawal and/or depletion of groundwater reserves in subsurface aquifers causes considerable land subsidence in multiple parts of the world. Further, warming and droughts have been responsible for the already observed, and expected to worsen, increased frequency and severity of fires globally. In particular, considerable advances have been documented in our understanding of how fires transform surface processes through: loss and subsequent transformation of vegetation cover, surface hydrophobicity, rerouting of the hydrological flow regimes on land and increased rates of erosion, loss of soil nutrients, and introduction of harmful sediments, and chemicals to adjacent aquatic bodies.

Since its formalization near the end of the last century, soil science research took center stage in critical zone science. The critical zone framework allowed earth and life scientists to advance fundamental knowledge regarding the co-evolution of ecosystems and landscapes – in particular on variables regulated by climate, nature of the geologic parent material, biota, and more. Moreover, the CZ framework has allowed a more integrative approach that brings together field, lab, modeling work on weathering of parent material, surface transport of topsoil, and associated hydrologic and biogeochemical processes that control the functioning of life from the top of tree canopies to the depths of the water table and soil-bedrock contact.

Louis Derry. The Critical Zone (CZ) is a highly dynamic region at the Earth's surface where rock, soil, water, the atmosphere and biota interact in complex ways that form the life-sustaining environment on the terrestrial surface. The CZ remains a relatively young concept in the Earth and Environmental Sciences, having only been defined in the last twenty years. However, many of the concepts it embraces have deep roots, and the CZ concept has successfully advanced the idea that the intentional integration of multiple subdisciplines is necessary to investigate and understand the Earth surface environment. Investigative concepts and tools as diverse as microbial genomics, reactive transport and seismic surveys are being brought to bear on the same system and enabling a deeper understanding of the structure and function of the CZ.

Among the recent advances in understanding is the recognition of the need to consider long temporal and broad spatial scales in studying the CZ. Few modern CZs can be considered to be at anything like steady state, given the ubiquity of climate and land use change. Important antecedent history includes the tectonic history that may set the scale and pattern of fractures that control the initial infiltration of water, or climate history that may have led to the development of a deep regolith under previous climates or determine modern sensitivity to anthropogenic acidification, or itself influenced fracture generation through freeze-thaw processes. On the spatial scale, the vertical extent of the CZ can extend tens of meters or more below the surface. Water held in deep fractures can be surprisingly important for ecosystems above, as trees can "pump" water from considerable depths when necessary. Moreover, water passing through the CZ can penetrate deeply, resulting in long transit times and potentially equilibrated chemical signatures, in contrast to water that moves through the shallow subsurface quickly and cannot reach chemical equilibrium with the overall geological matrix.

Fundamentally the CZ is a highly open system, with inputs from below provided by weathering and hydraulic lifting by plants, lateral inputs from subsurface hillslope hydrologic flow and down-slope movement, and inputs from above including net primary production and subsequent addition of organic matter to soils, and atmospheric deposition of both solutes and dust. Researchers have made significant advances in understanding and quantifying all of these processes in recent years.

An important question looking forward is how initial rock structure, including fractures and intrinsic porosity, is modified by water, weathering and in some cases microbial activity. These changes can either increase or decrease porosity and permeability, and can have profound impacts on the mechanical properties of CZ materials with consequences for soil dilation or compaction, water flow and hillslope transport. While seismic techniques are mostly sensitive to the elastic properties of materials, the controls on the evolution of CZ inelastic properties that determine irreversible deformation are not well understood.

The roles of critical textural, compositional and biological interfaces are also key targets. Reaction fronts produced by water infiltration and biogeochemical reaction can have significant impacts on regolith properties[7]. Carbon, water and nutrient cycling appear particularly intense at some interfaces and the interaction between transport and biological activity at these interfaces is a fascinating problem down to the nanometer scale. The export of nutrients or pollutants such as nitrate and arsenic from a system may be controlled by intense activity at local chemical and redox interfaces, and the position and activity of these interfaces themselves can shift in response to seasonal, climatic and anthropogenic forcing[8]. The nested spatial and time scales of such interaction need to be better understood to permit broader predictive modeling of how such systems will respond to changing climates.

Despite intense study, pathways and time scales for subsurface water movement through the CZ remain important questions. Recent modeling work has significantly advanced our understanding of the potential dynamics of water transit time distributions in the CZ[9]. Integrating models with data that contains direct temporal information such as chlorofluorocarbon ages to test such models is proceeding. The extent of chemical disequilibrium in water moving through the CZ could contain rich information about transit and reaction time scales, as in principle multiple tracers might contain a range of “clocks” each sensitive to different processes. However, learning to read and exploit such information is still at a very early stage.

