# Big questions in geoscience and challenges for the geoscience community

*Rasoul Sorkhabi*

*Geoscience is relatively underrated in our public education. Public perception of big questions in science is often related to cosmology and physics. However, geoscience deals with its own big questions and offers a body of knowledge that directly benefits society. Twenty areas of significant questions, challenges and opportunities in geoscience articulated in a survey of 136 geoscientists are reported here. Global warming and the petroleum industry top the list. Prediction and mitigation of natural hazards, especially big earthquakes and explosive volcanoes, tackling environmental degradation and pollution of various types, as well as exploration of rare earth metals and energy minerals essential to everyday life are among the practical topics of study. Some of the big questions pertain to the most distant geologic past – Hadean and Eo-Archean times (4.5–3.5 Ga) – during which the primitive Earth's internal structure, crust, atmosphere, oceans and biosphere were formed. Other questions concern those physical parts of the Earth – the mantle and the core – that are not directly accessible to us. Geoscience is far from integrating crustal phenomena and plate tectonics with the dynamics, heterogeneities and evolution of the mantle. Causes of palaeoclimate changes and mass extinctions, and the relationships between these two remain fertile fields of research. Extraterrestrial influences such as lunar gravitational stresses and meteorite impacts should be better integrated into Earth system science. Many of the big questions in geoscience are multidisciplinary and require various methods and big data analytics.*

**Keywords:** Big questions, geoscience education, geoscience workforce, research and development, survey.

In 1998, John Maddox[1] (the former editor of *Nature*) authored a book in which he discussed the big questions in cosmology, physics, chemistry, biology, artificial intelligence and mathematics. Maddox, however, ignored geoscience arguing that major questions in geology and planetary science 'are all absorbing questions but no new principles are involved'[1]. When I first read Maddox's book, as a geoscientist, I was annoyed and felt that the ignorance of geoscience by a prominent science journalist was unfair and unjustified. After all, geoscience has made huge contributions to the modern knowledge and culture, including the discovery of deep time[2]. Nonetheless, as Valdiya[3] mentioned in the pages of this journal, it is necessary for geoscientists to convey the importance and relevance of geoscience to society. With this background, in 2019–2020 I conducted a survey of the most important questions in geoscience and crucial challenges facing the geoscience community. The survey was conducted through e-mails sent out to hundreds of geoscientists and also posted through community websites of the Geological Society of America (GSA), American Geophysical Union (AGU), and American Institute of Professional Geologists (AIPG). The scientists were asked to suggest (in their opinion) up to five of the most important questions in geoscience (including geology, geochemistry, geophysics and applied geology, but not regional geology), or issues faced in the geoscience profession. A total of 136 scientists (104 from USA, 14 from Europe, 13 from Asia, 4 from Canada and 1 from Australia) responded, and together they suggested 370 questions, many of which overlapped. I tallied and categorized these responses into 20 broad scientific topics and community issues, each suggested by four or more scientists. These are reported and briefly described and contextualized in this article (numbered according to the most suggested themes). Of the 136 respondents, 102 were from academia and 34 from industry (mining and petroleum), consulting firms or geological surveys. Therefore, the survey results are based heavily on the US academia. Nevertheless, given the global nature of science, these questions and issues are probably shared by a large section of the geoscience community. All surveys have epistemological limitations. The 'big questions' in geoscience are not

Rasoul Sorkhabi is in the University of Utah, Energy and Geoscience Institute and Department of Geology and Geophysics, Salt Lake City, UT 84108, USA.
e-mail: rsorkhabi@egi.utah.edu

limited to those mentioned in this article; nevertheless, the following articulate some valid points and issues for further considerations.

## Global warming (40)

A large number of respondents suggested global warming as a most critical issue of our time[4]. The carbon dioxide ($CO_2$) concentration in the atmosphere has increased from 280 ppm in the pre-industrial times to 410 ppm in 2019 (ref. 5). According to the Global Carbon Project, in 2019 the total $CO_2$ emission from all human activities was 43 billion tonnes, of which 36.4 billion tonnes came from the burning of fossil fuels[6]. The complex issue of global warming involves many areas of research, including: in-depth understanding of climate change, and carbon budget and cycle (sources and drivers as well as sinks and feedbacks), better forecasts and modelling its impact on the environment and societies, and more importantly, working out technological and policy procedures to reduce the atmospheric greenhouse gases, especially $CO_2$ emission from fossil fuels.

