Check for updates

VIEWPOINT

Reflections on solid Earth research

Shuichi Kodaira, Maria Seton, Laura J. Sonter, Christy B. Till and Helen M. Williams

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

***Q** Broadly, what are some of the key advances and exciting future prospects in your discipline within solid Earth research?*

Shuichi Kodaira. Several notable advances have been made in earthquake seismology over the last decade, expanding our understanding of earthquake mechanics, rupture processes and slip behaviour during the seismic cycle. Understanding the physical mechanisms and temporal evolution of fault slip and coupling is not only a scientific problem but also a deeply socially relevant problem that earthquake scientists must answer, as even short warning periods before earthquakes or tsunamis can save lives.

This year marks the tenth anniversary of the 2011 Tohoku-Oki earthquake, which, together with the ensuing tsunami, caused extensive damage to the Japanese islands. The Tohoku-Oki earthquake was a magnitude 9.0 earthquake caused by the ongoing subduction of the Pacific tectonic plate, and it occurred in the vicinity of the world's most densely deployed seismic, geodetic and tsunami observation networks. These networks have provided massive amounts of data on ground motion, tsunami height and crustal deformation caused by the Tohoku-Oki earthquake. This earthquake revealed much about the current state of scientific understanding of earthquake processes and our ability to foresee earthquakes, leading the research community to reconsider the future direction of earthquake science.

Offshore observations were critical in revealing the nature of the large coseismic slip to the trench. The central part of the Japan Trench has been repeatedly ruptured by magnitude 7–8 class earthquakes, and, hence, many detailed images of the bathymetry and the plate boundary fault, and seafloor geodetic data had been obtained before the Tohoku-Oki earthquake occurred. Comparison of data obtained before and after the earthquake provided conclusive evidence of more than 50 m of coseismic slip on the shallow plate boundary fault that reached the trench[1,2]. Before the Tohoku-Oki earthquake, it was widely accepted that aseismic slip dominated the shallow part of a plate boundary fault and that coseismic fault slip was unlikely to propagate up-dip during earthquakes — yet, the data from the Tohoku-Oki earthquake clearly showed that this conceptual model needed reconsideration.

Moreover, in the seafloor geodetic data obtained before the earthquake, slow-slip events were detected[3], which may have the potential to help monitor temporal variations in fault coupling. After the earthquake, viscoelastic relaxation of the mantle was observed[4], which is essential information for quantitative evaluation of slip behaviour after an earthquake. Neither of these important phenomena can be observed by on-land observation stations. Such crucial seafloor observations show that, even in regions such as Japan with well-developed observation networks, much remains to be discovered about plate boundary earthquakes.

Subduction zones, where huge earthquakes occur repeatedly in space and time, are ideal for discovering more about earthquake processes. Continuous monitoring of surface (seafloor) deformation in a region where the next major earthquakes are likely to occur in the near future will allow us to translate the observed data into fault coupling and slip behaviour models, which, in turn, will allow us to quantitatively evaluate stress accumulation, release and recovery processes throughout the earthquake cycle (before, during and after an earthquake).

One such region is the Nankai Trough, where magnitude 8 class earthquakes occurred every 100–200 years due to subduction of the Philippine Sea Plate beneath central western Japan. The dense seismic and geodetic monitoring networks that have been established on land enable us to monitor this region continuously in real time, but the seafloor infrastructure necessary for continuous real-time monitoring of plate coupling and slip has yet to be developed. Some continuous real-time geodetic observations in the Nankai Trough have detected repeated slow-slip events, but these data are available from only a few stations that do not cover the entire presumed rupture zone. However, now a seafloor cable observation network for seismic and tsunami early warning has recently been permanently deployed. By connecting geodetic sensors to this cable system, it would be possible to use this infrastructure to construct a continuous real-time seafloor geodetic network covering most of the rupture zone — which may lead to exciting advances in monitoring the temporal change of plate coupling during an earthquake cycle. Considering the approximate time interval between occurrences of large earthquakes, once such a seafloor geodetic monitoring system is developed, the Nankai Trough will be the only plate boundary fault on Earth where plate coupling and slip can be monitored continuously throughout the earthquake cycle.