Because the Critical Zone is a complex system, substantial and varied data sets are required to understand it. In addition to whole system attributes like detailed LiDAR topography and geophysical imaging of 3-D structure, time series data are essential for constraining the system response to forcing, whether it be diurnal, storm event, seasonal or longer. New observing systems can yield high frequency data on gas fluxes, water fluxes and chemistry, and soil attributes[10]. Such high frequency and ultimately voluminous data sets pose real challenges for data assimilation, storage and visualization systems. Another essential challenge will be how the scientific community and funding agencies can work together to respond to the needs for integrative, multi-disciplinary and long-term study of this vitally important and complex environment.

Vamsi Ganti: In geomorphology and sedimentology, variability is a hallmark of sediment dispersal systems from the erosional source to the depositional sink. The distance sediment travels on a hillside after a wildfire, the size of sand grains on a riverbed, the scales and rates of quasiperiodic landform evolution, and the external forces that shape rivers and floodplains are all inherently variable. Traditionally, efforts to relate process and landscape form were focused on developing deterministic, continuum-based models for sediment motion that average over the variability that typify natural systems. The natural variability in the forces that shape Earth's surface is often thought to manifest only as fluctuations around a 'mean-field' behavior. This assumption has led to major advances in the field such as the channel-threshold theory, controls on bankfull geometry of alluvial rivers, and geomorphic transport laws that describe landscape evolution on long timescales. The mean-field approach has also perpetuated into interpreting ancient strata, where it is often assumed that preserved fluvial deposits are representative of the bankfull, channel-forming floods, and that changes in the stratigraphic architecture are a result of deterministic changes in the boundary conditions of the sediment dispersal systems.

Emerging research, however, is demonstrating the central role that variability can play in shaping landscapes and their deposits. We are witnessing a rapid surge in the development of mechanistic models that explicitly couple both deterministic and stochastic components of surface processes. These models reveal that, sometimes, the effects of variability should not be interpreted as fluctuations around a mean-field behavior but instead, interpreted as the primary signal. Here, I highlight three recent advances across the source-to-sink spectrum, where acknowledging the inherent natural variability was central in gaining new insights into the mechanics of surface processes and their deposits.

First, the recognition of the stochastic nature of sediment motion has led to a shift from continuum-based to probabilistic, particle-based models that describe the trajectory of sediment motion on steep hillslopes[11]. These models, together with field observations, reveal how the surface roughness of hillslopes can rapidly reduce during wildfires with the incineration of vegetation, and result in heavy-tailed particle travel distances on burned hillslopes[11]. This phenomenon causes the loading of adjoining channels with dry ravel that triggers debris flows during subsequent storms[12].

Second, theory, experiments, and field observations indicate that natural flood discharge variability results in predictable patterns of erosion and deposition within the lowermost reaches of alluvial rivers due to the nonuniform flows caused by the effects of sea level. These flood-event-based sedimentation patterns do not average out over time but instead result in preferential sedimentation at a consistent location on lowland rivers, which coincides with the site of river avulsions—abrupt and periodic channel switching events that are a major flooding hazard. The natural flood discharge variability can also cause broad erosional surfaces in fluvio-deltaic stratigraphy[13], which are often considered diagnostic of changes in relative sea-level and sediment supply, complicating the interpretation of sedimentary signals of past tectonic and climate changes.

Finally, fluvial strata present a puzzling paradox in that the preserved time is extremely sparse; however, the preserved events are predominantly mundane—the low-to-moderate magnitude, high frequency transport conditions, not the extremes. Probabilistic modeling revealed that this paradox is a natural consequence of the tendency of rivers to self-organize into a morphodynamic hierarchy, from the scale of a ripple to the channel belt and beyond, which causes spatiotemporally variable sedimentation rates that fossilize the mundane transport conditions across scales in strata[14]. This new insight may pave the way for reconstructing ancient fluvial sediment fluxes, and suggests that major unidirectional changes in stratigraphic architecture can result from relative changes in the rates of hierarchical landform evolution[14].