## Petroleum industry and geoscience (39)

Closely related with global warming is the status of the petroleum industry. For nearly a century, the petroleum industry has been associated with geoscience research and universities. It has traditionally hired a large number of geology, geophysics and engineering graduates, and has funded numerous research consortia and graduate theses, aside from research laboratories that major oil companies operated themselves. Indeed, certain fields in geoscience such as basin analysis, micropalaeontology, sequence stratigraphy, organic geochemistry, subsurface imaging, petrophysics, well logging, and seismic and other geophysical surveys were developed and financed by the petroleum industry. Therefore, oil market crashes and oil price volatility as we witnessed during the COVID-19 pandemic[7] have adversely affected geoscience programmes in many universities. Given worldwide movements to combat global warming, the future growth of the petroleum industry is not clear: Will the industry evolve and reinvent itself, or will it give way to other energy, mineral and environmental industries; and if the latter, will these industries be geoscience-intensive and highly supportive of research and education? These questions currently facing the geoscience community are at the heart of discussions on how to reform and develop geoscience education and research[8].

In order for the petroleum industry to reform or reinvent itself, it has to address environmental sustainability and financial challenges. To be environment-friendly and reduce its carbon footprint, the industry has to invest in the science and technology of carbon capture, reuse or storage, avoid gas flaring and control methane emissions from shale oil and gas fields.

To reduce its costs per barrel of oil production and be profitable, the petroleum industry must utilize smart data science and more efficient technologies for better subsurface imaging and improved recovery factors of oil and gas from reservoirs.

## Earthquake prediction (26)

Seismology and plate tectonics have made great strides in our knowledge of earthquakes – how and where they occur. Today, a global network of seismic stations monitors and reports on earthquakes. Catalogues of earthquake records, mapping of seismic gaps and probabilistic assessment of big earthquakes are all important tasks for seismologists. Nevertheless, predicting the timing of earthquakes remains a most serious problem, despite the recognition that certain physical precursors provide helpful clues. Given that a large number of megacities are situated along the tectonically active circum-Pacific and Alpine-Himalayan belts, big earthquakes are indeed silent ‘time bombs’ and require intense studies[9]. Earthquake prediction is also closely associated with studies of mechanisms and patterns of crustal seismicity, not only along the active plate boundaries but also in intraplate settings. In this sense, no major earthquake should be ignored. Therefore, earthquake-prone low-income countries are in dire need of scientific contributions from the developed nations.

## Birth of plate tectonics (17)

Plate tectonics was a revolutionary discovery in the 20th century science. It has provided a unified theory for various, seemingly unrelated, geologic phenomena from the rock cycle and mountain uplifts to mineral deposits and earthquakes. However, we still do not know when, why, and how plate tectonics began in the Precambrian Earth; how our planet functioned before plate tectonics, what critical mass of conditions triggered plate tectonics and how best we can quantify indicators to answer these questions[10,11]. The significance of these questions becomes amplified when we consider that Earth is the only planet in the Solar System that enjoys active plate tectonics and that plate tectonics has influenced every part of the planet, including the biosphere[12]. Studying the onset and chronology of plate tectonics also involves understanding the development of the continental crust through geologic time: was it a slow, progressive growth or an early massive development?[13]

## Plate tectonics questions (17)

Plate tectonics currently constitutes the fundamental paradigm of Earth science education. Nevertheless, many aspects of plate tectonics still remain enigmatic. Some of the questions included in the survey were: How has plate tectonics influenced the evolution of life forms (a subject recently phrased as biogeodynamics[14])? How and when do ophiolites obduct in a convergent oceanic plate setting? What controls symmetric versus asymmetric rifting processes and how best can we image these two? What is the mechanism of low-angle normal faulting? How does a passive margin transform to an active margin, and what triggers and directs the incipient subduction? How can vertical uplifts be reconciled with horizontal plate tectonics? How do some passive continental margins, intraplate basins or aulacogens (failed rift basins) rejuvenate with renewed phases of massive sedimentation? How can we clearly distinguish igneous rocks based on their geochemical signatures from various tectonic settings?