Although it may be difficult to translate the data from continuous real-time seafloor geodetic monitoring directly to forecasting the next large earthquake, detection of previously unobserved slip behaviour before a large earthquake or during the earthquake cycle has the potential to enable society to prepare for the next earthquake. To apply this information to effective risk mitigation, however, requires collaboration among the Earth science, disaster science and social science communities.

Maria Seton. Geodynamics explores the forces and dynamics that operate deep within the Earth, which have a profound influence on the Earth's surface. Major disruptive planetary-scale events, such as changes in the Earth's magnetic field direction and intensity, the break-up and assembly of supercontinents, global climate crises, mass extinctions and the emplacement and concentration of mineral and energy resources, are expressions of deep Earth and surface interactions.

An inescapable issue that geodynamics faces is that the window into the deep interior is small and fragmentary in both space and time. We rely on sparse rock samples as 'messengers from the deep' to provide thermal and chemical proxies for the mantle, while geophysical data and models are used to image its heterogeneous structure. Laboratory experiments and numerical simulations mimicking deep Earth conditions are providing increasingly sophisticated conceptual breakthroughs, addressing key issues such as the influence of deep Earth structure on surface topography[5] and the reorganization of the plate-mantle system[6]. These simulations are being aided by the emergence of petascale computing infrastructure (capable of performing 10^{15} operations per second) and high-performance computing software, which are allowing increasingly complex models to be run faster and more efficiently than ever before.

Community-driven, open-source geodatabases are providing platforms for ground-breaking developments in our understanding of deep Earth processes. With such community databases, it is now straightforward to download vast catalogues of Earth monitoring and imaging data, such as gravity and magnetic anomaly maps, satellite remote sensing data and seismological images, each of which provide a present-day snapshot of the Earth's surface and internal structure. Equally important is unlocking data that represent the legacy of several decades of geoscience research, for example, databases comprising a substantial number of data points describing the geochemistry of rocks formed through Earth history, such as EarthChem, or the records of sedimentation recovered from ocean drilling since the 1960s, such as through the International Ocean Discovery Program. These digital resources are providing access to previously undiscoverable data, building a foundation for multidisciplinary research and opening the geosciences up to powerful data science and machine learning approaches.

The recent emergence of global plate kinematic models that extend as far back as 1 billion years[7] are facilitating the linking of observations, simulations and data science. They provide a means of adding a spatio-temporal component to observational data and are increasingly being used to drive sophisticated numerical simulations. Machine learning and data science techniques, when used in conjunction with these global plate models, have the potential for discovering pervasive patterns and associations between both data and models, and allows assessment of their uncertainties.

Future research in geodynamics lies in the transformation of the field from one that has focused on individual Earth domains and processes (which rely on sparse datasets and approaches) to one that unlocks the vast potential of the geological record by combining cutting-edge computational and data-science techniques with innovative open-access digital resources. It is the assimilation of geophysical, geological and geochronological observations into tectonic and geodynamic models that will allow us to understand the physical and chemical processes that drive the temporal and multiscale nature of Earth's evolution. These techniques will help us to answer some of the most pressing open questions remaining in geodynamics, such as: What combination of forces drives solid Earth structure through time? What causes major perturbations in the intricate equilibrium between tectonic plate motion and the ductile deep interior of the planet? How are surges of mineralization, surface environmental crises and bursts in biological evolution related to plate tectonic processes?