For far too long, the effects of natural variability were considered as 'noise' around the primary mean-field behaviour of sediment dispersal systems. Exciting new opportunities exist to unravel the causes and consequences of natural variability in a myriad of geomorphic and sedimentologic systems. To do so, we need to merge deterministic and stochastic approaches and treat surface processes and their deposits as two sides of the same coin. Modern observations and physical experiments should be used to quantify how, and which, surface processes are preserved in strata, and detailed field observations from ancient strata should be used to quantify a baseline for how landscapes will respond to changes in climate and sediment supply. While equifinality and sparse time preservation present major stumbling blocks in stratigraphic interpretation, it is imperative that we embrace a mechanistic and quantitative approach to characterize the ancient sedimentary environments, and classify the 'plausible' dynamics of past landscapes that are supported by theory and empirical data, rather than treating them as 'unknowable'. As we realize how human activities and climate change are altering the forces that shape our planet, the payoff from solving the mysteries of modern and ancient landscape mechanics can yield valuable insight into how we sustainably manage the long-term trajectory of our planet's evolution.

Alice A Horton: Environmental pollution research is key to understanding the consequences of human activities on environmental health, especially in the context of a growing global population. We have seen enormous progress in science, technology and engineering over the past few decades. However, with rapid and often unregulated development and manufacturing come consequences. Many of these developments rely on the use of materials and chemicals that defy or alter natural processes, for example resistance to natural degradation processes, or enabling an abnormal level of productivity.

Synthetic chemicals can be extremely effective and provide a valuable function when retained within the intended item or location. However, chemicals frequently leach and disperse from their original application into the wider surrounding environment through terrestrial and aquatic systems via runoff, drainage and diffuse processes. Persistent organic pollutants (POPs) can pose a particular problem as they do not readily degrade and so persist and accumulate within the environment. Depending on the environmental conditions, half-lives of POPs can be in the order of months to decades. This persistence leads to a higher likelihood and increased duration of human and ecosystem exposure.

While many commonly used POPs have now been banned or heavily regulated, based on evidence of toxicity and environmental longevity, these regulations are often put in place only after negative consequences are observed. By then, the distribution and effects of a chemical are often widespread. A key example is polychlorinated biphenyls (PCBs). PCBs were widely used as flame retardants, coolants, plasticisers and dyes until their widespread ban in the 1970s when their risk to human and environmental health became apparent in the form of bioaccumulation, reproductive toxicity (endocrine disruption), immunotoxicity and potential carcinogenicity.

Despite restrictions, PCBs and many other restricted POPs are ubiquitous throughout the environment and within organisms. High concentrations of POPs have even been reported in the Arctic where there are no records of in-situ use, demonstrating the potential for long-range transport of these chemicals, and highlighting that the marine environment may act as a sink for POPs[15]. Where organisms come into contact with such chemicals, they can have devastating consequences. A key example is that of the killer whale (*Orcinus orca*); PCBs have been observed in killer whales at very high concentrations as a result of biomagnification through the trophic web, and it has recently been suggested that as a result, half the global orca populations are at risk of collapse[16].

Rivers have long been the receiving environments for the majority of treated and untreated liquid waste derived from homes, industry, agriculture and urban areas, and while they transport some of this waste to the oceans, much will also be retained. Despite improving regulations on chemical use and release to the environment, including Registration, Evaluation, Authorisation & restriction of CHemicals (REACH), and the Stockholm Convention on Persistent Organic Pollutants, pollutants continue to make their way into rivers from a variety of sources. For example, all UK rivers have recently been shown to fail to meet chemical quality standards according to new stringent chemical quality regulations within the EU Water Framework Directive. This is primarily due to the ubiquity of POPs, highlighting the scale of the issue. Further, there is evidence to suggest that POPs including PCBs and polybrominated diphenyl ethers (PBDEs, flame retardants) are chronically damaging freshwater invertebrate populations, resulting in reduced taxonomic diversity and altered food web structure[17].

Bans and heavy restrictions on a range of legacy compounds have inevitably led to the development of replacement substances. However, these are often chemically (and functionally) similar products with equally, or potentially even greater, harmful impacts. These are known as regrettable substitutions. For flame retardants, examples include perfluorinated compounds (PFCs) and organophosphates, which are also now starting to be found widely throughout the environment. These chemicals are often insufficiently risk assessed before their widespread application and subsequent dispersal throughout the environment, leading to further potential for unforeseen chronic environmental impacts. It is important to prospectively evaluate the range of possible environmental exposures and harms before products are commercialised. Degradation products are also important to consider as these resulting chemical compounds are not necessarily inert and may cause further damage. Further, pollutants in the environment exist as complex mixtures with behaviours which are difficult to predict.