## Mantle dynamics: plumes versus plates (16)

Our geologic knowledge largely pertains to the crust accessible to us; but the crust is merely a thin skin of the global volume. Lithospheric plates are controlled by dynamic forces in the mantle, from the asthenosphere immediately below the lithosphere all the way down to the low shear velocity provinces surrounding the outer core[15,16]. Seismic tomography and high pressure–temperature experimental mineralogy and petrology provide insights into the internal structure and composition of Earth. Isotope geochemistry and geochronology of kimberlites and ultra-deep (400–700 km) earthquakes on subducting slabs (‘cold plumes’) also provide valuable clues regarding the upper mantle. Nevertheless, the mantle remains terra incognita and thus a new frontier. Our physical access to mantle plumes is restricted to hot-spot magmatism on the Earth’s surface. Where do plumes rise from? How can we classify plumes, physically and compositionally, to understand the processes of their formation? How can we explain triple junctions and large igneous provinces (LIPs) in terms of deep plumes versus shallow plate tectonics? How can we study the evolution of the mantle over geologic time as we do for crustal rocks?

## Mineral resources (16)

Everyday life and modern industries all depend on a vast number of minerals and elements extracted from Earth. Mineral exploration has always been at the heart of geoscience, and the field is expected to grow as global demand for minerals will increase and strategic minerals will dominate national security and geopolitics. Rare-earth metals and critical (strategic) minerals as identified by the US Geological Survey will attract particular attention and intense exploration[17]. Improved knowledge of reserve estimates, geographic distributions, geological concentrations, and industrial recovery of critical minerals and elements will be important tasks for economic geologists.

## Public education and policy (15)

Most people, including young children, are interested to learn about minerals, fossils, dinosaurs, how mountains uplift, and other geological lore[18]. Ironically, however, Earth science is relatively underrated in our high school education. A 2015 US survey found that only 22 states in that country accepted an Earth and space science course for graduation, and only two states required a year-long Earth/environmental science course, whereas the number of states which required life science and physical science courses for graduation was 50 and 30 respectively[19].

How can we communicate the value of geoscience to the public, school boards and policy makers? This is a crucial challenge for the geoscience community; it is also a task that only geoscientists should perform. In introducing geoscience to the public and students, it is important to present it not as an isolated dry science, but a broad field that uses and integrates all sciences to study the Earth[20]. We should also present a new public image of the geologist beyond one who mainly digs for fossil fuels and loves earthquake incidents.

## Palaeoclimate (13)

Studies of the Earth’s palaeoclimate history involve a wide range of questions such as: What were the causes and effects of drastic variations in the atmospheric composition (especially $O_2$ and $CO_2$) over the geological time? What factors determined the onset and termination of greenhouse periods and glacial periods? How did the biota respond to such drastic climate changes? Some of these geologic periods are particularly attractive for geoscientists, such as Snowball Earth of the Cryogenic period, mid-Cretaceous hothouse, Palaeocene–Eocene thermal maximum and Quaternary ice ages.

How can we resolve the chicken-and-egg relationship between climate change and variations in the atmospheric $CO_2$? This question is particularly important for the Quaternary glacial–interglacial ages, ascribed to Milankovitch cycles, but is also displayed in the see-saw pattern in atmospheric $pCO_2$. Another question regarding the Quaternary glacial–interglacial ages revolves around the two end-member values of $pCO_2$, roughly 180 and 280 ppm: What regulated these limits? The current global warming should motivate a fuller understanding of the Holocene climate changes in various parts of the world, such as the Little Ice Age of Europe.

A significant improvement in palaeoclimate science is to better quantify the rates of drastic palaeoclimate changes by high-resolution dating of proxy records, including plankton fossils, sediment cores and ice cores.

## Natural hazards (12)

Natural hazards are routine geologic processes. However, their tragic impacts on human life, structures and properties have increased due to population growth and concentration in megacities prone to natural hazards as well as unpreparedness, especially in developing countries. Natural hazards include a diverse set of events resulting from tectonic, hydrological, meteorological and climatic processes, and many of them are inter-related, such as offshore earthquake–tsunami coupling. During 2000–2019, more than 7000 geophysical disasters killed approximately 1.23 million people worldwide[21]. Geoscientists and engineers can greatly contribute to studies of precise mechanisms of natural hazards, risk assessments and mapping, warning systems, mitigation and construction of hazard-resistant structures.