Communicating the pivotal role that geodynamics plays in addressing many of the challenges facing our planet today, such as climate change, natural hazards, biodiversity and sustainability, is becoming an increasingly important undertaking. Our need to live and prosper in a low-carbon society requires an unprecedented global investment in renewable energy. However, vast quantities of base metals and critical minerals are needed to construct the photovoltaics systems, powerful magnets

The contributors

Shuichi Kodaira is the Director and Principal Scientist at the Institute for Marine Geodynamics, Japan Agency for Marine-Earth Science and Technology (JAMSTEC). His research career has centred on the structure and dynamics of oceanic plates in various tectonic settings using marine geophysical and seismological approaches. Recently, he and his team have concentrated on imaging, monitoring and modelling seismogenic subduction zones, which demonstrate how marine geoscience contributes to understanding subduction zone processes and mitigation of their associated geohazards. He has been an elected Fellow of the American Geophysical Union since 2014 and was elected Beno Gutenberg Lecturer of the American Geophysical Union in 2017.

Maria Seton is a Senior Lecturer at the School of Geosciences at the University of Sydney. She is a marine geoscientist with expertise in plate tectonics and explores the role of the plate-mantle system in explaining major perturbations in Earth's evolution. While much of her research is global in scale and scope, she has a particular interest in the geodynamic evolution of the South West Pacific and Zealandia. Maria has been the recipient of two research fellowships from the Australian Research Council and the Dorothy Hill Award from the Australian Academy of Sciences.

Laura J. Sonter is a Senior Lecturer in Environmental Management and ARC DECRA Fellow at the School of Earth and Environmental Sciences and Centre for Biodiversity and Conservation Science at The University of Queensland, Australia. She also holds an affiliate position at the Gund Institute for Environment at the University of Vermont, USA. Her research seeks to understand the spatial distribution of mining activities and develop methods to mitigate negative impacts on species and ecosystems. Dr Sonter teaches undergraduate-level and postgraduate-level courses on environmental management in mining and supervises a team of doctoral students working on these issues.

Christy B. Till is an Associate Professor and the Associate Director for an Inclusive Community at the School of Earth and Space Exploration at Arizona State University. Her research focuses on the role of magma in planetary processes, including those leading to volcanic eruptions and mantle magma genesis on Earth and exoplanets. Her work has been recognized in a variety of ways, including an NSF CAREER grant, an Early Career Award from the Geological Society of America, features in National Geographic and the New York Times, and election to a variety of scientific leadership positions.

Helen M. Williams is a Reader in Geochemistry at the University of Cambridge. Her research centres on the application of non-traditional (high-atomic-mass) stable isotope systems to the evolution of planetary interiors. She is particularly interested in understanding the chemical evolution of the Earth's interior and its surface over the entire history of the planet and its relationship to planetary habitability.

and batteries needed for solar panels, wind turbines and electric vehicles. Research in geodynamics will be a key driver for understanding the broad-scale formation and location of key base metals and critical minerals in the Earth's crust. For example, the key control of inherited lithospheric structure on the global distribution of sediment-hosted metals was recently demonstrated by geodynamics-led research[8].

Finally, one of the great challenges in the future will be how to train the next generation of geoscientists in a rapidly changing world. Data science and machine learning techniques that allow us to see complex patterns and associations in our data, were unattainable just a few years ago. An emerging challenge will be to ensure that future geoscience research continually adapts to find the right balance between advances in data analysis methods and in preserving the depth of knowledge from individual domains, by both fostering the creation of multidisciplinary teams and promoting the value of scientists with a range of skills spanning geology, geophysics and computational methods.

Laura J. Sonter. The mining sector can benefit from and contribute towards progress on sustainable development. One central challenge relates to how the industry addresses climate change and efforts to limit global warming to well below the 1.5 °C considered safe for humanity. More frequent fires, droughts and floods will create a range of potentially expensive technical challenges for mine sites to overcome. As a major contributor to global carbon emissions, the industry also has a role in mitigating climate change throughout the entire mining life cycle, for example, through corporate commitments to climate action and by improving energy efficiencies at the site level. Potentially more pervasive, yet less certain, will be the effects of a green energy transition on the sector, which will create enormous shifts in commodity demands and redistribute mining economies globally. These changes, among others, pose a rare opportunity for sector-wide transition towards sustainable mining. The academic community must be ready with evidence and tools to guide it.