Given the evidence shown for persistent legacy chemicals and the apparent lack of lessons learnt when introducing new products to market without sufficient risk assessments, there is cause for concern. It is clear that greater regulation is needed when introducing new, potentially persistent, bioaccumulative and toxic (PBT) substances to market, where they are likely to be used in uncontrolled (or insufficiently controlled) applications. However, it is evident that legislation alone cannot always effectively control for the potential hazard posed by POPs once released. Therefore, chemical companies must take responsibility for the products they develop and sell, to ensure that these do not cause harm for decades to come.

Min Sub Sim: Over the past 20 years, the barriers between the life and Earth sciences have been lifted at an unprecedented pace, and the field of geobiology, as a core component of this collaboration, has made substantial progress in understanding surface processes. Biology, especially microbial metabolism, dominates the cycles of energy and elements at the Earth's surface, where abiotic reactions are often too slow to reach equilibrium. In turn, geochemistry dictates what microbial processes take place. Given the billions of years of these mutual influences, our understanding of the

Earth's surface environments comes from investigations of microbial activities in the deep past as well as today. Microbial fingerprints preserved in the rock record have allowed us to explore the Earth's past, but it has been a challenging task to properly locate interpretation of these signatures within the context of microbial physiology and biochemistry, due to limited knowledge about the cellular mechanisms responsible for geobiological phenotypes. Although microorganisms are often treated as black boxes, recent advances in microanalysis, combined with modern molecular biological approaches, provide an opportunity to probe geobiologically-relevant, microbial processes at subcellular levels.

Stable isotope fractionation by microorganisms is commonly used to explore the cycles of biologically active elements, but it is also a dynamic research field that has undergone explosive development with evolving technologies in the past two decades. Sulfur, perhaps one of the most intensively studied isotope systems, is an example that illustrates recent advances well. Since the 1950s, sulfur isotope fractionation has been diagnostic of sulfate respiration, but a complete understanding of what controls the variations in fractionation has not been achieved, largely due to the cellular black box. Like many metabolic pathways, sulfate reduction involves a series of enzymatic reactions, and theoretically, the relative rate of each reaction, tied to intracellular metabolite levels, provides a mechanism that underlies the varying fractionations[18]. Sulfur isotopic studies on intracellular metabolites, however, have begun only recently since the development of multi-collector ICP-MS techniques, which have provided the ability to analyze trace amounts of sulfur. Moreover, it was also in the last decade that the kinetic isotope effects of the enzymes involved were experimentally determined *via* collaboration between geochemists and biochemists. The analysis of all three isotopic ratios of sulfur have also added a new dimension in modeling the sulfur metabolic network. Insights gained from these recent studies have changed the interpretation of the sulfur cycle; for example, we can no longer consider muted isotope fractionation to be a quantitative constraint on sulfate concentration. Of course, much remains to be done to establish a firm biochemical basis for microbial sulfur isotope fractionation. Greater opportunities may lie in combining molecular phylogeny and omics approaches with isotope geochemistry. In particular, isotope discriminations by sulfur-dissimilating enzymes have only been measured for a few model organisms[19], necessitating the extension of this approach across a wider phylogenetic range of taxa to examine whether homologous enzymes fractionate sulfur isotopes to the same extent. If not, sulfur isotope variations in the sedimentary record may hint at the evolutionary history of sulfate reducing microorganisms.

Another example of the revolution in geobiology comes from biomarkers, resilient organic compounds produced by biological sources. Biomarkers have been used to investigate changes in near-surface environments because of their potential to trace the taxonomy, metabolism or physiology of source organisms. The diagnostic value of some biomarkers was inferred by screening a large number of organisms for the presence of particular compounds rather than their biological functions or biosynthetic pathways. These empirical approaches were the necessary first steps toward understanding biomarkers, but as described above for sulfur isotope biogeochemistry, technical and conceptual advances provide additional information to bridge the gap in our knowledge. The identification of the genes needed for the synthesis of biomarker compounds, followed by genomic and biochemical analyses, helps clarify their functions and distribution across the tree of life, as exemplified by recent investigations of aromatic carotenoid biomarkers for anoxygenic phototrophic sulfur bacteria[20]. Such progress in geobiology, though calling into question some of the existing empirical correlations, will ground the interpretation of biomarker records in a solid theoretical basis, leading to a better understanding of the complex interactions between microorganisms and their surroundings. Nevertheless, only a few biomarkers have been studied in this context.