## Water resources (11)

Underground and surface freshwater resources used for drinking, irrigation and other residential or industrial needs constitute only 1% of the global water budget[22]. Although water is a renewable resource, freshwater resources are unevenly distributed both seasonally and spatially, depending on terrain and climate. Geoscientists and engineers will play an important role in detailed studies of the hydrological cycle and water budget, reservoir mapping and extraction of groundwater, water resource management especially in arid environments, optimal practices of watershed modification, desalination projects and so forth.

## Mass extinctions (10)

Extinction is a rule rather than an exception: at the species level, over 99% of life forms have become extinct over geologic time. In a mass extinction, a large percentage of higher taxa in several biological groups vanish within a brief interval of geologic time due to either 'bad genes' (natural selection) or 'bad luck' (catastrophic events)[23]. 'Five big' mass extinctions in the Late Ordovician (Ashgillian), Late Devonian (Fransnian), Late Permian (Changhsingian), Late Triassic (Rhaetian) and Late Cretaceous (Maastrichtian) have each wiped out more than two-thirds of species, although almost every stratigraphic period during the Phanerozoic is marked by at least one considerable mass extinction event[24]. Obviously, understanding the causes and consequences of these mass extinctions is not only a matter of curiosity, but also required for our own survival. Sadly, humankind in recent decades has also been responsible for the 'sixth' big mass extinction through habitat destruction, which is alarming because it harms the planet's genetic pool (aside from ethical and scientific grounds)[25].

## Energy resources (10)

The world (as well as the geoscience community) is facing a big dilemma. On the one hand, the catastrophic threat of global warming (mainly from the burning of fossil fuels) is the real reason to move towards energy sources with least carbon footprint. On the other hand, energy-dense fossil fuels currently account for 85% of the world's energy supply, and a rapid transition to replace fossil fuels will have its own political, economic and technological challenges. Added to this dilemma is the fact that global energy demand will grow (not decline) in the coming decades, as the flow of affordable and abundant energy is critical to life standards of the developed world and development of low-income nations. These trends provide geoscientists with both challenges and opportunities in exploring and developing energy resources. For developing renewable energy sources and massive electrification of transportation to replace oil, exploration and production of energy minerals such as rare-earth magnetic metals for wind turbines and lithium for batteries will be crucial.

## Precambrian–Cambrian transition and the Cambrian explosion (9)

The Precambrian–Cambrian boundary has long been a major stratigraphic debate both in terms of a numerical date (from 600 ± 20 Ma, first reported by Arthur Holmes in 1960, to the present date of 541 ± 1 Ma), and the criteria for defining and locating this stratigraphic boundary in various parts of the world. The problem is not simply semantic. The transition from the Ediacaran to the Cambrian was indeed a time of drastic changes in the atmosphere (oxygenation), tectonics (assembly of Gondwana), and evolution (proliferation of multicellular organisms or what has been dubbed as the Cambrian explosion)[26,27]. Therefore, understanding the nature of this time interval and the inter-connected phenomena leading to the Cambrian explosion of life is important in the history of our planet.

## Environmental geology (7)

Despite the obvious relationships between environmental quality and human health, rapid industrialization of the world has caused various types of environmental pollution. Humans are now a geological force and the recent declaration of the Anthropocene (beginning at around the 1950s) is a testimony to our (often adverse) impacts on almost every part of the planet, from the atmosphere and the oceans to landscape and forests[28]. Global warming is a type of effect on the environment due to pollution. Loss of biodiversity due to destruction of forests (with species that will never come back), desertification, the silent erosion of topsoil (that will take centuries to recover) and plastic pollution of the oceans are some of the tragic records of the Anthropocene. Our failure to maintain the Biosphere 2 in Arizona experiment demonstrates how precious and irreplaceable the Earth's biosphere is, and one which we cannot afford to fail[29]. Environmental geology is thus a great contribution of geoscientists to society, and the significance of this field and the workforce needed for its multitude tasks are expected to rise in the coming decades as human–Earth interactions will intensify further.