Using the terms 'mining' and 'sustainability' in the same sentence often evokes an eye-roll. Some critics consider these terms oxymoronic, since mineral resources are non-renewable (at least, not in time frames meaningful to society) and, thus, mining activities cannot be sustained in perpetuity. Others see the use of 'sustainability' by mining companies as a red flag for corporate greenwash. This is understandable, given that many mining projects claim to successfully balance private economic interests with broader social and environmental risks (the so-called triple bottom line approach), while also causing widespread damage to people and nature. However, conceptual thinking on sustainable mining has evolved considerably since the inception of the triple bottom line concept over 30 years ago. Much research now aims to improve mining sector performance by understanding the suite of environmental, social and governance risks to and from mining and developing tools that incorporate these risks into corporate policies and decisions.

Yet, despite this effort, mining remains a leading cause of social and environmental degradation in many parts of the world, and climate change is set to escalate risks to mining for some commodities in future[9]. Clearly, a much more radical shift in practice is needed to truly embed sustainable development into mining sector policies and decision-making. To this end, some have argued that a 'sustainable mine' should be defined as one that makes a substantial positive contribution towards achieving Sustainable Development Goals. For example, rather than avoiding mining impacts on protected areas, land use and rehabilitation plans would be aligned with biodiversity conservation goals. Rather than committing to minimize impacts to people, companies would seek to build long-term and mutually beneficial relationships with local communities. Indeed, the International Council on Mining and Metals — the leading industry body — supports this idea, encouraging its members to align their operations with the United Nation's 17 Sustainable Development Goals to end poverty, protect the planet and ensure prosperity for all.

Alongside major conceptual advances, technical capability and a corresponding body of evidence have grown enormously, revealing the social and environmental consequences of mining. As a biodiversity conservation scientist, I am most excited by the research advancing our understanding of where mining will occur in future and the development of approaches best suited to predict and mitigate negative impacts on species and ecosystems. Particularly rapid improvements have been made in the data and methods used to assess impacts of mining at the global scale. These studies combine remote sensing and image classification tools to map mining activities and their expansion over time[10], revealing factors that explain the extent and distribution of mining operations[11] and illustrating the direct and indirect impacts of mineral extraction on ecosystems across a diversity of mining regions[12]. This knowledge is needed to develop tools that factor biodiversity risks into mining decisions by governments and industry alike.

While the science is advancing, much work remains to be done to support a sustainable mining transition. In my opinion, two topics are worth noting. First, given the growing number of government and corporate commitments to achieving a net gain in environmental and social outcomes from mining, there needs to be better data, knowledge and guidance from the research community. At present, corporate commitments are unsubstantiated and outcomes highly uncertain. Second, we need to better integrate ecological and socio-economic impact assessments in mining to identify opportunities to link mine site rehabilitation and closure plans with the needs and goals of a diverse range of local stakeholders. If successful, co-designed post-mining landscapes could create a landscape that is truly valued by local communities and constitutes a long-lasting legacy of the mined resource.

Christy B. Till. The study of magmatic processes in subduction zones, and magmatism overall, is poised for a breakthrough. It is possible to envision a not too distant future where we can forecast magmatic activity and eruptions in much the way we forecast the weather, and view magmatic processes from mantle genesis to emplacement as a phylogenetic tree, with key parameters controlling the evolutionary path a specific magma follows.

This propitious forecast has been made possible by new research methodologies and insights arising in the last decade. Advances include the expansion of the field of diffusion chronometry, which has unlocked a rich view of the magmatic processes occurring over the human timescales of minutes to centuries. Likewise, innovation in the study of volcanic gas emissions has led to the recognition of changes in gas chemistry immediately prior to eruption and their promise for eruption forecasting. By linking shorter-term magmatic processes with the longer-term processes captured by radiometric geochronology, and measurements at the surface to magmatic processes at depth, a unified and real-time model of magmatic processes is becoming tangible.