In addition to isotope effects and biomarkers, there are many other examples in which taking subcellular mechanisms into account has provided a new perspective of mutual influences between microorganisms and the Earth's surface environments. Although not detailed here, the development of Nano-SIMS technology to visualize metabolic activities at single-cell and even higher resolution also represents one of the more exciting advances in recent years. Last but not least, the emerging geobiological view of the surface processes on our planet and possibly elsewhere has benefited, and will benefit, greatly from nurturing a new generation of students who are conversant with both bio- and geochemistry.

Affiliations

[1]Institute of Geography, National Autonomous University of Mexico (UNAM), Mexico City, Mexico

[2]Life & Environmental Sciences Dept., University of California Merced, Merced, CA, USA

[3]Earth & Atmospheric Sciences, Cornell University, Ithaca, NY, USA

[4]Institute de Physique du Globe de Paris, Paris, France

[5]Dept. of Geography, University of California Santa Barbara, Santa Barbara, CA, USA

[6]Dept. of Earth Science, University of California Santa Barbara, Santa Barbara, CA, USA

[7]National Oceanography Centre, Southampton, UK

[8]School of Earth and Environmental Sciences, Seoul National University, Seoul, Korea

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Competing interests

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The contributors

Irasema Alcántara-Ayala is former Director and current Professor and Researcher at the Institute of Geography at the National Autonomous University of Mexico (UNAM). Her research seeks to understand the root causes and drivers of disaster risk through forensic investigations of disasters, and to promote integrated research on disaster risk. She is particularly interested in bridging the gap between science and policymaking and practice in the developing world. She has been the recipient of several prestigious awards, among them the 2009 TWAS Young Affiliate Fellow; 2011 TWAS Young Scientists Award; 2012 Young Scientists Research Award of the Mexican Academy of Science, and the Sergey Soloviev Medal of the European Geosciences Union in 2016.

Asmeret Asefaw Berhe is a Professor of Soil Biogeochemistry; Ted and Jan Falasco Chair in Earth Sciences and Geology at the Department of Life and Environmental Sciences; and the Interim Associate Dean for the Graduate Division at University of California, Merced. Her research interest lies at the intersection of soil science, global change science, and political ecology, and seeks to improve our understanding of how the soil system regulates the earth's climate and the dynamic two-way relationship between soil and human communities. She has published more than 100 publications and received several awards and honors and is a Fellow of the American Geophysical Union and the Geological Society of America.

Louis Derry is a Professor of Geological Sciences at Cornell University, and a Professeur Associe at the Institute de Physique du Globe de Paris. He is the former Director of the Critical Zone Observatories National Office (U.S.) and a PI in the Make Our Planet Great Again program of the Agence National de la Recherche (France). His group works on coupled geochemical and hydrological processes in the Critical Zone, modeling the global carbon cycle over multiple time scales, and the relationship between landscape evolution and hydrological and geochemical fluxes. He is a Fellow of the Geological Society of America, of the Canadian Institute for Advanced Research, and Co-Editor-in-Chief for the journal Earth & Planetary Science Letters.

Vamsi Ganti is an Assistant Professor of Geomorphology and Land Surface Processes in the Department of Geography at the University of California Santa Barbara. His group combines theory, physical experiments, and field observations to quantify the mechanics of physical processes that shape landscapes on Earth and other planets, and to decode the information about these processes stored in the ancient sedimentary record. Vamsi's work has been recognized by multiple awards, including the American Geophysical Union's Luna B. Leopold Young Scientist Award, Robert Sharp Lecture, and the Horton Research Grant.

Alice A. Horton is an Anthropogenic Contaminants Scientist at the National Oceanography Centre in Southampton, UK. Her research primarily focusses on microplastics and organic chemical contaminants in the aquatic environment: their accumulation, behaviour and ecological effects. She has a BSc in Biology, an MSc in Oceanography and a PhD in Ecotoxicology. She has previously held a NERC Knowledge Exchange Fellowship and continues to work closely with stakeholders to integrate academic research with industry, policymakers and businesses to efficiently address the many remaining questions on microplastics within the environment. She is a member of the Royal Society of Biology and is a Chartered Biologist.

Min Sub Sim is a geomicrobiologist in the School of Earth and Environmental Sciences at Seoul National University, South Korea. At the interface between microbiology and geology, his research has focused on the interpretations of geochemical and isotopic biosignatures in modern and past environments, grounded in microbial physiology and biochemistry.