## Origin of life (6)

The formation of life on Earth, like other phenomena, has a naturalistic explanation. Nevertheless, how, when and where life first emerged remains a scientific mystery. Did life originate independently on Earth some four billion years ago from a 'primordial organic soup' in the Earth's early oceans (as Charles Darwin, A. Oparin, J. B. Haldane and the famous Miller–Urey experiment have suggested), or were biological molecules brought to Earth from the outer space by asteroids and meteorites (as envisioned by Kelvin, Svante Arrhenius, Fred Hoyle, and Francis Crick)?[30,31] How did the first cells with lipid membranes, replicating genetic code, and metabolic molecules emerge? In a typical chicken-or-egg relationship, was replication ('RNA world') or metabolism (proteins) the first jumping board to life? Where did the first cells emerge: In the primitive warm oceans in contact with an atmosphere free of oxygen but rich in organic molecules and subjected to lightening and ultraviolent radiation? Or in deep-sea hydrothermal vents (black smokers or white smokers)? Or possibly in terrestrial hydrothermal environments? The main problem is that we do not have access to the abiotic soup and its environment (abiogenesis) that produced the earliest cells. We have also not been able to produce living cells, even though we have synthesized organic molecules and conducted genome replacement. Even if a living cell is produced in the laboratory, it does not necessarily mean that the same processes created life on Earth in the first place. Nevertheless, the search for 'theories of life' aids exploration of life on other planets and also deepens our understanding of survival mechanisms of microorganisms in extreme environments.

## The Moon–Earth relationship (6)

Earth's only natural satellite is a unique feature in the Solar System. Isotopic signatures indicate that the Moon resembles an early lifeless rocky Earth. Also, according to a widely held hypothesis, the rock material that formed the Moon was split-off from Earth when Theia, hit the proto-Earth. Whatever the mechanism for the origin of the Moon, the Earth–Moon companionship has been a long story of mutual gravitational influences. Aside from the tidal waves on Earth, we also know of moonquakes produced by Earth's gravity. Does the Moon's gravity also influence earthquakes and exert tidal stresses on the Earth's topography and fluid pressures in rocks[32]? We also need a better understanding of the day-length and Earth–Moon distance over the geological time – a field of research that amazingly still relies on coral palaeontology, pioneered by John Wells in the 1960s.

## Volcanic eruptions (5)

Volcanic eruptions are associated with earthquakes, and together they form the main tectonics hazards at active plate boundaries and interplate hotspots. In some ways, prediction of volcanic eruptions (especially their effusive phases) is easier than that of earthquakes. Volcanic eruptions pose threats to society (such as pyroclastic flow, volcanic ash falls, and distruption of air flights). One significant question is how a volcanic eruption starts and ends, and how can we model these two conditions. Predicting the explosive activity of a volcano indeed remains a challenge. Another problem pertains to quantifying the effects of volcanic eruptions on the atmosphere and climate.

## Reversals of the Earth's magnetic field (4)

The Earth's magnetic field, as the pioneering work of Walter Elsasser showed in the 1940s, originates in the metallic fluid outer core and accounts for 95% of the geomagnetic field on the Earth's surface. Its influence reaches beyond the solid Earth, and protects life from harmful solar and cosmic radiations. Understanding and predicting variability in the geomagnetic field is important because these variations provide clues to the behaviour and properties of the Earth's outer core, including its interactions with the lower mantle. Discovery of the reversals of the Earth's magnetic field over geological time in the 1950s helped establish the ideas of sea-floor spreading and plate tectonics. However, we still do not know exactly how and when these reversals take place.