What is needed to unlock this envisioned future? First, we need to focus our attention on sufficiently large scale and mechanistic questions. Questions like: What is the flux of mantle-derived magma and how does it vary along-strike within a tectonic setting, in time and in volatile content? How does mantle magma flux correlate with how much is erupted (and what is left behind as crustal intrusions)? And what are the primary controls (for example, magma buoyancy, crystallinity, crustal stress fields) on how this flux is discretized into individual magma bodies and eruptions? Simple time-integrated conservation of mass dictates that there must be a relationship between the magmatic flux into the base of the crust and what exits the top. About a year ago, I made a plot that hints at such a relationship[13], comparing the average Holocene volcanic repose time to the volume of mantle-derived magma required for the Cascade Arc volcanoes. The results showed a clear curvilinear relationship where higher mantle magmatic fluxes yielded shorter repose times[13].

Second, in order to document a causal relationship between mantle magma flux and eruption frequency at arc volcanoes, and address similar mechanistic questions, we need to produce more representative, averaged and time-sequenced magmatic datasets. For example, despite extensive geochronology of eruptions at individual volcanoes, our current understanding of the distribution of eruptions over time at any given volcano is biased towards larger and younger eruptions. Simple statistical tests reveal that undersampling a non-linear (or non-stationary) distribution of eruptions through time at a given volcano by 30–50% can cause the eruption distribution to appear linear (or stationary)[14] — producing a completely different picture of the eruption history solely as an artefact of sampling. Not only is eruption distribution an important variable in our mechanistic understanding of volcanism but it is often used in assessments of volcanic hazard and eruption forecasting. Similarly, despite the importance of volumetric estimates of volcanic products erupted over time in addressing these questions, there is a paucity of such volumetric estimates in the literature. Volcanic compositional data in databases and publications also tend to be biased to well-known locations and events, rather than being representative of a system as a whole, a challenge that must be addressed to gain process-based understanding. It also goes without saying that science funding must support these advances and changes in approach. Ongoing efforts to study subduction science in new ways, such as the proposed SZ4D (Subduction Zones in 4D) programme in the USA, offers that hope.

Third and finally, the most critical step in attaining this promising future is creating a more equitable and inclusive scientific community. Recent articles highlight geosciences' glaring records in these areas[15], which are demonstrated as barriers to innovation[16]. True progress requires individual action, systemic change and commitment from each of us, starting today.

Every day, each of us makes hundreds of decisions that affect inclusion, deciding who we hire and fire, deciding how much to pay them, deciding how to allocate resources, deciding whose voices we listen to, deciding who we give the benefit of the doubt, deciding what success looks like, deciding who is doing well and who is not, deciding who wins awards and deciding how we spend our time.

As a result, each of us decides who is excluded every day. And so, it is up to each of us to create change.

Helen M. Williams. The field of isotope geochemistry has rapidly expanded over the last couple of decades with the use of heavy metal stable isotope systems as tracers of planetary-scale processes and solid Earth evolution. Just under 20 years ago, as a new postdoc, I carried out some of the first iron stable isotope measurements on a range of mantle rocks from different tectonic settings. The results[17], which revealed the presence of substantial and systematic stable iron isotope variations apparently generated by magmatic processes, stunned me, even though they were exactly what I had hoped to find.

Discoveries like these, which showed that the stable isotopes of elements as heavy as iron could be modified by high-temperature processes such as mantle melting, paved the way for a new field of research. This field has exploded over the last decade, thanks to both developments in mass spectrometer instrumentation and improved chemical purification and analytical protocols. These advances have yielded improvements in both analytical precision as well as the sheer number of measurements that it is possible to make. Consequently, it is now possible to carry out such extensive isotope studies on large and diverse sample sets in a relatively straightforward manner. These advances have resulted in the widespread adoption of iron stable isotopes and other novel heavy stable isotope systems, including the transition metals, as well as more unusual elements like tin, thallium, selenium, uranium and tellurium, as tracers of solid Earth and planetary interior processes.