## Meteorite impacts (4)

There are 190 confirmed impact structures on Earth, dating from 7 years to 2.4 billion years old, and they are found in all continents, except for the ice-covered Antarctica[33]. (Antarctica, however, is a hunting ground for meteorites themselves.) All of the impact structures have been recognized since 1950 and are only tiny portion of impact events whose records have been obliterated by erosional processes. Impact structuring as preserved on the Moon has been closely associated with

**Table 1.** Priority Earth science research questions for the US National Science Foundation (NSF) 2020–2030 envisioned by the American National Academies in 2020, and critical needs in applied geoscience suggested by the American Geoscience Institute in 2020

| American National Academies and NSF | American Geoscience Institute |
|---|---|
| How is Earth's internal magnetic field generated? | Climate change |
| When, why, and how did plate tectonics start? | Water |
| How are critical elements distributed and recycled on Earth? | Energy |
| What is an earthquake? | Natural hazards |
| What drives volcanism? | Soils |
| What are the causes and consequences of topographic change? | Mineral resources |
| How does the critical zone influence climate? | Oceans and coasts |
| What does Earth's past reveal about the dynamics of the climate system? | Waste disposal |
| How do biogeochemical cycles evolve? | Workforce |
| How do geological processes influence biodiversity? | |
| How can Earth science research reduce the risk and toll of geohazards? | |

the early history of planets, including Earth. The disastrous consequence of extraterrestrial impacts on ecosystems is obvious although its details require in-depth studies[34,35]. At least in one popular case – the Cretaceous–Palaeocene boundary – impacting seems to be responsible for global mass extinction. This necessitates monitoring large asteroids or meteors approaching Earth head-on, and if necessary, destroying them or diverting their courses physically. Another question is: Do large impacts affect the Earth's surface only or do they also cause perturbations in the mantle, perhaps even as deep as the core–mantle boundary?

## A sum-up

Geoscience, like any other science, progresses by addressing big questions and unresolved problems, both theoretically and methodologically. The above-mentioned issues are only a selection. Nevertheless, the results of this survey are consistent with the 12-point vision for Earth sciences 2020–2030 by the US National Science Foundation[36], and the recent report on critical needs in applied geology by the American Geoscience Institute[37] (Table 1). Big questions are somewhat subjective and depend on the questioner. Questions like 'what was there before the big bang' or 'what happens inside a black hole' are not in the scope of geoscience. However, for geoscientists, understanding the evolution and operation of our one and only planet and providing humanity with vital resources are of utmost importance.

1. Maddox, J., *What Remains to Be Discovered? Meeting the Secrets of the Universe, the Origins of Life, and the Future of Human Race*, Simon & Schuster, New York, USA, 1998.
2. Rudwick, M. S., *Earth's Deep History*, The University of Chicago Press, Chicago, USA, 2014.
3. Valdiya, K. S., The tragedy of being a geologist. *Curr. Sci.*, 2012, **102**, 581–589.
4. IPCC, Fifth Assessment Report, Intergovernmental Panel on Climate Change, 2014; https://www.ipcc.ch/report/ar5/syr/
5. Lindsey, R., Climate change: atmospheric carbon dioxide, 14 August 2020; https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide (accessed on 11 January 2021).
6. Global carbon budget, summary highlights, 2020; https://www.globalcarbonproject.org/carbonbudget/20/highlights.htm (accessed on 11 January 2021).
7. Sorkhabi, R., How will the 2020 oil crisis end? *First Break*, 2020, **38**(10), 31–34.
8. Simmons, M., Davies, A., Hill, A. W. and Stephenson, M., Who needs geoscientists? *GEOExPro*, 2020, **17**(3), 14–18.
9. Yeats, R., *Earthquake Time Bombs*, Cambridge University Press, Cambridge, UK, 2015.
10. Condie, K. C., A planet in transition: the onset of plate tectonics between 3 and 2 Ga? *Geosci. Front.*, 2018, **9**, 51–60.
11. Cawford, P. A., Hawkesworth, C. J., Pisarevsky, S. A., Dhuime, B., Capitanio, F. A. and Nebel, O., Geological archive of the onset of plate tectonics. *Philos. Trans. R. Soc. London, Ser. A*, 2018, **376**, 21170405.
12. Stern, R. J., Is plate tectonics needed to evolve technological species on exoplanets? *Geosci. Front.*, 2016, **7**, 573–580.
13. Harrison, T. M., *Hadean Earth*, Springer, Nature, Switzerland, 2020.
14. Zerkle, A., Biogeodynamics: bridging the gap between surface and deep Earth processes. *Philos. Trans. R. Soc. London, Ser. A*, 2018, **376**, 2132.
15. Davies, G. F., *Dynamic Earth: Plates, Plumes and Mantle Convention*, Cambridge University Press, 2008.
16. Khan, A. and Deschamps, F. (eds), *The Earth's Heterogenous Mantle: A Geophysical, Geodynamical, and Geochemical Perspective*, Springer, Cham, Switzerland, 2015.
17. Frontier, S. M. *et al.*, Draft critical mineral list, US Geological Survey Open-File Report 2018–1021, 2018.
18. Sorkhabi, R., How popular is Earth science? *Curr. Sci.*, 2018, **115**(7), 1245–1246.
19. Benbow, A. and Hoover, M., Earth and Space Sciences Education in the U.S. Secondary Schools: Key Indicators and Trends, American Geoscience Institute, Alexandria, Virginia, USA, 2015, p. 10.
20. Sorkhabi, R., Understanding Earth in a wider sense of science. *Earth*, 2016, 8–9.
21. Center for Research on the Epidemiology of Disasters, Human cost of disaster (2000–2019). CRED Crunch No. 61. Université catholique de Louvain, Brussels, Belgium, December 2020; https://cred.be/sites/default/files/CRED-Disaster-ReportHuman-Cost2000-2019.pdf (accessed on 11 January 2021).
22. Shiklomanov, I., World fresh water resources. In *Water in Crisis: A Guide to the World's Fresh Water Resources* (ed. Gleick, P. H.), Oxford University Press, New York, USA, 1993.
23. Raup, M. D., *Extinction: Bad Genes or Bad Luck?* W.W. Norton, New York, USA, 1991.

24. Stanley, S. M., Estimates of the magnitude of major marine mass extinctions in earth history. *Proc. Natl. Acad. Sci.*, 2016, **113**(42); www.pnas.org/cgi/doi/10.1073/pnas.1613094113
25. Kolbert, E., *The Sixth Extinction: An Unnatural History*, Henry Holt, New York, USA, 2014.
26. Gould, S. J., *Wonderful Life: The Burgess Shale and the Nature of History*, W.W. Norton, New York, USA, 1990.
27. Erwin, D. and Valentine, J., *The Cambrian Explosion: The Construction of Animal Biodiversity*, W. H. Freeman, New York, USA, 2013.
28. Zalasiewicz, J. *et al.*, Are we now living in the Anthropocene? *GSA Today*, 2018, **18**(2), doi:10.1130/GSAT01802A.1
29. Nelson, M., *Pushing Our Limits: Insights from Biosphere 2*, University of Arizona Press, Tucson, USA, 2018.
30. De Duve, Ch., *Vital Dust: The Origin and Evolution of Life on Earth*, Basic Books, New York, USA, 1995.
31. Schopf, W. (ed.), *Life's Origins: The Beginnings of Biological Evolution*, University of California Press, Berkley, CA, USA, 2002.
32. Ide, S., Yabe, S. and Tanaka, Y., Earthquake potential revealed by tidal influence on earthquake size–frequency statistics. *Nature Geosci.*, 2016, **9**(11), 834–837.
33. The Planetary and Space Science Center, Earth Impact Database, 2020; http://www.passc.net/EarthImpactDatabase/New%20-website_05-2018/Index.html
34. Grieve, R. A. F., Impact cratering on the Earth. *Sci. Am.*, 1990, **262**, 66–73.
35. Gehrels, T. (ed.), *Hazards Due to Comets and Asteroids*, University of Arizona Press, Tucson, Arizona, USA, 1994.
36. National Academies of Sciences, Engineering, and Medicine. *A Vision for NSF Earth Sciences 2020–2030: Earth in Time*, The National Academies Press, Washington DC, USA, 2020.
37. AGI, Geoscience Supporting a Thriving Society in a Changing World. American Geosciences Institute, Alexandria, Virginia, USA, 2020; https://www.americangeosciences.org/policy/critical needs/2020 (accessed on 11 January 2021).

ACKNOWLEDGEMENTS. I thank all the survey respondents for their suggestions, comments and feedback, and to GSA, AGU and AIPG for offering valuable community forums which were utilized in this survey. Review and editorial comments by *Current Science* improved the paper and are much appreciated.

Received 11 January 2021; revised accepted 18 January 2021

doi: 10.18520/cs/v120/i9/1426-1432