The utility of these nascent isotope systems stems from how the different stable isotopes of a given element become distributed, or partitioned, between different phases that are in chemical equilibrium with each other. This equilibrium-partitioning behaviour of stable isotopes can be loosely regarded as a function of bond strength. Contrasts in bonding environment and oxidation state, and, hence, bond strength, can therefore be expected to yield substantial stable isotope effects, even at high temperatures. Iron isotopes are an excellent case in point, as iron is a ubiquitous element in planetary objects that can exist in three different oxidation states. Processes such as core formation, which involves equilibrium between iron metal and iron-bearing silicate and sulfide phases, should, thus, in principle, generate stable isotope effects. The impact of core formation on the iron isotope composition of the Earth's mantle, as well as those of the other terrestrial planets, has proved a fruitful area of research over the last decade. Other applications of iron isotopes that have also leveraged substantial contrasts in iron bonding environment and oxidation state include subduction zone processes, where the devolatilization of slab serpentinites in subduction zones results in the release of Fe-bearing oxidizing fluids, and mantle partial melting, involving partitioning between silicate melt and ubiquitous mantle silicate, oxide and sulfide phases.

However, understanding the processes that drive iron stable isotope fractionation in nature is fundamentally dependent on being able to predict and quantify stable isotope fractionation in the system of interest under the relevant conditions. The partitioning behaviour of stable isotope systems between species is a function of bond strength, or more formally, differences in the vibrational energies of the iron-ligand bonds between different species. Over the years, I have been particularly struck by the concerted effort to quantify iron isotope partitioning in systems associated with processes relevant to the solid Earth and planetary sciences[18,19]. The extent of iron isotope partitioning between different phases can be calculated using ab initio models and from spectroscopic techniques, in which element bonding in a single phase is characterized. However, exciting as these techniques are, it is worth noting that spectroscopic methods are only applicable to phases that are in solid state and, while silicate melts can be quenched as glasses, this is a rapid structural change that may be associated with shifts in element coordination and oxidation state. This is a major limitation in trying to use these results to understand Earth and planetary processes, as they often involve reactions between molten phases. An obvious alternative approach is to carry out experimental studies of isotope partitioning between phases equilibrated under controlled conditions. However, such experiments are often difficult and challenging to carry out, due to the need to create samples of sufficient size to analyse and to demonstrate equilibrium.

Nonetheless, this quantification of stable isotope partitioning under relevant conditions has provided a powerful conceptual framework that has allowed stable isotope systems like iron to be used across a wide range of fields. For example, recent research[20] has incorporated iron stable isotope fractionation factors into thermodynamic phase equilibria models of mantle partial melting to investigate the extent of heterogeneity in the source regions supplying mantle plumes. In the future, it should be possible to extend this approach to other stable isotope systems (for example, magnesium, calcium, chromium, titanium), enabling us to predict how they may behave with respect to each other during planetary mantle and crustal melting and differentiation processes, with applications ranging from the internal structure of planetary mantles to the formation of the Earth's early crust.

However, it is worth remembering that, as promising as these new stable isotope systems are, our current framework for interpreting their behaviour during high-temperature processes like mantle melting and core–mantle equilibrium is strongly biased towards equilibrium partitioning. One of the most exciting future challenges, in my opinion, will be the identification and quantification of kinetic isotope effects induced by disequilibrium processes operating within planetary interiors.

Shuichi Kodaira[1]✉, Maria Seton[2]✉, Laura J. Sonter[3,4]✉, Christy B. Till[5]✉ and Helen M. Williams[6]✉

[1]Research Institute for Marine Geodynamics, Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokohama, Japan.

[2]EarthByte Group, School of Geosciences, The University of Sydney, Sydney, New South Wales, Australia.

[3]School of Earth and Environmental Sciences, The University of Queensland, St Lucia, Queensland, Australia.

[4]Centre for Biodiversity and Conservation Science, The University of Queensland, St Lucia, Queensland, Australia.

[5]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA.

[6]Department of Earth Sciences, University of Cambridge, Cambridge, UK.

✉*e-mail: kodaira@jamstec.go.jp; maria.seton@sydney.edu.au; l.sonter@uq.edu.au; Christy.Till@asu.edu; hmw20@cam.ac.uk*

https://doi.org/10.1038/s43017-020-00127-7

Published online 13 January 2021

1. Fujiwara, T. et al. The 2011 Tohoku-Oki earthquake: Displacement reaching the trench axis. *Science* **334**, 1240–1240 (2011).
2. Sato, M. et al. Displacement above the hypocenter of the 2011 Tohoku-Oki earthquake. *Science* **332**, 1395–1395 (2011).
3. Ito, Y. et al. Episodic slow slip events in the Japan subduction zone before the 2011 Tohoku-Oki earthquake. *Tectonophysics* **600**, 14–26 (2013).
4. Sun, T. et al. Prevalence of viscoelastic relaxation after the 2011 Tohoku-oki earthquake. *Nature* **514**, 84–87 (2014).
5. Davies, D. R. et al. Earth's multi-scale topographic response to global mantle flow. *Nat. Geosci.* **12**, 845–850 (2019).
6. Coltice, N., Husson, L., Faccenna, C. & Arnould, M. What drives tectonic plates? *Sci. Adv.* **5**, eaax4295 (2019).
7. Merdith, A. S., Williams, S. E., Brune, S., Collins, A. S. & Müller, R. D. Rift and plate boundary evolution across two supercontinent cycles. *Glob. Planet. Change* **173**, 1–14 (2019).
8. Hoggard, M. J. et al. Global distribution of sediment-hosted metals controlled by craton edge stability. *Nat. Geosci.* **13**, 504–510 (2020).
9. Northey, S. A. et al. The exposure of global base metal resources to water criticality, scarcity and climate change. *Glob. Environ. Change* **44**, 109–124 (2017).
10. Maus, V. et al. A global-scale data set of mining areas. *Sci. Data* **7**, 289 (2020).
11. Werner, T. T. et al. Global-scale remote sensing of mine areas and analysis of factors explaining their extent. *Glob. Environ. Change* **60**, 102007 (2020).
12. Bebbington, A. J. et al. Resource extraction and infrastructure threaten forest cover and community rights. *Proc. Natl Acad. Sci. USA* **115**, 13164–13173 (2018).
13. Till, C. B. et al. The causes of spatiotemporal variations in erupted fluxes and compositions along a volcanic arc. *Nat. Commun.* **10**, 1350 (2019).
14. Shamloo, H. I., Till, C. B., Kent, A. J. R. & Cooper, K. M. Constraining first-order controls on volcanic repose time by examining cumulative distribution functions. *AGU Fall Meeting Abstracts* https://ui.adsabs.harvard.edu/abs/2019AGUFM.V23G0279S/abstract (2019).
15. Dutt, K. Race and racism in the geosciences. *Nat. Geosci.* **13**, 2–3 (2020).
16. Hofstra, B. et al. The diversity–innovation paradox in science. *Proc. Natl. Acad. Sci. USA* **117**, 9284–9291 (2020).
17. Williams, H. M. et al. Iron isotope fractionation and the oxygen fugacity of the mantle. *Science* **304**, 1656–1659 (2004).
18. Shahar, A. & Young, E. D. An assessment of iron isotope fractionation during core formation. *Chem. Geol.* **554**, 119800 (2020).
19. Sossi, P. A. & St. O'Neill, H. C. The effect of bonding environment on iron isotope fractionation between minerals at high temperature. *Geochim. Cosmochim. Acta* **196**, 121–143 (2017).
20. Soderman, C. R. et al. Heavy δ57Fe in ocean island basalts: A non-unique signature of processes and source lithologies in the mantle. *Geochim. Cosmochim. Acta* **292**, 309–332 (2021).

Acknowledgements
M.S. would like to acknowledge funding from the Australian Research Council (DP200100966). L.J.S. receives support from the Australian Research Council (DE170100684). H.M.W. acknowledges funding from an ERC Consolidator Grant (306655, 'HabitablePlanet') and a NERC Consortia Grant ('Mantle Reservoirs, volumes and fluxes' NE/M000303/1).

Competing interests
The authors declare no competing interests

Publisher's note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.